Selection method Step II - based on fragility functions

Calculation tool - documentation

Nationaal Coördinator Groningen

5 January 2022

Project	Selection method Step II - based on fragility functions
Client	Nationaal Coördinator Groningen

Document	Calculation tool - documentation
Status	Final version
Date	5 January 2022
Reference	124217/22-000.067

Project code	124217
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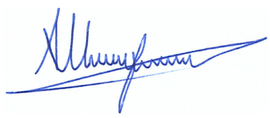

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The Quality management system of Witteveen+Bos has been approved based on ISO 9001.

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Industrial companies in Groningen conduct engineering reviews on their industrial plants containing hazardous substances to assure structural integrity for earthquakes as a consequence of gas production in Groningen. A specific prescribed assessment framework is in place. In short, this framework consists of instruments to perform a qualitative assessment in order to make an inventory of potential consequences and a prioritization for further verifications (Phase 1) and quantitative assessment methods in which the seismic resistance of structures is further assessed based on modelling (Phase 2).

Most industrial companies have completed Phase 1. However, only for a limited number of structures Phase 2 has been completed. In order to decrease (unnecessary) time consuming calculations for the earthquake resistance of (process) installations with hazardous substances, two selection steps can be performed between the Phase 1 qualitative assessment and the Phase 2 quantitative assessments.
The selection between these 2 phases consists of the following two steps:

1 With the selection method step I, process installations identified in Phase 1 are uniformly further tested for safety risk (Arcadis, 2020).
2 For the remaining objects, the selection method step II can be performed to identify whether an installation is globally sufficiently earthquake-resistant for identified scenarios:
    - The earthquake load follows from site specific earthquake hazard curves, which can also include time dependent developments, such as the phasing out of gas production.
    - The probability of exceeding a limit state is tested on the basis of available generic fragility curves for the type of structure considered and the probabilistic earthquake hazard.

Selection method Step II allows to perform a generic quantitative assessment of seismic risks of industrial assets, based on information which is typically available from Phase 1 qualitative risk evaluations. The selection process ultimately results in: i) a list of objects which no longer require further investigation, and ii) a list of objects for which further investigation is required in Phase 2 (the quantitative risk analysis). The selection instruments are included in the Groningen earthquake-resistant industry compensation policy rule.

This report provides the background of the so-called 'Selection method Step II - based on fragility functions' (NL: 'Selectiemethodiek Industrie Stap II - op basis van fragility functions'). The tool has been developed by Witteveen+Bos and has been reviewed by TU Delft. The development has been initiated and facilitated by Nationaal Coördinator Groningen.

This document reports the relevant background for the use of the method and calculation tool of Selection method Step II for earthquake risk assessments for industrial assets in Groningen. Applicability of empirical fragility functions from international literature is evaluated by means of comparison with all the available Phase 2 calculation results. This evaluation in general shows a consistent pattern. For elevated tanks and the non-structural components, the fragility curves proposed in Hazus (FEMA, 2020) are not recommended to be used for evaluation of assets in Groningen and more conservative fragility curves are proposed which are included in the calculation tool.

Finally, the performance of the tool has be evaluated through pilot calculations performed for four industrial companies in Groningen. The pilot calculations show that the Selection method Step II tool performs as expected. Compared to the Phase 1 assessments, the calculated scenario probabilities with the Selection method Step II tool are in principle lower and more consistent with the outcome of the Phase 2 calculations.

MANAGEMENT SAMENVATTING

Chemiebedrijven in Groningen voeren beoordelingen uit van de aardbevingsbestendigheid van hun constructies en installaties, als gevolg van de toegenomen aardbevingsdreiging door de gaswinning. Hiervoor is een toetsingskader vastgesteld. Kort samengevat omvat dit toetsingskader instrumenten om de beoordeling van aardbevingsbestendigheid uit te voeren, te beginnen met een kwalitatieve beschouwing van risico's per installatie welke resulteert in een prioritering voor vervolgonderzoeken (Fase 1), en vervolgens rekenmethodieken waarmee de aardbevingsbestendigheid rekenkundig gekwantificeerd kan worden (Fase 2).

De meeste bedrijven hebben inmiddels de Fase 1 onderzoeken afgerond. Er zijn echter pas een beperkt aantal bedrijven welke ook Fase 2 volledig hebben afgerond. Om de benodigde inspanningen voor tijdrovende Fase 2 berekeningen waar mogelijk te verminderen, kunnen een tweetal Selectiemethodieken worden doorlopen aan de hand van de resultaten van Fase 1 onderzoeken. De twee selectiestappen zijn:

1. selectiemethodiek Stap I, geüniformeerde beoordeling van Fase 1 resultaten op basis van de veiligheidsrisico's in geval van falen (Arcadis, 2020);
2. selectiemethodiek Stap II, voor de resterende objecten een globale beschouwing of de aardbevingsbestendigheid voor het betreffende objecttype voldoende is voor de geïdentificeerde kritische scenario's. Deze beschouwing is gebaseerd op;
   - de locatie specifieke aardbevingsbelasting in lijn met de meest recente modellen, waarbij de afname van de gaswinning in rekening wordt gebracht;
   - een inschatting van de typische weerstand van de constructie of installatie op basis van 'fragility' functies passend bij de betreffende type constructie of installatie.

Selectiemethodiek Stap II biedt de mogelijkheid om een generieke kwantitatieve beoordeling van aardbevingsbestendigheid uit te voeren, waarbij gebruik wordt gemaakt van de resultaten die in de meeste gevallen beschikbaar zijn vanuit de Fase 1 onderzoeken. Uiteindelijk resulteert deze beoordeling in een lijst van objecten waarvoor geen verder onderzoek nodig is en een lijst met objecten waarvoor een volledig Fase 2 onderzoek nodig is. De Selectiemethodieken zijn opgenomen in de Beleidsregel vergoeding aardbevingsbestendige industrie Groningen.

Het voorliggende rapport geeft de achtergronden bij de zogenoemde 'Selectiemethodiek Stap II - op basis van fragility functions'. Het instrument en de bijbehorende rekentool zijn ontwikkeld door Witteveen+Bos en is getoetst door de TU Delft. De ontwikkeling is geïnitieerd en gefaciliteerd door Nationaal Coördinator Groningen.

In dit rapport worden achtergronden welke van belang zijn voor het gebruik van de rekentool nader toegelicht. De toepasbaarheid van beschikbare empirische fragility functies is, voor objecten waarvan deze reeds beschikbaar zijn, beschouwd op basis van een vergelijking met de beschikbare Fase 2 resultaten. Over het algemeen laat dit vergelijk een consistent beeld zien, wat vertrouwen geeft in de algemene toepasbaarheid van de methode voor de meeste typen objecten. Voor een tweetal typen objecten, zijnde verhoogde tanks (elevated tanks) en niet-constructieve componenten (non-structural components), is vastgesteld dat de fragility functies uit Hazus (FEMA, 2020) niet gebruikt dienen te worden voor objecten in Groningen en zijn meer conservatieve functies geïmplementeerd in de rekentool.

Uiteindelijk is de werking van de rekentool getest aan de hand van pilots voor objecten van een viertal bedrijven. De pilots hebben laten zien dat de werking van het instrument 'Selectiemethodiek Stap II' en de bijbehorende rekentool overeenkomen met de verwachtingen. Voor de pilotbedrijven zijn de scenariokansen welke zijn berekend met Selectiemethodiek Stap II zijn lager dan de Fase 1 inschattingen en meer in lijn met de uitkomsten van Fase 2 berekeningen.

1

INTRODUCTION

The province of Groningen in the north of the Netherlands has one of the world's largest producing onshore gas fields. Due to gas production induced earthquakes occur, which have caused damage to buildings and potentially result in safety risks. It has been decided to reduce gas production from the Groningen field in the coming years and ultimately stop production by 2030. Seismic hazard levels are reduced due to this decision and are expected to reduce further in the years to come.

Industrial companies in Groningen conduct engineering reviews on their industrial plants containing hazardous substances to assure structural integrity for earthquakes as a consequence of gas production in Groningen. A specific prescribed assessment framework is in place. In short, this framework consists of instruments to perform a qualitative assessment in order to make an inventory of potential consequences and a prioritization for further verifications (Phase 1) and quantitative assessment methods in which the seismic resistance of structures is further assessed based on modelling (Phase 2).

Most industrial companies have completed Phase 1. However, only for a limited number of structures Phase 2 has been completed. In order to decrease (unnecessary) time consuming calculations for the earthquake resistance of (process) installations with hazardous substances, two selection steps can be performed between the Phase 1 qualitative assessment and the Phase 2 quantitative assessments.
The selection between these 2 phases consists of the following two steps:

1. With the selection method step I, process installations identified in Phase 1 are uniformly further tested for safety risk (Arcadis, 2020).
2. For the remaining objects, the selection method step II can be performed to identify whether an installation is globally sufficiently earthquake-resistant for identified scenarios:
   - The earthquake load follows from site specific earthquake hazard curves, which can also include time dependent developments such as the phasing out of gas production.
   - The probability of exceeding a limit state is tested on the basis of available generic fragility curves for the type of structure considered and the probabilistic earthquake hazard.

For the position of the Selection method Step II (NL: 'Selectiemethodiek Stap II') within the framework for seismic risk assessment for industrial assets in Groningen the reader is referred to (Witteveen+Bos, In progress).

Selection method Step II allows to perform a generic quantitative assessment of seismic risks of industrial assets, based on information which is typically available from Phase 1 qualitative risk evaluations. The selection process ultimately results in: i) a list of objects which no longer require further investigation, and ii) a list of objects for which further investigation is required in Phase 2 (the quantitative risk analysis). The selection instruments are included in the Groningen earthquake-resistant industry compensation policy rule.

This report provides the background of the so-called 'Selection method Step II - based on fragility functions' (NL: 'Selectie methodiek Industrie Stap II - op basis van fragility functions'). The tool has been developed by Witteveen+Bos and has been reviewed by TU Delft. The development has been initiated and facilitated by Nationaal Coördinator Groningen.

2

SCOPE

2.1 Objectives

The main objective of this project is to develop a quick generic quantitative calculation tool that enables the probability quantification of identified seismic hazard scenarios that are related to industrial assets in Groningen. The tool should be capable to quantitatively differentiate between structures having sufficient seismic resistance and structures that need structural upgrading. The underlying objective is therefore to develop an instrument which can serve as a basis for appropriate decision-making regarding structures for which further studies are required.

The tool should be easy to use, combining seismic hazard analysis and fragility curves, rather than performing additional specific Phase 2 finite element method calculations which are time consuming, costly and still involve quite some uncertainty when it comes to the actual Loss of Containment risks.

Available results from finished Phase 2 assessments are used where possible to verify if there are indications to assume that pre-code fragility functions are not applicable in Groningen and to substantiate object type specific fragility functions where necessary.

2.2 Development process

The development of the Selection method Step II started with a proof-of-concept phase in year 2020. During the proof-of-concept phase of the development of the calculation tool the following aspects have been covered:
- Substantiation of the content of the key components of the tool based on literature or other relevant sources.
- Implementation of all key components into a basic interactive interface linked to a calculation module.
- Comparison of the calculation tool to other methods developed for earthquake risk assessments for Groningen.
- Application of the tool to some test cases.

The results of the proof-of-concept phase are reported in (Witteveen+Bos, 2020 (B)).

Based on the proof-of-concept phase results the Werkgroep Gereedschapskist concluded that the tool was to be developed further towards future release to other parties. This report describes the results of this phase of further development and forms a background document to the calculation software. The following aspects are covered:
- Assessment of fragility curves against all the available Phase 2 calculation reports.
- Review of the general method and fragility curves of particular typologies by TU Delft.
- Modify certain fragility curves based on the outcome of the assessment procedure and the review from TU Delft.
- Development of a stand-alone easy to use executable of the tool accompanied by a user’s manual.
- Perform test cases for four industrial companies in Groningen.

2.3 Range of applicability

The tool allows for all possible structural typologies of industrial assets in Groningen to be evaluated. However, given the limited number of Phase 2 calculation reports the applicability of fragility curves for only specific number of structural typologies has been validated. These typologies are listed below:
- Pipeline systems.
- Process equipment.
- On-ground storage tanks.
- Non-structural industrial components.
- Elevated storage tanks.
- Building structures.

3

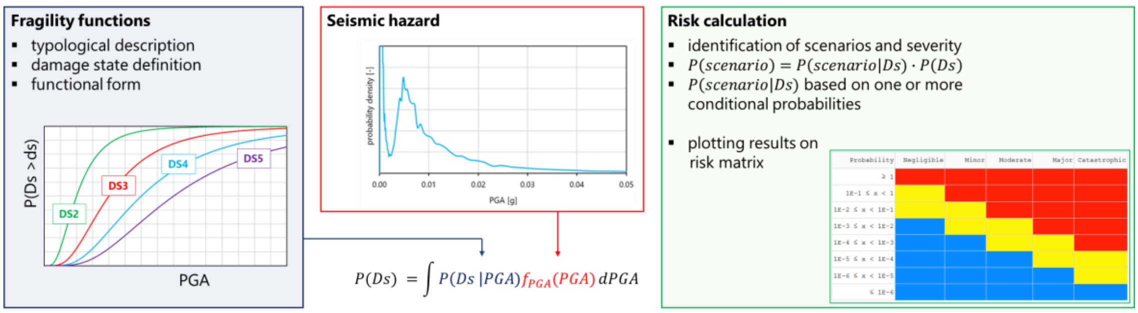
CALCULATION FRAMEWORK

3.1 Framework

In this section the framework of the calculation tool is described. The calculation tool quantitatively calculates the probability of a certain scenario identified in Phase 1. The risk calculation framework is presented in figure 3.1. Risk depends on both probability and consequences and is evaluated as such in a risk matrix representation. The consequence categorization depends on the considered scenario and therefore the focus in this chapter is on the calculation of the probability. The order in which the different elements of the framework are discussed throughout this chapter is as follows:

- The seismic hazard as provided by KNMI in paragraph 3.2.
- Fragility functions from literature in paragraph 3.3.
- Conditional factors, which are the conditional probabilities that a scenario occurs, provided that a damage state is exceeded [$= P(scenario|D_S)$] in paragraph 3.5.
- The risk matrix in paragraph 3.6.

Figure 3.1 Selection method Step II tool framework



3.2 Seismic hazard

The calculation tool is equipped with the seismic hazard for five specific locations (refer to table 3.1). The seismic hazard curves have been provided by KNMI for 3 different time periods (T4 (1 October 2020 until 30 September 2021), T5 (1 October 2021 until 30 September 2023) and T6 (1 October 2023 until 30 September 2029)).

Table 3.1 Industrial location where seismic hazard is provided in the tool

Location	X_{RD}	Y_{RD}
Eemshaven	251,037	607,066
Delfzijl	258,899	592,966
Hoogezand	244,513	576,987

Location	X_{RD}	Y_{RD}
Veendam	256,043	571,034
Winschoten	262,585	576,405

The seismic hazard is provided as the exceedance probability of the spectral acceleration at various spectral periods. For the calculation of the seismic hazard KNMI has used V6 of the ground motion model and the source model M7. The epistemic uncertainty related to the maximum earthquake magnitude M_{max} is accounted for by using a weighted average for three different scenarios.

$$PoE_{average} = 0.46 \cdot PoE_{M_{max}=4.5} + 0.43 \cdot PoE_{M_{max}=5.4} + 0.11 \cdot PoE_{M_{max}=6.8}$$

To obtain the final used probability density ($f_{PGA}(PGA)$ in figure 3.1) the followings steps were taken:

- The $PoE_{average}$ data series was extrapolated from the largest PGA value provided by KNMI (0.94g) to 3.00g. This is required to correctly calculate $P(Ds)$ in case some of the fragility curves have high median values (refer to figure 3.2).
- The cumulative density function (CDF) is obtained as $1 - PoE_{average}$.
- The CDF is integrated to verify that the total probability equals 1.

The resulting probability density is presented in figure 3.3. This is intentionally plotted on log-log scale as linear scales would show only a very distinct peak near PGA = 0g.

Figure 3.2 Extrapolation of the provided PGA probability of exceedance - Eemshaven T4

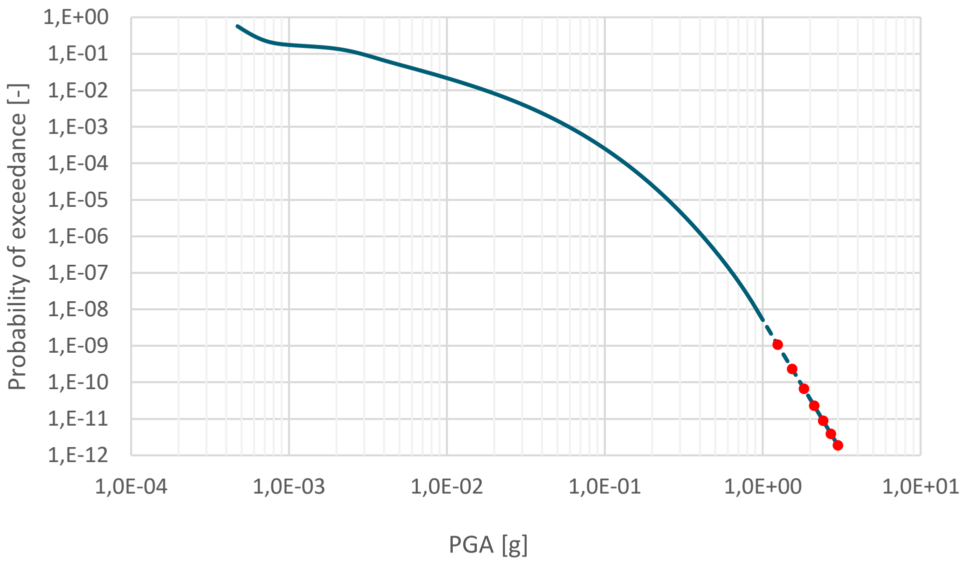
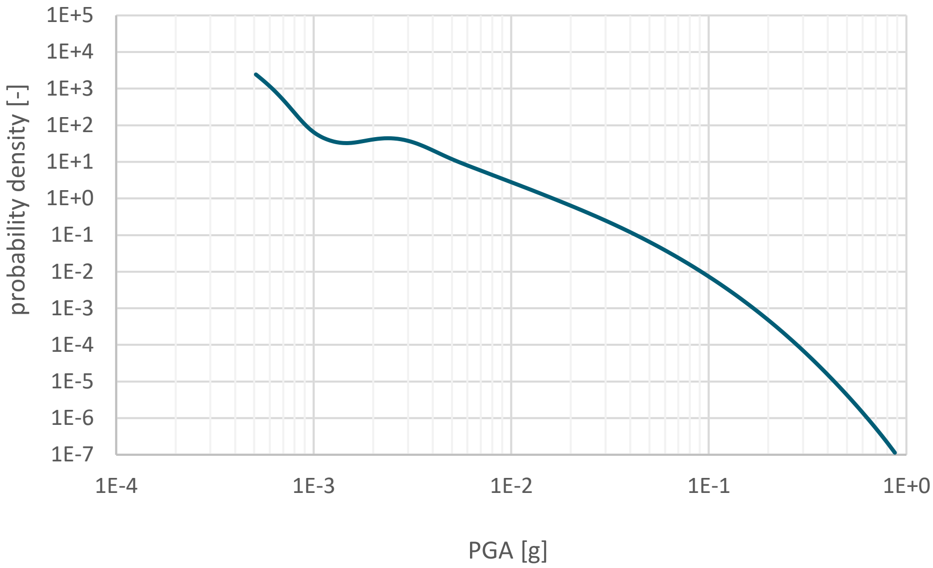


Figure 3.3 Resulting probability density of PGA - Eemshaven T4

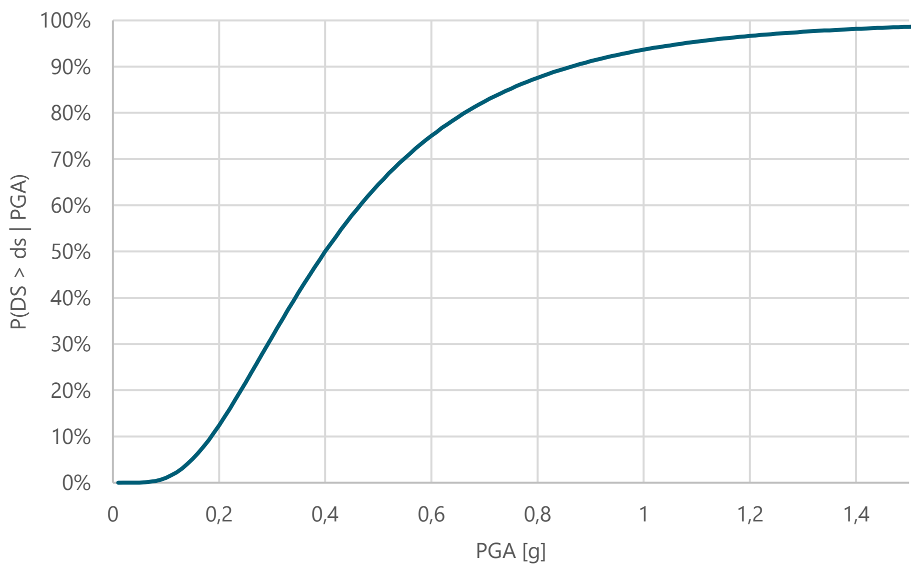


3.3 Fragility curves

3.3.1 Introduction

Fragility functions provide the probability of exceeding a certain damage state (Ds) given a certain intensity measure (IM). In figure 3.4 a typical fragility curve is shown. On the horizontal axis any intensity measure or load can be shown, but for earthquakes a commonly applied intensity measure is the horizontal peak ground acceleration (PGA). Often a lognormal distribution is used for describing the shape of the fragility curve, in the example below with a median (= exceedance probability of 50 %) of 0.4g and dispersion β of 0.6.

Figure 3.4 Typical fragility curve

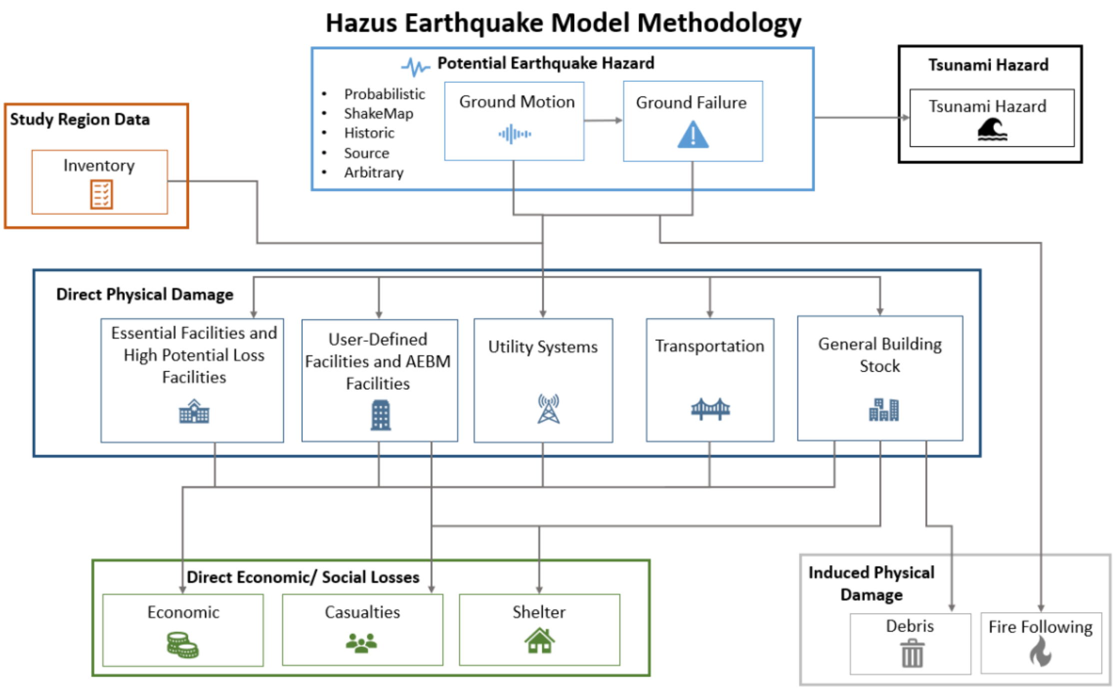


In the United States an extensive inventory from past events has been made for the purpose of making expected loss estimations due to earthquakes, among other natural disasters. This has resulted in the Hazus methodology of which the technical manual version 4.2 SP3 (FEMA, 2020) is the latest when it comes to earthquakes. Other resources on fragility functions can be found too, but often these are (partially) based on the same databases on which the Hazus functions are based.

Due to the fact that the Hazus fragility curves have been developed based on large worldwide database of past events, the vertical component of the ground motion is implicitly included, even though the intensity measure that is used is the horizontal PGA. However, it is noted that since the ratio of vertical-to-horizontal component in Groningen is significant, the effect of the vertical component of the seismic event is probably underestimated. Due to the fact that data of the ratio vertical-to-horizontal component are not available in Hazus, this effect cannot be quantified. It is recommenced to mention this in structures for which it is judged that the vertical motion can be critical.

The full framework related to seismic hazards is presented in figure 3.5. Herein the expected direct physical damage through the use of fragility curves is of particular interest in this study. This holds in particular for the following identified systems:
- General building stock:
  - Several building structures.
  - Non-structural components.
- Utility systems:
  - On-ground tanks.
  - Elevated tanks.
  - Chemical tanks.
  - Elevated pipes and stacks.
  - Vessels.

Figure 3.5 Hazus Earthquake Model methodology schematic (FEMA, 2020)



In the following paragraphs the following fundamental aspects related to fragility functions are presented:
- The typological descriptions which determine the background and thereby applicability of the fragility functions.
- The damage definitions for those specific typologies. The general description of the damage states according to the Hazus methodology (FEMA, 2020) is as follows:
  - DS1: no damage.

- · DS2: slight/minor damage.
  - · DS3: moderate damage.
  - · DS4: extensive damage.
  - · DS5: complete damage.
- The definition and parameters of the fragility functions.

Each of the following paragraphs correspond to a specific typology. Descriptions of typology and damage states are copied from Hazus (FEMA, 2020). Most other related literature addressing fragility curves is following the common Hazus definitions.

3.3.2 General building stock

In Section 5 of the Hazus technical manual (FEMA, 2020), fragility curves for the general building stock are described. In particular, the pre-code[1] equivalent-PGA fragility curves are of interest for the calculation tool. The equivalent-PGA fragility curves developed in Hazus manual are based on a demand spectrum for large magnitude, Western United States (WUS) ground shaking at soil sites. Hence, these functions are only appropriate for use in the evaluation of scenario earthquakes whose demand spectrum shape is based on, or similar to, these types of spectra.

Given the considerable different typical response spectrum for induced earthquakes in Groningen, the equivalent-PGA fragility curves from Hazus cannot be applied directly in the assessment. In Appendix I, median values of equivalent-PGA fragility curves are developed using response spectra for Groningen. In this way, separate set of building fragility curves are derived for each of the five industry locations. It is noted that since the method for the derivation of the capacity curve in Hazus is based on pushover analysis, the vertical ground motion is not considered. As a result the Groningen-specific effect of high ratio between vertical and horizontal motion is not reflected in this approach.

In the rest of this paragraph, general description of the building types and corresponding damage states is given. More details regarding the methodology followed to derive the parameters for the fragility functions and the values of these parameters can be found in Appendix I.

Table 3.2 lists the 35 specific building types that are described in the Hazus technical manual (FEMA, 2020) (excluding mobile homes). Typologies that are implemented in the calculation tool are highlighted; the other building types are merely used to verify the method for derivation of equivalent-PGA fragility curves. A general description, including sketches of typical configurations of each of the 16 structural systems of the building types is given in FEMA 454 (FEMA 454, 2006).

Table 3.2 Overview building types; Table 5-1 from Hazus (FEMA, 2020)

#	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Meter*
1	W1	Wood, Light Frame (≤ 465 m2)		1-2	1	4.27
2	W2	Wood, Commercial & Industrial (> 465 m2)		All	2	7.32
3	S1L	Steel Moment Frame	Low-Rise	1-3	2	7.32
4	S1M		Mid-Rise	4-7	5	18.29
5	S1H		High-Rise	8+	13	47.55
6	S2L	Steel Braced Frame	Low-Rise	1-3	2	7.32

[1] Pre-code seismic design in the United States refers to the time in which no measures were taken, which is mostly applicable to the Groningen case.

#	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Meter*
7	S2M		Mid-Rise	4-7	5	18.29
8	S2H		High-Rise	8+	13	47.55
9	S3	Steel Light Frame		All	1	4.57
10	S4L	Steel Frame with Cast-in-Place Concrete Shear Walls	Low-Rise	1-3	2	7.32
11	S4M		Mid-Rise	4-7	5	18.29
12	S4H		High-Rise	8+	13	47.55
13	S5L	Steel Frame with Unreinforced Masonry Infill Walls	Low-Rise	1-3	2	7.32
14	S5M		Mid-Rise	4-7	5	18.29
15	S5H		High-Rise	8+	13	47.55
16	C1L	Concrete Moment Frame	Low-Rise	1-3	2	6.10
17	C1M		Mid-Rise	4-7	5	15.24
18	C1H		High-Rise	8+	12	36.58
19	C2L	Concrete Shear Walls	Low-Rise	1-3	2	6.10
20	C2M		Mid-Rise	4-7	5	15.24
21	C2H		High-Rise	8+	12	36.58
22	C3L	Concrete Frame with Unreinforced Masonry Infill Walls	Low-Rise	1-3	2	6.10
23	C3M		Mid-Rise	4-7	5	15.24
24	C3H		High-Rise	8+	12	36.58
25	PC1	Precast Concrete Tilt-Up Walls		All	1	4.57
26	PC2L	Precast Concrete Frames with Concrete Shear Walls	Low-Rise	1-3	2	6.10
27	PC2M		Mid-Rise	4-7	5	15.24
28	PC2H		High-Rise	8+	12	36.58
29	RM1L	Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms	Low-Rise	1-3	2	6.10
30	RM1M		Mid-Rise	4+	5	15.24
31	RM2L	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	Low-Rise	1-3	2	6.10
32	RM2M		Mid-Rise	4-7	5	15.24
33	RM2H		High-Rise	8+	12	36.58
34	URML	Unreinforced Masonry Bearing Walls	Low-Rise	1-2	1	4.57
35	URMM		Mid-Rise	3+	3	10.67

* Unit conversion 1 feet = 0.3048 meter.

Steel Moment Frame (S1)

General description

These buildings have a frame of steel columns and beams. In some cases, the beam-column connections have very small moment resisting capacity but, in other cases, some of the beams and columns are fully developed as moment frames to resist lateral forces. Usually, the structure is concealed on the outside by exterior non-structural walls, which can be of almost any material (curtain walls, brick masonry, or precast concrete panels), and on the inside by ceilings and column furring.

Diaphragms transfer lateral loads to moment-resisting frames. The diaphragms can be almost any material. The frames develop their stiffness by full or partial moment connections. The frames can be located almost anywhere in the building. Usually, the columns have their strong directions oriented so that some columns act primarily in one direction while the others act in the other direction. Steel moment frame buildings are typically more flexible than shear wall buildings. This low stiffness can result in large interstory drifts that may lead to relatively greater non-structural damage.

A distinction is made between low-rise, mid-rise and high-rise buildings within this typological classification.

Damage state definitions
- **DS2**: Minor deformations in connections or hairline cracks in few welds.
- **DS3**: Some steel members have yielded exhibiting observable permanent rotations at connections; few welded connections may exhibit major cracks through welds, or few bolted connections may exhibit broken bolts or enlarged bolt holes.
- **DS4**: Most steel members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some of the structural members or connections may have exceeded their ultimate capacity exhibited by major permanent member rotations at connections, buckled flanges and failed connections. Partial collapse of portions of structure is possible due to failed critical elements and/or connections.
- **DS5**: Significant portion of the structural elements have exceeded their ultimate capacities, or some critical structural elements or connections have failed resulting in dangerous permanent lateral displacement, partial collapse or collapse of the building. Approximately 8 % (low-rise), 5 % (mid-rise) or 3 % (high-rise) of the total area of S1 buildings with Complete damage is expected to be collapsed.

Steel Braced Frame (S2)

General description
These buildings are similar to steel moment frame buildings except that the vertical components of the lateral-force-resisting system are braced frames rather than moment frames. A distinction is made between low-rise, mid-rise and high-rise buildings within this typological classification.

Damage state definitions
- **DS2**: Few steel braces have yielded which may be indicated by minor stretching and/or buckling of slender brace members; minor cracks in welded connections; minor deformations in bolted brace connections.
- **DS3**: Some steel braces have yielded exhibiting observable stretching and/or buckling of braces; few braces, other members or connections have indications of reaching their ultimate capacity exhibited by buckled braces, cracked welds, or failed bolted connections.
- **DS4**: Most steel brace and other members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some structural members or connections have exceeded their ultimate capacity exhibited by buckled or broken braces, flange buckling, broken welds, or failed bolted connections. Anchor bolts at columns may be stretched. Partial collapse of portions of structure is possible due to failure of critical elements or connections.
- **DS5**: Most the structural elements have reached their ultimate capacities, or some critical members or connections have failed resulting in dangerous permanent lateral deflection, partial collapse or collapse of the building. Approximately 8 % (low-rise), 5 % (mid-rise) or 3 % (high-rise) of the total area of S2 buildings with Complete damage is expected to be collapsed.

Steel Frame with Cast-in-Place Concrete Shear Walls (S4)

General description
The shear walls in these buildings are cast-in-place concrete and may be bearing walls. The steel frame is designed for vertical loads only. Diaphragms of almost any material transfer lateral loads to the shear walls. The steel frame may provide a secondary lateral-force-resisting system depending on the stiffness of the frame and the moment capacity of the beam-column connections. In modern, 'dual' systems, the steel moment frames are designed to work together with the concrete shear walls.

Damage state definitions
This is a ‘composite’ structural system where the concrete shear walls are the primary lateral force-resisting system. Hence, Slight, Moderate, and Extensive damage states are likely to be determined by damage to the shear walls, while the Complete damage state would be determined by the failure of the structural frame.

- **DS2**: Diagonal hairline cracks on most concrete shear wall surfaces; minor concrete spalling at a few locations.
- **DS3**: Most shear wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities, as exhibited by larger diagonal cracks and concrete spalling at wall ends.
- **DS4**: Most concrete shear walls have exceeded their yield capacities; a few walls have reached or exceeded their ultimate capacity, as exhibited by large through-the-wall diagonal cracks, extensive spalling around the cracks, and visibly buckled wall reinforcement. Partial collapse may occur due to failed connections of steel framing to concrete walls. Some damage may be observed in steel frame connections.
- **DS5**: Structure may be collapsed or in danger of collapse due to total failure of shear walls and loss of stability of the steel frames. Approximately 8 % (low-rise), 5 % (mid-rise) or 3 % (high-rise) of the total area of S4 buildings with Complete damage is expected to be collapsed.

Steel Frame with Unreinforced Masonry Infill Walls (S5)

General description
This is one of the older types of buildings. The infill walls usually are offset from the exterior frame members, wrap around them, and present a smooth masonry exterior with no indication of the frame. Solidly infilled masonry panels, when they fully engage the surrounding frame members (i.e., lie in the same plane), may provide stiffness and lateral load resistance to the structure.

Damage state definitions
This is a ‘composite’ structural system where the initial lateral resistance is provided by the infill walls. Upon cracking of the infills, further lateral resistance is provided by the steel frames ‘braced’ by the infill walls acting as diagonal compression struts. Collapse of the structure results when the infill walls disintegrate (due to compression failure of the masonry ‘struts’) and the steel frame loses its stability.

- **DS2**: Diagonal (sometimes horizontal) hairline cracks on most infill walls; cracks at frame-infill interfaces.
- **DS3**: Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam-column connections.
- **DS4**: Most infill walls exhibit large cracks; some bricks may be dislodged and fall; some infill walls may bulge out-of-plane; a few walls may fall off partially or fully; some steel frame connections may have failed. Structure may exhibit permanent lateral deformation or partial collapse due to failure of some critical members.
- **DS5**: Structure is collapsed or in danger of imminent collapse due to total failure of many infill walls and loss of stability of the steel frames. Approximately 8 % (low-rise), 5 % (mid-rise) or 3 % (high-rise) of the total area of S5 buildings with Complete damage is expected to be collapsed.

Reinforced Concrete Moment Resisting Frames (C1)

General description
These buildings are similar to steel moment frame buildings except that the frames are reinforced concrete. There are a large variety of frame systems. Some older concrete frames may be proportioned and detailed such that brittle failure of the frame members can occur in earthquakes, leading to partial or full collapse of the buildings. Modern frames in zones of high seismicity are proportioned and detailed for ductile behaviour and are likely to undergo large deformations during an earthquake without brittle failure of frame members or collapse.

Damage state definitions
- **DS2**: Flexural or shear type hairline cracks in some beams and columns near joints or within joints.

- **DS3**: Most beams and columns exhibit hairline cracks. In ductile frames, some of the frame elements have reached yield capacity, as indicated by larger flexural cracks and some concrete spalling. Nonductile frames may exhibit larger shear cracks and spalling.
- **DS4**: Some of the frame elements have reached their ultimate capacity, as indicated in ductile frames by large flexural cracks, spalled concrete, and buckled main reinforcement; nonductile frame elements may have suffered shear failures or bond failures at reinforcement splices, broken ties or buckled main reinforcement in columns which may result in partial collapse.
- **DS5**: Structure is collapsed or in imminent danger of collapse due to brittle failure of nonductile frame elements or loss of frame stability. Approximately 13 % (low-rise), 10 % (mid-rise) or 5 % (high-rise) of the total area of C1 buildings with Complete damage is expected to be collapsed.

Concrete Shear Walls (C2)

General description

The vertical components of the lateral force-resisting system in these buildings are concrete shear walls that are usually bearing walls. In older buildings, the walls often are quite extensive, and the wall stresses are low, but reinforcing is light. In newer buildings, the shear walls often are limited in extent, generating concerns about boundary members and overturning forces.

Damage state definitions

- **DS2**: Diagonal hairline cracks on most concrete shear wall surfaces; minor concrete spalling at a few locations.
- **DS3**: Most shear wall surfaces exhibit diagonal cracks; some shear walls have exceeded yield capacity, as indicated by larger diagonal cracks and concrete spalling at wall ends.
- **DS4**: Most concrete shear walls have exceeded their yield capacities; some walls have exceeded their ultimate capacities, as indicated by large, through-the-wall diagonal cracks, extensive spalling around the cracks, and visibly buckled wall reinforcement or rotation of narrow walls with inadequate foundations. Partial collapse may occur due to failure of nonductile columns not designed to resist lateral loads.
- **DS5**: Structure has collapsed or is in imminent danger of collapse due to failure of most of the shear walls and failure of some critical beams or columns. Approximately 13 % (low-rise), 10 % (mid-rise) or 5 % (high-rise) of the total area of C2 buildings with Complete damage is expected to be collapsed.

Concrete Frame with Unreinforced Masonry Infill Walls (C3)

General description

These buildings are similar to steel frame buildings with unreinforced masonry infill walls except that the frame is of reinforced concrete. In these buildings, the shear strength of the columns, after cracking of the infill, may limit the semi-ductile behaviour of the system.

Damage state definitions

This is a ’composite’ structural system where the initial lateral resistance is provided by the infill walls. Upon cracking of the infills, further lateral resistance is provided by the concrete frame, ’braced’ by the infill, acting as diagonal compression struts. Collapse of the structure results when the infill walls disintegrate (due to compression failure of the masonry ’struts’) and the frame loses stability, or when the concrete columns suffer shear failures due to reduced effective height and the high shear forces imposed on them by the masonry compression struts.

- **DS2**: Diagonal (sometimes horizontal) hairline cracks on most infill walls; cracks at frame-infill interfaces.
- **DS3**: Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam-column connections. Diagonal shear cracks may be observed in concrete beams or columns.
- **DS4**: Most infill walls exhibit large cracks; some bricks may dislodge and fall; some infill walls may bulge out-of-plane; a few walls may fall partially or fully; a few concrete columns or beams may fail in shear resulting in partial collapse. Structure may exhibit permanent lateral deformation.
- **DS5**: Structure has collapsed or is in imminent danger of collapse due to a combination of total failure of the infill walls and nonductile failure of the concrete beams and columns. Approximately 15 % (low-rise),

13 % (mid-rise) or 5 % (high-rise) of the total area of C3 buildings with Complete damage is expected to be collapsed.

Precast Concrete Frames with Concrete Shear Walls (PC2)

General description
These buildings contain floor and roof diaphragms, typically composed of precast concrete elements with or without cast-in-place concrete topping slabs. Precast concrete girders and columns support the diaphragms. The girders often bear on column corbels. Closure strips between precast floor elements and beam-column joints are usually cast-in-place concrete. Welded steel inserts are often used to interconnect precast elements. Precast or cast-in-place concrete shear walls resist lateral loads. For buildings with precast frames and concrete shear walls to perform well, the details used to connect the structural elements must have sufficient strength and displacement capacity; however, in some cases, the connection details between the precast elements have negligible ductility.

Damage state definitions
- **DS2**: Diagonal hairline cracks on most shear wall surfaces; minor concrete spalling at a few connections of precast members.
- **DS3**: Most shear wall surfaces exhibit diagonal cracks; some shear walls have exceeded their yield capacities, as indicated by larger cracks and concrete spalling at wall ends; observable distress or movement at connections of precast frame connections, some failures at metal inserts and welded connections.
- **DS4**: Most concrete shear walls have exceeded their yield capacities; some walls may have reached their ultimate capacities indicated by large, through-the-wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement. Some critical precast frame connections may have failed, resulting in partial collapse.
- **DS5**: Structure has collapsed or is in imminent danger of collapse due to failure of the shear walls and/or failures at precast frame connections. Approximately 1 5 % (low-rise), 13 % (mid-rise) or 10 % (high-rise) of the total area of PC2 buildings with Complete damage is expected to be collapsed.

3.3.3 Non-structural components

Non-structural components include a large variety of different architectural, mechanical and electrical components (e.g., components listed in the NEHRP seismic design provisions for new buildings).

Non-structural components are grouped as either ‘drift-sensitive’ or ‘acceleration-sensitive’ components, in order to assess their damage due to an earthquake. Damage to drift-sensitive non-structural components is primarily a function of interstory drift (e.g., full-height drywall partitions) while for acceleration-sensitive components (e.g., mechanical equipment) damage is a function of the floor acceleration. Since in the industrial facilities in Groningen non-structural components are usually associated with mechanical and electrical equipment (acceleration-sensitive components), the damage is expressed as a function of the floor acceleration (refer to table 3.3).

Table 3.3 List of Typical Non-structural Components and Contents of Buildings. Part of Table 5-2 (FEMA, 2020), P means primary cause of damage, and S indicates the secondary damage

Type	Item	Drift-Sensitive	Acceleration-Sensitive
Mechanical and Electrical	General Mechanical (boilers, etc.)		P
	Manufacturing and Process Machinery		P
	Piping Systems	S	P
	Storage Tanks and Spheres		P
	HVAC Systems (chillers, ductwork, etc.)	S	P
	Elevators	S	P
	Trussed Towers		P
	General Electrical (switchgear, ducts, etc.)	S	P
	Lighting Fixtures		P

The general description of the damage states of non-structural components as described in (FEMA, 2020) is presented bellow:

- **DS2**: The most vulnerable equipment (e.g., unanchored or on spring isolators) moves and damages attached piping or ducts.
- **DS3**: Movements are larger, and damage is more extensive; piping leaks at few locations; elevator machinery and rails may require realignment.
- **DS4**: Equipment on spring isolators topples and falls; other unanchored equipment slides or falls breaking connections to piping and ducts; leaks develop at many locations; anchored equipment indicate stretched bolts or strain at anchorages.
- **DS5**: Equipment is damaged by sliding, overturning or failure of their supports and is not operable; piping is leaking at many locations; some pipe and duct supports have failed causing pipes and ducts to fall or hang down; elevator rails are buckled or have broken supports and/or counterweights have derailed.

Anchorage/bracing of non-structural components improves earthquake performance of most components although routine or typical anchorage/bracing provides only limited damage protection. Therefore, it is assumed that typical non-structural components and building contents have limited anchorage/bracing.

In the calculation tool a distinction is made between non-structural components with rigid supports and with weak supports. The difference is explained in the following paragraphs.

Non-structural components with rigid supports

In this category belong all non-structural components that are connected monolithically to the main structure (none of the supports relies on friction). This type of non-structural components is assessed according to the floor acceleration thresholds defined in Hazus for pre-code design level. The pre-code design level refers to the time in which no seismic design measures were taken, which is mostly applicable to the Groningen case.

The median value of the peak floor acceleration threshold and the corresponding logstandard deviation (β), essential for generating the fragility curves for each damage state are presented in table 3.4.

Table 3.4 Median peak floor acceleration [g] and logstandard deviation (β) at the threshold of Non-structural damage. Part of table 5-21 and table 5-25 (FEMA, 2020)

Damage state	median	β*
DS2 - Slight	0.20	0.65

Damage state	median	β*
DS3 - Moderate	0.40	0.67
DS4 - Extensive	0.80	0.67
DS5 - Complete	1.60	0.67

* The logstandard deviation (β)depends among other factors on the building typology in which the non-structural component is located. However, the influence of the building typology is insignificant. Therefore, in order to simplify the calculations, the average value of the variability is taken among the different building typologies relevant for Groningen.

Since the threshold is expressed in peak floor acceleration, an additional formula is required to convert the threshold into peak ground acceleration. The formula 4.25 from NEN-EN 1998-1 is used to perform this conversion.

$$S_a = a \cdot S \cdot \left[\frac{3\left(1+\frac{z}{H}\right)}{\left(1+\left(1-\frac{T_a}{T_1}\right)^2\right)} - 0.5 \right]$$

$$=> a = \frac{S_a}{S \cdot \left[\frac{3\left(1+\frac{z}{H}\right)}{\left(1+\left(1-\frac{T_a}{T_1}\right)^2\right)} - 0.5 \right]}$$

Where:

a: Is the ratio of the design ground acceleration on type A ground, a_g, to the acceleration of gravity g.

S: Is the soil factor.

T_a: Is the fundamental vibration period of the non-structural element.

T_1: Is the fundamental vibration period of the building in the relevant direction.

Z: Is the height of the non-structural element above the level of application of the seismic action (foundation or top of a rigid basement); and

H: is the building height measured from the foundation or from the top of a rigid basement.

Since defining the fundamental vibration period of the building and the non-structural element requires modelling of the structure, a ratio of T_a/T_1 = 1 is assumed (conservative approach). In the calculation tool the user is asked to input the height of the non-structural element over the building height ratio (z/H). When this is not known a ratio of 1 is assumed (conservative approach). In the limit case where the z/H ratio is 1, the ratio between peak floor acceleration and peak ground acceleration is S_a / a = 5.5. The parameters for the fragility functions for non-structural components located at 100 % building height are listed in table 3.5. The median PGA values are obtained by dividing the values above with 5.5. It is assumed that the dispersion β remains unchanged, meaning that the conversion from peak floor acceleration to PGA does not introduce additional uncertainty.

Table 3.5 Median peak ground acceleration [g] and logstandard deviation (β) at the threshold of Non-structural damage for components located at 100% building height (i.e., z/H = 1)

Damage state	median	β
DS2 - Slight	0.04	0.65
DS3 - Moderate	0.07	0.67
DS4 - Extensive	0.15	0.67
DS5 - Complete	0.29	0.67

Non-structural components with weak supports

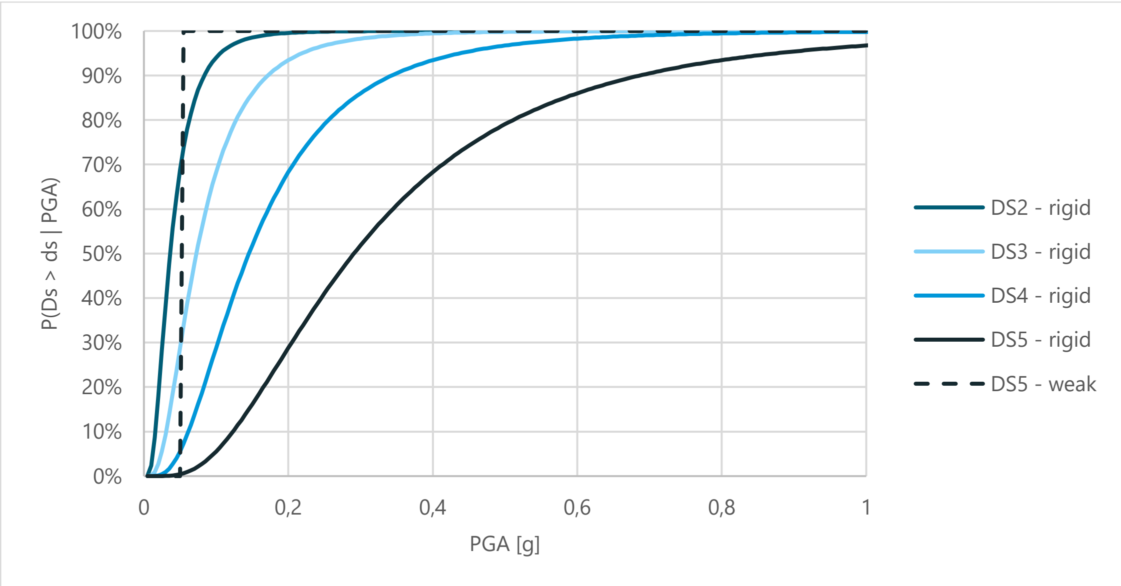
In this category belong all non-structural components whose at least one of the supports relies on friction. In this case a stricter fragility curve is adopted. This curve has the form of the step function with a (threshold) value for the peak ground acceleration equal to 0.05 g. This type of fragility curve corresponds to the complete damage limit state (DS5) of non-structural components.

The (threshold) peak ground acceleration value of the step function has been chosen in accordance with the 'very low seismicity' threshold defined in NEN-EN 1998-1 and NPR9998 bellow which no assessment for seismic actions is required. Therefore, it is assumed that:

- Bellow this threshold the probability of reaching compete damage of the non-structural component is equal to 0.
- Above this threshold the probability of reaching compete damage of the non-structural component is equal to 1.

The fragility functions for non-structural components are shown in figure 3.6. Recall, for the components with weak supports only DS5 is defined corresponding to the step function.

Figure 3.6 Fragility functions for non-structural components, rigid supports and weak supports



3.3.4 Storage tanks

(FEMA, 2020) and (ALA, 2001) primary focus on water storage tanks. However, the same fragility curves are adopted for tanks with different contents (e.g., oil system tank farms, refer to table B3-6 (FEMA, 2020)). Additionally, the database of (ALA, 2001) includes among others diesel fuel oil tanks, hydrogen peroxide tanks, lube oil fuel tanks, bulk storage tanks etc.

Storage tanks can be elevated steel, on ground steel (anchored/unanchored), on ground concrete (anchored/unanchored), buried concrete, or on ground wood tanks. Anchored tanks in general refer to tanks designed with special seismic tiedowns or tiebacks, while unanchored tanks refer to tanks designed with no special considerations other than the manufacturer's normal requirements. Unanchored tanks are mostly applicable to the Groningen case.

In the following paragraphs the following typologies are described as being mostly applicable to industries in Groningen:

- On ground unanchored steel and concrete tanks.
- Elevated unanchored tanks.

On ground storage tanks

The general description of the damage states of on ground tanks as described in (FEMA, 2020) is presented bellow:

- **DS2**: Slight damage is defined by the tank suffering minor damage without loss of its contents or functionality. Minor damage to the tank roof due to water sloshing, minor cracks in concrete tanks, or localized wrinkles in steel tanks fits the description of this damage state.
- **DS3**: Moderate damage is defined by the tank being considerably damaged, but only minor loss of content. Elephant foot buckling for steel tanks without loss of content, or moderate cracking of concrete tanks with minor loss of content fits the description of this damage state.
- **DS4**: Extensive damage is defined by the tank being severely damaged and going out of service. Elephant foot buckling for steel tanks with loss of content, stretching of bars for wood tanks, or shearing of wall for concrete tanks fits the description of this damage state.
- **DS5**: Complete damage is defined by the tank collapsing and losing all of its content.

Table 3.6 Peak ground acceleration fragility functions for storage tanks. Part of Table 8-10 (FEMA, 2020)

Tank type	Damage state	Median	β
On-ground Unanchored Steel Tank (PSTGS)	DS2 - Slight	0.15	0.70
	DS3 - Moderate	0.35	0.75
	DS4 - Extensive	0.68	0.75
	DS5 - Complete	0.95	0.70
On-ground Unanchored Concrete Tank (PSTGC)	DS2 - Slight	0.18	0.60
	DS3 - Moderate	0.42	0.70
	DS4 - Extensive	0.70	0.55
	DS5 - Complete	1.04	0.60

Elevated storage tanks

Regarding the elevated storage tanks in (FEMA, 2020) there is relevant typology which is named 'Above Ground Steel Tank'. However, this specific typology seems to have non-strict peak ground acceleration limits. As an indication it is mentioned that for complete collapse of an above ground steel tank a median peak ground acceleration of 1.5 g is adopted.

As it is shown later in this report (refer to paragraph 4.1) the fragility curves for above ground steel tanks are not applicable for the Groningen case. Instead, it is suggested (and adopted in the developed calculation tool) to distinguish between two typologies of elevated storage tanks:

- Elevated tanks whose support structure is laterally supported in both horizontal direction with braces.
- Elevated tanks whose support structure is not supported in at least one horizontal direction with braces.

Elevated tank laterally supported (braced)

Very often the support structure of elevated tanks is lateral supported in both directions in order to withstand the wind action. However, this lateral support can be insufficient to withstand the lateral seismic action. For this typology of elevated tanks, the stricter peak ground acceleration limit suggested by (ALA, 2001) is adopted. This limit corresponds to a PGA of 0.7 g and a corresponding β = 0.55 for total collapse damage state (DS5).

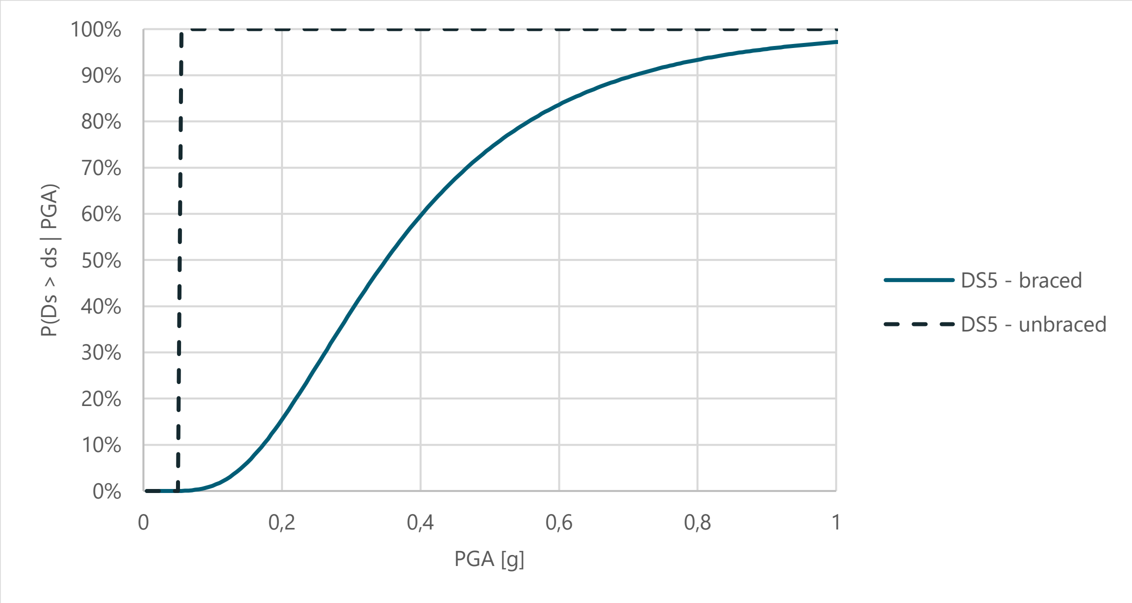
This PGA corresponds to elevated tanks on rock sites. as suggested by (ALA, 2001) half of this limit PGA needs to be adopted for other soil sites. Therefore, the following values for the construction of the fragility curves of elevated tanks laterally supported are applicable for Groningen:

- Median of peak ground acceleration: 0.35 g.
- Dispersion β: 0.55.

Elevated tank not laterally supported (unbraced)
Sometimes elevated tanks that are not lateral supported in one of the two horizontal directions are encountered. In these cases, a stricter fragility curve is applied in the developed calculation tool. This curve has the form of the step function with a (threshold) value for the peak ground acceleration equal to 0.05 g, same as in the case of non-structural components with weak supports (refer to par. 3.3.3) This type of fragility curve corresponds to the complete damage limit state (DS5) of elevated tanks.

The (threshold) peak ground acceleration value of the step function has been chosen in accordance with the 'very low seismicity' threshold defined in NEN-EN 1998-1 and NPR9998 bellow which no assessment for seismic actions is required. Therefore, it is assumed that:
- Bellow this threshold the probability of reaching compete damage of the elevated tank is equal to 0.
- Above this threshold the probability of reaching compete damage of the elevated tank is equal to 1.

Figure 3.7 Fragility functions for elevated tank, braced and unbraced support structure



Chemical tanks
Another type of storage tank that is encounter often in water treatment facilities is the chemical tank which is necessary for coagulation and other destabilization processes.

The general description of the damage states of elevated pipes as described in (FEMA, 2020) is presented bellow:
- **DS2**: Slight damage is defined by considerable damage to chemical tanks.
- **DS3**: Moderate damage is defined by extensive damage to chemical units.

Table 3.7 presents the median value of the peak ground acceleration and the logstandard deviation (β) for unanchored chemical tanks. Here the word unanchored also refers to components designed with no special considerations other than the manufacturer's normal requirements. Thus, are mostly applicable to the Groningen case.

Table 3.7 Peak ground acceleration fragility functions for chemical tanks of water treatment plants, Part of table B1-7 (FEMA, 2020)

Damage state	Median	β
DS2 - Slight	0.25	0.60
DS3 - Moderate	0.40	0.60

3.3.5 Elevated pipes and stacks

Pipelines are essential components of most refineries, oil tank farms, water treatment and wastewater treatment facilities. Damage functions for Elevated pipes as part of (waste)water treatment facilities, refineries and oil system tank farms are expressed in terms of PGA.

The general description of the damage states of elevated pipes as described in (FEMA, 2020) is presented bellow:
- **DS4:** For tank farms, Extensive damage is defined by extensive damage to elevated pipes. For water treatment plants extensive damage to pipes connecting different basins and chemical units.
- **DS5:** For water treatment farms, refineries and tank farms, Complete damage is defined by the complete failure of all elevated pipes.

Stacks are essentially tall cylindrical chimneys, and they are mainly encounter in refineries.

Only one damage state is evaluated in (FEMA, 2020) for the stacks:
- **DS4:** For refineries, Extensive damage is defined by stacks collapsing.

Table 3.8 presents the median value of the peak ground acceleration and the logstandard deviation (β) for unanchored elevated pipes and stacks. Here the word unanchored also refers to components designed with no special considerations other than the manufacturer's normal requirements. Thus, are mostly applicable to the Groningen case.

Table 3.8 Peak ground acceleration fragility functions for elevated pipes of water treatment plants, wastewater treatment plant, refineries and oil system tank farms. Part of Table B1-7, Table B3-2 and Table B3-6 (FEMA, 2020)

Component	Damage state	Median	β*
Elevated pipes	DS4 - Extensive	0.53	0.60
	DS5 - Complete	1.00	0.60
Stacks	DS4 - Extensive	0.60	0.70

3.3.6 Vessels

As vessels the following 5 categories are distinguished:
- Boilers and pressure vessels.
- Large vertical vessels with formed heads.
- Large horizontal vessels.
- Braced spherical pressure vessels.
- Non-braced / moment resisting spherical pressure vessels.

The first three types of vessels are encountered in (FEMA, 2020) and the last two (spherical pressure vessels) in the paper (Moschonas, Karakostas, Lefkidis, & Papadopoulos, 2014).

Boilers and pressure vessels, large vertical vessels with formed heads and large horizontal vessels

Boilers and pressure vessels, large vertical vessels with formed heads and large horizontal vessels are all referred to as subcomponents of generation facilities in (FEMA, 2020).

The general description of the damage states of Boilers and pressure vessels and large horizontal vessels as described in (FEMA, 2020) is presented bellow:
- **DS3:** Moderate damage is defined by considerable damage to boilers and pressure vessels.
- **DS5:** Complete damage is defined by extensive damage to large horizontal vessels beyond repair.

For Large vertical vessels with formed heads no explicit definition is given in (FEMA, 2020). Therefore, is assumed that the name corresponds directly to the level of damage globally.

Table 3.9 presents the median value of the peak ground acceleration and the logstandard deviation (β) for unanchored boilers and pressure vessels, large vertical vessels with formed heads and large horizontal vessels. Here, the word unanchored also refers to components designed with no special considerations other than the manufacturer's normal requirements. Thus, are mostly applicable to the Groningen case.

Table 3.9 Peak ground acceleration fragility functions for boilers and pressure vessels, large vertical vessels with formed heads and large horizontal vessels, as subcomponents of generation facilities. Part of Table B4-8 (FEMA, 2020)

Component	Damage state	Median	β
Boilers and pressure vessels	DS3 - Moderate	0.36	0.70
Large vertical vessels with formed heads	DS3 - Moderate	0.46	0.50
	DS4 - Extensive	0.68	0.48
Large horizontal vessels	DS5 - Complete	1.05	0.75

Spherical pressure vessels

The fragility curves presented in (Moschonas, Karakostas, Lefkidis, & Papadopoulos, 2014) that correspond to spherical pressure vessels are developed on the basis of static nonlinear (pushover) analysis. Damage states are defined considering only damage developed at the supporting structure and they are quantified using the displacement of the vessel as the damage parameter. Important assumption of the study is that the shell of the pressure vessel is designed to remain in the elastic range during the earthquake.

The general description of the damage states of on ground tanks as described in (Moschonas, Karakostas, Lefkidis, & Papadopoulos, 2014) is presented bellow:
- **DS2:** Slight damage is defined by minor yields that correspond to minor permanent deformations at critical sections of a small percentage of columns and/or braces.
- **DS3:** Moderate damage definition depends on cross-section class according to EC3:
  - For class 1 sections, DS3 is defined by moderate yields corresponding to moderate permanent deformations at critical sections of a moderate percentage of columns and/or braces without any global buckling failure of columns.
  - For class 2 and 3 sections, DS3 is defined by minor-to-moderate yields that correspond to minor-to-moderate permanent deformations at critical sections of a moderate percentage of columns and/or braces without any local buckling at critical sections of columns.
- **DS4:** Extensive damage definition depends on cross-section class according to EC3:
  - For class 1 sections, DS4 is defined by major yields causing major permanent deformations at critical sections of a large percentage of columns and/or braces with global buckling failure of columns where maximum compression occurs.
  - For class 2 and 3 sections, DS4 is defined by minor-to-major yields that cause minor-to-major permanent deformations at critical sections of a large percentage of columns and/or braces with local buckling of critical sections at the columns where maximum compression occurs.
- **DS5**: Complete damage is defined by buckling failure with subsequent collapse of the pressure vessel.

Table 3.10 presents the median value of the peak ground acceleration and the logstandard deviation (β) for spherical pressure vessels. Here, the word unanchored also refers to components designed with no special considerations other than the manufacturer's normal requirements. Thus, are mostly applicable to the Groningen case.

Table 3.10 Peak ground acceleration fragility functions for spherical pressure vessels (Moschonas, Karakostas, Lefkidis, & Papadopoulos, 2014)

Tank type	Damage state	Median	β
Braced spherical pressure vessels	DS2 - Slight	0.34	0.55
	DS3 - Moderate	0.60	0.55
	DS4 - Extensive	0.81	0.55
	DS5 - Complete	1.05	0.55
Non-braced / moment resisting spherical pressure vessels	DS2 - Slight	0.37	0.55
	DS3 - Moderate	1.74	0.55
	DS4 - Extensive	3.42	0.55
	DS5 - Complete	5.67	0.55

3.3.7 Another typology

It is possible that for certain specific structures or installations none of the typologies described above are applicable. For such special typologies:
- Either there is no available fragility curve in the literature due to insufficient data,
- Or there are available fragility curves which are not applicable for Groningen, since they refer to seismically designed structures.

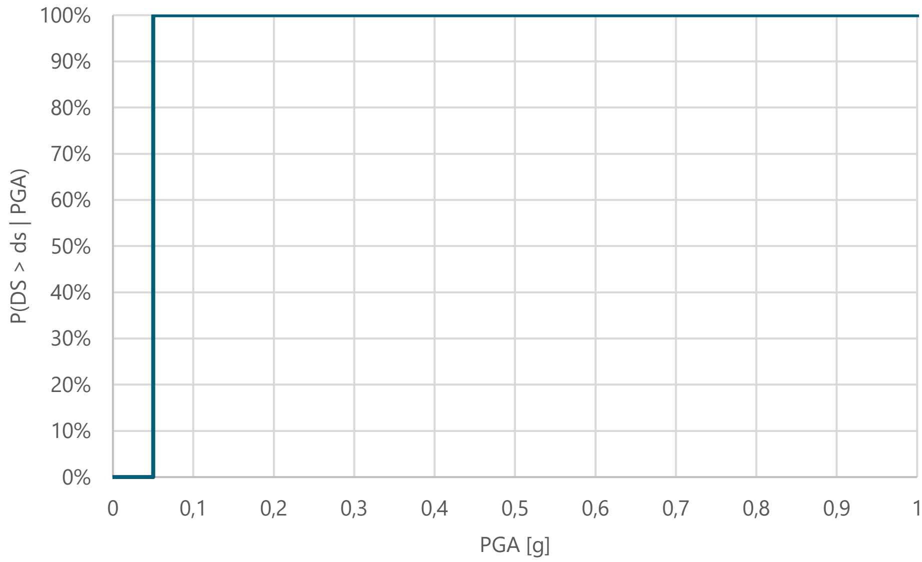
For the case of such a special structure, a step function fragility has been included in the tool in order to allow for risk quantification, based on conservatively estimated seismic resistance of special structures. For this step function is crucial to properly select a (threshold) value for the peak ground acceleration and justify this choice:
- Bellow this threshold the probability of reaching compete damage of the non-structural component is equal to 0.
- Above this threshold the probability of reaching compete damage of the non-structural component is equal to 1.

Such step-function should be used with caution because in common fragility functions there is always some probability of damage at low seismic loads. But using the step-function, the probability of damage becomes zero below the selected (threshold) value for the peak ground acceleration.

It is advised to select a (threshold) peak ground acceleration value of the step function of 0.05 g. This is in accordance with the 'very low seismicity' threshold defined in NEN-EN 1998-1 and NPR9998 bellow which no assessment for seismic actions is required.

An example hereof is presented in figure 3.8 where the median (value for the peak ground acceleration) is 0.4 g and the dispersion β is infinitesimal (see figure 3.4 for comparison).

Figure 3.8 Step function fragility curve



3.4 Foundation assessment

In addition to the scenario probability that the Selection method Step II tool calculates, it also provides a recommendation for the type of further assessment of the foundation. The recommendation depends on the type of foundation and the hazard level. In the following paragraphs it is described the type of recommendation provided by the tool based on the type of foundation and the hazard level.

Plie foundations

PGA < 0,15 g (MRP 2475 years)
The risk of loss of bearing capacity due to structural damage of piles is sufficiently low for the seismic hazard level that applies to the location. Only a GEO limit state assessment (liquefaction verification) is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen+Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

PGA > 0,15 g (MRP 2475 years)
For the seismic hazard level at the location according to NPR 9998:2020 risks associated with loss of bearing capacity of piles cannot be neglected and both STR and GEO limit state assessment is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen+Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

Shallow foundations

PGA < 0.125 g (MRP 2475 years)
For CC1 and CC2 structures on shallow foundations on cohesionless soil layers no verification of liquefaction is required for the seismic hazard level that applies to the location. Liquefaction induced settlements will be limited and do not contribute significantly to the structure collapse risk (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen+Bos)). For structures of higher Consequence Class or structures with shallow foundation on cohesive soil refer to Handreiking Fase 2 (Deltares/TNO) and Seismic verification of foundations of industrial assets in Groningen (Witteveen+Bos). Reference also to NPR 9998:2020 par. 10.3.1 and NPR 9998 par. 10.3.2.1.

PGA > 0.125 g (MRP 2475 years)
For the seismic hazard level that applies to the location seismic failure of the foundation may contribute significantly to the structure damage/collapse risk and needs to be verified (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen+Bos)). Reference also to NPR 9998:2020 par. 10.3.1.

Unknown foundation
No recommendation can be given for unknown typology of foundation.

3.5 Conditional factors

The basic idea behind application of conditional factors is to relate the occurrence probability of a considered scenario $P(scenario)$ to the damage state exceedance probability $P(DS)$ of the reference object, i.e., in formula form

$$P(scenario) = P(scenario|DS) \cdot P(DS)$$

where $P(scenario|DS)$ is the conditional probability that a scenario occurs, provided that a damage state is exceeded. This probability is based on one or more independent conditional probabilities.

The conditional factors apply in order to cover:
- Specific object properties for which correction of the general fragility function-based calculation is required, like system behaviour (multiple components) and current state of construction.
- Relations between probability of occurrence of a damage state of an object and corresponding safety or environmental risk scenario probability, like pounding probability, common-cause effects, person(s) presence and fail-safe Line of Defence systems.

In the Selection method Step II tool, a fixed set of conditional factors is implemented that could be relevant for many scenarios However, some objects or scenarios are too specific so there is also room for the expert to input user-defined conditional factors. The definition of the conditional factors is aligned with the Selectiemethodiek Stap I by Arcadis (Arcadis, 2020).

Person(s) presence
The consequences of a failure are likely to be less severe when less people are present on-site/in the area around the industrial object. Hence, the risk will be lower. Therefore, the computed probability of damage state exceedance can be adapted based on the occupation of industrial site within the area of the effects of a damaged structure or installation. By default, 24/7 people presence is assumed, lower conditional factors apply for permanent, partially, limited and very limited person(s) presence, refer to table 3.11.

Table 3.11 Conditional factors for person(s) presence

Description	Conditional factor
Permanent (24/7 people presence)	1
Partially (regular people presence)	0.5
Limited (occasional people presence)	0.1
Very limited (typically no people presence)	0.01

Safe shutdown
Industrial facilities/structures that have a fail-safe line of defence (LoD) system installed will have less severe consequences. By default, we assume that such a system is not available (conditional factor is 1.0), while the risks are lowered by a factor 10 in case safe shutdown can be ensured. The factors in table 3.12 are based on

rough estimates, where the factor of 0.1 reflects a shift of row in the risk matrix to lower probability. Other values may need to be selected for specific cases.

Table 3.12 Conditional factors for safe shutdown LoD

Description	Conditional factor
Safe shutdown	0.1
No safe shutdown	1

Construction state

The probability of damage state exceedance computed with the fragility functions assumes a 'normal' construction state. Table 3.13 lists the possible options of conditional factors implemented in the Selection method Step II tool. The conditional factors are based on expert judgment. The limit values for Excellent state and significantly degraded state correspond to a shift of row in the risk matrix to lower and higher probability, respectively. Other values may need to be selected for specific cases.

Table 3.13 Conditional factor for construction state

Description	Conditional factor
Excellent	0.1
Good	0.5
Neutral	1
Slightly degraded	5
Significantly degraded	10

Common-cause or pounding

The common-cause or pounding scenarios conditional factor is defined but no conditional factor is assigned. The conditional factors are defined based on expert judgment.

Especially for evaluating the contribution of pounding to the total scenario probability the following procedure is suggested:

- Calculate the scenario probability of the installation under investigation (object A) without pounding scenario.
- Calculate the scenario probability of the installation(s) that introduce(s) risk of pounding (object B). This is done by filling in separate scenario probability sheet for the installation that introduces the risk of pounding.
- Calculate the conditional probability of the object under investigation (object A) being damaged given the probability of the installation(s) that introduce(s) risk of pounding (object B) to collapse. This is the conditional factor for pounding.
- The tool then calculates the probability of pounding scenario by multiplying the two aforementioned probabilities.

3.6 Risk evaluation

Risk matrices are a tool very often used in (chemical) industry to assess risks based on a combined evaluation of likelihood of a scenario to happen and the severity of the scenario consequences.

Risk matrices do typically represent the evaluation of criticality of scenario visually by means of a colour scheme, which is often specified as:
- Red: Risk not tolerable.
- Yellow: ALARP: as low as reasonably possible.
- Blue: Risk tolerable.

In the Selection method Step II tool, by default, risk matrices are included based on (SIL Platform, 2018). SIL[1] Platform matrices are selected because these can be considered widely supported best-practice matrices, which are probably well aligned with many company risk matrices used by many industrial companies in Groningen.

For the definition of the consequence categories in the current version of the tool use is made of table 3.14 (which is translated from (Witteveen+Bos, 2020 (A)). The consequence categories are thereby based both on the assessment of safety and environmental impact.

Table 3.14 Definition of consequence categories

	1 Negligible	2 Minor	3 Moderate	4 Major	5 Catastrophic
safety	minor injury ('first aid')	serious injury ('staying at home')	major injury ('hospital') or multiple serious injuries	1-2 fatal injuries or permanent disability	>2 fatal injuries
environment	marginal emission and/or damage withing site boundary (<1 ha)	minor emission and/or damage within site boundary (>1 ha)	emission and/or damage within site boundary. No permanent damage to surrounding environment (>10 ha)	emission and/or damage to surrounding environment (>100 ha)	major emission and/or damage to surrounding environment (>1,000 ha)

Differentiation has been made between a risk matrix that applies to on-site safety risks and a risk matrix that applies to public exposure, the latter being one probability category stricter in its classification. The default SIL on-site and public exposure risk matrices are shown in figure 3.9 and figure 3.10 respectively.

The calculation tool provides next to the SIL matrix the functionality allowing the user to input a custom set of risk matrices (PGS 6, 2016). This enables a company to implement their own risk matrix, provided that the custom matrix has:
- The same set of probabilities of exceedance (rows of the matrix). And
- The same levels of severity effects (columns of the risk matrix.

The definition of the severity effects can be redefined and the colours in the risk matrix can be altered. By this means companies are able to more or less reproduce their own risk matrices in the calculation tool.

Which actions are required associated with the colour scores in the matrix should be established in consultation with the main governmental institutions authorized for supervision of the industry in the region.

[1] The SIL Platform is an independent group of experienced users or adopters of the SIL philosophy, according to the IEC standards 61508 and 61511, in the Dutch process industry. The SIL Platform is linked to the Royal Dutch national standardization committee NEC 65 that follows the international work of IEC/TC65, industrial measurement, control, and automation.

Figure 3.9 Risk matrix on-site exposure

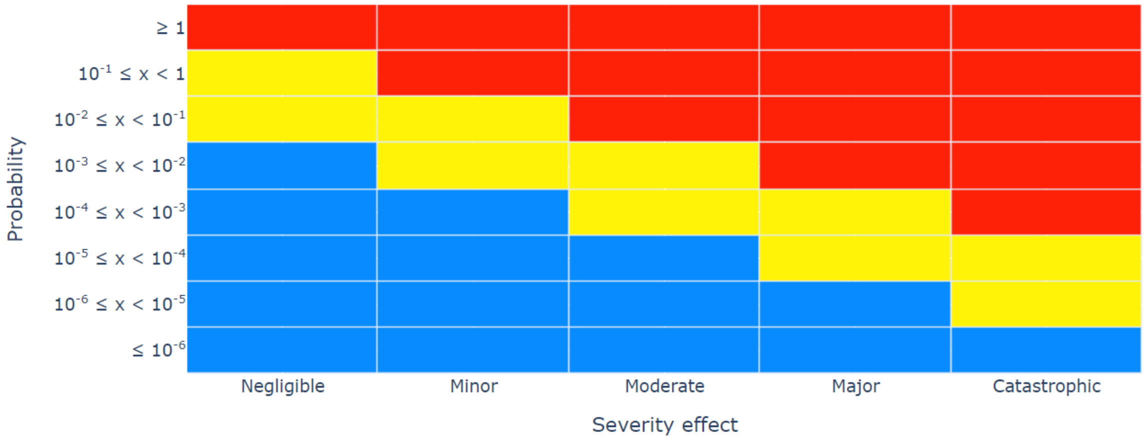
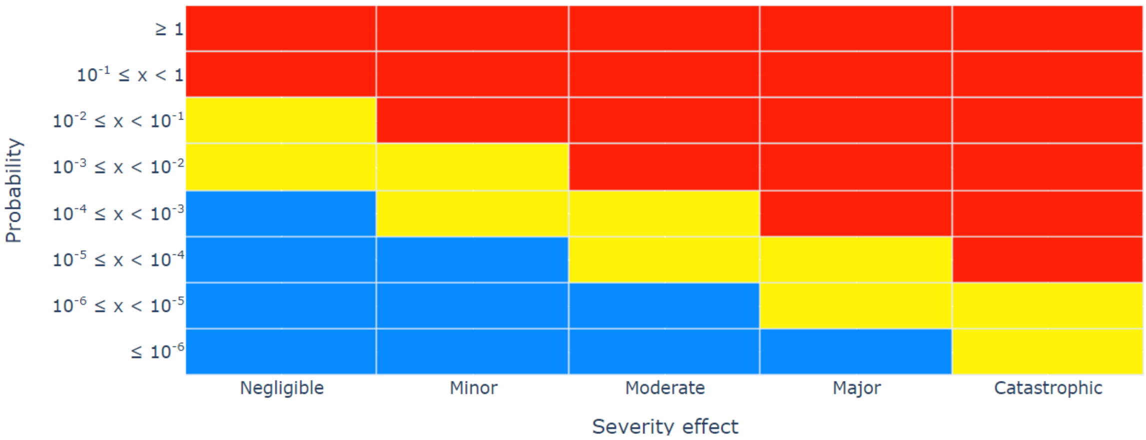


Figure 3.10 Risk matrix public exposure



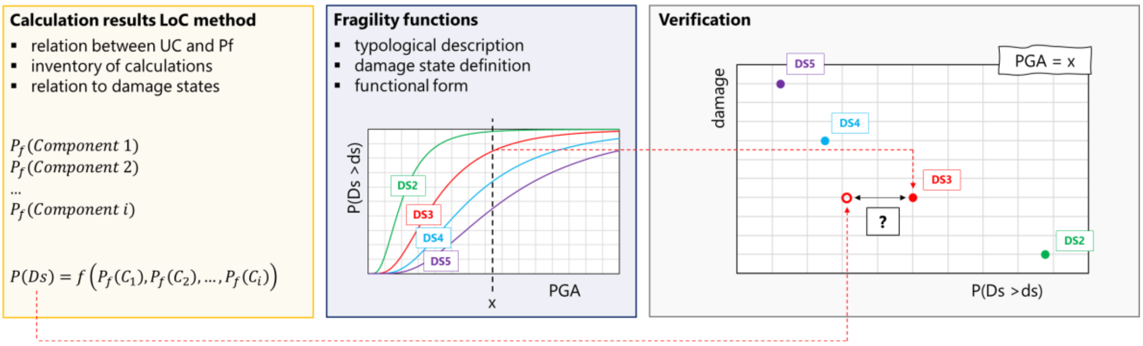
4

VERIFICATIONS

4.1 Fragility functions verification

In this section the verification of the fragility functions against finished Phase 2 calculation reports is reported. The framework used is presented in figure 4.1. Referring to this framework, the followings aspects are discussed in this section:
- The relation between the unity checks from available 'LoC method' calculation reports and the probability of damage state exceedance P(Ds), in paragraph 4.1.1.
- The overview of objects from the available Phase 2 calculation report paragraph 4.1.2.
- The comparison of these results with the fragility curves from literature (see section 3.3) to verify their applicability in paragraph 4.1.3.
- Summary of results and conclusions paragraph 4.1.4.

Figure 4.1 Fragility function verification framework



4.1.1 Relating a unity check to the probability of failure

Fragility curves present an expected probability of exceeding a certain damage state given a certain level of seismic load. In the 'LoC method' calculation reports, structural capacity checks have been performed on element level using a deterministic earthquake load. The relation between structural reliability and a unity checks of 1.0 is discussed in this paragraph.

Partial factors

In general, the failure function of a system is described by Z = R - S, in which R represents the resistance of the system and S the load (solicitation) and Z <0 is defined as failure. By performing a probabilistic analysis, accounting for the variation in R and S, the actual reliability level β can be determined.

Depending on the target reliability β_t, partial factors can be derived using the following equations:

$$\gamma_R = \frac{R_{char}}{\mu_R + \alpha_R \beta_t \sigma_R}$$

$$\gamma_S = \frac{\mu_S + \alpha_S \beta_t \sigma_S}{S_{char}}$$

Here α_R and α_S are the influence factors of R and S, respectively. By applying the partial factors γ_R and γ_S on the characteristic values R_{char} and S_{char} the target reliability β_t is met.

In the LoC method a deterministic earthquake scenario is adopted ($\alpha_S = \alpha_{eq} = 0$), applying partial factors only on the resistance side. By keeping these partials factors γ_R equal to the values in the applicable (Euro-) code, an ultimate limit state (ULS) calculation is performed which represents a certain reliability if the verification criterion is met. Subsequent paragraphs explain the relation between Eurocode unity check and structural reliability in more detail.

Eurocode with and without earthquakes

When considering the Eurocode without earthquakes, for structures identified as CC2 the target reliability for a reference period of 50 years is $\beta_t = 3.8$ and for a reference period of 1 year $\beta_t = 4.7$. Given the chosen Design Approach in the Dutch Eurocode this target reliability is achieved by applying partial factors on both the resistance and the load.

When earthquake loads are relevant from (NEN-EN 1990+A1+A1/C2:2019) equation (6.12b) as shown below can be applied. Herein G represents the self-weight, P the prestress (if relevant) and A_{Ed} the design value of the earthquake load. For the majority of the non-dominant loads ψ_2 is equal to 0.

(2) De belastingscombinatie tussen haken { } mag ook zijn geformuleerd als:

$$\sum_{j \geq 1} G_{k,j} \text{"+"} P \text{"+"} A_{Ed} \text{"+"} \sum_{i \geq 1} \psi_{2,i} Q_{k,i} \qquad (6.12b)$$

To determine A_{Ed} the characteristic value of the earthquake load A_{Ek} has to be multiplied with the importance factor γ_I. This characteristic value in accordance with (NEN-EN 1998-1) is recommended as the earthquake load with a return period of 475 years for the No Collapse limit state. For CC2 the importance factor by definition is equal to 1.0. This return period is chosen to aim for an exceedance probability of the limit state of 10 % in 50 years. The target reliability according to (NEN-EN 1998-1) therefore appears to be $\beta_t \approx 1.4$ for a 50-year reference period. Possible explanation for this lower reliability level compared to the situation without earthquake loads is the shift in economic optimum; the marginal costs to increase the seismic resistance are so high that the criterium to accept damage is lower.

By applying partial factors on the resistance (both the case in (NEN-EN 1998-1) and the LoC method), the actual reliability will be larger than the target reliability of $\beta_t \approx 1.4$. How much exactly is difficult to quantify and will depend on the failure mechanism and the corresponding variability of the input parameters. The relative influence of parameters depends both on the Z function and on the variability of the parameters and can be represented by the influence factors α_i. In general, α_i for earthquakes loads is very large, implying that the load is governing and the additional safety from partial factors on other parameters is limited.

Reliability using fragility curves

When using the approach of fragility curves, the probability of failure given a load is multiplied by the probability of that load occurring. This means that the relative importance of load and resistance is no longer relevant as explained below.

The minimal distance to the failure surface (in standard normal space) is defined as the Hasofer-Lind reliability index β which can be defined as (Phoon, 2015):

$$\beta = \min_{x \epsilon F} \sqrt{\boldsymbol{n}^T \boldsymbol{R}^{-1} \boldsymbol{n}}$$

Herein β represents the shortest distance to the failure surface for all possible solutions of input parameter vector $\boldsymbol{x}$. Herein $\boldsymbol{n}$ is the vector that represents the distance of $\boldsymbol{x}$ to the origin in standard normal space and $\boldsymbol{R}$ is the correlation matrix of the variables.

$$n_i = \frac{x_i - \mu_i^N}{\sigma_i^N}$$

The relative magnitude of all n_i values is also known as the set of influence factors α_i of which the sum of the squares is by definition equal to 1. The relative magnitude of n_i and α_i depends on the combined influence of parameter i on the limit state function and the variability of parameter i. For uncorrelated parameters it holds that $n_i = -\alpha_i \beta$.

Suppose the load and resistance are uncorrelated and normally distributed with parameters (μ_S, σ_S) and (μ_R, σ_R) and the target reliability β_t and the values of α_R^2 and α_S^2 are known. Then:

$\alpha_R = +1 \cdot \sqrt{\alpha_R^2}$ (the positive sign indicates that β increases as R increases)
$\alpha_S = -1 \cdot \sqrt{\alpha_S^2}$ (the negative sign indicates that β decreases as S increases)

$n_R = -\alpha_R \beta_t$ (the negative sign indicates that the design point value is below the mean)
$n_S = +\alpha_S \beta_t$ (the positive sign indicates that the design point value is above the mean)
As the sum of all squared influence factors is equal to 1 it indeed holds that:

$$\beta_t = \sqrt{[-\alpha_R\beta_t \quad -\alpha_S\beta_t]\begin{bmatrix}-\alpha_R\beta_t \\ -\alpha_S\beta_t\end{bmatrix}} = \sqrt{\alpha_R^2\beta_t^2 + \alpha_S^2\beta_t^2} = \sqrt{\beta_t^2(\alpha_R^2 + \alpha_S^2)} = \sqrt{\beta_t^2} \cdot \sqrt{(\alpha_R^2 + \alpha_S^2)}$$

However, if we consider a deterministic load scenario without partial factors then the actual reliability β is affected because by definition there is no safety on the load side, implying $\alpha_S = 0$.

$$\beta = \sqrt{[-\alpha_R\beta_t \quad 0]\begin{bmatrix}-\alpha_R\beta_t \\ 0\end{bmatrix}} = \sqrt{\alpha_R^2\beta_t^2} = \alpha_R\beta_t = -n_R$$

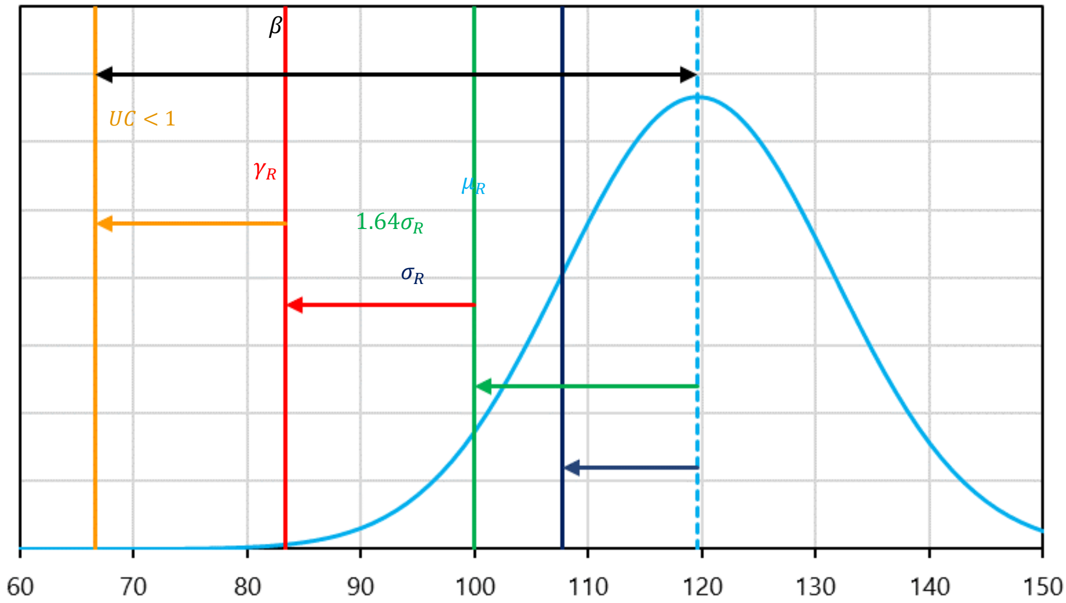
In other words, regardless of the initial relative influence of the load and resistance, given a certain deterministic load, the level of safety fully depends on the number of standard deviations from the mean on the resistance side.

Reliability from a unity check

To obtain the reliability from a unity check, a method is presented here using the observations that the level of safety fully depends on the number of standard deviations from the mean on the resistance side and the assumption that the resistance is normally distributed with parameters μ_R and σ_R. Referring to figure 4.2 we suppose the followings is known:

- The Coefficient of Variation (CoV) of the resistance (thus the ratio between σ_R and μ_R). In figure 4.2 the mean is represented by the light-blue dashed vertical line and the 1 standard deviation offset is represented by the dark blue vertical line.
- The definition of the characteristic value $R_{char} = \mu_R - 1.64\sigma_R$ without having to know its exact value. In figure 4.2 the characteristic value is represented by the green vertical line with a (dummy) value of 100.
- The partial factor on the resistance γ_R. By applying this factor to the characteristic value, the design value of the resistance is found, represented by the red vertical line in figure 4.2.

Figure 4.2 Reliability on the resistance



Using these known parameters, the resistance means μ_R and standard deviation σ_R can be determined as:

$$\mu_R = \frac{R_{char}}{1 - 1.64\,CoV} \qquad \sigma_R = CoV\ \mu_R$$

Lastly, the actual reliability that is determined by the distance from the mean, depends on the calculated unity check. For a unity check lower than 1 this is represented in figure 4.2 by the orange vertical line. If the unity check is linear with R, then the actual reliability is:

$$\beta = -n_R = -\frac{x_R - \mu_R^N}{\sigma_R^N} = -\frac{(R_{char}\,/\,\gamma_R)\cdot UC - \mu_R}{\sigma_R}$$

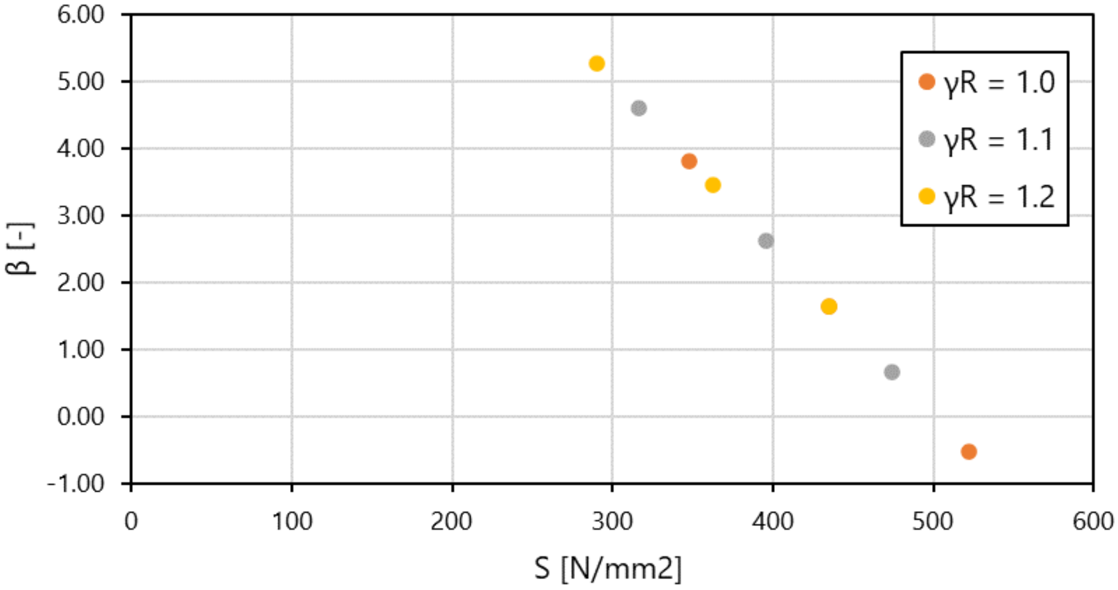
Above is exemplified by considering the unity check of a steel cross-section where UC = S/R_d. It is assumed that $R_{char} = 435\ N/mm^2$, $CoV = 0.08$ and the value of γ_R is varied. Hereby $\mu_R = 500.7\ N/mm^2$ and $\sigma_R = 40.0\ N/mm^2$. In table 4.1 the results are shown for different unity checks and partial factors on resistance.

Table 4.1 Relation between unity check, load S and reliability for unity check that is linear with R

$\gamma_R = 1.0$			$\gamma_R = 1.1$			$\gamma_R = 1.2$		
Unity check	S [N/mm^2]	β	Unity check	S [N/mm^2]	β	Unity check	S [N/mm^2]	β
0.8	349	3.81	0.8	316	4.60	0.8	290	5.26
1.0	435	1.64	1.0	395	2.63	1.0	363	3.45
1.2	522	-0.53	1.2	475	0.65	1.2	435	1.64

Although the partial factors vary, the relation between the deterministic load S and the calculated reliability (based on the safety in R) is linear as presented in figure 4.3. If the deterministic load S is equal to 500.7 N/mm^2 it can be seen that the reliability index $\beta = 0$ as this is the expected value of R.

Figure 4.3 Relation between load S and reliability index β for unity check that is linear with R



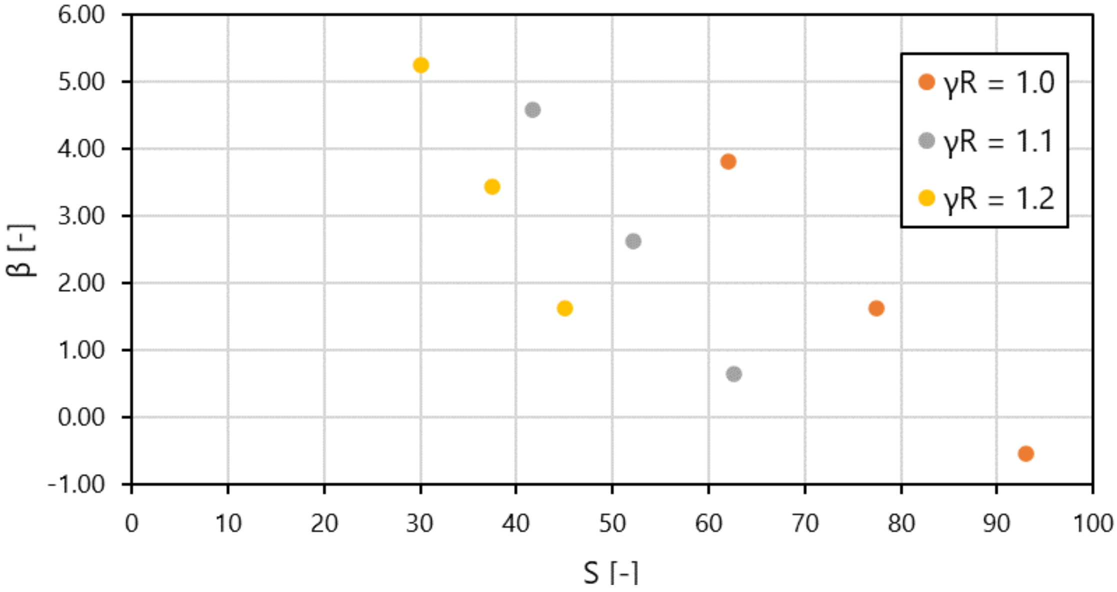
Now consider the unity check below that is not linear with R. By using the equation above for the actual reliability β the results presented in table 5.2 are obtained. Naturally in this case the same values of the reliability are found as they depend only on R_{char} and UC. By considering the results in figure 4.4 it can however be seen that the relation between load and reliability is not linear.

$$UC = \frac{S}{\exp\left(\frac{R_d}{100}\right)}$$

Table 4.2 Relation between unity check, load S and reliability for unity check that is not linear with R

$\gamma_R = 1.0$			$\gamma_R = 1.1$			$\gamma_R = 1.2$		
Unity check	S	β	Unity check	S	β	Unity check	S	β
0.8	62.0	3.81	0.8	41.7	4.60	0.8	30.0	5.26
1.0	77.5	1.64	1.0	52.2	2.63	1.0	37.5	3.45
1.2	93.0	-0.53	1.2	62.6	0.65	1.2	45.0	1.64

Figure 4.4 Relation between load S and reliability for unity check that is not linear with R



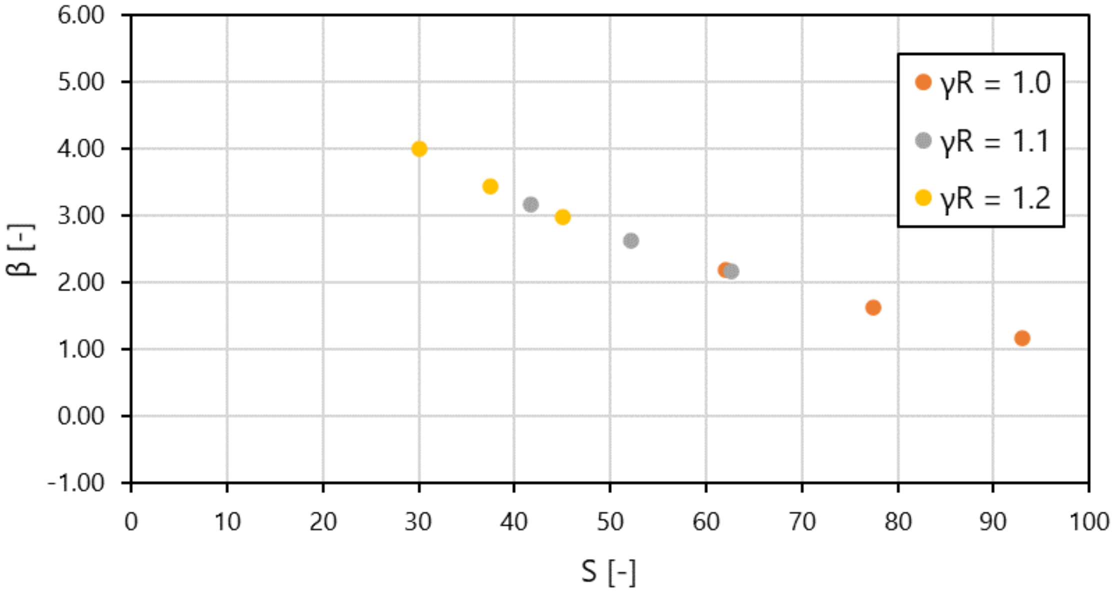
If we consider at each of the deterministic loads from table 4.2 the value of R_{char} to obtain a unity check equal to 1.0, the reliability indices and values presented in table 4.3 are found. These reliability indices are calculated with the equation below. Here it is emphasized that μ_R and σ_R are still determined by the initial input value of R_{char}. It can be seen that the reliability indices at UC = 0.8 and UC = 1.2 vary less from the reliability at UC = 1.0 than presented in table 4.2.

$$\beta_{act} = -\frac{(R_{char} \,/\, \gamma_R) \cdot \left(\frac{R_{char}(UC = 1.0)}{R_{char}}\right) - \mu_R}{\sigma_R} = -\frac{(R_{char}(UC = 1.0) \,/\, \gamma_R) - \mu_R}{\sigma_R}$$

Table 4.3 Characteristic values of R and corresponding reliability to obtain UC = 1.0 at given load S

$\gamma_R = 1.0$			$\gamma_R = 1.1$			$\gamma_R = 1.2$		
S [-]	R_{char} $(UC = 1.0)$ [N/mm²]	β	S	R_{char} $(UC = 1.0)$ [N/mm²]	β	S	R_{char} $(UC = 1.0)$ [N/mm²]	β
62.0	412.6	2.20	41.7	410.4	3.19	30.0	408.2	4.01
77.5	435.0	1.64	52.2	435.0	2.63	37.5	435.0	3.45
93.0	453.2	1.19	62.6	455.0	2.17	45.0	456.8	3.00

Figure 4.5 Relation between load S and reliability for unity check that is not linear with R



Summary

Based on the elaborated examples above, the findings can be summarized as follows:

- For deterministic loads the reliability depends only on the safety on the resistance R.
- A specific unity check can be translated to a failure (or 'actual' unity check exceedance) probability if for the resistance R the coefficient of variation and partial factor γ_R are known.
- If a unity check depends linearly on resistance R.

$$\beta = -\frac{(R_{char} \,/\, \gamma_R) \cdot UC - \mu_R}{\sigma_R}$$

- if unity does not depend linearly on R:

$$\beta = -\frac{(R_{char}(UC = 1.0) \,/\, \gamma_R) - \mu_R}{\sigma_R}$$

4.1.2 Overview of Phase 2 calculation reports

The applicability of the selected fragility functions from literature, is evaluated with respect to all Phase 2 calculation reports that have been made available. Phase 2 calculations are clearly not elaborate enough to fully substantiate or develop revised fragility relations. They can however be used to evaluate if we have reason to believe that fragility functions from literature are not applicable for Groningen, and only for this purpose the Phase 2 reports are considered for development of the calculation tool.

For the analysis we distinguish the following industrial components:

- Building structures.
- Non-structural components.
- Elevated steel tanks.
- Horizontal/vertical vessels.
- On-ground storage tanks.
- Vertical stacks.
- Elevated pipes.

The components correspond to the ones listed in section 3.3, but with some small changes to better group the objects and corresponding fragility curves for the analysis. In the fragility curve verification study presented here both the companies and the objects under consideration are represented by random names in order to anonymize them.

As explained through figure 4.1, the applicability of fragility functions is checked by comparing the damage state exceedance probability P(Ds) from literature with the probability of failure that follows from the reported unity checks on element level. A consistent mismatch between these two probabilities leads to disqualification of the examined fragility curve and replacement with an alternative fragility function. As it is explained in the following paragraphs, this appeared to be the case for two specific typologies: the elevated steel tanks and the non-structural components.

Building structures

The building structures cover a broad range of industrial facilities, including control rooms, storage buildings, process buildings but also pipeline bridges and storage racks. In most cases, failure of the building itself is not considered critical for 'LoC toets' but the buildings serve as housing or support structure for process equipment with high risks in case of failure. In the calculation reports, the integrity of the building subjected to earthquake load has been assessed and therefore the results are compared with building fragility curves (even though the critical component might of different typology, e.g., silos). Unity checks are available on element level for checks such as buckling, yielding, bolts and capacity of foundation footings/piles.
Table 4.4 lists the 23 objects that have been related to a fragility curve from the building stock. The labels in the last column refer to building fragility curves from Hazus (FEMA, 2020) as described in section 3.3.2.

Table 4.4 Industrial objects assigned to one of the fragility curves from general building stock

Object ID	Type of structure	Fragility curve (Label)
building a	building	S5L
building b	silos in dry building	S2H
building e	silos in steel braced frame	S2M
building f	silos in steel braced frame	S2M
building h	building	S2M
building i	building	C1L
building j	pipeline bridge	S2L
building l	building	S2M
building m	steel braced building, approximately 30 m high	S2H
building n	steel braced building, approximately 12 m high	S2M
building o	concrete frame with unreinforced masonry infill walls, two stories	C3L
building p	steel braced frame, approximately 23 m high	S2M
building q	steel braced frame, approximately 21 - 35 m high	S2H
building r	concrete frame structure with concrete infill walls, height 8.25 m	PC2L
building s	steel braced frame, height 14-18m	S2L
building t	concrete structure, height 11m	C2L
building u	steel support structure, H=3.7m	S2L
equipment c/building d	silos components in steel braced frame	S2M
pipeline bridge a	pipeline bridge	S2L
pipeline bridge b	pipeline bridge	S1L
pipeline bridge c	steel moment frame, height 3 m	S1L
storage rack a	steel braced frame, approximately 13 m high	S2M
storage rack B	steel braced frame, height 6 m, length 11.4 m, width 0.88 - 2.08 m	S2M

Non-structural components

The non-structural components mostly consist of process equipment such as small vessels, pipelines inside/ attached to a building, and they are not part of the main bearing structure. In the calculation reports, these types of objects are assessed according to the method for non-structural elements described in NEN-EN 1998-1 paragraph 4.3.5. The assessed failure mechanisms in the 'LoC toets' are mostly related to the lateral resistance (or sliding resistance) of the non-structural component subjected to earthquake load. Unity checks are available on element level for checks such as buckling, yielding, sliding and connections.

Table 4.5 lists the 5 objects classified as non-structural components. The meaning of the labels in the last column is explained in section 3.3.3. The reason for this distinction is based on the verification results as will be explained further in the next section.

Table 4.5 Industrial objects assigned to fragility curve for non-structural component

Object ID	Type of structure	Fragility curve (Label)
equipment D	non-structural components	NS-WEAK
equipment E	non-structural components	NS-WEAK
equipment F	non-structural components	NS-WEAK
equipment G	non-structural components in structure	NS-WEAK
equipment H	steel vessel inside building, $V=19m^3$	NS-RIGID

Elevated steel tanks

The elevated steel tanks are characterized by a steel storage tank at height and support structure attached to the ground. In the calculation reports, the support structures have very different configurations which results quite some variations in the verification results as will be shown in the next section. Typical support structures of the elevated tanks from the reports are steel frame structure braced in one or two directions, steel moment frames or just columns with limited lateral resistance. Unity checks are available on element level, mostly related to failure of the support structure, such as buckling, yielding, connections and capacity of foundation footings/piles.

Table 4.6 lists the six objects classified as elevated steel tank structure. The meaning of the labels in the last column is explained in section 3.3.4. Distinction has been made between elevated tanks with braced supports (in two directions) and non-braced supports. The reason for this distinction is based on the verification results as will be explained further in the next section.

Table 4.6 Industrial objects assigned to fragility curve for elevated steel tank

Object ID	Type of structure	Fragility curve (Label)
elevated tank A	elevated tank	PSTAS-NB
elevated tank B	elevated tank	PSTAS-NB
elevated tank C	elevated steel tank	PSTAS-B
elevated tank D	elevated steel tank	PSTAS-NB
elevated tank E	elevated tank (H=6.7+27m, D=5.6m), rigid/braced support structure	PSTAS-B
elevated tank F	elevated tank structure, height 6.3m	PSTAS-B

On-ground storage tanks

Table 4.7 lists the five objects classified as on-ground storage tank, all made of steel. The meaning of the label and corresponding typology is explained in section 3.3.4.

Table 4.7 Industrial objects assigned to fragility curve for on-ground storage tank

Object ID	Type of structure	Fragility curve (Label)
storage tank A	storage tank	PSTGS
storage tank B	storage tank	PSTGS
storage tank C	storage tank, V = 120m^3	PSTGS
storage tank E	on-ground steel tank, V = 285 m^3	PSTGS
storage tank F	on-ground tank structure, V = 17500m^3	PSTGS

Horizontal/vertical vessels

Two type of vessel structures are distinguished by Hazus (FEMA, 2020); horizontal and vertical vessels. The horizontal vessels are characterized by height to width ratio lower than 1, while for vertical vessels this ratio is larger than 1.

Table 4.8 lists six objects classified as vertical vessel and one horizontal vessel. The meaning of the labels in the last column is explained in section 3.3.6. Most of the analysed objects are pressure vessels (containing some pressurized content). For some objects, the typology is somewhere in between the storage tank and vessel but based on the dimension it tends more towards a vessel and thus it is included here.

Table 4.8 Industrial objects assigned to fragility curve for horizontal- or vertical vessel

Object ID	Type of structure	Fragility curve (Label)
horizontal vessel A	horizontal reaction vessel	HV-SELF
vertical vessel A	storage tank 6m3	VV-SELF
vertical vessel B	storage tank/ vertical vessel	VV-SELF
vertical vessel C	vertical cylindrical tank	VV-SELF
vertical vessel D	vertical reaction vessel	VV-SELF
vertical vessel E	steel vertical vessel; H=27m, D=4.7m	VV-SELF
vertical vessel F	steel pressure vessel (H=3.3m, D=1.7m, operational internal pressure 12barg)	VV-SELF

Vertical stacks

Vertical stacks are characterized by a large vertical (steel) column with generally larger height to width ratio than the vertical vessel.

Table 4.9 lists the five objects classified as vertical stacks. The analysed objects consist of three vertical cylindrical columns, one chimney and one complex vertical structure. The latter is not a typical vertical stack structure, but it is classified as stack because from the available typologies it seems the most appropriate one (based on the expected behaviour of the structure).

Table 4.9 Industrial objects assigned to fragility curve for vertical stack

Object ID	Type of structure	Fragility curve (Label)
equipment B/building C	elevated shell structure with a vertical central shaft and self-supporting floors	ST-SELF
stack A	vertical cylindrical column	ST-SELF
stack B	chimney	ST-SELF
stack C	vertical cylindrical column	ST-SELF
stack D	vertical cylindrical column	ST-SELF

Elevated pipes

Elevated pipes can differ in size and length, and they are used to convey fluids are gasses. Elevated pipes are commonly supported by pipeline bridges. Pipelines directly attached to a storage tank, or a building is advised to be evaluated as non-structural components. For the sake of verification of applicability of the fragility curves of elevated pipelines, pipelines that are attached to storage tanks or buildings have been included.

The assessed failure mechanisms in the 'LoC toets' are mostly related to the pipe itself, connections with storage tanks and failure of nozzles. Unity checks are available on element level for checks such as yielding, and exceedance of capacity of connections.

Table 4.10 lists the 5 objects classified as elevated pipes. The analysed objects consist of three elevated pipelines, one pipeline attached to a vessel and one pipeline attached to a structure.

Table 4.10 Industrial objects assigned to fragility curve for elevated pipes

Object ID	Type of structure	Fragility curve (Label)
pipeline A	pipelines	EP-SELF
Pipeline B	pipeline on structure	EP-SELF
Pipeline D	pipeline attached to vessel	EP-SELF
Pipeline E	connected pipelines	EP-SELF
Pipeline F	pipelines	EP-SELF

4.1.3 Verification and discussion

In this paragraph the results from the Phase 2 calculation reports are compared with the fragility curves from literature to verify their applicability. The framework for the verification of the fragility functions is shown in Figure 4.1. In general, for each available calculation report, the following steps are performed:

1. The document is scanned, and the following information is extracted:
   - Type of structure, to determine typology from literature that best describes the structure.
   - Horizontal PGA level and location of object/company.
   - Results and description of relevant failure mechanisms (i.e., unity check, type of failure); if many failure mechanisms are described in the report, then only the mechanisms with UC larger than 0.5 are considered for the verification.
2. For each object an appropriate fragility function is assigned based on the typology of the object.
3. For each failure mechanism a damage state is chosen which corresponds to the state of the structure if this failure would occur (i.e., UC >1.0 for the particular failure mechanism).
4. The failure probabilities are computed for the extracted unity checks based on the method explained in paragraph 4.1.1.

5 The damage state exceedance probabilities P(Ds) are computed for the selected fragility function using the PGA level used in the report.
6 The computed probability of failures from step 4 and 5 are visualized in graphs.

The verification is based on the comparison of the damage state exceedance probabilities from the fragility curve against the derived probabilities from the calculation report. In general, two outcomes are possible:
- Damage state exceedance probability from fragility curves is larger than the probability derived for the failure mechanisms presented in the calculation report. Hence, the fragility curve yield more conservative results than the calculations in the report. Below we will denote this as 'conservative' based on the computed probabilities, even though the fragility function might yield much larger probabilities than the ones derived from the calculation reports.
- Damage state exceedance probability from fragility curve is smaller than the probability derived for the failure mechanisms presented in the calculation report. Hence, the fragility curve yields fewer conservative results than the calculations in the report. This only means that the fragility function is less conservative, but it remains unknown which of the two is closer to the 'true' failure probability. Therefore, this doesn't necessarily mean that the fragility function is not applicable, but the outcome might be less conservative.

A fragility curve is judged as not applicable and therefore is 'disqualified' when the damage state exceedance probability from fragility curve is consistently smaller than the probability derived for the failure mechanisms presented in the calculation report. In this case an alternative fragility is proposed, and its applicability is verified in the same manner. As it is explained in the following paragraphs, this appeared to be the case for two specific typologies: the elevated steel tanks and the non-structural components.

Building structures

The results for the building typologies are included in Appendix II. The applied fragility curves are the building fragility curves from (FEMA, 2020) adapted to the response spectra of Groningen as explained in paragraph 3.3.2.

In general, reasonable correspondence between the calculation results and the fragility functions is found. However, for 13 (out of 23) objects, for one up to three failure mechanisms, the calculated failure probability is higher than what is expected using the fragility function (i.e., fragility function is less conservative). This doesn't necessarily mean that the fragility functions are not applicable. The deviation in failure probability between the calculation reports and fragility function could be caused by several aspects, e.g., adopted calculation method in reports (linear elastic calculations), mismatch between typology and actual structure, method for conversion of unity check to probability of failure, uncertainty in parameters used in the report (if not explicitly given). Another reason for the deviations may be the fact that in the phase 2 analyses usually the three components of the seismic action are combined with several combination rules, while the fragility curves use as input the peak ground acceleration in a single horizontal direction. Below the most important observations for the calculation reports related to building structures are summarized.
- For objects with unreinforced masonry infill walls (Building A and Building O), the unity checks from 'LoC toets' verifications for the masonry are usually much larger than 1.0. This is not in line with the fragility functions. In the past the linear elastic methods used for masonry in the LoC program have been criticized. Based on the outcome of these discussions, the inconsistency between 'LoC toets' results is not considered a proper basis to revise fragility functions. Extensive effort has been made within (NPR 9998) program to develop appropriate calculation methods for masonry, which should be considered the best available method for assessment of masonry in industrial buildings in Groningen. Decisions on whether or not a masonry should be evaluated in detail can be made based on the severity of potential consequences of failure (people presence, pounding etc.).
- Objects which are not related to the whole building but represents the support structure of some critical object (e.g., storage tank, silo) which is located inside the building. In the report, the support structure, as part of the building, is analysed and thus a fragility curve from the general building stock seems most appropriate. Obviously, these fragility curves are derived for buildings without any (industrial) components inside and thus the dynamic effects of these objects are not included in the derivation of the fragility functions. Therefore, deviations could be expected.

- Building R is a concrete frame structure with lightweight concrete roof. The calculation report show that the structure does not satisfy the design requirements (with UC > 3.0). The computed probability of failure is 100 %, but this does not match the failure probability from the fragility curve of the selected typology 'Precast concrete frames with concrete shear walls'. However, this might be expected, as the lightweight concrete roof is not part of the typology description and related failure mechanisms are thus not included in the function. The mismatch between actual structure and the chosen typology might be one of the main sources of deviations in the computed failure probabilities. Careful selection of the fragility curve is thus important. It is recommended to either assign a 'conditional factor' in the tool, which is used as a multiplier on the total probability, or to choose for the conservative step function which is provided by the 'Other typology'.

Non-structural components

The results for the non-structural components are included in Appendix II. First, the calculation results are compared with the fragility curve for non-structural components from Hazus (FEMA, 2020). This analysis shows that the selected fragility curve is not appropriate in some cases (3 out of 10). It appears that mainly for components with non-rigid/weak supports (e.g., sliding support, friction support or non-braced frame/wall structure) the calculated failure probabilities are higher than what is expected using the fragility functions. Based on this outcome, it has been chosen to distinguish between non-structural components with weak support and rigid support:

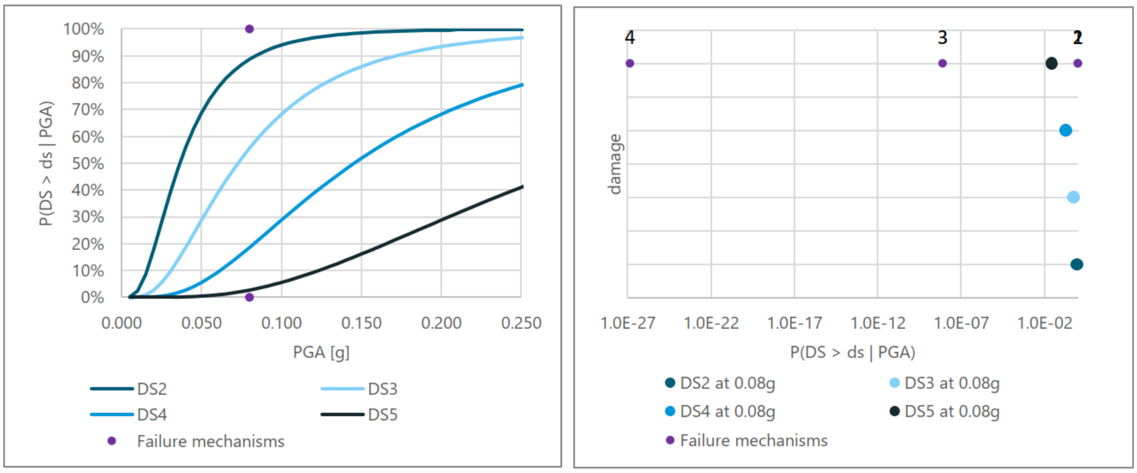
- Rigidly supported components have fixed supports in both horizontal directions and in vertical direction. For these components the fragility curve from Hazus (FEMA, 2020) may be used, where the median values are converted to PGA levels as described in paragraph 3.3.3.
- Weakly supported components have relative weak/free support in one of the horizontal directions. Weak support can be either sliding support, friction support, non-braced support frame/walls. For these components the step function fragility curve may be used where the step is located at 0.05 g.

It becomes apparent that for correct assignment of the typology in case of non-structural components the support type/structure must be known. If this is unknown, then one should choose the most conservative fragility curve corresponding to the components with weak support (i.e., step function).

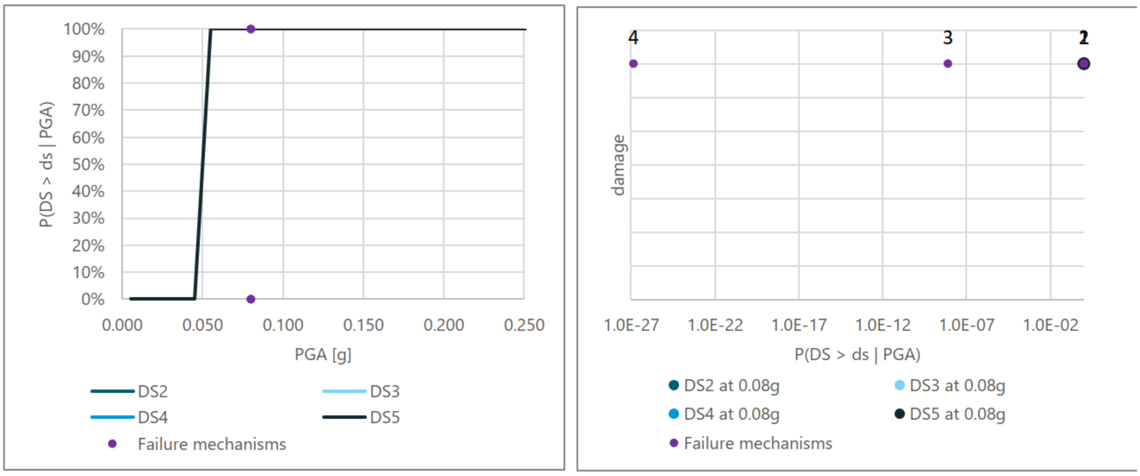
The effect of the adapted fragility curve on the verification results is presented in figure 4.6 for Equipment D. The top figure shows the verification results of the first analysis using the fragility curve from Hazus (FEMA, 2020), while the bottom figure shows the results for the updated fragility curve (i.e., procedure adopted in calculation tool). The support structure of the considered component is classified as weak and thus the step function is used as fragility curve.

Figure 4.6 Example verification results for non-structural components (Equipment D)

a) Initial results using Hazus



b) Final results where choice of fragility curve is based on type of support



Elevated steel tanks

The results for the elevated steel tanks are included in Appendix II. At first, the calculation results were compared with the fragility curve for above ground steel tank from Hazus (FEMA, 2020). This analysis shows that the selected fragility curve is not appropriate in most cases (4 out of 6 calculation results do not match). Further analysis of the (support) structure of the elevated tanks shows that the structures which do not match the fragility curve have very weak supports (at least in one horizontal direction). In general, the support structure appears to be the most critical part of the elevated tank. Therefore, for the selection of the fragility curve of elevated tanks, it is chosen to distinguish between braced support structure/moment frame or non-braced support structure (at least in one direction). The following applies (as explained in section 3.3.4):

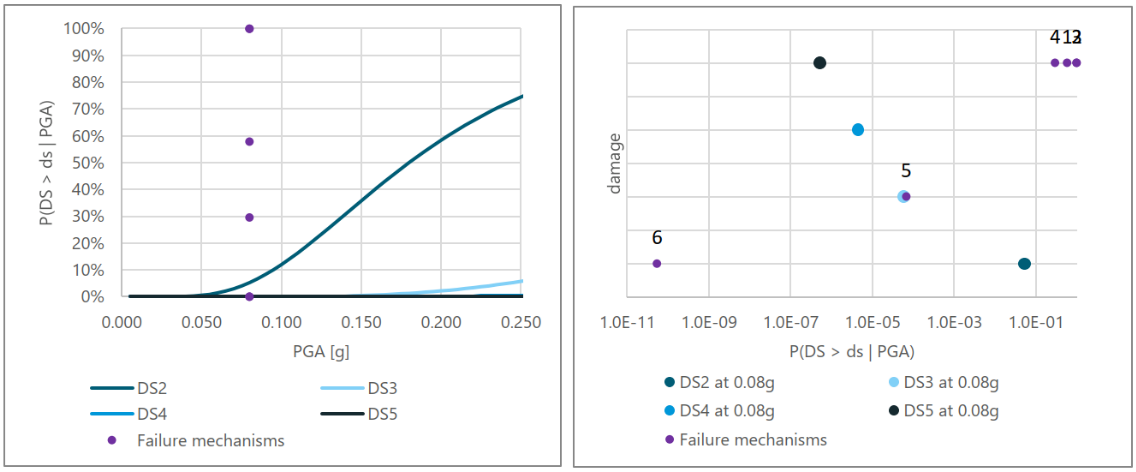
- For elevated tanks that are rigidly supported (e.g., braced frame, moment frame) in both lateral directions the fragility curve from ALA is used.
- For elevated tank that are weakly supported (e.g., non-braced frame) in at least one of the lateral directions the step function fragility curve with step at 0.05 g is used.

To assign the correct typology in case of an elevated tank structure the type of lateral support must be known. If this is unknown, then one should choose the most conservative fragility curve corresponding non-laterally supported elevated tank (i.e., step function).

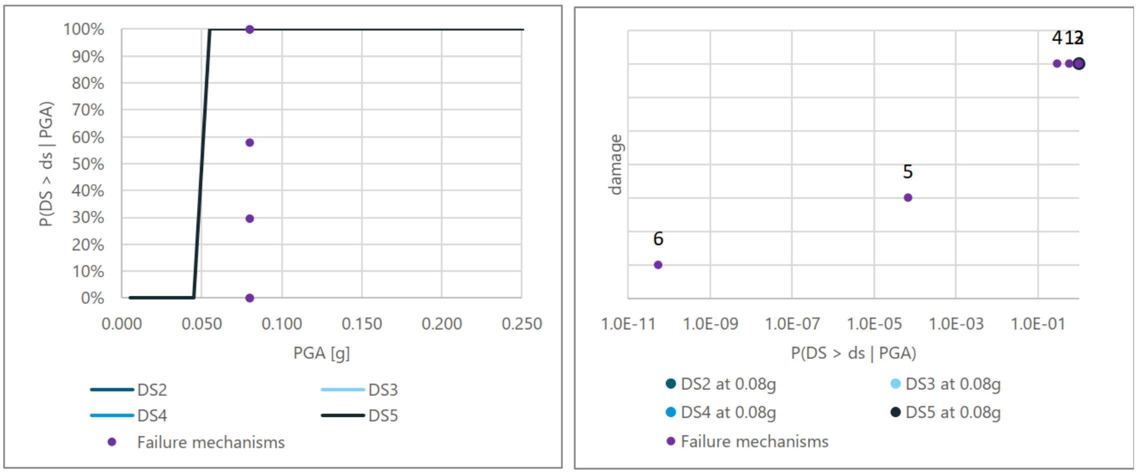
The effect of the adapted fragility curve on the verification results is presented for Elevated tank A in figure 4.7. The top figure shows the verification results of the first analysis using the fragility curve from Hazus (FEMA, 2020), while the bottom figure shows the results for the updated fragility curve (i.e., procedure adopted in calculation tool). The support structure of the considered tank is classified as non-braced structure and thus the step function is used as fragility curve.

Figure 4.7 Example verification results for non-structural components (Elevated tank A)

a) Initial results using Hazus



b) Final results using step function for non-laterally supported elevated tank structures



On-ground storage tanks

The results for the on-ground storage tanks are included in Appendix II. The calculation reports show good correspondence with the fragility curve for on-ground steel tank (unanchored) from Hazus (FEMA, 2020). For all failure mechanisms the computed probability of failure with the fragility curve is larger (i.e., more conservative) than derived from the calculation report. Except for some failure mechanisms related to the attached pipelines, which might indicate that the selected fragility curve should not be used for the assessment of attached pipelines.

Horizontal/vertical vessels

The results for the vessels are included in Appendix II In general, reasonable correspondence is found between the calculation results and the fragility curves for vertical and horizontal vessels. For three objects, one of the computed failure probabilities with the fragility function is lower (i.e., less conservative) than derived from the Phase 2 calculation reports. Notice, that this only applies to one of the failure mechanisms, while for the other failure mechanisms generally good correspondence is found. The differences are, however, not significant and therefore it is concluded that the fragility curves from Hazus (FEMA, 2020) are applicable.

Vertical stacks

The results for the vertical stacks are included in Appendix II. The calculation reports of the selected objects show good correspondence with the fragility curve for vertical stacks from Hazus (FEMA, 2020). Only for one deviation was observed but this is not considered typical for this typology. For all failure mechanisms the computed probability of failure with the fragility curve is larger (i.e., more conservative) than derived from the calculation report. The fragility function for vertical stacks is only defined for DS4, so a proper comparison of the failure probabilities for mechanisms with other damage state is not possible. Therefore, for the comparison, the damage state of all failure mechanisms is simply assumed to be DS4.

Elevated pipes

The results for the elevated pipes are included in Appendix II. The calculation reports of the selected objects show good correspondence with the fragility curve for elevated pipes from Hazus (FEMA, 2020).

Two deviations are observed for Pipeline B/ Company 12 and Pipeline F/ Company 14. However, these pipes do not match the typical description of elevated pipes. These two pipelines are attached to a building and to a vessel respectively. Therefore, for these types of objects it is recommended to use the more conservative fragility curves of non-structural components.

4.1.4 Summary

Table 4.11 summarizes the available number of reports per typology and how many of them consistent results show with the selected fragility curves for the typology. The labels/typology are grouped by category in accordance with previous paragraphs.

The verification results show that for some of the Phase 2 calculation reports the calculated failure probabilities are higher than what is expected based on the fragility functions (i.e., no conservative results results). However, this does not necessarily mean that the particular fragility function is not applicable as the comparison of failure probabilities has some implications. The most important points regarding the verification method are summarized below.

- Seismic load levels in Groningen are relatively low resulting in very small probabilities for both the failure and damage state exceedance. This means that in some cases the comparison is rather complex, and the use of a particular fragility function cannot be verified nor falsified.
- Unity checks in 'LoC toets' verifications refer to element level. Translating them to object level failure comes with some assumptions. In our evaluation we attempt to assign the best matching global damage state to the 'LoC toets' results. Especially for higher damage state results this is not always straight forward in case multiple components need to fail to result in global failure. For this reason, the comparisons made in this paragraph are not relevant for complete validation of fragility curves especially for higher damage states.
- For some objects a high failure probability (~100 %) is found for one or multiple failure mechanisms (related to a certain damage state). The obvious question is then whether the provided unity checks depict actual failure behaviour and whether exceedance of the linear capacity indeed implies that the element no longer provides any contribution to the overall structural stability? The applied q-factor in the 'LoC method' is relatively low at 1.5. For steel structures applying higher factors is allowed as long as certain detailing criteria are met. Likely these criteria are not met for the considered structures, but this does not necessarily mean it wouldn't give a better description of the actual behaviour.

The following conclusions can be drawn based on the comparison of the fragility functions with the Phase 2 calculation reports:

- Multiple typologies might be applicable to the structure (e.g., building type and non-structural component). If this is the case, then it is recommended to choose the typology which yield the highest failure probability (i.e., with lowest median values).
- Structures with unreinforced masonry (infill) walls shall not be assessed based on fragility functions. Decisions on whether or not a masonry should be evaluated in detail can be made based on the severity of potential consequences of failure (people presence, pounding etc.). The available fragility curves for steel or concrete frames with masonry infill are recommended only for the assessment of the structural frame and not of the infill.
- Structures with lightweight concrete roof shall not be assessed based on the fragility functions. Instead, a detailed analysis should always be performed.

- For the non-structural components two fragility curves are differentiated: 1) for laterally supported components the fragility curve from Hazus (FEMA, 2020) shall be used, 2) for non-laterally supported components the step function with threshold 0.05 g should be used.
- For elevated steel tanks two fragility curves are differentiated: 1) for elevated tanks with braced support structure the fragility function from ALA should be used, 2) for elevated tanks with non-braced support structure the step function with threshold 0.05 g should be used.
- From the verification of the calculation reports with on-ground storage tanks it was found that the assessment of the attached pipelines shows higher failure probabilities than expected from the fragility function. Therefore, the fragility function for on-ground storage tank from Hazus (FEMA, 2020) should not be used to assess connected pipelines.
- The fragility curve for elevated pipelines is recommended to be used for pipelines on pipeline bridges. For pipelines attached to vessels and buildings it is recommended to use the fragility curve for non-structural components.
- If an appropriate fragility function is not available, then the step function fragility function can be used (see paragraph 3.3.7). The threshold value below which the expected failure probability is assumed to be equal to 0 can be determined based on the verification results. In this manner the knowledge acquired through past engineering efforts can be used as well as possible within the presented risk calculation framework.

Table 4.11 Summary of verification results

Category	Label	Typology	No. reports	Disqualification of fragility curve from Hazus (FEMA, 2020)
building structures	C1L	concrete moment frame, low rise, 1-3 stories (typical height 7.3 m)	1	no, adapted to Groningen response spectra
	C2L	concrete shear walls, low rise, 1-3 stories (typical height 7.3 m)	1	no, adapted to Groningen response spectra
	C3L	concrete frame with unreinforced masonry infill walls, low rise, 1-3 stories (typical height 7.3 m)	1	no, adapted to Groningen response spectra. Not applicable for assessment of infill
	PC2L	precast concrete frames with concrete shear walls, low rise, 1-3 stories (typical height 7.3 m)	1	no, adapted to Groningen response spectra
	S1L	steel moment frame, low rise, 1-3 stories (typical height 7.3 m)	2	no, adapted to Groningen response spectra
	S2H	steel braced frame, high rise, 8+ stories (typical height 47.5 m)	3	no, adapted to Groningen response spectra
	S2L	steel braced frame, low rise, 1-3 stories (typical height 7.3 m)	4	no, adapted to Groningen response spectra
	S2M	steel braced frame, medium rise, 4-7 stories (typical height 18.3 m)	9	no, adapted to Groningen response spectra
	S5L	steel frame with unreinforced masonry infill walls, low rise, 1-3 stories (typical height 7.3 m)	1	no, adapted to Groningen response spectra. Not applicable for assessment of infill
non-structural components	NS-WEAK	non-structural components in structure (weak supports)	9	yes, propose step function as fragility curve
	NS-RIGID	non-structural components in structure (rigid supports, 100 % building height)	1	no
elevated steel tanks	PSTAS-B	elevated tank (braced)	3	yes, propose fragility curve from ALA
	PSTAS-NB	elevated tank (non-braced)	3	yes, propose step function as fragility curve

Category	Label	Typology	No. reports	Disqualification of fragility curve from Hazus (FEMA, 2020)
on-ground steel tanks	PSTGS	on-ground unanchored steel tank	5	no
horizontal/ vertical vessel	VV-SELF	large vertical vessels with formed heads, unanchored	6	no
	HV-SELF	large horizontal vessels, unanchored	1	no
vertical stacks	ST-SELF	stacks, unanchored	5	no
elevated pipes	EP-SELF	elevated pipes	5	no

4.2 Considerations in relation to other methods

In this section a brief comparison is made to other methods developed within the prescribed framework for seismic risk assessments of industrial facilities in Groningen, being the Deltares/TNO Phase 1 - Phase 2 risk-based method (Deltares & TNO, 2018) and the Arcadis 'Selectiemethodiek' (Arcadis, 2020). The Deltares/TNO Phase 1 method is used for Phase 1 assessments of all industries in the Groningen field area. The Deltares/TNO Phase 2 and the 'LoC toets' methods are two alternative methods developed in parallel for Phase 2 (quantitative) assessments of earthquake resistance of structures. No comparison is made here to the 'LoC toets' method, because this method is based on a deterministic seismic load which cannot be expressed in terms of annual probability of exceedance. An overview of all methods referred to is presented in (Witteveen+Bos, In progress).

4.2.1 Considerations in relation Deltares/TNO risk-based method

The Selection method Step II tool presented in this report is not directly comparable to the Deltares/TNO risk-based method - Phase 2. The method described in this report however is directly comparable to the Deltares/TNO risk-based method - Phase 1. The important difference is that the Selection method Step II tool reported in the present document results in risk quantification whereas the prescribed Phase 1 approach was in essence more qualitative, differentiating between low seismic risk, medium seismic risk and high seismic risk structures. Industrial assets qualifying as low seismic risk in Phase 1 were not selected for further Phase 2 calculations.

From this perspective one could argue that a risk matrix-based assessment focussing directly on LoC consequences rather than indirectly by means of consequence classes was integrated in the Deltares/TNO approach. What the present method basically incorporates is an upgrade of the Phase 1 approach to a standardized and quantitative assessment tool. Standardization here applies to the structural failure probability estimation, the conditional factors to be taken into account and the risk matrix to be used.

A structure selected for a Phase 2 assessment according to the Deltares/TNO risk-based method is assigned to a consequence class, based on the potential safety and environmental risks of failure of the structure. The basis of the consequence class framework of the Deltares/TNO risk-based method is twofold:

1. Failure probabilities of industrial structures due to earthquake exposure shall comply with external safety regulations, which implies that the risk increase due to earthquakes shall be less than 10 % of the risk level without earthquake contribution.
2. Return periods of design seismic loads are consistent with international practice, in order to ensure that not only compliance with Dutch external safety targets is ensured, but also compliance with safety for people working on industrial sites and environment pollution risks.

On this basis acceptable annual failure probabilities of typical industrial installations and corresponding return periods of seismic loads are defined. At the level of acceptable annual failure probabilities, the method is comparable to the method described in this report. In terms of seismic load return period no direct comparison can be made because hazard levels have been reduced over time. In terms of acceptable scenario probabilities, a comparison however could be made.

The risk-matrix based approach does not directly incorporate consequence class differentiation and directly relates the identified severity of consequences of LoC to a likelihood category that is considered to be acceptable. The highest severity category typically assigned in risk matrices used in industry practice represents >2 fatalities. When comparing to the Deltares/TNO risk-based method this would, based on the number of fatalities, be roughly equivalent to consequence class III or IV. It is noted by Deltares/TNO that consequence class V only applies to structures having exceptional risks in case of failure and we will not focus on this category in the comparison presented here. Table 4.12 summarizes the comparison made, concluding that the methods are in reasonable agreement for high consequence low probability events. The risk matrix-based approach seems to be a bit stricter, qualifying the 'tolerable' scenario probabilities according to Deltares/TNO as ALARP.

Table 4.12 Comparison of the Selection method Step II tool to the Deltares/TNO risk-based assessment framework

	Consequence class II	Consequence class III	Consequence class IV
acceptable probability major LoC/major failure per year according to Deltares/TNO*	$5*10^{-5}$	10^{-5}- $5*10^{-6}$	$5*10^{-6}$ - 10^{-6}
anticipated conditional probability of fatalities on-site given failure by Deltares/TNO	<0.1 (0.01 - 0.1)	<0.3 (0.1 - 0.3)	<1.0 (0.3 - 1.0)
anticipated conditional probability of fatalities public given failure by Deltares/TNO	<0.01 (0.001 - 0.01)	<0.1 (0.01 - 0.1)	<0.3 (0.1 - 0.3)
anticipated probability of fatalities scenario on-site	$<5*10^{-6}$	$<1.5*10^{-6}$ - $3*10^{-6}$	$<5*10^{-6}$ - 10^{-6}
anticipated probability of fatalities scenario public	$<5*10^{-7}$	$<5*10^{-7}$ - 10^{-6}	$<3*10^{-7}$ - $1.5*10^{-6}$
equivalent risk matrix severity category	IV	V	V
SIL Platform risk matrix classification following from failure probability and fatalities conditional probability - on-site	blue	yellow	yellow
SIL Platform risk matrix classification following from failure probability and fatalities conditional probability - public	blue	yellow	yellow
conclusion about consistency of methods	SIL platform risk matrix in agreement with Deltares/TNO method	SIL platform risk matrix tolerates lower risks compared to Deltares/TNO method	SIL platform risk matrix tolerates lower risks compared to Deltares/TNO method

* Depending on the type of object/equipment, in some cases indirectly derived in relation to the acceptable probability of minor damage/leakage.

A few remarks should be made here, which are planned to be addressed in the upcoming review Phase:

- The Deltares/TNO risk targets are derived based on high consequence low probability events. Although these events are important, comparison with low consequence high probability cannot be made because this has not been evaluated as a basis for the Deltares/TNO method.
- Strictly speaking there is no differentiation between consequence classes III, IV en V (according to the Deltares/TNO method) in risk matrix approach. All three consequence classes are associated with multiple fatalities.

- Return periods are function of the hazard level, which was at the time of development of the Deltares/TNO risk-based approach the KNMI v1/NPR 2015 model. The conversion to return periods needs to be updated to match the most recent hazard level predictions. For the comparison made here there are no implications of this limitation.

4.2.2 Considerations in relation to Arcadis Selectiemethodiek

Whereas the method described in the present report performs a full, but simplified, risk calculation, this is not the case for the Selectiemethodiek. The Selectiemethodiek instead is more like a filter and/or correction to be applied to the variety of Phase 1 risk assessments performed for industry in Groningen. The method applies corrections to risk assessment results based on new insights that have developed over the last few years relating to hazard levels, fragility of structures and other factors that influence the ultimate safety and environmental risks.

A direct comparison between the two methods in terms of results therefore cannot be made. However, the Selectiemethodiek is conclusive when it comes to conditional factors that shall be taken into account when performing seismic risk assessments for industrial assets. These factors have been adopted in the risk assessment tool describe in the present report, with some slight modifications in order to ensure internal consistency of the method developed here. A summary is provided by table 4.13.

Table 4.13 Summary of conditional factors of the Arcadis Selectiemethodiek Stap I and outline how these are incorporated in the Selection method Step II

Conditional factor Selectiemethodiek Stap I	Integration in Selection method Step II
probability reduction piping and storage tanks	should already be covered by the fragility function parameters of piping and tanks and this trend is confirmed by the fragility function parameters listed in paragraph 3.3
probability reduction people presence (blootstellingskans)	directly adopted in the present selection method step II
probability reduction pounding	pounding and common cause are mechanisms that relate to a link between failure of different objects. a specific conditional factor is included in the method to address these relations
effect limitation fail-safe systems	directly adopted in the present selection method step ii method. actual value of conditional factor that applies for a specific case is to be selected by the user
effect limitation secondary containment	risk limitation due to secondary containment should already be well reflected in the scenario definition. in this case any further reduction factor does not apply. if under specific circumstances the factor is for a good reason not applied on the effect but on the probability, this is allowed for by introducing a specific other conditional factor. this alternative option allows for example to also better cover common-cause scenarios
effect limitation emergency-protocols being in place	not adopted because not in any case a reliable risk mitigation measure as it would rely on human behaviour under totally new, highly stressful, untrained conditions

4.3 Pilot studies

This paragraph summarizes the observations from the pilot calculations that have been performed with the Selection method Step II tool. The pilot calculations have been performed for 8 different installations of 4 different industrial companies. For these randomly selected installations both a Phase 1 assessment and Phase 2 calculation were available. Since for all these installations (at least) a Phase 2 calculation has been performed, implies that all these 8 installations have been prioritized based on the Phase 1 assessment.

Comparison of the outcome of the pilot calculations against the Phase 1 assessment and the Phase 2 calculations helps us understand whether the Selection method Step II tool can be applied and provides reasonable results.

The pilot calculations have been performed for two-time windows of the seismic hazard in Groningen, in order observe the sensitivity of the hazard in the final outcome:
- T4: 01 October 2020 until 30 September 2021.
- T6: 01 October 2023 until 30 September 2029.

Regarding the pilot calculations it is noted that:
- The consequence class that was selected during the Phase 1 assessment is adopted unless the company representative indicated differently.
- For all the installation only the LoC scenario of total collapse has been assessed.

Table 4.14 summarizes the results of the pilot calculations performed with the Selection method Step II tool for 8 installations. For comparison the same table presents the results from Phase 1 assessment and Phase 2 calculations. For the evaluation of the risk for each installation (refer to colours in table 4.14) the risk matrix adopted by the corresponding industrial company is used.

Table 4.14 Summary of pilot calculations. With the colour in parenthesis is indicated the risk in the company specific risk matrix

Object no.	Object type	Phase 2		Phase 1 result	Selection method Step II, T4	Selection method Step II, T6
		max UC	Conclusion			
1	steel braced frame 1-3 stories	0.84	no LoC	Prob: E (1.61E-3) Cons: 3 out of 4 (RED)	9.48E-05 (YELLOW)	3.83E-05 (YELLOW)
2	non-structural components (weak supports)	4	not sufficient capacity (LoC)	Prob: D (2.43E-4) Cons: 4 out of 4 (RED)	3.05E-04 (RED)	1.33E-04 (RED)
3	concrete moment frame, low rise, 1-3 stories.	0.6	no LoC	Prob: D (4.86E-4) Cons: 4 out of 4 (RED)	6.50E-06 (YELLOW)	2.81E-06 (YELLOW)
4	large horizontal vessels, unanchored	0.95	no LoC	Prob: C Cons: 5 out of 5 (RED)	8.42E-06 (YELLOW)	3.68E-06 (YELLOW)
5	elevated pipe	0.92	no LoC	Prob: C Cons: 5 out of 5 (RED)	3.53E-05 (YELLOW)	1.54E-05 (YELLOW)
6	large vertical vessels with formed heads, unanchored	0.9	no LoC	Prob: C Cons: 3 out of 5 (YELLOW)	7.00E-07 (BLUE)	3.06E-07 (BLUE)
7	elevated tank, non-braced	1.25	not sufficient capacity (LoC)	Prob: C Cons: III out of V (YELLOW)	6.10E-03 (YELLOW)	2.66E-03 (YELLOW)
8	elevated tank, non-braced	2.44	not sufficient capacity (LoC)	Prob: E Cons: IV out of V (RED)	6.10E-03 (RED)	2.66E-03 (RED)

The most interesting observations from the pilot calculations are summarized below:

- Compared to the Phase 1 assessments, the calculated scenario probabilities with the Selection method Step II tool are in principle lower and more consistent in connection with the outcome of the Phase 2 calculations.
- One reason for lower scenario probability is the reduced seismic hazard level, even of the T4 time window, compared to the hazard predictions at the time back in 2015/2016 when most Phase 1 assessments were done.
- Another reason for lower scenario probability is that in the Phase 1 assessments of two companies the liquefaction probability is accounted for in the total scenario probability. In the selection method Step II tool liquefaction probability is not accounted for in the total scenario probability. The scenario probability is disregarded from any geotechnical consideration. The geotechnical aspect is treated separately, by providing a recommendation with respect to further assessment of the foundation based on the type of foundation and the seismic hazard at the specific location. This assessment can be very efficiently performed for multiple assets of a company at once.
- Due to decreased hazard (from T4 to T6) it is observed that the scenario probability is decreased by a factor of more than 2. However, the risk as evaluated by the risk matrix colours remains the same.
- All the installations that are assessed in the pilots are founded on pile foundations. Due to reduced hazard (from T4 to T6) the recommendation for foundation assessment has also been reduced:
    - **For T4**: For the seismic hazard level at the location according to NPR 9998:2020 risks associated with loss of bearing capacity of piles cannot be neglected and both STR and GEO limit state assessment is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen+Bos)). Reference also to NPR 9998:2020 par. 10.4.1.
    - **For T6**: The risk of loss of bearing capacity due to structural damage of piles is sufficiently low for the seismic hazard level that applies to the location. Only a GEO limit state assessment (liquefaction verification) is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen+Bos)). Reference also to NPR 9998:2020 par. 10.4.1.
- Risk of pounding is covered in the Selection method Step II tool by filling in a separate scenario probability sheet for the installation that introduces the risk of pounding. The calculated scenario probability of the installation that introduces the risk of pounding is added to the scenario probability of the under-investigation installation in terms of a conditional factor. In the Phase 1 assessment of two companies this scenario is directly coupled to the object that contains the hazardous materials.
- All the Phase 1 assessments considered in pilot calculations are using company specific risk matrices. The selection method Step II tool gives the opportunity to use either a company specific risk matrix or the SIL risk matrix.
- Phase 1 assessment of one company is performed quantitatively and is very close to the approach followed in the Selection method Step II tool. Phase 1 assessment from the other company is performed semi-quantitatively. The Phase 1 assessment of the other two companies is performed purely qualitatively.
- The pilot calculations of two of the companies have been performed in collaboration with company representatives. Based on the pilot cases it is concluded that the Selection method Step II tool allows to incorporate the required scenario redundancy factors that were addressed by the company representatives.

5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This document reports the relevant background for the use of the method and calculation tool of Selection method Step II for earthquake risk assessments for industrial assets in Groningen. The Selection method Step II method combines latest insights in the location specific probabilistic seismic hazard in Groningen, empirical generic functions of seismic resistance of buildings and installations and common principles of scenario-based risk assessments for the chemical- or process industry (SIL Platform, 2018).

Applicability of empirical fragility functions from international literature is evaluated by means of comparison to all available Phase 2 calculation results. This evaluation in general results a consistent pattern. However, for specific structure typologies comparison with the Phase 2 reports implies that fragility curves consistently overestimate resistance. These typologies are the elevated tanks and the non-structural components. For these typologies it has been decided to disqualify the fragility curves proposed in Hazus (FEMA, 2020) for evaluation of assets in Groningen. For the elevated tanks and non-structural components more conservative fragility curves are proposed and as such included in the calculation tool. For steel or concrete structures with masonry infill the fragility curves provided in the tool are applicable only for the assessment of the steel or concrete frame. For the masonry infill it is recommended to perform a detailed analysis in case severe consequences can be associated with out of plane failure of masonry walls.

The developed Selection method Step II tool is compared on a basic level to previously developed instruments/ methods for seismic assessment of industrial assets in Groningen. It is concluded that the developed tool seems well aligned with the Deltares/TNO risk-based framework (Deltares & TNO, 2018) and the Selectiemethodiek Stap I (Arcadis, 2020).

Finally, the performance of the tool has be evaluated through pilot calculations performed for four industrial companies in Groningen. The pilot calculations show that the Selection method Step II tool performs as expected. Compared to the Phase 1 assessments, the calculated scenario probabilities with the Selection method Step II tool are in principle lower and more consistent with the outcome of the Phase 2 calculations.

6

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Appendices

APPENDIX: BUILDING FRAGILITY CURVES

Witteveen+Bos

MEMORANDUM

Subject	Development fragility curves for buildings based on HAZUS technical manual
Project code	124217
Date	4 May 2021
Reference	-
Author(s)	J. de Bruijn MSc
Appendices	A response spectra according to NPR 9998:2020
	B median equivalent-PGA values from HAZUS(reproduced)
	C median equivalent-PGA values for Groningen
To	-
Copy	-

1 INTRODUCTION

1.1 Background

In Section 5 of the HAZUS technical manual (FEMA, 2020), fragility functions for the general building stock are described. The building fragility functions are in the form of lognormal distribution that relate the probability of being in, or exceeding, a damage state to a given earthquake hazard (e.g. PGA). Each fragility function is defined by a median value and by the variability (denoted as β) associated with that damage state. In HAZUS these median and variability values are given for the general building stock in terms of spectral displacement and PGA. The latter are referred to as equivalent-PGA fragility curves and the development of these functions is the main topic of this memo.

The equivalent-PGA fragility curves developed in HAZUS are based on a demand spectrum for large magnitude, Western United States (WUS) ground shaking at soil sites. Hence, these functions are only appropriate for use in the evaluation of scenario earthquakes whose demand spectrum shape is based on, or similar to, these type of spectra. Given the considerable different response spectrum for induced earthquakes in Groningen, the equivalent-PGA fragility curves from HAZUS cannot be applied directly in the assessment. In this memo, median values of equivalent-PGA fragility curves are developed using response spectra for Groningen. The variability β is not adjusted, assuming that the variability associated with ground shaking is mainly associated to the structure typology..

1.2 Aim

The aim of this memo is as follows:
- To give some background about the structural fragility curves for buildings developed in the HAZUS technical manual (FEMA, 2020).
- To develop equivalent-PGA fragility curves using location-specific response spectrum for Groningen.

2 BUILDING STOCK

2.1 Description building types

Table 2.1 lists the 35 specific building types that are described in the HAZUS technical manual (excluding mobile homes). Typologies that are implemented in the calculation tool are highlighted, the other building types are merely used to verify the method for derivation of equivalent-PGA fragility curves. A general description, including sketches of typical configurations of each of the 16 structural systems of the building types is given in FEMA 454 (FEMA 454, 2006).

The derivation of equivalent-PGA fragility curves according to HAZUS requires the following building-specific information:

- A capacity curve, specifying the strength of the building (section 2.2)
- A displacement fragility curve based on predefined drift-ratio for the building (section 2.3).

These input requirements are described in the next two sections.

Table 2.1 Overview building types; Table 5-1 from HAZUS (FEMA, 2020)

#	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Meter*
1	W1	Wood, Light Frame (≤ 465 m2)		1-2	1	4.27
2	W2	Wood, Commercial & Industrial (> 465 m2)		All	2	7.32
3	S1L	Steel Moment Frame	Low-Rise	1-3	2	7.32
4	S1M		Mid-Rise	4-7	5	18.29
5	S1H		High-Rise	8+	13	47.55
6	S2L	Steel Braced Frame	Low-Rise	1-3	2	7.32
7	S2M		Mid-Rise	4-7	5	18.29
8	S2H		High-Rise	8+	13	47.55
9	S3	Steel Light Frame		All	1	4.57
10	S4L	Steel Frame with Cast-in-Place Concrete Shear Walls	Low-Rise	1-3	2	7.32
11	S4M		Mid-Rise	4-7	5	18.29
12	S4H		High-Rise	8+	13	47.55
13	S5L	Steel Frame with Unreinforced Masonry Infill Walls	Low-Rise	1-3	2	7.32
14	S5M		Mid-Rise	4-7	5	18.29
15	S5H		High-Rise	8+	13	47.55
16	C1L	Concrete Moment Frame	Low-Rise	1-3	2	6.10
17	C1M		Mid-Rise	4-7	5	15.24
18	C1H		High-Rise	8+	12	36.58
19	C2L	Concrete Shear Walls	Low-Rise	1-3	2	6.10
20	C2M		Mid-Rise	4-7	5	15.24
21	C2H		High-Rise	8+	12	36.58
22	C3L		Low-Rise	1-3	2	6.10

#	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Meter*
23	C3M	Concrete Frame with Unreinforced Masonry Infill Walls	Mid-Rise	4-7	5	15.24
24	C3H		High-Rise	8+	12	36.58
25	PC1	Precast Concrete Tilt-Up Walls		All	1	4.57
26	PC2L	Precast Concrete Frames with Concrete Shear Walls	Low-Rise	1-3	2	6.10
27	PC2M		Mid-Rise	4-7	5	15.24
28	PC2H		High-Rise	8+	12	36.58
29	RM1L	Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms	Low-Rise	1-3	2	6.10
30	RM1M		Mid-Rise	4+	5	15.24
31	RM2L	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	Low-Rise	1-3	2	6.10
32	RM2M		Mid-Rise	4-7	5	15.24
33	RM2H		High-Rise	8+	12	36.58
34	URML	Unreinforced Masonry Bearing Walls	Low-Rise	1-2	1	4.57
35	URMM		Mid-Rise	3+	3	10.67

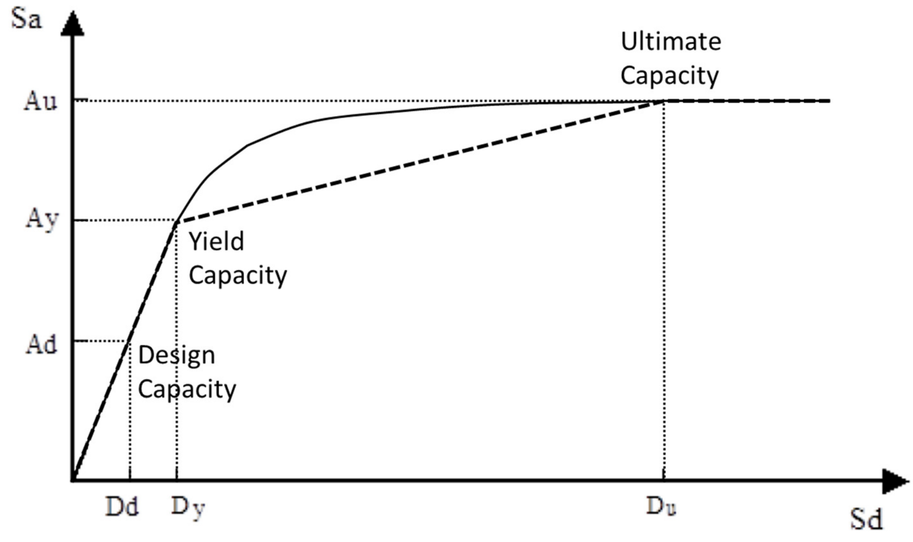
*unit conversion 1 feet = 0.3048 meter

2.2 Capacity curves

The building capacity curves developed for the HAZUS methodology are based engineering design parameters and judgement. Three control points that define model building capacity describe each curve: design capacity, yield capacity and ultimate capacity. Design capacity represents an estimate of the nominal strength for buildings not designed for earthquake loads. Wind design is not considered in the estimation of design capacity. Yield capacity represents the true lateral strength of the building considering redundancies in design, conservatism in code requirements, and true (rather than nominal) strength of materials. Ultimate capacity represents the maximum strength of the building when the global structural system has reached a fully plastic state.

A tri-linear capacity curve is assumed, that is defined by two control points provided in HAZUS: yield capacity and ultimate capacity (refer to Table 2.3.). The capacity curve is assumed to remain plastic past the ultimate point. An example building capacity curve is shown in Figure 2.1.

Figure 2.1 Example building capacity curve



The control points of the capacity curve are computed using the following expressions:

$A_y = C_s\gamma/\alpha_1$	acceleration at yield capacity point
$D_y = 9.81 * A_y * (T_e/2\pi)^2$	displacement at yield capacity point
$A_u = \lambda A_y$	acceleration at ultimate capacity point
$D_u = \lambda\mu D_y$	displacement at ultimate capacity point

These control points are defined based on estimates of engineering properties. These properties are defined by the following parameters:

C_s design strength coefficient (fraction of building's weight)
T_e true 'elastic' fundamental-mode period of building
α_1 fraction of building weight effective in push-over mode
α_2 fraction of building height location of push-over mode displacement
γ 'overstrength' factor relating 'true' yield strength to design strength
λ 'overstrength' factor relating ultimate strength to yield strength
μ 'ductility' factor relating ultimate displacement to λ times the yield displacement (i.e. assumed point of significant yielding of the structure)

The design strength, C_s, is based on the best estimate of typical design properties for a certain design level (High-Code, Moderate-Code, Low-Code and Pre-Code). For Groningen we assume the lowest seismic design level (i.e. Pre-Code) as the industrial structures were not designed to withstand earthquakes.

Values of the building capacity parameters are given in Table 5-4, Table 5-5 and Table 5-6 of the HAZUS technical manual. A summary of the parameters for Pre-Code design level is given in Table 2.2.

Table 2.2 Building capacity parameters for Pre-Code seismic design level (FEMA, 2020)

Label	**Height to roof** [m]*	**Period, T_e** [s]	**Modal factors**		**Overstrength ratios**		**Design strength, C_s**	**Ductility, μ**
			Weight, α_1	Height, α_2	Yield, γ	Ultimate, λ		
W1	4.27	0.35	0.75	0.75	1.50	3.00	0.100	6.0
W2	7.32	0.40	0.75	0.75	1.50	2.50	0.050	6.0
S1L	7.32	0.50	0.80	0.75	1.50	3.00	0.033	5.0

Label	Height to roof [m]*	Period, T_e [s]	Modal factors		Overstrength ratios		Design strength, C_s	Ductility, μ
			Weight, α_1	Height, α_2	Yield, γ	Ultimate, λ		
S1M	18.29	1.08	0.80	0.75	1.25	3.00	0.025	3.3
S1H	47.55	2.21	0.75	0.60	1.10	3.00	0.017	2.5
S2L	7.32	0.40	0.75	0.75	1.50	2.00	0.050	5.0
S2M	18.29	0.86	0.75	0.75	1.25	2.00	0.050	3.3
S2H	47.55	1.77	0.65	0.60	1.10	2.00	0.038	2.5
S3	4.57	0.40	0.75	0.75	1.50	2.00	0.050	5.0
S4L	7.32	0.35	0.75	0.75	1.50	2.25	0.040	5.0
S4M	18.29	0.65	0.75	0.75	1.25	2.25	0.040	3.3
S4H	47.55	1.32	0.65	0.60	1.10	2.25	0.030	2.5
S5L	7.32	0.35	0.75	0.75	1.50	2.00	0.050	5.0
S5M	18.29	0.65	0.75	0.75	1.25	2.00	0.050	3.3
S5H	47.55	1.32	0.65	0.60	1.10	2.00	0.038	2.5
C1L	6.10	0.40	0.80	0.75	1.50	3.00	0.033	5.0
C1M	15.24	0.75	0.80	0.75	1.25	3.00	0.033	3.3
C1H	36.58	1.45	0.75	0.60	1.10	3.00	0.017	2.5
C2L	6.10	0.35	0.75	0.75	1.50	2.50	0.050	5.0
C2M	15.24	0.56	0.75	0.75	1.25	2.50	0.050	3.3
C2H	36.58	1.09	0.65	0.60	1.10	2.50	0.038	2.5
C3L	6.10	0.35	0.75	0.75	1.50	2.25	0.050	5.0
C3M	15.24	0.56	0.75	0.75	1.25	2.25	0.050	3.3
C3H	36.58	1.09	0.65	0.60	1.10	2.25	0.038	2.5
PC1	4.57	0.35	0.50	0.75	1.50	2.00	0.050	5.0
PC2L	6.10	0.35	0.75	0.75	1.50	2.00	0.050	5.0
PC2M	15.24	0.56	0.75	0.75	1.25	2.00	0.050	3.3
PC2H	36.58	1.09	0.65	0.60	1.10	2.00	0.038	2.5
RM1L	6.10	0.35	0.75	0.75	1.50	2.00	0.067	5.0
RM1M	15.24	0.56	0.75	0.75	1.25	2.00	0.067	3.3
RM2L	6.10	0.35	0.75	0.75	1.50	2.00	0.067	5.0
RM2M	15.24	0.56	0.75	0.75	1.25	2.00	0.067	3.3
RM2H	36.58	1.09	0.65	0.60	1.10	2.00	0.050	2.5
URML	4.57	0.35	0.50	0.75	1.50	2.00	0.067	5.0
URMM	10.67	0.50	0.75	0.75	1.25	2.00	0.067	3.3

*unit conversion 1 feet = 0.3048 meter

Using the building capacity parameters from the table above, the control points of the capacity curve can be computed. Table 2.3 summarizes the yield- and ultimate capacity control point for Pre-code seismic design level.

Table 2.3 Building capacity curves for Pre-code seismic design level.

Label	Yield capacity point		Ultimate capacity point	
	Dy [m]	Ay [g]	Du [m]	Au [g]
W1	0.0061	0.200	0.1096	0.600
W2	0.0040	0.100	0.0596	0.250
S1L	0.0038	0.062	0.0577	0.186
S1M	0.0113	0.039	0.1121	0.117
S1H	0.0303	0.025	0.2270	0.075
S2L	0.0040	0.100	0.0398	0.200
S2M	0.0153	0.083	0.1011	0.167
S2H	0.0501	0.064	0.2503	0.129
S3	0.0040	0.100	0.0398	0.200
S4L	0.0024	0.080	0.0274	0.180
S4M	0.0070	0.067	0.0520	0.150
S4H	0.0220	0.051	0.1236	0.114
S5L	0.0030	0.100	0.0304	0.200
S5M	0.0087	0.083	0.0577	0.167
S5H	0.0278	0.064	0.1392	0.129
C1L	0.0025	0.062	0.0369	0.186
C1M	0.0072	0.052	0.0714	0.155
C1H	0.0130	0.025	0.0977	0.075
C2L	0.0030	0.100	0.0381	0.250
C2M	0.0065	0.083	0.0536	0.208
C2H	0.0190	0.064	0.1187	0.161
C3L	0.0030	0.100	0.0342	0.225
C3M	0.0065	0.083	0.0482	0.188
C3H	0.0190	0.064	0.1068	0.145
PC1	0.0046	0.150	0.0457	0.300
PC2L	0.0030	0.100	0.0304	0.200
PC2M	0.0065	0.083	0.0429	0.167
PC2H	0.0190	0.064	0.0949	0.129
RM1L	0.0041	0.134	0.0408	0.268
RM1M	0.0087	0.112	0.0574	0.223
RM2L	0.0041	0.134	0.0408	0.268
RM2M	0.0087	0.112	0.0574	0.223
RM2H	0.0250	0.085	0.1249	0.169
URML	0.0061	0.201	0.0612	0.402
URMM	0.0069	0.112	0.0458	0.223

*The values in this table are directly computed using the parameters from Table 2.2 instead of converting Table 5-10 from HAZUS technical manual.

2.3 Spectral displacement fragility curves

The development of median values of equivalent-PGA fragility curves is based on the structural fragility curves in terms of spectral displacement. In particular, the median values of spectral displacement for different damage states are used as the intersection point between capacity curve and demand spectrum (full derivation is explained in more detail in chapter 4). For now it is important to remember that the median values for structural fragility are included here because we need them later for the derivation of equivalent-PGA fragility.

In HAZUS the median values of structural component fragility are based on building drift ratio that describe the threshold of damage states. Damage state drift ratios are converted to a median value of spectral displacement using the following relation

$$\bar{S}_{d,ds} = \delta_{R,Sds} * \alpha_2 * h$$

where $\delta_{R,Sds}$ is the drift ratio at the threshold of the structural damage state, α_2 is the fraction of the building height at the location of push-over mode displacement and h is the typical roof height of the specific building type, refer to Table 2.2. Values of damage state drift ratios are given by HAZUS, and are partly based on a study by OAK Engineering (OAK, 1994) that reviewed and synthesized available drift/damage information from a number of published sources. Furthermore, some assumptions are made in HAZUS to relate drift ratios for different damage states and seismic design levels. Table 2.4 summarizes the drift ratios and median spectral displacement values for slight, moderate, extensive and complete structural damage states for Pre-code design level.

Table 2.4 Drift ratios and median spectral displacements for different damage states for Pre-code design level (FEMA, 2020)

Label	Height [m]	α_2	Drift ratio at threshold of damage state				Median spectral displacement [m]			
			DS2	DS3	DS4	DS5	DS2	DS3	DS4	DS5
W1	4.27	0.75	0.0032	0.0079	0.0245	0.0600	0.010	0.025	0.078	0.192
W2	7.32	0.75	0.0032	0.0079	0.0245	0.0600	0.018	0.043	0.134	0.329
S1L	7.32	0.75	0.0048	0.0076	0.0162	0.0400	0.026	0.042	0.089	0.219
S1M	18.29	0.75	0.0032	0.0051	0.0108	0.0267	0.044	0.070	0.148	0.366
S1H	47.55	0.60	0.0024	0.0038	0.0081	0.0200	0.068	0.108	0.231	0.571
S2L	7.32	0.75	0.0040	0.0064	0.0160	0.0400	0.022	0.035	0.088	0.219
S2M	18.29	0.75	0.0027	0.0043	0.0107	0.0267	0.037	0.059	0.147	0.366
S2H	47.55	0.60	0.0020	0.0032	0.0080	0.0200	0.057	0.091	0.228	0.571
S3	4.57	0.75	0.0032	0.0051	0.0128	0.0350	0.011	0.017	0.044	0.120
S4L	7.32	0.75	0.0032	0.0051	0.0128	0.0350	0.018	0.028	0.070	0.192
S4M	18.29	0.75	0.0021	0.0034	0.0086	0.0233	0.029	0.047	0.118	0.320
S4H	47.55	0.60	0.0016	0.0026	0.0064	0.0175	0.046	0.074	0.183	0.499
S5L	7.32	0.75	0.0024	0.0048	0.0120	0.0280	0.013	0.026	0.066	0.154
S5M	18.29	0.75	0.0016	0.0032	0.0080	0.0187	0.022	0.044	0.110	0.256
S5H	47.55	0.60	0.0012	0.0024	0.0060	0.0140	0.034	0.068	0.171	0.399
C1L	6.10	0.75	0.0040	0.0064	0.0160	0.0400	0.018	0.029	0.073	0.183
C1M	15.24	0.75	0.0027	0.0043	0.0107	0.0267	0.031	0.049	0.122	0.305
C1H	36.58	0.60	0.0020	0.0032	0.0080	0.0200	0.044	0.070	0.176	0.439

Label	Height [m]	α_2	Drift ratio at threshold of damage state				Median spectral displacement [m]			
			DS2	DS3	DS4	DS5	DS2	DS3	DS4	DS5
C2L	6.10	0.75	0.0032	0.0061	0.0158	0.0400	0.015	0.028	0.072	0.183
C2M	15.24	0.75	0.0021	0.0041	0.0105	0.0267	0.024	0.047	0.120	0.305
C2H	36.58	0.60	0.0016	0.0031	0.0079	0.0200	0.035	0.068	0.173	0.439
C3L	6.10	0.75	0.0024	0.0048	0.0120	0.0280	0.011	0.022	0.055	0.128
C3M	15.24	0.75	0.0016	0.0032	0.0080	0.0187	0.018	0.037	0.091	0.214
C3H	36.58	0.60	0.0012	0.0024	0.0060	0.0140	0.026	0.053	0.132	0.307
PC1	4.57	0.75	0.0032	0.0051	0.0128	0.0350	0.011	0.017	0.044	0.120
PC2L	6.10	0.75	0.0032	0.0051	0.0128	0.0350	0.015	0.023	0.059	0.160
PC2M	15.24	0.75	0.0021	0.0034	0.0086	0.0233	0.024	0.039	0.098	0.266
PC2H	36.58	0.60	0.0016	0.0026	0.0064	0.0175	0.035	0.057	0.140	0.384
RM1L	6.10	0.75	0.0032	0.0051	0.0128	0.0350	0.015	0.023	0.059	0.160
RM1M	15.24	0.75	0.0021	0.0034	0.0086	0.0233	0.024	0.039	0.098	0.266
RM2L	6.10	0.75	0.0032	0.0051	0.0128	0.0350	0.015	0.023	0.059	0.160
RM2M	15.24	0.75	0.0021	0.0034	0.0086	0.0233	0.024	0.039	0.098	0.266
RM2H	36.58	0.60	0.0016	0.0026	0.0064	0.0175	0.035	0.057	0.140	0.384
URML	4.57	0.75	0.0024	0.0048	0.0120	0.0280	0.008	0.016	0.041	0.096
URMM	10.67	0.75	0.0016	0.0032	0.0080	0.0187	0.013	0.026	0.064	0.150

3 RESPONSE SPECTRUM

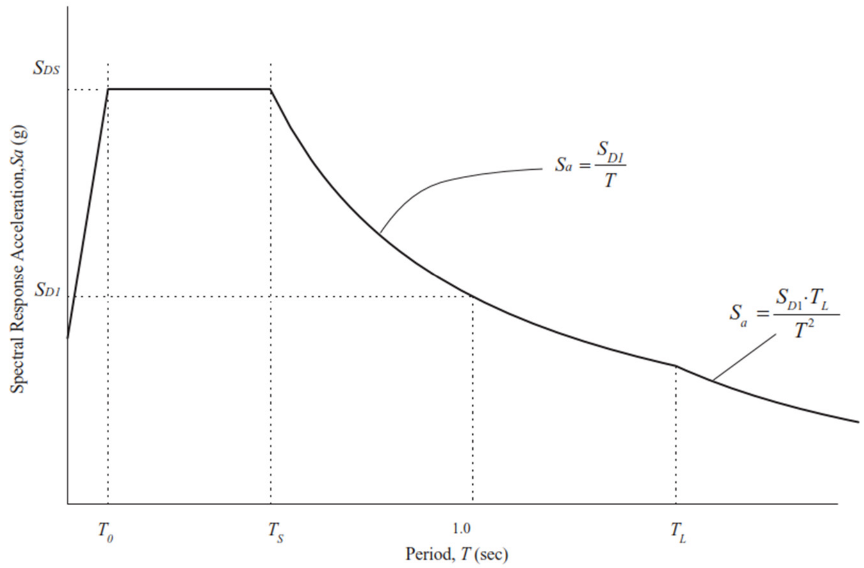
In this chapter the response spectra used for the derivation of the equivalent-PGA fragility curves are described. First the horizontal response spectrum according to NEHRP 2015 provisions and ASCE 7-10 (ASCE/SEI 7-10, 2010) is described in section 3.1. This spectrum will be used as reference for the verification of the method. Section 3.2 describes the shape of the horizontal response spectrum according to NPR 9998:2020 (NPR 9998, 2020) for the development of location-specific fragility curves.

3.1 American code ASCE 7-10

In HAZUS, equivalent-PGA fragility curves are developed for a single set of spectrum shape factors (the reference spectrum). The reference spectrum represents ground shaking of a large magnitude (i.e. M=7.0) western United States (WUS) earthquake for soil site class D at site-to-source distances of 15 km or greater. The information given in HAZUS technical manual is not sufficient to reconstruct the demand spectrum used for the determination of the median PGA values. Therefore, in this memo the horizontal response spectrum from (ASCE/SEI 7-10, 2010) is adopted for the verification of the proposed method.

In ASCE 7-10, the horizontal response spectrum is based on a Maximum Considered Earthquake (MCE) (an event with a 2% probability of exceedance in 50 years or a return period of 2475 years). The design earthquake is 2/3 the MCE. In Figure 3.1 the general shape of the response spectrum is presented.

Figure 3.1 Design response spectrum according to ASCE 7-10 (ASCE/SEI 7-10, 2010)



The spectral acceleration as function of structural period, based on (ASCE/SEI 7-10, 2010), is given by

$$S_a(T) = \begin{cases} S_{DS}\left(r + (1-r)\cdot\frac{T}{T_0}\right), & T \le T_0 \\ S_{DS}, & T_0 < T \le T_s \\ \frac{S_{D1}}{T}, & T_s < T \le T_L \\ \frac{S_{D1}T_L}{T^2}, & T > T_L \end{cases}$$

where r is the ratio between the PGA value and the design spectral response acceleration at short periods, S_{DS}. It is noted that this ratio is not part of the expressions given in ASCE 7-10[1], but it is included here because HAZUS also uses this ratio to differentiate between different earthquake events (refer to section 4 (FEMA, 2020)). The parameters S_{DS} and S_{D1} are the design spectral response acceleration at short and 1-second periods, respectively. The design values are 2/3 the maximum spectral response acceleration adjusted for site class effects.

$$S_{DS} = \frac{2}{3}S_{MS}$$
$$S_{D1} = \frac{2}{3}S_{M1}$$

where S_{MS} and S_{M1} are the maximum spectral response acceleration for short and 1-second periods, respectively, adjusted for site class effects.

$$S_{MS} = F_a S_s$$
$$S_{M1} = F_v S_1$$

where F_a and F_v are site coefficients defined in Table 3.1 and Table 3.2 for short and 1-second periods, respectively. S_s and S_1 are the mapped Maximum Considered Earthquake (MCE) (an event with a 2 % probability of exceedance in 50 years or a return period of 2475 years).

[1] In (ASCE/SEI 7-10, 2010) the ratio between the PGA value and S_{DS} is equal to 0.4.

The transition periods T_0 and T_s are defined as follows: $T_0 = 0.2 \cdot S_{D1}/S_{DS}$ and $T_s = S_{D1}/S_{DS}$. The period T_L defines the beginning of the constant displacement regime. This part was not present in older versions of this standard (e.g. ASCE 7-02) and is also not relevant for the case under consideration because these periods are much longer than the periods at the threshold of damage states.

Table 3.1 Site coefficient F_a (ASCE/SEI 7-10, 2010)

Site Class	maximum spectral acceleration at short period, S_s*				
	$S_s \leq 0.25$	$S_s = 0.5$	$S_s = 0.75$	$S_s = 1.0$	$S_s \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9

*Straight-line interpolation is used for intermediate values of S_s

Table 3.2 Site coefficient F_v (ASCE/SEI 7-10, 2010)

Site Class	maximum spectral acceleration at 1-sec period, S_1*				
	$S_1 \leq 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \geq 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4

*Straight-line interpolation is used for intermediate values of S_1

The parameters S_s and S_1 can be determined from contour maps (chapter 22 of ACSE 7-10) or from a webtool (e.g. https://hazards.atcouncil.org/). The magnitude of these parameters is not relevant for the analysis because the spectrum will be scaled in the derivation of equivalent-PGA fragility curves. What is relevant is the ratio S_s/S_1 because this determines the shape of the spectrum. Both the parameters S_s and S_1, and the ratio between them are not given in HAZUS. So the exact shape of the spectrum used in the development of equivalent-PGA fragility curves is unknown. Therefore, in our analysis the shape of the spectrum is determined through an optimization algorithm. That is, the ratios S_s/S_1 and $r = PGA/S_{DS}$ are determined as the values that minimize the mean absolute error between the computed equivalent-PGA values and the reported ones in HAZUS.

3.2 Dutch code NPR 9998

In this section the response spectrum for Groningen according to NPR 9998:2020 (NPR 9998, 2020) is introduced. This spectrum will be used for the development of equivalent-PGA values in chapter 4, for the location-specific fragility curves.

The elastic response spectrum for Groningen is defined as follows (NPR 9998, 2020)

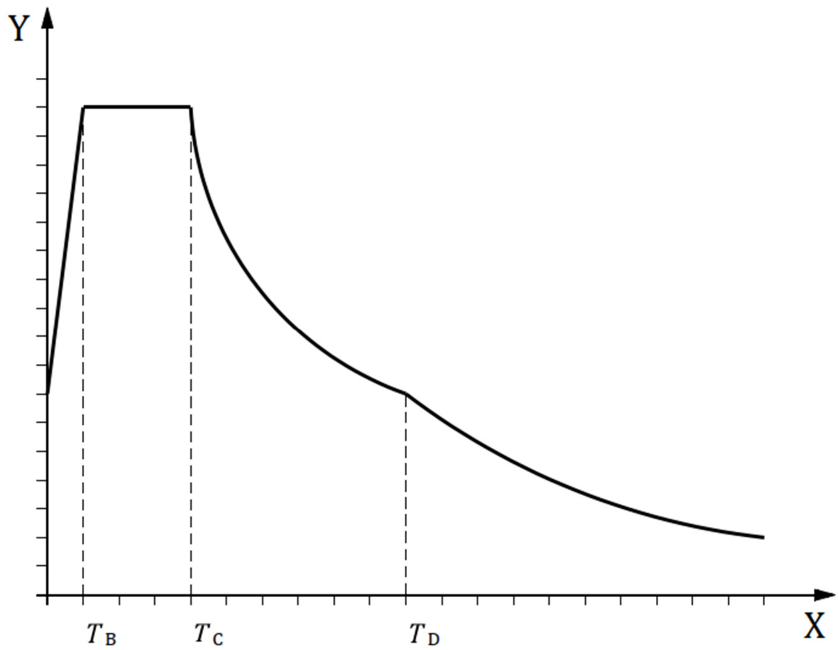
$$S_a(T) = \begin{cases} a_{g;d} \cdot \left(1 + \frac{T}{T_B} \cdot (\eta \cdot p - 1)\right), & 0 \leq T \leq T_B \\ a_{g;d} \cdot \eta \cdot p, & T_B < T \leq T_C \\ a_{g;d} \cdot \eta \cdot p \cdot \frac{T_c}{T}, & T_C < T \leq T_D \\ a_{g;d} \cdot \eta \cdot p \cdot \frac{T_c T_D}{T^2}, & T_D \leq T \leq 4 \end{cases}$$

where $S_a(T)$ is the spectral acceleration, $a_{g;d}$ is the design value of the PGA (including soil factor), p is the ratio between PGA and the maximum spectral acceleration (for $\eta = 1$), η is the dimensionless correction factor for damping ratios other than 5 %. The periods T_B, T_C and T_D define the transition between different branches in the spectrum, refer to Figure 3.2. Values of these parameters for different locations, time windows and return periods are given in the webtool https://seismischekrachten.nen.nl/map.php.

It is noted that the response spectra for Groningen correspond to induced-type of earthquakes with relative small magnitude and short duration. For the development of equivalent-PGA fragility, however, the response spectrum requires scaling to much larger values/magnitudes for which the initial shape of the spectrum is not realistic. The large spectral values implies strong tectonic earthquakes which are characterized by longer duration than the induced-earthquakes found in Groningen. Therefore the shape of the spectrum is slightly modified in accordance with NEN-EN 1998-1 (NEN-EN 1998-1, 2005) for large magnitude earthquakes (type 1 M_s > 5.5). In particular, the corner period T_D, specifying the beginning of the constant displacement branch, is fixed to 2 seconds.

For the current analysis, five different locations (Delfzijl, Hoogezand, Veendam, Eemshaven and Winschoten) are considered and three different time windows (T4, T5 and T6). For each location-window combination, four different spectra are used corresponding to different return periods (and thus different maximum magnitude of the earthquake). Linear interpolation and extrapolation is used when scaling the spectrum in the development of median PGA values. An overview with parameter values for all the response spectra used in the analysis is given in Appendix A.

Figure 3.2 Elastic response spectrum (NPR 9998, 2020)



4 EQUIVALENT-PGA FRAGILITY CURVES

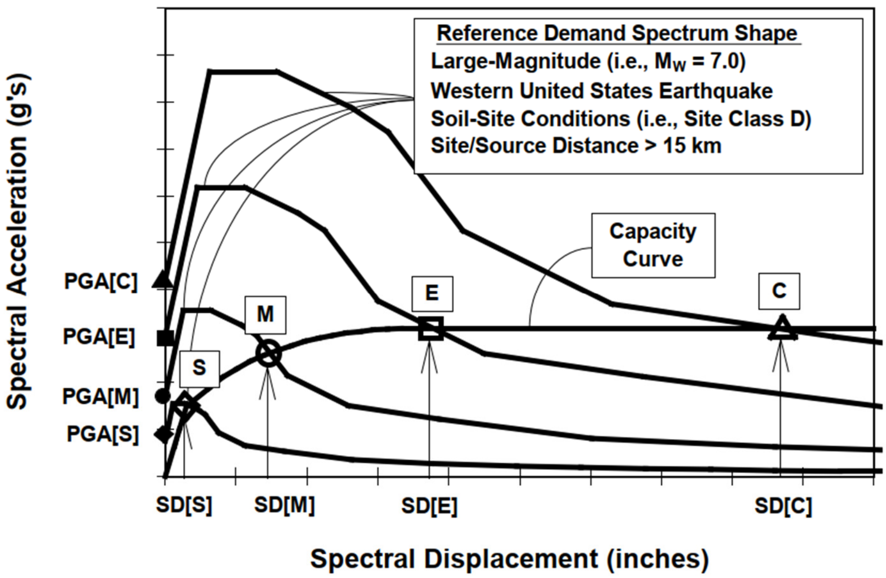
In this chapter equivalent-PGA fragility curves are derived. First the calculation steps are explained in section 4.1. The adopted method is verified through the analysis in section 4.1, where the equivalent-PGA values from HAZUS are reproduced. Finally, in section 4.3 the equivalent-PGA values for Groningen are computed.

4.1 Calculation steps

For the derivation of the median PGA values for building fragility curves the following input is required:
- Building capacity curve (section 2.2).
- Spectral displacement values corresponding to different damage states (section 2.3).
- Response spectrum of the location under consideration (chapter 3).

The response spectrum is scaled uniformly at each period such that the spectrum intersects the building capacity curve at the spectral displacement of the median value of the damage state of interest. The PGA of the scaled demand spectrum defines the median value of equivalent-PGA fragility curve Figure 4.1 illustrates this scaling and intersection process for a typical building capacity curve and slight (S), moderate (M), extensive (E) and complete (C) damage states.

Figure 4.1 Development of equivalent-PGA median damage values (FEMA, 2020)



In summary, the derivation of median values for equivalent-PGA fragility curves consists of the following steps:
1. For a specific building type of interest, define the capacity curve using the values for the yield and ultimate point in Table 2.2. Plot the capacity curve in Sd-Sa graph.
2. For a specific location, define the demand spectrum. Plot the demand spectrum in the same Sd-Sa graph, use the following formula to relate spectral acceleration with spectral displacement

$$S_d = 9.81 * \left(\frac{T}{2\pi}\right)^2 * S_a$$

3. For the damage state of interest, calculate the median spectral displacement value as the product of drift ratio, building height and fraction of building height at the location of push-over mode displacement (refer to Table 2.4).

4 Uniformly scale the demand spectrum (from step 2) such that the spectrum interests the building capacity curve (from step 1) at the median value of spectral displacement (from step 3).
5 The intersection of the vertical axis of the scaled demand spectrum defines the median value of the equivalent-PGA fragility function.
6 Repeat step 3 to 5 to obtain median PGA values for different damage states.

In the next section the method described above is verified by reproducing the values from HAZUS using a demand spectrum specific for western United States. In section 4.3, the same method is applied to derive median PGA values using demand spectrum for Groningen.

4.2 Verification method

In this section the equivalent-PGA median values are reproduced in order to verify the method described in previous section. For each building type the equivalent-PGA median values for different damage states are computed by intersecting the building capacity curve and the demand spectrum at the spectral displacement of the specific damage state. The analysis is performed using the response spectrum described in section 3.1. As mentioned before, the exact values of the parameters of the response spectrum are not given in HAZUS. Therefore, the analysis is performed for different sets of shape factors and the 'reference' spectrum is defined by the values that minimizes the mean absolute error between the computed equivalent-PGA values and the reported ones in HAZUS. For the optimization, the shape factors are defined by the ratios S_s/S_1 and $r = PGA/S_{DS}$ where S_{DS} depends on S_s. The initial value of S_s is 1.0 but this is not relevant because the optimization algorithm is invariant to this choice. The ratios are determined as $S_s/S_1 = 1.658$ and $r = PGA/S_{DS} = 0.749$ for site class D. The resulting shape of the 'best fit' response spectrum is shown in Figure 4.2. It is recalled that the absolute values of S_s and S_1 are not that important because the spectrum will be scaled in the derivation of equivalent-PGA values.

Figure 4.2 Design response spectrum according to ASCE 7-10 for S_s = 1.0, S_1 = 0.603, r = 0.749 and site class D

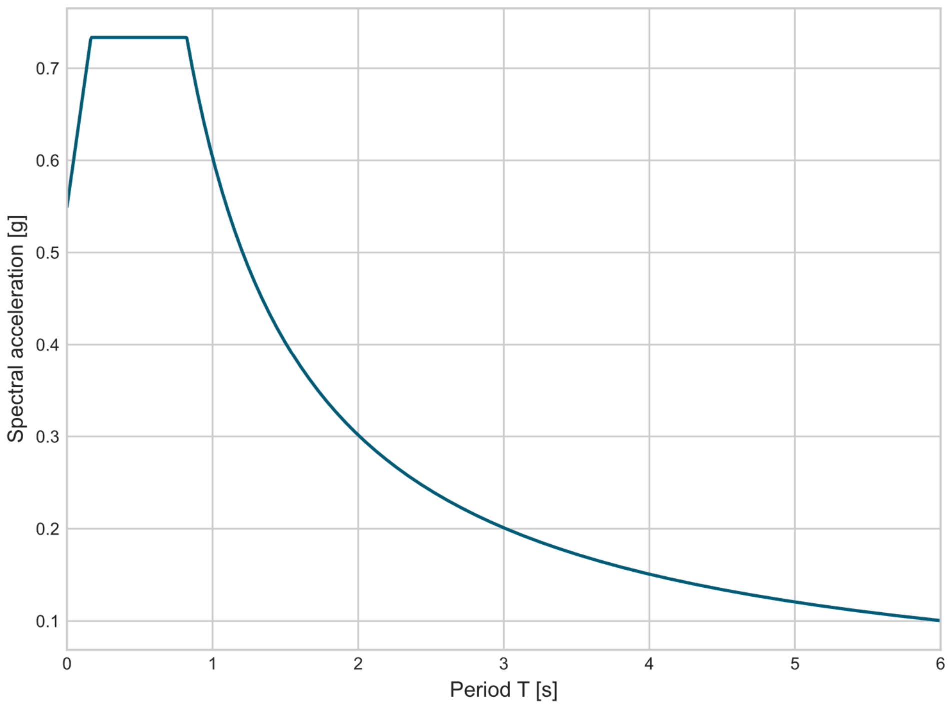


Figure 4.3 shows the results for building type S2M. The reference spectrum is shown as dashed line. It is noted that the constant period line T_s (corner period at end of plateau) is not the same for the scaled spectra due to different site coefficients depending on the magnitude of S_s and S_1. The scaled spectrum of a damage state intersects the building capacity curve at the median spectral displacement of the particular damage state. The median equivalent-PGA value for the damage state is defined by the value of the scaled demand spectrum at T = 0 (equivalent to S_d = 0). The exact median PGA values from HAZUS are also shown in this figure.

Figure 4.3 Development of equivalent-PGA values for building type S2M based on WUS spectrum

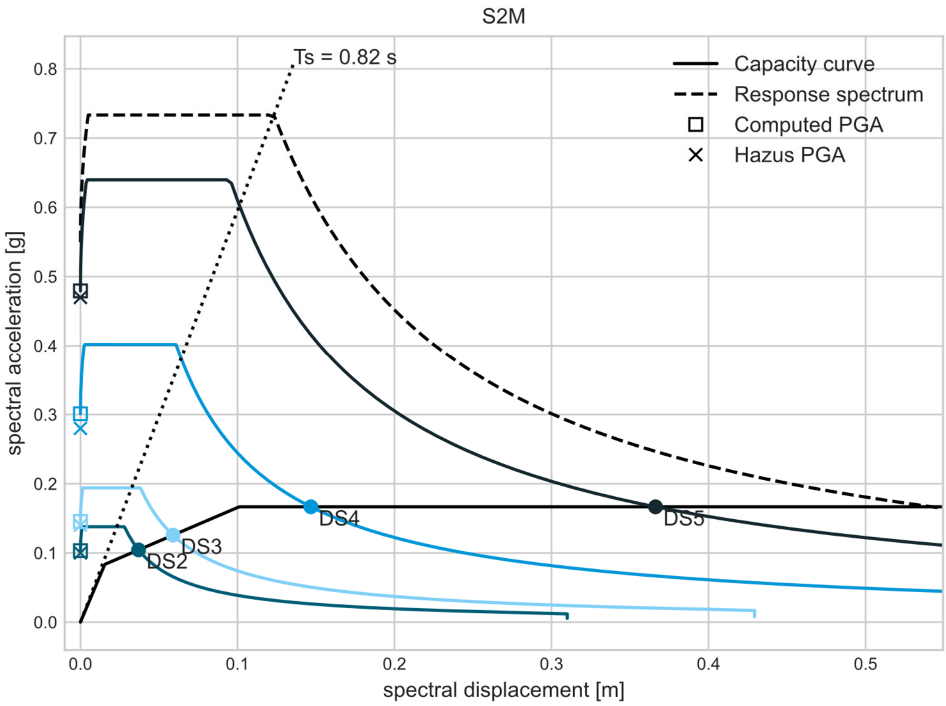


Figure 4.4 shows the computed median equivalent-PGA values and the exact values from HAZUS for all building types. The error between these two values is illustrated in Figure 4.5 (tabulated values are added in Appendix B). From these figures it can be observed that the calculated median PGA values does not match exactly the values from HAZUS. However, most errors are smaller than +/- 10 % and there are only a few cases where the error is larger than +/-20 %. The deviation can be explained by the following points:

- The exact shape of the demand spectrum used by HAZUS is not known. Instead, the response spectrum from ASCE 7-10 is assumed for the calculations.
- There might be some numerical errors in the reported values from HAZUS; e.g. the parameter values for the capacity curve might contain errors, these errors will be reflected in the calculated median PGA values.

Despite the small deviations in the results, it is reasonable that the correct method is followed and this method will also be applied in the next section to derive median-PGA values specifically for locations in Groningen.

Figure 4.4 Median equivalent-PGA values based on WUS spectrum; computed (☐) and exact values from HAZUS (X)

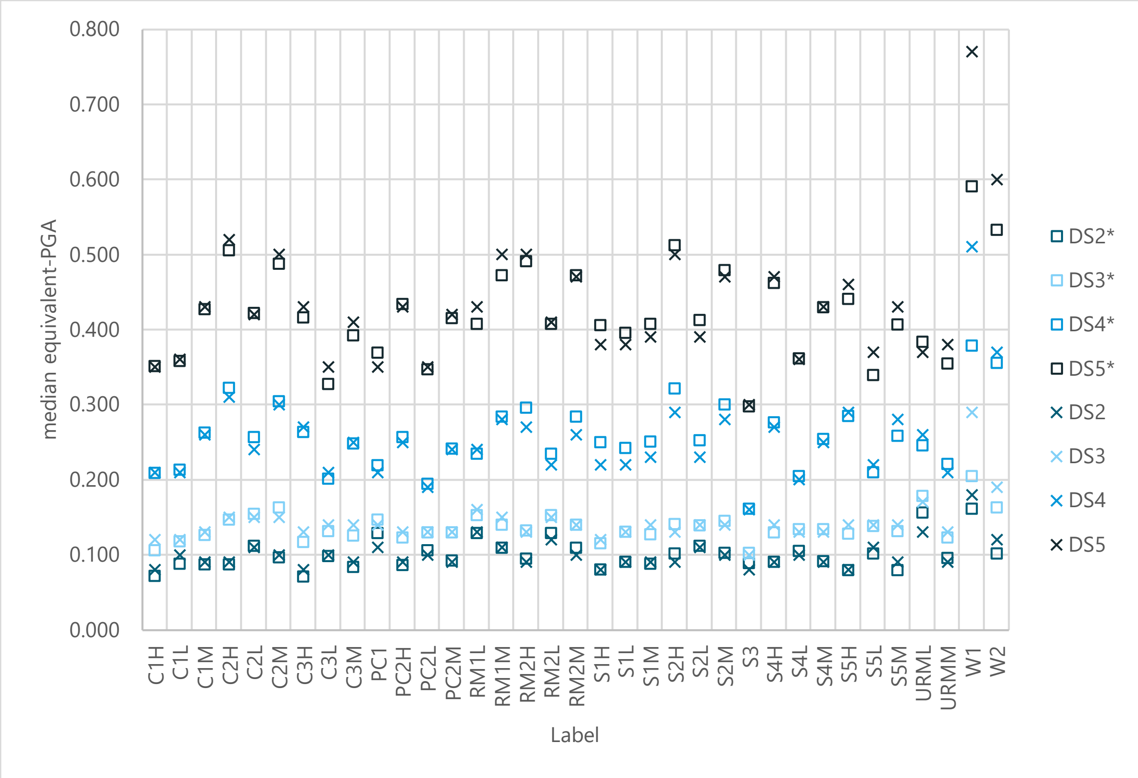
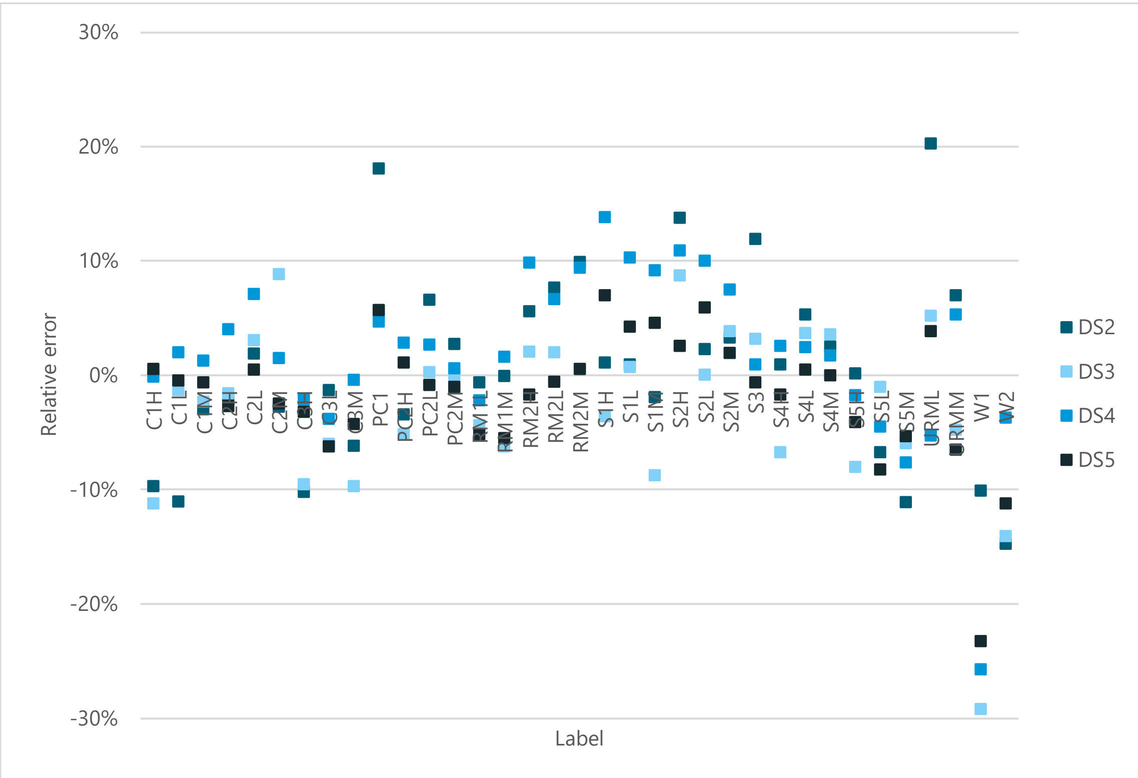


Figure 4.5 Relative error for the computed median equivalent-PGA values from HAZUS



4.3 Equivalent-PGA values for Groningen

The calculation method described in section 4.1 is now applied to compute the median equivalent-PGA for five locations in Groningen. The main difference with previous section is the definition of the demand spectrum in step 2 of the method. Here, a location-specific demand spectrum for Groningen is used as described in section 3.2. It is recalled that the spectra have fixed transition period T_D = 2.0 s in accordance with NEN-EN 1998-1. This choice will be justified below when the results are presented. The analysis is performed with 15 different demand spectra corresponding to five different locations and three different time windows (T4, T5 and T6). The shape factors of all spectra used in the analysis are given in Appendix A. The response spectrum for location Delfzijl and time window T4 is presented in Figure 4.6.

Figure 4.6 Response spectrum according to NPR 9998 for location Delfzijl and time window T4

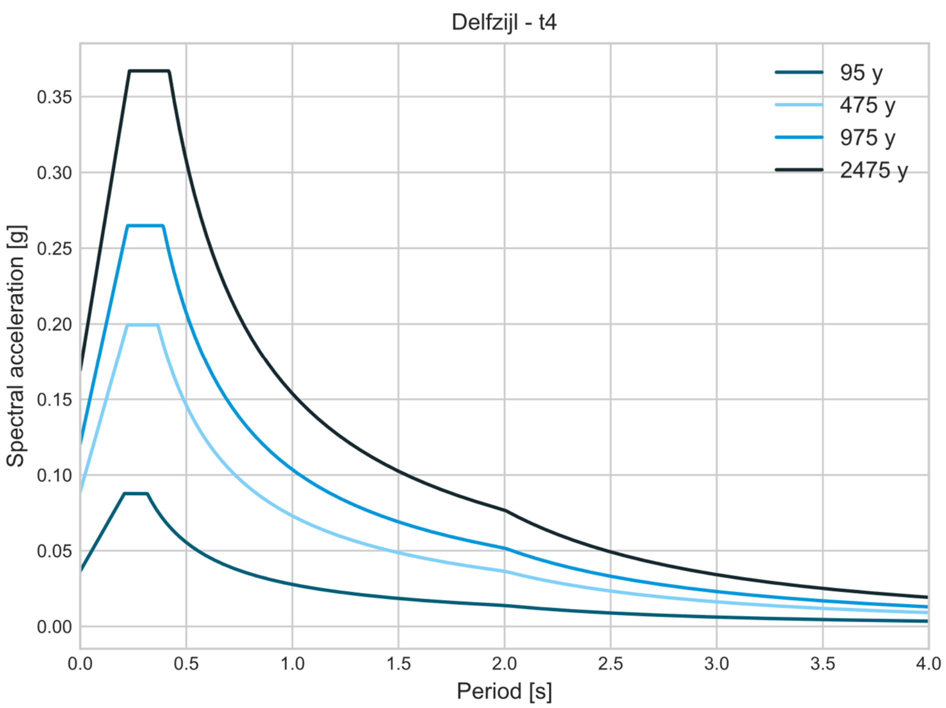
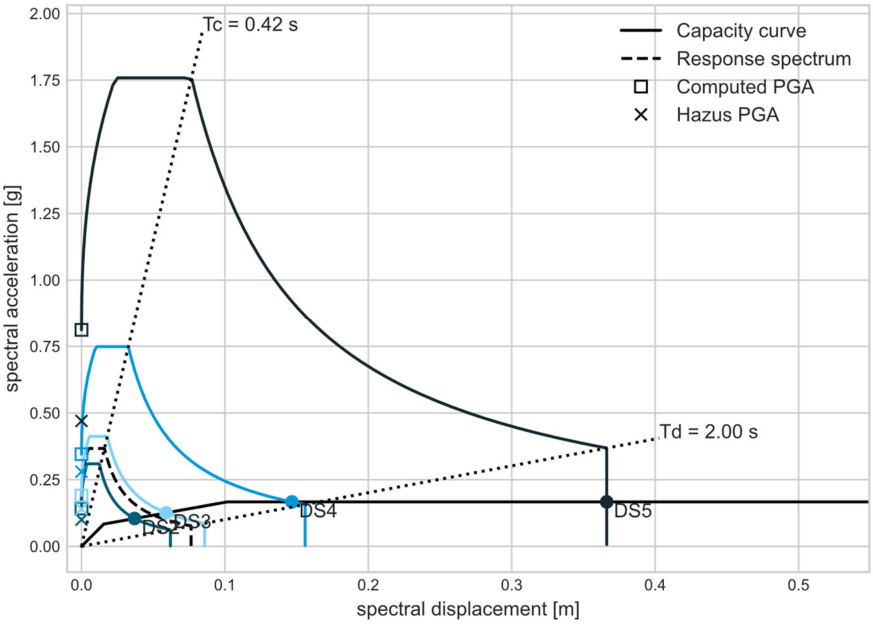


Figure 4.7 (a)-(d) show the results for building type S2M for the locations Delfzijl, Eemshaven, Hoogezand, Veendam and Winschoten, respectively. The reference demand spectrum (with return period 2475 y) for the specific location is shown as dashed line. It can be observed that for most locations the demand spectrum is smaller than any damage state's median spectral displacement value. Hence, the spectrum requires upscaling to spectral values above the ones described by NPR (even for the most severe spectrum with return period 2475 y). It is, however, not likely that the scaled spectra are still related to induced-type of earthquakes found in Groningen. Instead, the magnitude of the spectral values tend more to tectonic-type of earthquakes with larger magnitude. These types of earthquakes have generally longer duration than induced earthquakes and the constant displacement phase occurs at higher periods. For this reason the transition period T_D is set to the value given in NEN-EN 1998-1 for type 1 earthquakes. The median equivalent-PGA values from HAZUS are also included in the figures. The computed median values based on NPR spectrum are larger than the ones given in HAZUS (this is generally the case for almost all building types and damage states). This means that the location-specific fragility curves are less strict than the ones from HAZUS and will yield lower damage state probabilities when combined with the hazard probability density.

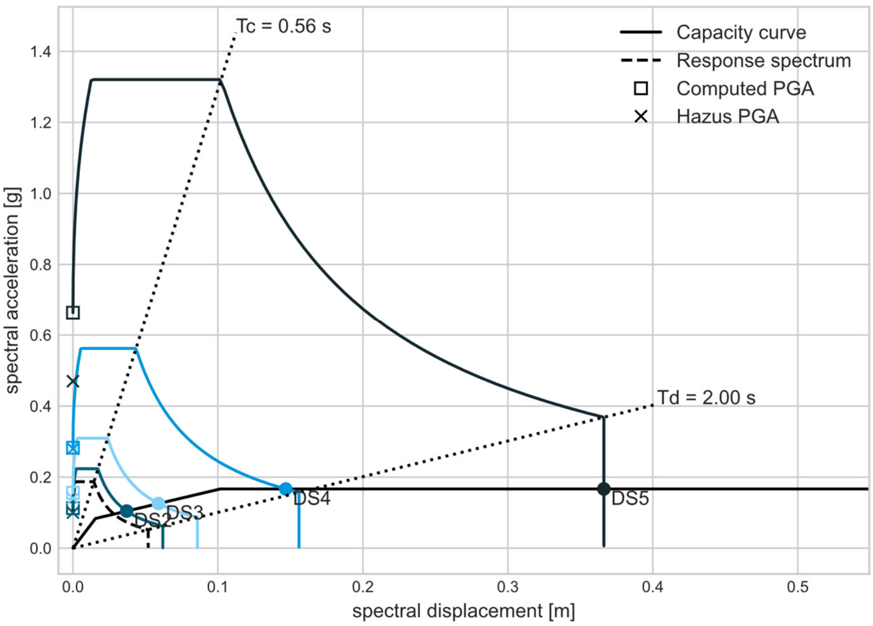
The computed median equivalent-PGA values for all building types, locations and time windows are included in Appendix C.

Figure 4.7 Development of equivalent-PGA values for building type S2M based on NPR spectrum for Winschoten-T4

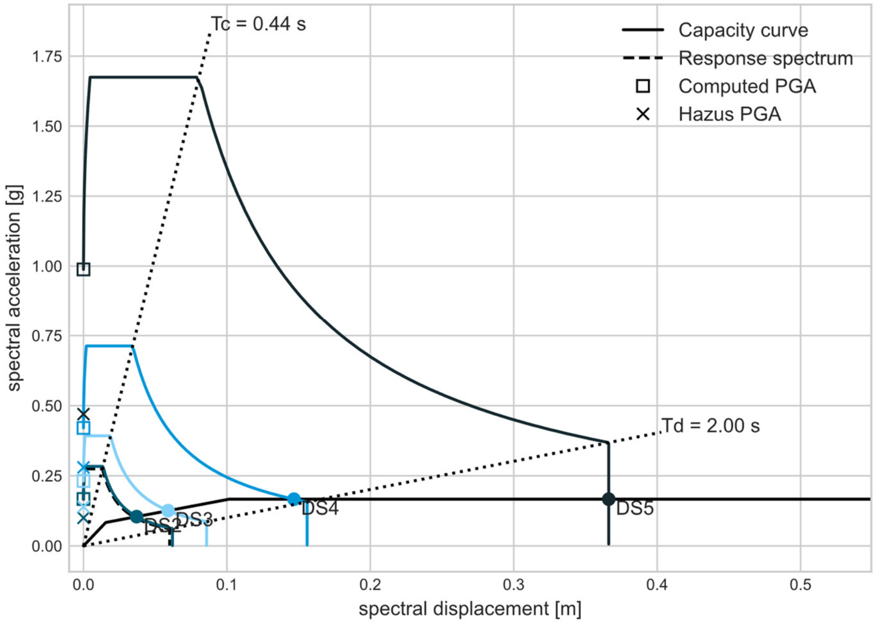
(a) Delfzijl (T4)



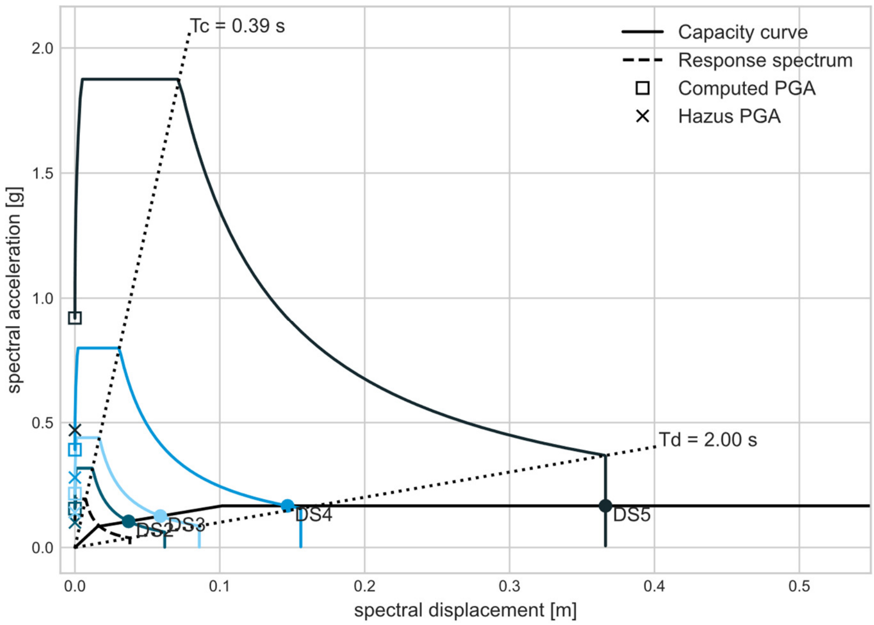
(b) Eemshaven (T4)



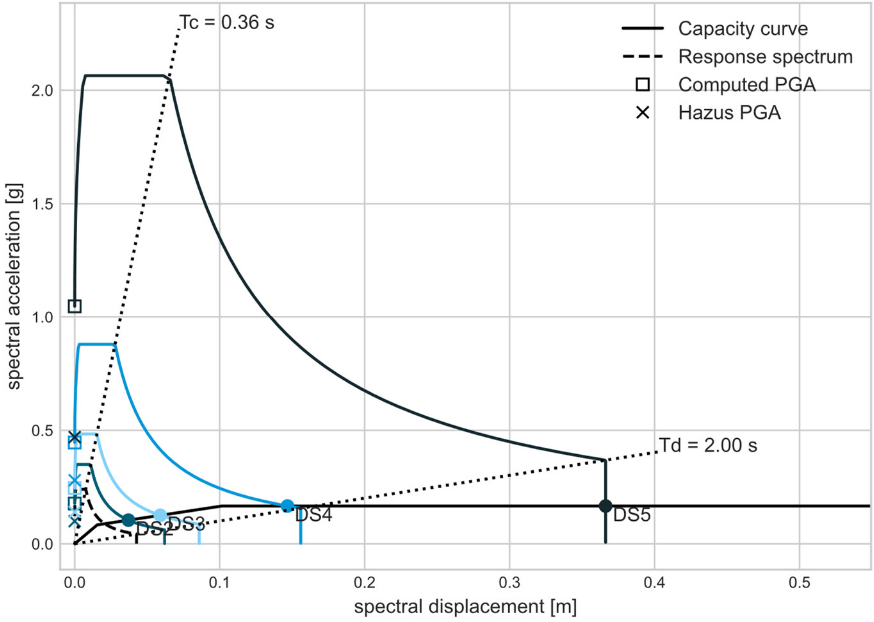
(c) Hoogezand (T4)



(d) Veendam (T4)



(e) Winschoten (T4)



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A

APPENDIX: RESPONSE SPECTRA ACCORDING TO NPR 9998:2020

Tables with parameter values for response spectra according to NPR 9998:2020.

- Table A.1 gives RDX, RDY coordinates of the considered locations
- Table A.2 gives parameter values for response spectra at location Delfzijl
- Table A.3 gives parameter values for response spectra at location Eemshaven
- Table A.4 gives parameter values for response spectra at location Hoogezand
- Table A.5 gives parameter values for response spectra at location Veendam
- Table A.6 gives parameter values for response spectra at location Winschoten

Table A.1 Coordinates of considered locations in Groningen

Location	RDX	RDY
Delfzijl	258900	592963
Eemshaven	251037	607071
Hoogezand	244513	576988
Veendam	256043	571038
Winschoten	262586	576412

Table A.2 Parameter values of response spectra for location Delfzijl

Window	T_r [year]	a_g [g]	p [-]	T_B [s]	T_C [s]	T_D* [s]
T4	95	0.037	2.400	0.208	0.316	2.000
	475	0.089	2.240	0.222	0.366	2.000
	975	0.121	2.194	0.223	0.391	2.000
	2475	0.169	2.167	0.232	0.419	2.000
T5	95	0.026	2.480	0.203	0.310	2.000
	475	0.071	2.271	0.215	0.354	2.000
	975	0.100	2.205	0.216	0.379	2.000
	2475	0.145	2.157	0.227	0.409	2.000
T6	95	0.016	2.668	0.201	0.299	2.000
	475	0.051	2.440	0.219	0.339	2.000
	975	0.074	2.339	0.224	0.362	2.000
	2475	0.112	2.270	0.229	0.389	2.000

*Changed to 2 seconds in accordance with NEN-EN 1998-1 to account for strong-event earthquakes

Table A.3 Parameter values of response spectra for location Eemshaven

Window	T_r [year]	a_g [g]	p [-]	T_B [s]	T_C [s]	T_D* [s]
T4	95	0.021	2.200	0.173	0.387	2.000
	475	0.049	1.982	0.172	0.503	2.000
	975	0.067	1.976	0.181	0.534	2.000
	2475	0.094	1.988	0.196	0.558	2.000
T5	95	0.018	2.231	0.170	0.365	2.000
	475	0.046	1.981	0.170	0.487	2.000
	975	0.063	1.927	0.150	0.592	2.000
	2475	0.090	1.948	0.185	0.550	2.000
T6	95	0.014	2.327	0.173	0.335	2.000
	475	0.039	1.997	0.169	0.460	2.000
	975	0.055	1.954	0.171	0.508	2.000
	2475	0.080	1.945	0.181	0.546	2.000

*Changed to 2 seconds in accordance with NEN-EN 1998-1 to account for strong-event earthquakes

Table A.4 Parameter values of response spectra for location Hoogezand

Window	T_r [year]	a_g [g]	p [-]	T_B [s]	T_C [s]	T_D* [s]
T4	95	0.034	1.957	0.116	0.288	2.000
	475	0.086	1.757	0.113	0.356	2.000
	975	0.116	1.738	0.115	0.386	2.000
	2475	0.162	1.695	0.105	0.440	2.000
T5	95	0.020	2.180	0.125	0.282	2.000
	475	0.059	1.835	0.115	0.347	2.000
	975	0.085	1.761	0.112	0.379	2.000
	2475	0.125	1.715	0.110	0.423	2.000
T6	95	0.013	2.294	0.126	0.273	2.000
	475	0.048	1.877	0.115	0.326	2.000
	975	0.072	1.771	0.112	0.354	2.000
	2475	0.109	1.724	0.112	0.393	2.000

*Changed to 2 seconds in accordance with NEN-EN 1998-1 to account for strong-event earthquakes

Table A.5 Parameter values of response spectra for location Veendam

Window	T_r [year]	a_g [g]	p [-]	T_B [s]	T_C [s]	T_D* [s]
T4	95	0.017	2.352	0.102	0.286	2.000
	475	0.046	2.126	0.097	0.341	2.000
	975	0.065	2.078	0.098	0.366	2.000
	2475	0.095	2.039	0.098	0.393	2.000
T5	95	0.008	2.704	0.115	0.300	2.000
	475	0.023	2.485	0.148	0.362	2.000
	975	0.033	2.367	0.128	0.394	2.000
	2475	0.052	2.257	0.128	0.423	2.000
T6	95	0.006	2.328	0.070	0.296	2.000
	475	0.017	2.576	0.126	0.354	2.000
	975	0.025	2.484	0.148	0.382	2.000
	2475	0.040	2.322	0.127	0.422	2.000

*Changed to 2 seconds in accordance with NEN-EN 1998-1 to account for strong-event earthquakes

Table A.6 Parameter values of response spectra for location Winschoten

Window	T_r [year]	a_g [g]	p [-]	T_B [s]	T_C [s]	T_D* [s]
T4	95	0.020	2.348	0.114	0.288	2.000
	475	0.057	2.076	0.106	0.323	2.000
	975	0.082	2.008	0.108	0.338	2.000
	2475	0.122	1.969	0.110	0.357	2.000
T5	95	0.010	2.532	0.080	0.298	2.000
	475	0.026	2.524	0.148	0.347	2.000
	975	0.039	2.413	0.152	0.367	2.000
	2475	0.061	2.285	0.146	0.395	2.000
T6	95	0.008	2.103	0.057	0.288	2.000
	475	0.020	2.372	0.083	0.345	2.000
	975	0.030	2.307	0.097	0.370	2.000
	2475	0.047	2.211	0.099	0.399	2.000

*Changed to 2 seconds in accordance with NEN-EN 1998-1 to account for strong-event earthquakes

B

APPENDIX: MEDIAN EQUIVALENT-PGA VALUES FROM HAZUS (REPRODUCED)

Table B.1 Overview reproduced median equivalent-PGA values from HAZUS based on response spectrum from ASCE-7-10

Label	Median PGA values											
	DS2			DS3			DS4			DS5		
	HAZUS [g]	Computed [g]	Rel. error [%]	HAZUS [g]	Computed [g]	Rel. error [%]	HAZUS [g]	Computed [g]	Rel. error [%]	HAZUS [g]	Computed [g]	Rel. error [%]
C1H	0.080	0.072	-9.65	0.120	0.107	-11.16	0.210	0.210	-0.07	0.350	0.352	0.58
C1L	0.100	0.089	-11.03	0.120	0.119	-1.24	0.210	0.214	2.01	0.360	0.358	-0.44
C1M	0.090	0.087	-2.92	0.130	0.127	-2.25	0.260	0.263	1.30	0.430	0.428	-0.58
C2H	0.090	0.088	-2.20	0.150	0.148	-1.52	0.310	0.323	4.05	0.520	0.506	-2.68
C2L	0.110	0.112	1.93	0.150	0.155	3.13	0.240	0.257	7.13	0.420	0.422	0.55
C2M	0.100	0.097	-2.73	0.150	0.163	8.89	0.300	0.305	1.53	0.500	0.488	-2.42
C3H	0.080	0.072	-10.17	0.130	0.118	-9.52	0.270	0.264	-2.10	0.430	0.416	-3.18
C3L	0.100	0.099	-1.28	0.140	0.132	-5.96	0.210	0.202	-3.78	0.350	0.328	-6.22
C3M	0.090	0.084	-6.11	0.140	0.126	-9.65	0.250	0.249	-0.38	0.410	0.393	-4.25
PC1	0.110	0.130	18.10	0.140	0.148	5.52	0.210	0.220	4.73	0.350	0.370	5.73
PC2H	0.090	0.087	-3.40	0.130	0.123	-5.13	0.250	0.257	2.86	0.430	0.435	1.13
PC2L	0.100	0.107	6.61	0.130	0.130	0.28	0.190	0.195	2.70	0.350	0.347	-0.79
PC2M	0.090	0.092	2.78	0.130	0.130	0.00	0.240	0.242	0.65	0.420	0.416	-0.96
RM1L	0.130	0.129	-0.57	0.160	0.153	-4.37	0.240	0.235	-2.19	0.430	0.408	-5.15
RM1M	0.110	0.110	-0.06	0.150	0.141	-6.18	0.280	0.285	1.63	0.500	0.473	-5.46
RM2H	0.090	0.095	5.61	0.130	0.133	2.10	0.270	0.297	9.86	0.500	0.492	-1.66
RM2L	0.120	0.129	7.71	0.150	0.153	2.01	0.220	0.235	6.70	0.410	0.408	-0.53
RM2M	0.100	0.110	9.94	0.140	0.141	0.52	0.260	0.285	9.44	0.470	0.473	0.58
S1H	0.080	0.081	1.13	0.120	0.116	-3.56	0.220	0.250	13.83	0.380	0.407	7.03
S1L	0.090	0.091	0.98	0.130	0.131	0.72	0.220	0.243	10.32	0.380	0.396	4.26
S1M	0.090	0.088	-1.91	0.140	0.128	-8.74	0.230	0.251	9.20	0.390	0.408	4.62
S2H	0.090	0.102	13.77	0.130	0.141	8.76	0.290	0.322	10.94	0.500	0.513	2.59
S2L	0.110	0.113	2.32	0.140	0.140	0.09	0.230	0.253	10.05	0.390	0.413	5.97
S2M	0.100	0.103	3.34	0.140	0.145	3.91	0.280	0.301	7.54	0.470	0.479	1.98
S3	0.080	0.090	11.97	0.100	0.103	3.22	0.160	0.162	0.99	0.300	0.298	-0.62
S4H	0.090	0.091	0.98	0.140	0.131	-6.68	0.270	0.277	2.61	0.470	0.462	-1.65
S4L	0.100	0.105	5.33	0.130	0.135	3.74	0.200	0.205	2.50	0.360	0.362	0.54
S4M	0.090	0.092	2.53	0.130	0.135	3.60	0.250	0.254	1.76	0.430	0.430	0.00
S5H	0.080	0.080	0.21	0.140	0.129	-7.99	0.290	0.285	-1.73	0.460	0.441	-4.08
S5L	0.110	0.103	-6.72	0.140	0.139	-0.98	0.220	0.210	-4.46	0.370	0.340	-8.19
S5M	0.090	0.080	-11.05	0.140	0.132	-5.94	0.280	0.259	-7.57	0.430	0.407	-5.33
URML	0.130	0.156	20.29	0.170	0.179	5.22	0.260	0.246	-5.23	0.370	0.384	3.91
URMM	0.090	0.096	7.00	0.130	0.124	-4.72	0.210	0.221	5.34	0.380	0.355	-6.48
W1	0.180	0.162	-10.07	0.290	0.205	-29.16	0.510	0.379	-25.70	0.770	0.591	-23.21
W2	0.120	0.102	-14.71	0.190	0.163	-14.01	0.370	0.356	-3.66	0.600	0.533	-11.16

C

APPENDIX: MEDIAN EQUIVALENT-PGA VALUES FOR GRONINGEN

The median equivalent-PGA values based on demand spectrum of Groningen are listed in the following tables:

- Table C.1, Table C.2, Table C.3 for location Delfzijl time window T4, T5 and T6, respectively.
- Table C.4, Table C.5, Table C.6 for location Eemshaven time window T4, T5 and T6, respectively.
- Table C.7, Table C.8, Table C.9 for location Hoogezand time window T4, T5 and T6, respectively.
- Table C.10, Table C.11, Table C.12 for location Veendam time window T4, T5 and T6, respectively.
- Table C.13, Table C.14, Table C.15 for location Winschoten time window T4, T5 and T6, respectively.

Table C.1 Median equivalent-PGA values for location Delfzijl and time window T4

Label	DS2	DS3	DS4	DS5
C1H	0.105	0.158	0.389	0.973
C1L	0.111	0.153	0.257	0.407
C1M	0.123	0.169	0.304	0.676
C2H	0.123	0.193	0.384	0.973
C2L	0.111	0.168	0.297	0.472
C2M	0.129	0.209	0.349	0.676
C3H	0.104	0.158	0.305	0.681
C3L	0.093	0.142	0.245	0.375
C3M	0.108	0.168	0.289	0.474
PC1	0.104	0.135	0.251	0.419
PC2H	0.122	0.165	0.311	0.851
PC2L	0.109	0.145	0.239	0.395
PC2M	0.126	0.173	0.283	0.590
RM1L	0.118	0.155	0.277	0.458
RM1M	0.136	0.185	0.327	0.590
RM2H	0.132	0.176	0.341	0.851
RM2L	0.118	0.155	0.277	0.458
RM2M	0.136	0.185	0.327	0.590
S1H	0.154	0.240	0.512	1.264
S1L	0.127	0.174	0.284	0.486
S1M	0.124	0.170	0.328	0.812
S2H	0.141	0.202	0.506	1.264
S2L	0.132	0.179	0.293	0.486
S2M	0.142	0.190	0.346	0.812
S3	0.089	0.116	0.207	0.342
S4H	0.127	0.174	0.405	1.106
S4L	0.117	0.159	0.248	0.426
S4M	0.129	0.179	0.294	0.708
S5H	0.114	0.171	0.379	0.885
S5L	0.102	0.156	0.254	0.387
S5M	0.114	0.175	0.299	0.568
URML	0.100	0.143	0.257	0.434
URMM	0.098	0.147	0.264	0.404
W1	0.111	0.184	0.428	0.750
W2	0.115	0.209	0.405	0.730

Table C.2 Median equivalent-PGA values for location Delfzijl and time window T5

Label	DS2	DS3	DS4	DS5
C1H	0.105	0.160	0.400	1.001
C1L	0.110	0.155	0.265	0.419
C1M	0.123	0.174	0.313	0.696
C2H	0.123	0.198	0.395	1.001
C2L	0.111	0.173	0.306	0.486
C2M	0.129	0.215	0.360	0.696
C3H	0.103	0.161	0.314	0.701
C3L	0.092	0.142	0.253	0.386
C3M	0.108	0.173	0.298	0.488
PC1	0.104	0.135	0.258	0.431
PC2H	0.122	0.169	0.320	0.876
PC2L	0.108	0.145	0.246	0.407
PC2M	0.126	0.178	0.291	0.607
RM1L	0.118	0.157	0.285	0.471
RM1M	0.136	0.191	0.337	0.607
RM2H	0.132	0.182	0.351	0.876
RM2L	0.118	0.157	0.285	0.471
RM2M	0.136	0.191	0.337	0.607
S1H	0.156	0.247	0.527	1.301
S1L	0.127	0.179	0.292	0.501
S1M	0.124	0.175	0.338	0.835
S2H	0.141	0.208	0.521	1.301
S2L	0.132	0.184	0.301	0.501
S2M	0.142	0.196	0.356	0.835
S3	0.088	0.116	0.213	0.352
S4H	0.127	0.179	0.416	1.139
S4L	0.117	0.161	0.256	0.438
S4M	0.129	0.184	0.302	0.729
S5H	0.114	0.176	0.390	0.911
S5L	0.102	0.159	0.261	0.399
S5M	0.114	0.180	0.308	0.585
URML	0.099	0.143	0.265	0.447
URMM	0.098	0.148	0.272	0.416
W1	0.111	0.189	0.441	0.772
W2	0.115	0.215	0.417	0.751

Table C.3 Median equivalent-PGA values for location Delfzijl and time window T6

Label	DS2	DS3	DS4	DS5
C1H	0.101	0.160	0.400	1.000
C1L	0.106	0.155	0.265	0.419
C1M	0.119	0.174	0.312	0.695
C2H	0.120	0.198	0.395	1.000
C2L	0.107	0.172	0.305	0.486
C2M	0.127	0.215	0.359	0.695
C3H	0.100	0.161	0.314	0.700
C3L	0.089	0.141	0.252	0.386
C3M	0.104	0.173	0.297	0.487
PC1	0.100	0.133	0.258	0.431
PC2H	0.119	0.169	0.320	0.875
PC2L	0.104	0.145	0.246	0.406
PC2M	0.124	0.178	0.291	0.607
RM1L	0.114	0.157	0.285	0.470
RM1M	0.135	0.190	0.337	0.607
RM2H	0.130	0.181	0.350	0.875
RM2L	0.114	0.157	0.285	0.470
RM2M	0.135	0.190	0.337	0.607
S1H	0.156	0.247	0.527	1.300
S1L	0.124	0.179	0.292	0.500
S1M	0.121	0.175	0.338	0.834
S2H	0.140	0.208	0.520	1.300
S2L	0.130	0.184	0.301	0.500
S2M	0.141	0.196	0.355	0.834
S3	0.085	0.112	0.213	0.352
S4H	0.124	0.179	0.416	1.138
S4L	0.113	0.161	0.255	0.438
S4M	0.126	0.184	0.302	0.728
S5H	0.110	0.176	0.390	0.910
S5L	0.098	0.159	0.261	0.398
S5M	0.110	0.180	0.307	0.584
URML	0.096	0.142	0.264	0.446
URMM	0.094	0.148	0.272	0.415
W1	0.107	0.189	0.441	0.771
W2	0.111	0.215	0.416	0.750

Table C.4 Median equivalent-PGA values for location Eemshaven and time window T4

Label	DS2	DS3	DS4	DS5
C1H	0.081	0.127	0.318	0.796
C1L	0.086	0.123	0.211	0.333
C1M	0.095	0.138	0.249	0.554
C2H	0.096	0.158	0.314	0.796
C2L	0.086	0.137	0.243	0.387
C2M	0.101	0.171	0.286	0.554
C3H	0.080	0.128	0.250	0.557
C3L	0.072	0.112	0.201	0.307
C3M	0.084	0.138	0.237	0.388
PC1	0.087	0.106	0.205	0.343
PC2H	0.095	0.134	0.255	0.697
PC2L	0.084	0.115	0.196	0.324
PC2M	0.098	0.141	0.231	0.483
RM1L	0.091	0.125	0.226	0.374
RM1M	0.107	0.152	0.268	0.483
RM2H	0.103	0.144	0.279	0.697
RM2L	0.091	0.125	0.226	0.374
RM2M	0.107	0.152	0.268	0.483
S1H	0.124	0.197	0.419	1.035
S1L	0.099	0.143	0.232	0.398
S1M	0.096	0.139	0.269	0.664
S2H	0.111	0.166	0.414	1.035
S2L	0.104	0.147	0.240	0.398
S2M	0.112	0.156	0.283	0.664
S3	0.069	0.090	0.169	0.280
S4H	0.099	0.142	0.331	0.906
S4L	0.090	0.128	0.203	0.348
S4M	0.100	0.146	0.241	0.580
S5H	0.088	0.140	0.310	0.724
S5L	0.079	0.126	0.208	0.317
S5M	0.088	0.143	0.245	0.465
URML	0.105	0.120	0.210	0.355
URMM	0.076	0.118	0.216	0.331
W1	0.109	0.151	0.351	0.614
W2	0.089	0.171	0.332	0.597

Table C.5 Median equivalent-PGA values for location Eemshaven and time window T5

Label	DS2	DS3	DS4	DS5
C1H	0.081	0.132	0.330	0.824
C1L	0.087	0.127	0.218	0.345
C1M	0.098	0.143	0.258	0.573
C2H	0.099	0.163	0.326	0.824
C2L	0.087	0.142	0.252	0.400
C2M	0.105	0.177	0.296	0.573
C3H	0.079	0.133	0.258	0.577
C3L	0.068	0.116	0.208	0.318
C3M	0.084	0.143	0.245	0.401
PC1	0.089	0.110	0.213	0.355
PC2H	0.098	0.139	0.264	0.721
PC2L	0.084	0.119	0.203	0.335
PC2M	0.102	0.146	0.240	0.500
RM1L	0.094	0.129	0.234	0.388
RM1M	0.111	0.157	0.277	0.500
RM2H	0.107	0.150	0.289	0.721
RM2L	0.094	0.129	0.234	0.388
RM2M	0.111	0.157	0.277	0.500
S1H	0.129	0.204	0.434	1.072
S1L	0.102	0.148	0.240	0.412
S1M	0.099	0.144	0.278	0.688
S2H	0.115	0.171	0.429	1.072
S2L	0.108	0.152	0.248	0.412
S2M	0.116	0.161	0.293	0.688
S3	0.064	0.092	0.175	0.290
S4H	0.102	0.147	0.343	0.938
S4L	0.093	0.133	0.211	0.361
S4M	0.104	0.151	0.249	0.600
S5H	0.090	0.145	0.321	0.750
S5L	0.077	0.131	0.215	0.328
S5M	0.090	0.148	0.253	0.482
URML	0.107	0.123	0.218	0.368
URMM	0.073	0.122	0.224	0.342
W1	0.111	0.156	0.363	0.636
W2	0.092	0.177	0.343	0.618

Table C.6 Median equivalent-PGA values for location Eemshaven and time window T6

Label	DS2	DS3	DS4	DS5
C1H	0.083	0.133	0.333	0.832
C1L	0.088	0.129	0.220	0.348
C1M	0.099	0.144	0.260	0.578
C2H	0.100	0.165	0.328	0.832
C2L	0.088	0.143	0.254	0.404
C2M	0.105	0.178	0.299	0.578
C3H	0.082	0.134	0.261	0.582
C3L	0.073	0.117	0.210	0.321
C3M	0.086	0.144	0.247	0.405
PC1	0.089	0.111	0.214	0.358
PC2H	0.099	0.140	0.266	0.728
PC2L	0.086	0.120	0.204	0.338
PC2M	0.103	0.148	0.242	0.505
RM1L	0.095	0.130	0.237	0.391
RM1M	0.112	0.158	0.280	0.505
RM2H	0.108	0.151	0.291	0.728
RM2L	0.095	0.130	0.237	0.391
RM2M	0.112	0.158	0.280	0.505
S1H	0.130	0.205	0.438	1.081
S1L	0.103	0.149	0.243	0.416
S1M	0.100	0.145	0.281	0.694
S2H	0.116	0.173	0.432	1.081
S2L	0.108	0.153	0.250	0.416
S2M	0.117	0.163	0.295	0.694
S3	0.070	0.093	0.177	0.293
S4H	0.103	0.149	0.346	0.946
S4L	0.094	0.134	0.212	0.364
S4M	0.105	0.153	0.251	0.606
S5H	0.091	0.146	0.324	0.757
S5L	0.080	0.132	0.217	0.331
S5M	0.091	0.150	0.255	0.486
URML	0.107	0.123	0.220	0.371
URMM	0.077	0.123	0.226	0.345
W1	0.111	0.157	0.366	0.641
W2	0.093	0.179	0.346	0.624

Table C.7 Median equivalent-PGA values for location Hoogezand and time window T4

Label	DS2	DS3	DS4	DS5
C1H	0.128	0.189	0.474	1.184
C1L	0.134	0.183	0.313	0.496
C1M	0.146	0.206	0.370	0.823
C2H	0.147	0.235	0.468	1.184
C2L	0.134	0.204	0.361	0.575
C2M	0.153	0.254	0.425	0.823
C3H	0.126	0.190	0.371	0.829
C3L	0.114	0.167	0.299	0.457
C3M	0.131	0.205	0.352	0.577
PC1	0.127	0.159	0.305	0.510
PC2H	0.146	0.200	0.379	1.036
PC2L	0.131	0.171	0.291	0.481
PC2M	0.150	0.210	0.344	0.719
RM1L	0.141	0.186	0.337	0.557
RM1M	0.160	0.225	0.399	0.719
RM2H	0.156	0.215	0.415	1.036
RM2L	0.141	0.186	0.337	0.557
RM2M	0.160	0.225	0.399	0.719
S1H	0.185	0.292	0.623	1.539
S1L	0.151	0.212	0.345	0.592
S1M	0.148	0.207	0.400	0.988
S2H	0.166	0.246	0.616	1.539
S2L	0.156	0.218	0.356	0.592
S2M	0.167	0.232	0.421	0.988
S3	0.110	0.139	0.252	0.417
S4H	0.151	0.211	0.493	1.347
S4L	0.140	0.191	0.302	0.518
S4M	0.152	0.217	0.358	0.862
S5H	0.137	0.209	0.462	1.078
S5L	0.124	0.188	0.309	0.471
S5M	0.137	0.213	0.364	0.692
URML	0.122	0.169	0.313	0.528
URMM	0.120	0.175	0.322	0.492
W1	0.135	0.224	0.522	0.913
W2	0.139	0.254	0.493	0.888

Table C.8 Median equivalent-PGA values for location Hoogezand and time window T5

Label	DS2	DS3	DS4	DS5
C1H	0.122	0.195	0.487	1.217
C1L	0.129	0.188	0.322	0.509
C1M	0.145	0.211	0.380	0.846
C2H	0.146	0.241	0.481	1.217
C2L	0.129	0.210	0.372	0.591
C2M	0.154	0.261	0.437	0.846
C3H	0.121	0.196	0.382	0.852
C3L	0.109	0.172	0.307	0.469
C3M	0.126	0.211	0.362	0.593
PC1	0.121	0.162	0.314	0.525
PC2H	0.145	0.205	0.390	1.065
PC2L	0.126	0.176	0.299	0.495
PC2M	0.151	0.216	0.354	0.739
RM1L	0.139	0.191	0.346	0.573
RM1M	0.164	0.232	0.410	0.739
RM2H	0.158	0.221	0.426	1.065
RM2L	0.139	0.191	0.346	0.573
RM2M	0.164	0.232	0.410	0.739
S1H	0.190	0.301	0.641	1.583
S1L	0.151	0.218	0.355	0.609
S1M	0.147	0.213	0.411	1.016
S2H	0.170	0.253	0.633	1.583
S2L	0.159	0.224	0.366	0.609
S2M	0.172	0.238	0.432	1.016
S3	0.104	0.136	0.259	0.428
S4H	0.151	0.217	0.506	1.385
S4L	0.137	0.196	0.311	0.533
S4M	0.154	0.224	0.368	0.886
S5H	0.133	0.214	0.475	1.108
S5L	0.119	0.193	0.317	0.485
S5M	0.133	0.219	0.374	0.711
URML	0.121	0.173	0.322	0.543
URMM	0.114	0.180	0.331	0.505
W1	0.130	0.230	0.536	0.939
W2	0.135	0.261	0.507	0.913

Table C.9 Median equivalent-PGA values for location Hoogezand and time window T6

Label	DS2	DS3	DS4	DS5
C1H	0.130	0.209	0.521	1.303
C1L	0.138	0.201	0.345	0.546
C1M	0.156	0.226	0.407	0.906
C2H	0.157	0.258	0.515	1.303
C2L	0.139	0.225	0.398	0.633
C2M	0.165	0.280	0.468	0.906
C3H	0.128	0.210	0.409	0.912
C3L	0.113	0.184	0.329	0.503
C3M	0.134	0.225	0.388	0.635
PC1	0.129	0.174	0.336	0.562
PC2H	0.155	0.220	0.417	1.141
PC2L	0.135	0.189	0.320	0.530
PC2M	0.161	0.232	0.379	0.791
RM1L	0.149	0.204	0.371	0.613
RM1M	0.176	0.248	0.439	0.791
RM2H	0.169	0.236	0.456	1.141
RM2L	0.149	0.204	0.371	0.613
RM2M	0.176	0.248	0.439	0.791
S1H	0.203	0.322	0.686	1.695
S1L	0.162	0.233	0.380	0.652
S1M	0.157	0.228	0.440	1.088
S2H	0.182	0.271	0.678	1.695
S2L	0.170	0.240	0.392	0.652
S2M	0.184	0.255	0.463	1.088
S3	0.108	0.145	0.277	0.459
S4H	0.162	0.233	0.542	1.483
S4L	0.147	0.210	0.333	0.570
S4M	0.164	0.239	0.394	0.949
S5H	0.143	0.230	0.508	1.186
S5L	0.126	0.207	0.340	0.519
S5M	0.143	0.235	0.400	0.762
URML	0.123	0.186	0.344	0.582
URMM	0.120	0.193	0.354	0.541
W1	0.139	0.247	0.574	1.005
W2	0.145	0.280	0.543	0.978

Table C.10 Median equivalent-PGA values for location Veendam and time window T4

Label	DS2	DS3	DS4	DS5
C1H	0.110	0.176	0.441	1.102
C1L	0.117	0.170	0.292	0.461
C1M	0.132	0.191	0.344	0.766
C2H	0.133	0.218	0.435	1.102
C2L	0.117	0.190	0.336	0.535
C2M	0.140	0.237	0.396	0.766
C3H	0.108	0.177	0.346	0.771
C3L	0.095	0.155	0.278	0.425
C3M	0.114	0.191	0.328	0.537
PC1	0.109	0.147	0.284	0.475
PC2H	0.131	0.186	0.353	0.964
PC2L	0.114	0.159	0.271	0.448
PC2M	0.136	0.196	0.320	0.669
RM1L	0.126	0.173	0.314	0.518
RM1M	0.149	0.210	0.371	0.669
RM2H	0.143	0.200	0.386	0.964
RM2L	0.126	0.173	0.314	0.518
RM2M	0.149	0.210	0.371	0.669
S1H	0.172	0.272	0.580	1.433
S1L	0.137	0.197	0.322	0.551
S1M	0.133	0.192	0.372	0.920
S2H	0.154	0.229	0.573	1.433
S2L	0.144	0.203	0.332	0.551
S2M	0.156	0.216	0.392	0.920
S3	0.091	0.123	0.235	0.388
S4H	0.137	0.197	0.458	1.254
S4L	0.124	0.178	0.281	0.482
S4M	0.139	0.202	0.333	0.802
S5H	0.121	0.194	0.430	1.003
S5L	0.106	0.175	0.287	0.439
S5M	0.121	0.198	0.339	0.644
URML	0.104	0.157	0.291	0.492
URMM	0.102	0.163	0.299	0.458
W1	0.118	0.208	0.485	0.850
W2	0.123	0.237	0.459	0.827

Table C.11 Median equivalent-PGA values for location Veendam and time window T5

Label	DS2	DS3	DS4	DS5
C1H	0.093	0.148	0.370	0.925
C1L	0.098	0.143	0.245	0.387
C1M	0.110	0.161	0.289	0.643
C2H	0.111	0.183	0.365	0.925
C2L	0.098	0.159	0.282	0.449
C2M	0.117	0.199	0.332	0.643
C3H	0.091	0.149	0.290	0.648
C3L	0.080	0.130	0.233	0.357
C3M	0.095	0.160	0.275	0.450
PC1	0.092	0.123	0.239	0.399
PC2H	0.110	0.156	0.296	0.809
PC2L	0.096	0.134	0.227	0.376
PC2M	0.114	0.164	0.269	0.561
RM1L	0.106	0.145	0.263	0.435
RM1M	0.125	0.176	0.311	0.561
RM2H	0.120	0.168	0.324	0.809
RM2L	0.106	0.145	0.263	0.435
RM2M	0.125	0.176	0.311	0.561
S1H	0.144	0.228	0.487	1.203
S1L	0.115	0.166	0.270	0.463
S1M	0.112	0.162	0.312	0.772
S2H	0.129	0.192	0.481	1.203
S2L	0.121	0.170	0.278	0.463
S2M	0.131	0.181	0.329	0.772
S3	0.076	0.103	0.197	0.326
S4H	0.115	0.165	0.385	1.052
S4L	0.104	0.149	0.236	0.405
S4M	0.117	0.170	0.280	0.674
S5H	0.101	0.163	0.361	0.842
S5L	0.089	0.147	0.241	0.368
S5M	0.101	0.167	0.284	0.541
URML	0.092	0.132	0.244	0.413
URMM	0.085	0.137	0.251	0.384
W1	0.099	0.175	0.407	0.713
W2	0.103	0.199	0.385	0.694

Table C.12 Median equivalent-PGA values for location Veendam and time window T6

Label	DS2	DS3	DS4	DS5
C1H	0.090	0.144	0.361	0.901
C1L	0.095	0.139	0.239	0.377
C1M	0.108	0.157	0.282	0.627
C2H	0.108	0.179	0.356	0.901
C2L	0.096	0.155	0.275	0.438
C2M	0.114	0.193	0.324	0.627
C3H	0.089	0.145	0.283	0.631
C3L	0.078	0.127	0.227	0.347
C3M	0.093	0.156	0.268	0.439
PC1	0.089	0.120	0.232	0.388
PC2H	0.107	0.152	0.288	0.789
PC2L	0.093	0.130	0.221	0.366
PC2M	0.111	0.160	0.262	0.547
RM1L	0.103	0.141	0.256	0.424
RM1M	0.121	0.172	0.303	0.547
RM2H	0.117	0.163	0.316	0.789
RM2L	0.103	0.141	0.256	0.424
RM2M	0.121	0.172	0.303	0.547
S1H	0.141	0.223	0.475	1.172
S1L	0.112	0.161	0.263	0.451
S1M	0.109	0.157	0.304	0.752
S2H	0.126	0.187	0.469	1.172
S2L	0.118	0.166	0.271	0.451
S2M	0.127	0.176	0.320	0.752
S3	0.074	0.100	0.192	0.317
S4H	0.112	0.161	0.375	1.025
S4L	0.102	0.145	0.230	0.394
S4M	0.114	0.165	0.272	0.656
S5H	0.099	0.159	0.352	0.820
S5L	0.087	0.143	0.235	0.359
S5M	0.099	0.162	0.277	0.527
URML	0.090	0.128	0.238	0.402
URMM	0.083	0.133	0.245	0.374
W1	0.096	0.170	0.397	0.695
W2	0.100	0.193	0.375	0.676

Table C.13 Median equivalent-PGA values for location Winschoten and time window T4

Label	DS2	DS3	DS4	DS5
C1H	0.126	0.201	0.503	1.256
C1L	0.133	0.194	0.333	0.526
C1M	0.150	0.218	0.393	0.874
C2H	0.151	0.249	0.496	1.256
C2L	0.134	0.217	0.384	0.610
C2M	0.159	0.270	0.451	0.874
C3H	0.123	0.202	0.394	0.879
C3L	0.110	0.177	0.317	0.484
C3M	0.130	0.217	0.374	0.612
PC1	0.124	0.168	0.324	0.542
PC2H	0.149	0.212	0.402	1.099
PC2L	0.130	0.182	0.309	0.511
PC2M	0.155	0.223	0.365	0.762
RM1L	0.143	0.197	0.357	0.591
RM1M	0.169	0.239	0.423	0.762
RM2H	0.163	0.228	0.440	1.099
RM2L	0.143	0.197	0.357	0.591
RM2M	0.169	0.239	0.423	0.762
S1H	0.196	0.310	0.661	1.633
S1L	0.156	0.225	0.367	0.628
S1M	0.152	0.219	0.424	1.048
S2H	0.176	0.261	0.653	1.633
S2L	0.164	0.231	0.378	0.628
S2M	0.177	0.246	0.446	1.048
S3	0.105	0.140	0.267	0.442
S4H	0.156	0.224	0.523	1.429
S4L	0.142	0.203	0.321	0.550
S4M	0.158	0.231	0.380	0.915
S5H	0.138	0.221	0.490	1.143
S5L	0.121	0.199	0.327	0.500
S5M	0.138	0.226	0.386	0.734
URML	0.119	0.179	0.332	0.561
URMM	0.116	0.186	0.341	0.522
W1	0.134	0.238	0.553	0.969
W2	0.140	0.270	0.523	0.942

Table C.14 Median equivalent-PGA values for location Winschoten and time window T5

Label	DS2	DS3	DS4	DS5
C1H	0.098	0.157	0.391	0.978
C1L	0.104	0.151	0.259	0.410
C1M	0.117	0.170	0.306	0.680
C2H	0.118	0.194	0.387	0.978
C2L	0.104	0.169	0.299	0.475
C2M	0.124	0.210	0.351	0.680
C3H	0.096	0.157	0.307	0.685
C3L	0.085	0.138	0.247	0.377
C3M	0.101	0.169	0.291	0.477
PC1	0.097	0.131	0.252	0.422
PC2H	0.116	0.165	0.313	0.856
PC2L	0.101	0.142	0.240	0.398
PC2M	0.121	0.174	0.284	0.594
RM1L	0.112	0.153	0.278	0.460
RM1M	0.132	0.186	0.329	0.594
RM2H	0.127	0.178	0.343	0.856
RM2L	0.112	0.153	0.278	0.460
RM2M	0.132	0.186	0.329	0.594
S1H	0.153	0.242	0.515	1.272
S1L	0.122	0.175	0.285	0.489
S1M	0.118	0.171	0.330	0.816
S2H	0.137	0.204	0.509	1.272
S2L	0.128	0.180	0.294	0.489
S2M	0.138	0.191	0.348	0.816
S3	0.081	0.109	0.208	0.344
S4H	0.122	0.175	0.407	1.113
S4L	0.110	0.158	0.250	0.428
S4M	0.123	0.180	0.296	0.712
S5H	0.107	0.172	0.382	0.890
S5L	0.094	0.155	0.255	0.390
S5M	0.107	0.176	0.301	0.572
URML	0.092	0.139	0.259	0.437
URMM	0.090	0.145	0.266	0.406
W1	0.105	0.185	0.431	0.754
W2	0.109	0.210	0.407	0.734

Table C.15 Median equivalent-PGA values for location Winschoten and time window T6

Label	DS2	DS3	DS4	DS5
C1H	0.100	0.160	0.400	1.001
C1L	0.106	0.155	0.265	0.419
C1M	0.120	0.174	0.313	0.696
C2H	0.120	0.198	0.395	1.001
C2L	0.106	0.173	0.306	0.486
C2M	0.127	0.215	0.360	0.696
C3H	0.098	0.161	0.314	0.701
C3L	0.086	0.141	0.253	0.386
C3M	0.103	0.173	0.298	0.488
PC1	0.099	0.134	0.258	0.431
PC2H	0.119	0.169	0.320	0.876
PC2L	0.104	0.145	0.246	0.407
PC2M	0.124	0.178	0.291	0.607
RM1L	0.114	0.157	0.285	0.471
RM1M	0.135	0.191	0.337	0.607
RM2H	0.130	0.182	0.351	0.876
RM2L	0.114	0.157	0.285	0.471
RM2M	0.135	0.191	0.337	0.607
S1H	0.156	0.247	0.527	1.301
S1L	0.124	0.179	0.292	0.501
S1M	0.121	0.175	0.338	0.835
S2H	0.140	0.208	0.521	1.301
S2L	0.131	0.184	0.301	0.501
S2M	0.141	0.196	0.356	0.835
S3	0.082	0.112	0.213	0.352
S4H	0.124	0.179	0.416	1.139
S4L	0.113	0.161	0.256	0.438
S4M	0.126	0.184	0.302	0.729
S5H	0.110	0.176	0.390	0.911
S5L	0.097	0.159	0.261	0.399
S5M	0.110	0.180	0.308	0.585
URML	0.094	0.143	0.265	0.447
URMM	0.092	0.148	0.272	0.416
W1	0.107	0.189	0.441	0.772
W2	0.111	0.215	0.417	0.751

II

APPENDIX: VERIFICATION FRAGILITY CURVES

II.1 Building structures

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 3
object name: Building A
location: Eemshaven
peak ground acceleration: 0.050 [g]

Typology

label: S5L - Eemshaven
typology: Steel frame with unreinforced masonry infill walls, low rise, 1-3 stories (typical height 7.3 m)

CALCULATION

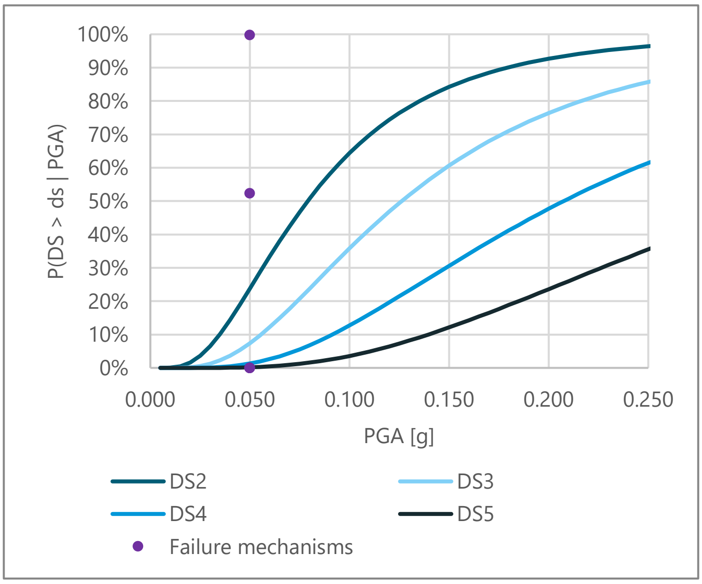
Fragility curves

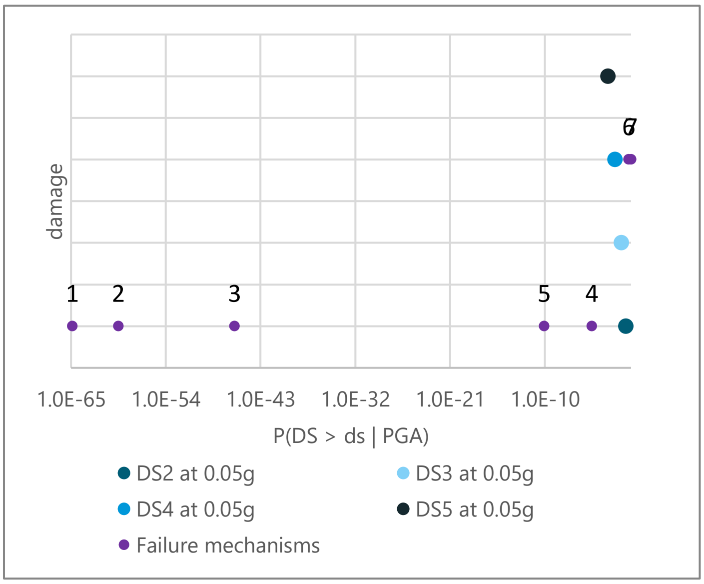
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.08	0.64	2.38E-01	0.10
DS3	0.13	0.64	7.39E-02	0.30
DS4	0.21	0.64	1.31E-02	0.50
DS5	0.32	0.64	1.95E-03	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	buckling of columns	0.16	0.05	1.00	DS2	17.06	1.41E-65
2	yielding beams	0.20	0.05	1.00	DS2	16.33	3.12E-60
3	yielding braces	0.31	0.05	1.00	DS2	14.31	9.70E-47
4	pull-out failure of anchor	0.63	0.15	1.20	DS2	4.03	2.82E-05
5	anchor failure	0.54	0.10	1.25	DS2	6.39	8.38E-11
6	out-of-plane failure wall	1.72	0.25	1.00	DS4	-0.06	5.24E-01
7	out-of-plane failure wall	6.40	0.25	2.20	DS4	-2.87	9.98E-01
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 4
object name: Building B
location: Veendam
peak ground acceleration: 0.034 [g]

Typology

label: S2H - Veendam
typology: Steel braced frame, high rise, 8+ stories (typical height 47.5 m)

CALCULATION

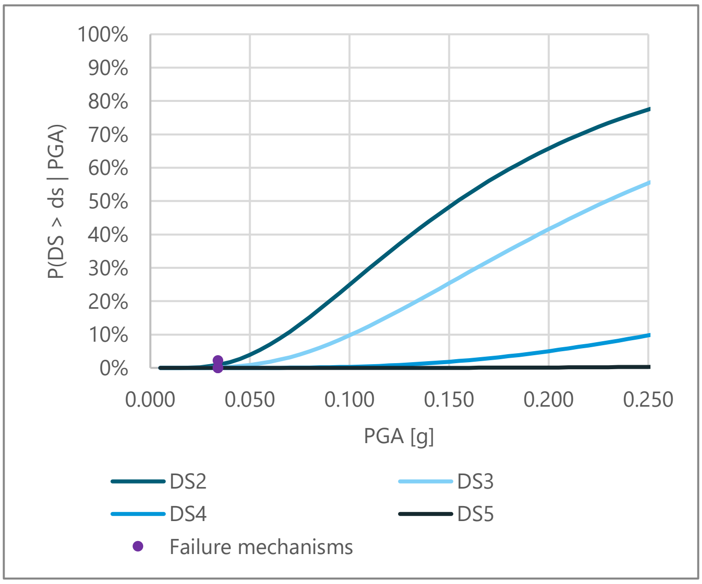
Fragility curves

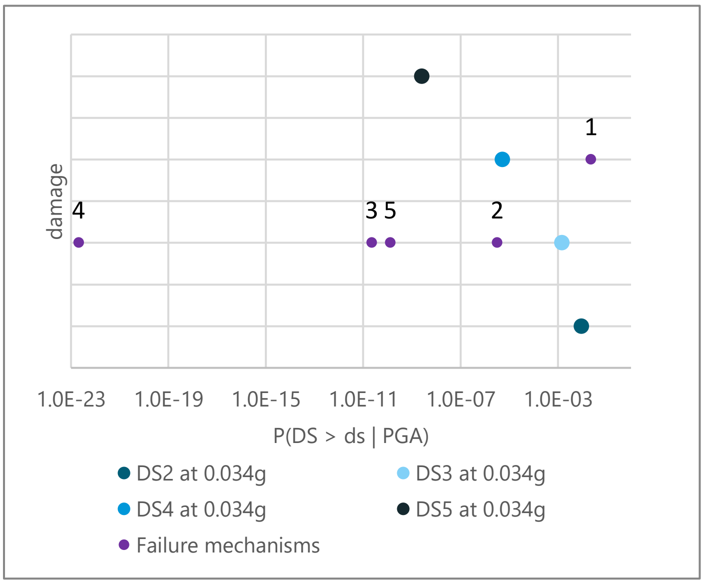
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.15	0.64	9.06E-03	0.10
DS3	0.23	0.64	1.43E-03	0.30
DS4	0.57	0.64	5.08E-06	0.50
DS5	1.43	0.64	2.53E-09	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	buckling support columns	0.98	0.05	1.00	DS4	2.01	2.24E-02
2	bolt failure anchors	0.82	0.10	1.25	DS3	4.52	3.15E-06
3	bolt failure top of columns	0.51	0.10	1.25	DS3	6.59	2.21E-11
4	shear failure beams	0.55	0.05	1.00	DS3	9.90	2.04E-23
5	bolt failure floor beams	0.55	0.10	1.25	DS3	6.32	1.29E-10
6							
7							
8							
9							
10							

RESULTS





Witteveen+Bos	project: Selectiemethodiek Industrie Stap 2	spreadsheet FRAGILITY CURVES	version 0.1
	projectcode: 124217		
	part: Verification fragility curves	format by:	J. de Bruijn MSc
	description:	date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 4	
object name:	Equipment C / Building D	
location:	Veendam	
peak ground acceleration:	0.034	[g]

Typology

label:	S2M - Veendam
typology:	Steel braced frame, medium rise, 4-7 stories (typical height 18.3 m)

CALCULATION

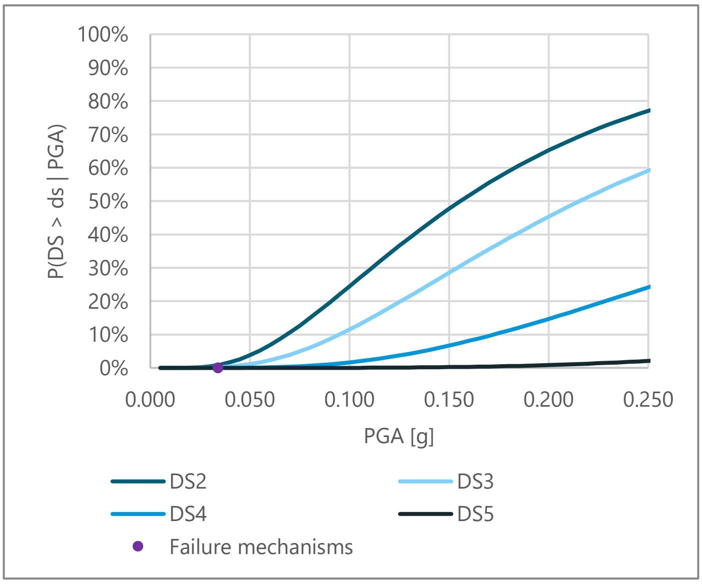
Fragility curves

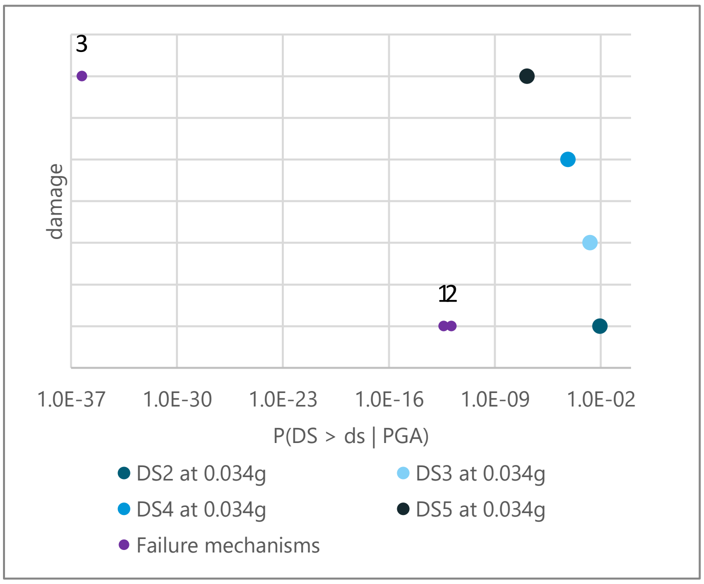
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.16	0.64	8.72E-03	0.10
DS3	0.22	0.64	1.95E-03	0.30
DS4	0.39	0.64	6.72E-05	0.50
DS5	0.92	0.64	1.29E-07	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding weigh cell modulus	0.34	0.10	1.00	DS2	7.16	4.11E-13
2	shear dumb support	0.36	0.10	1.00	DS2	6.99	1.37E-12
3	buckling support columns	0.40	0.05	1.00	DS5	12.66	5.18E-37
4							
5							
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 5
object name: Building E
location: Delfzijl
peak ground acceleration: 0.060 [g]

Typology

label: S2M - Delfzijl
typology: Steel braced frame, medium rise, 4-7 stories (typical height 18.3 m)

CALCULATION

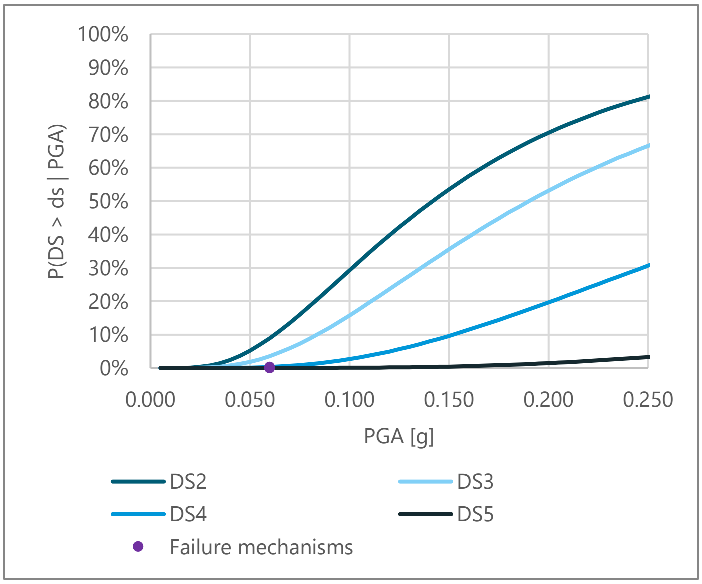
Fragility curves

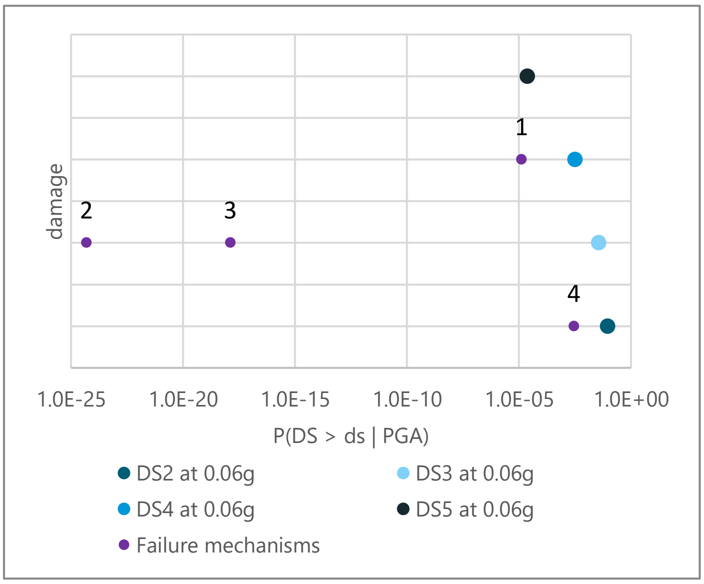
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.14	0.64	8.95E-02	0.10
DS3	0.19	0.64	3.57E-02	0.30
DS4	0.35	0.64	3.11E-03	0.50
DS5	0.81	0.64	2.35E-05	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	buckling support columns	0.86	0.05	1.00	DS4	4.21	1.27E-05
2	yielding support frame	0.53	0.05	1.00	DS3	10.27	4.85E-25
3	bolt failure	0.19	0.10	1.25	DS3	8.73	1.28E-18
4	shear failure pile	0.93	0.15	1.20	DS2	2.77	2.79E-03
5							
6							
7							
8							
9							
10							

RESULTS





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	part:	Verification fragility curves	format by:	J. de Bruijn MSc
	description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 5	
object name:	Building F	
location:	Delfzijl	
peak ground acceleration:	0.060	[g]

Typology

label:	S2M - Delfzijl
typology:	Steel braced frame, medium rise, 4-7 stories (typical height 18.3 m)

CALCULATION

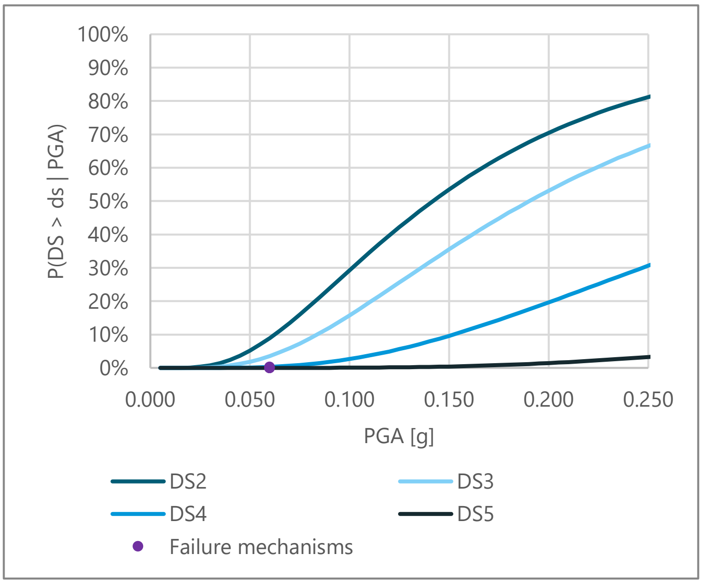
Fragility curves

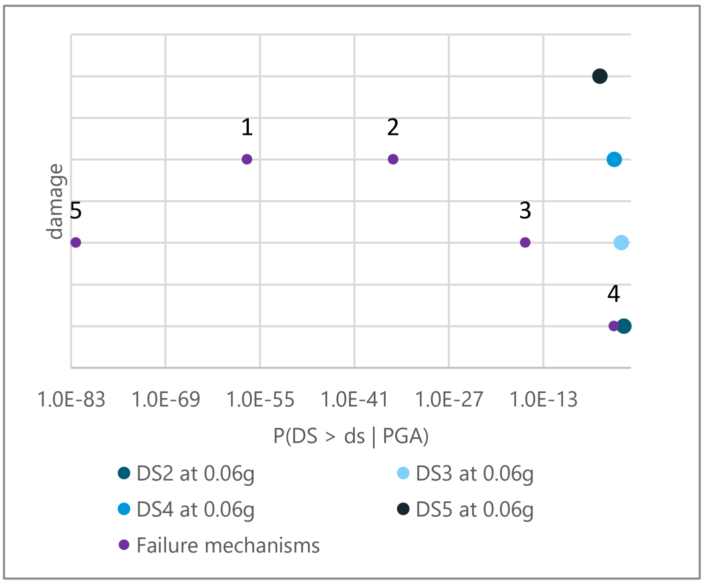
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.14	0.64	8.95E-02	0.10
DS3	0.19	0.64	3.57E-02	0.30
DS4	0.35	0.64	3.11E-03	0.50
DS5	0.81	0.64	2.35E-05	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	buckling support columns	0.22	0.05	1.00	DS4	15.96	1.20E-57
2	yielding support frame	0.41	0.05	1.00	DS4	12.47	5.28E-36
3	bolt failure	0.28	0.10	1.25	DS3	8.13	2.19E-16
4	shear failure pile	0.93	0.15	1.20	DS2	2.77	2.79E-03
5	pounding	0.04	0.05	1.00	DS3	19.27	5.22E-83
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 6
object name: Pipeline bridge A
location: Delfzijl
peak ground acceleration: 0.080 [g]

Typology

label: S2L - Delfzijl
typology: Steel braced frame, low rise, 1-3 stories (typical height 7.3 m)

CALCULATION

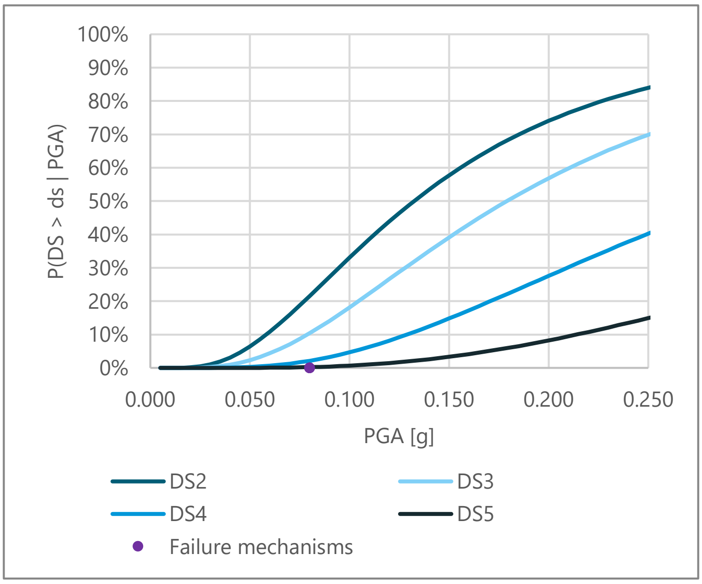
Fragility curves

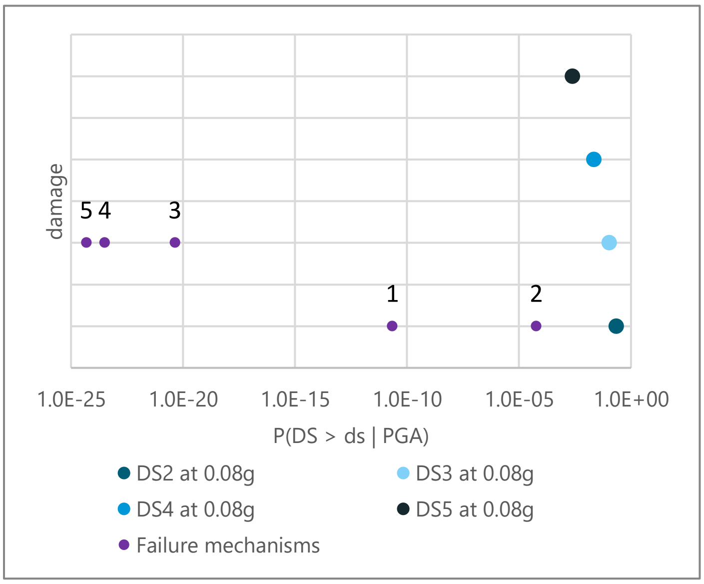
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.13	0.64	2.16E-01	0.10
DS3	0.18	0.64	1.04E-01	0.30
DS4	0.29	0.64	2.13E-02	0.50
DS5	0.49	0.64	2.40E-03	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	foundation - yielding reinforcement	0.84	0.05	1.15	DS2	6.59	2.21E-11
2	foundation - concrete crushing	0.84	0.15	1.50	DS2	3.85	5.86E-05
3	buckling columns - bridge 3	0.58	0.05	1.00	DS3	9.35	4.33E-21
4	buckling beams	0.54	0.05	1.00	DS3	10.09	3.20E-24
5	buckling columns - bridge 4	0.53	0.05	1.00	DS3	10.27	4.85E-25
6							
7							
8							
9							
10							

RESULTS





project:	Selectiemethodiek Industrie Stap 2	spreadsheet	version 0.1
projectcode:	124217	FRAGILITY CURVES	
part:	Verification fragility curves	format by:	J. de Bruijn MSc
description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 6	
object name:	Building H	
location:	Delfzijl	
peak ground acceleration:	0.080	[g]

Typology

label:	S2M - Delfzijl
typology:	Steel braced frame, medium rise, 4-7 stories (typical height 18.3 m)

CALCULATION

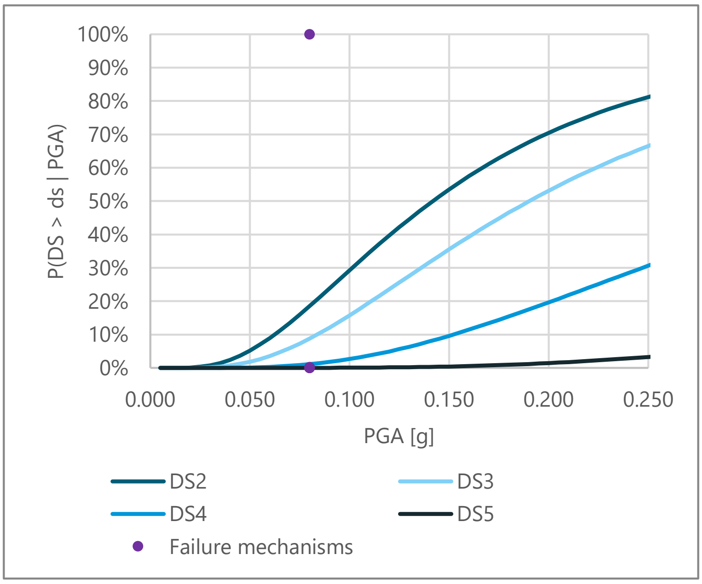
Fragility curves

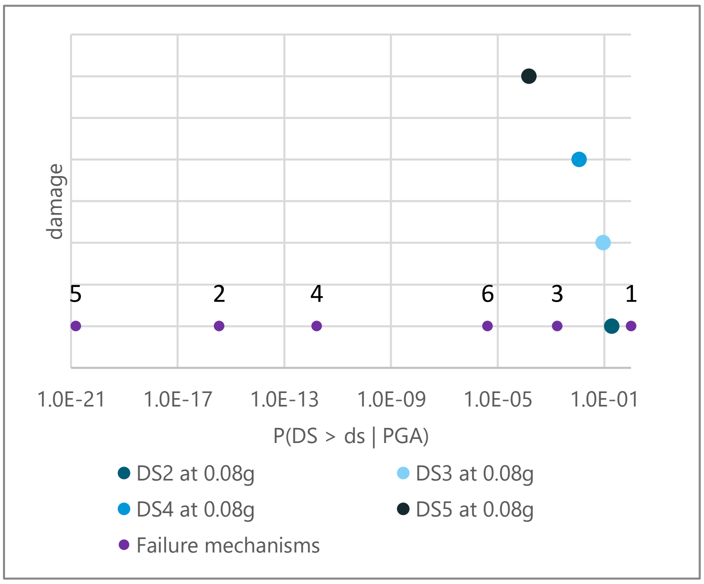
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.14	0.64	1.86E-01	0.10
DS3	0.19	0.64	8.79E-02	0.30
DS4	0.35	0.64	1.11E-02	0.50
DS5	0.81	0.64	1.47E-04	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding beams	1.53	0.05	1.00	DS2	-8.09	1.00E+00
2	buckling columns	0.65	0.05	1.00	DS2	8.07	3.63E-16
3	yielding column web	0.93	0.05	1.00	DS2	2.93	1.72E-03
4	yielding column web	0.71	0.05	1.00	DS2	6.96	1.65E-12
5	foundation slab - yielding reinforcement	0.66	0.05	1.15	DS2	9.46	1.50E-21
6	foundation slab - shear	0.66	0.15	1.50	DS2	4.45	4.20E-06
7							
8							
9							
10							

RESULTS





Witteveen+Bos	project: Selectiemethodiek Industrie Stap 2	spreadsheet version 0.1
	projectcode: 124217	FRAGILITY CURVES
	part: Verification fragility curves	format by: J. de Bruijn MSc
	description:	date of format: 6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 6	
object name:	Building I	
location:	Delfzijl	
peak ground acceleration:	0.080	[g]

Typology

label:	C1L - Delfzijl
typology:	Concrete moment frame, low rise, 1-3 stories (typical height 7.3 m)

CALCULATION

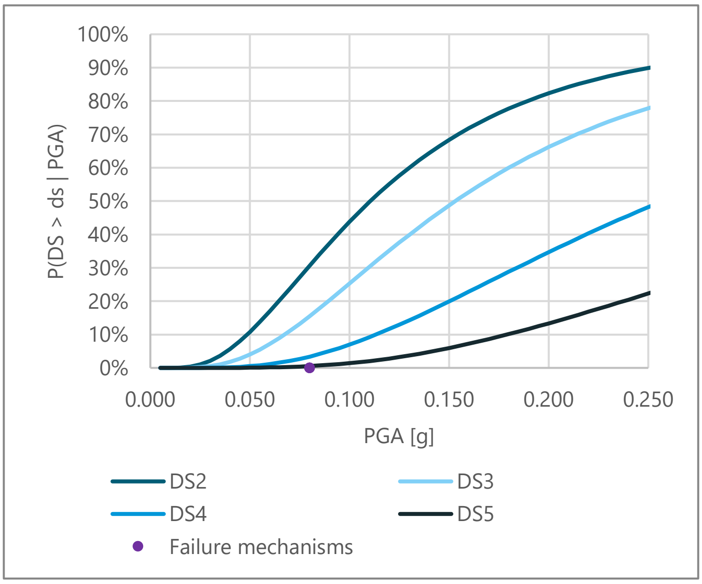
Fragility curves

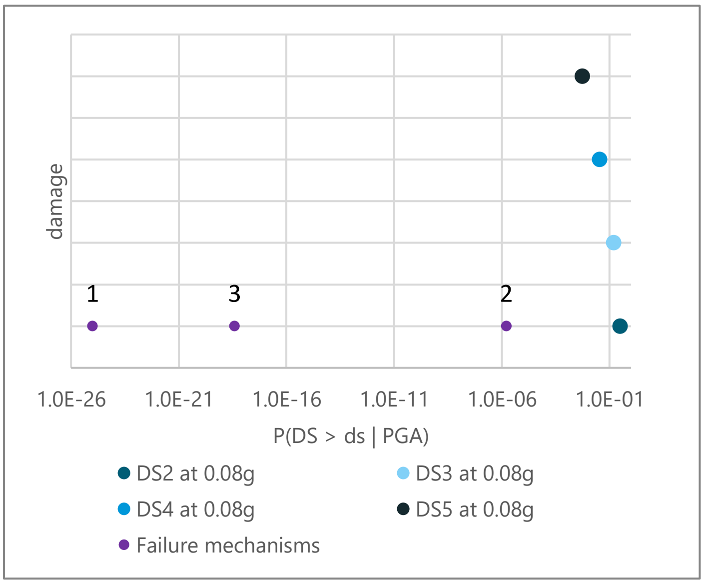
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.11	0.64	3.07E-01	0.10
DS3	0.15	0.64	1.55E-01	0.30
DS4	0.26	0.64	3.39E-02	0.50
DS5	0.41	0.64	5.51E-03	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	foundation slab - yielding reinforcement	0.60	0.05	1.15	DS2	10.42	9.96E-26
2	table top deck - shear failure	0.60	0.15	1.50	DS2	4.66	1.61E-06
3	pile foundation	0.70	0.05	1.15	DS2	8.86	3.95E-19
4							
5							
6							
7							
8							
9							
10							

RESULTS





spreadsheet FRAGILITY CURVES — version 0.1

project: Selectiemethodiek Industrie Stap 2
projectcode: 124217
part: Verification fragility curves
description:

format by: J. de Bruijn MSc
date of format: 6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 6
object name: Building J
location: Delfzijl
peak ground acceleration: 0.140 [g]

Typology

label: S2L - Delfzijl
typology: Steel braced frame, low rise, 1-3 stories (typical height 7.3 m)

CALCULATION

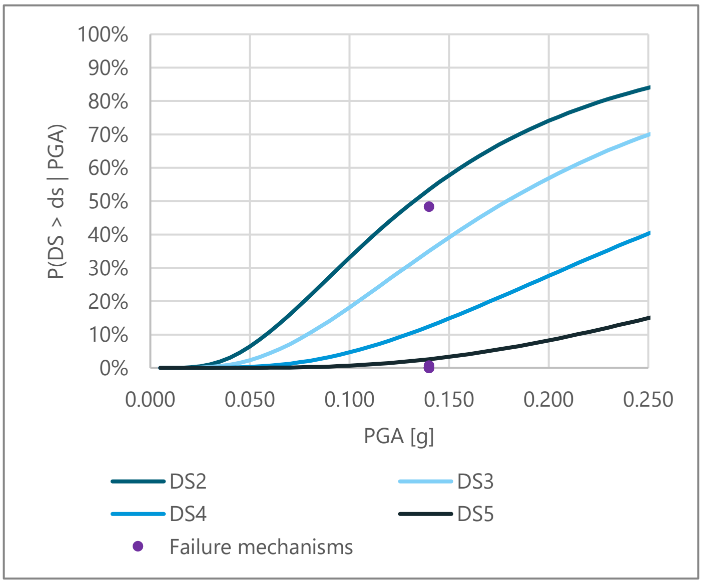
Fragility curves

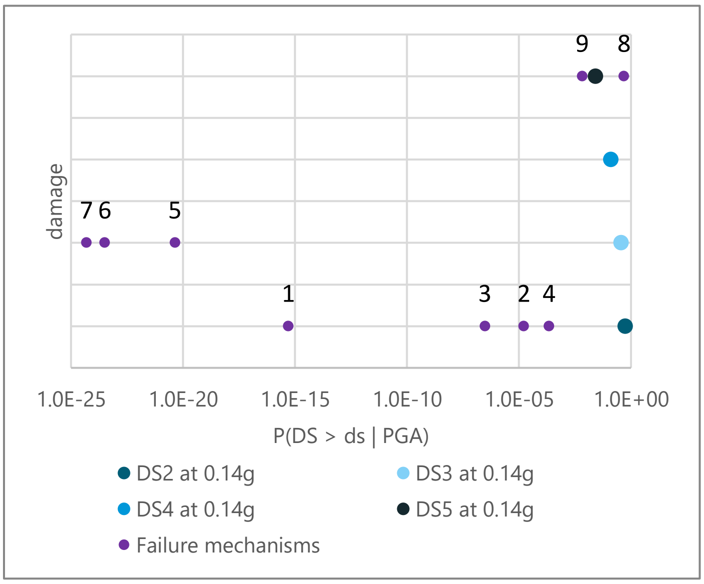
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.13	0.64	5.35E-01	0.10
DS3	0.18	0.64	3.50E-01	0.30
DS4	0.29	0.64	1.25E-01	0.50
DS5	0.49	0.64	2.58E-02	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	foundation LB3 - yielding reinforcement	0.75	0.05	1.15	DS2	8.03	5.03E-16
2	foundation LB3 - concrete crushing	0.75	0.15	1.50	DS2	4.15	1.64E-05
3	foundation LB4 - yielding reinforcement	0.94	0.05	1.15	DS2	4.99	2.98E-07
4	foundation LB4 - concrete crushing	0.94	0.15	1.50	DS2	3.52	2.19E-04
5	buckling columns LB3	0.58	0.05	1.00	DS3	9.35	4.33E-21
6	stability beams LB3	0.54	0.05	1.00	DS3	10.09	3.20E-24
7	buckling columns LB4	0.53	0.05	1.00	DS3	10.27	4.85E-25
8	foundation LB3 - yielding reinforcement	1.25	0.05	1.15	DS5	0.04	4.83E-01
9	foundation LB3 - concrete crushing	1.25	0.15	1.50	DS5	2.48	6.61E-03
10							

RESULTS





Witteveen + Bos

project:	Selectiemethodiek Industrie Stap 2	spreadsheet	version 0.1
projectcode:	124217	FRAGILITY CURVES	
part:	Verification fragility curves	format by:	J. de Bruijn MSc
description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 7	
object name:	Building L	
location:	Delfzijl	
peak ground acceleration:	0.110	[g]

Typology

label:	S2M - Delfzijl
typology:	Steel braced frame, medium rise, 4-7 stories (typical height 18.3 m)

CALCULATION

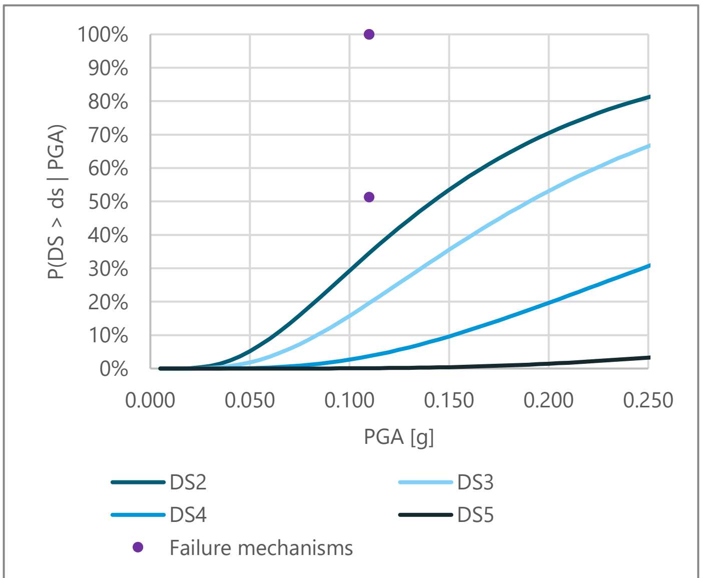
Fragility curves

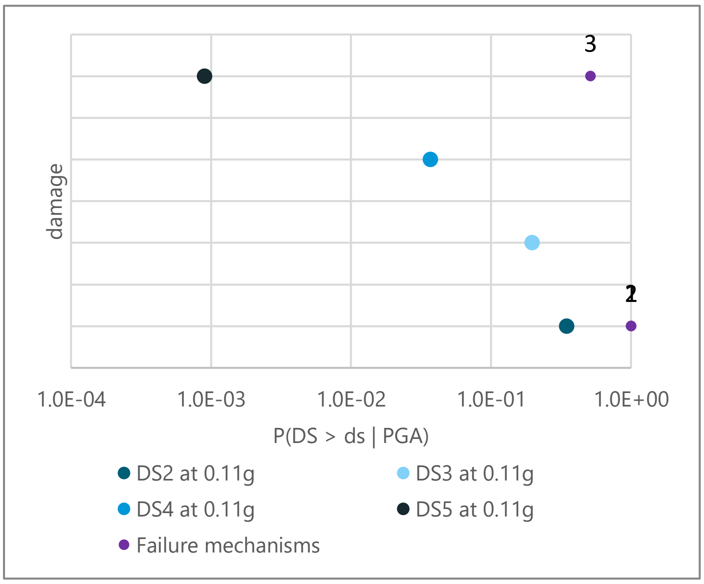
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.14	0.64	3.46E-01	0.10
DS3	0.19	0.64	1.96E-01	0.30
DS4	0.35	0.64	3.68E-02	0.50
DS5	0.81	0.64	8.96E-04	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	pile - yielding reinforcement	2.21	0.05	1.15	DS2	-15.28	1.00E+00
2	yielding braces	3.00	0.05	1.00	DS2	-35.08	1.00E+00
3	shear failure bolted connections	1.50	0.10	1.25	DS5	-0.03	5.13E-01
4							
5							
6							
7							
8							
9							
10							

RESULTS





project:	Selectiemethodiek Industrie Stap 2	spreadsheet	version 0.1
projectcode:	124217	FRAGILITY CURVES	
part:	Verification fragility curves	format by:	J. de Bruijn MSc
description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 7
object name: Pipeline bridge B
location: Delfzijl
peak ground acceleration: 0.080 [g]

Typology

label: S1L - Delfzijl
typology: Steel moment frame, low rise, 1-3 stories (typical height 7.3 m)

CALCULATION

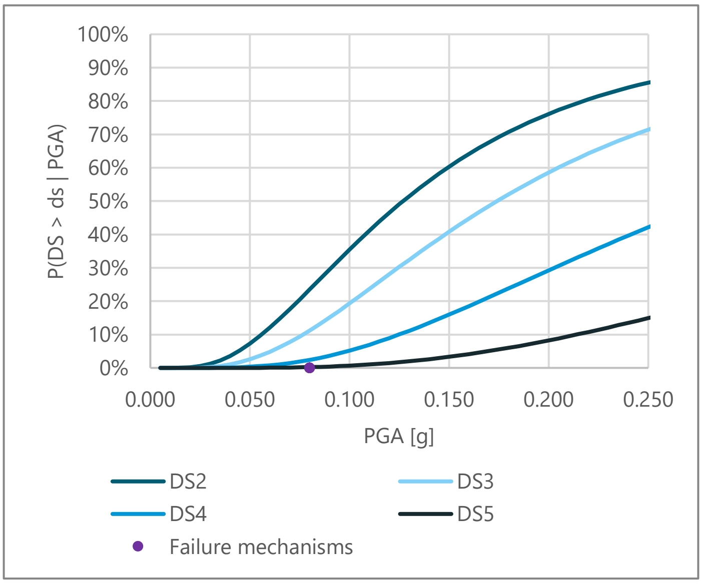
Fragility curves

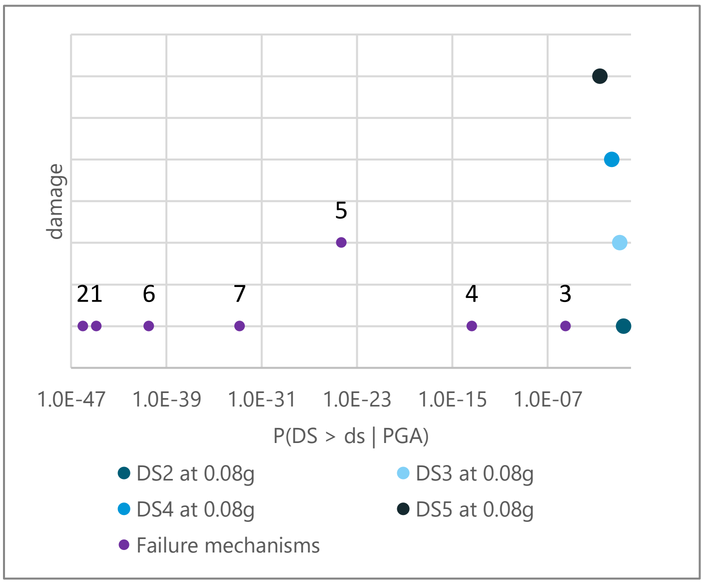
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.13	0.64	2.35E-01	0.10
DS3	0.17	0.64	1.12E-01	0.30
DS4	0.28	0.64	2.39E-02	0.50
DS5	0.49	0.64	2.40E-03	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding braces	0.32	0.05	1.00	DS2	14.12	1.34E-45
2	yielding and stability steel members	0.31	0.05	1.00	DS2	14.31	9.70E-47
3	failure bolted connections - braces	0.82	0.10	1.25	DS2	4.52	3.15E-06
4	failure bolted connections	0.38	0.10	1.25	DS2	7.46	4.37E-14
5	failure bolted connections - portals	0.53	0.05	1.00	DS3	10.27	4.85E-25
6	anchorage - shear failure	0.36	0.05	1.00	DS2	13.39	3.44E-41
7	pile foundation	0.50	0.05	1.15	DS2	12.02	1.44E-33
8							
9							
10							

RESULTS





Witteveen+Bos	project:	Selectiemethodiek Industrie Stap 2	spreadsheet FRAGILITY CURVES	version 0.1
	projectcode:	124217		
	part:	Verification fragility curves	format by:	J. de Bruijn MSc
	description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 8	
object name:	Building M	
location:	Delfzijl	
peak ground acceleration:	0.072	[g]

Typology

label:	S2H - Delfzijl
typology:	Steel braced frame, high rise, 8+ stories (typical height 47.5 m)

CALCULATION

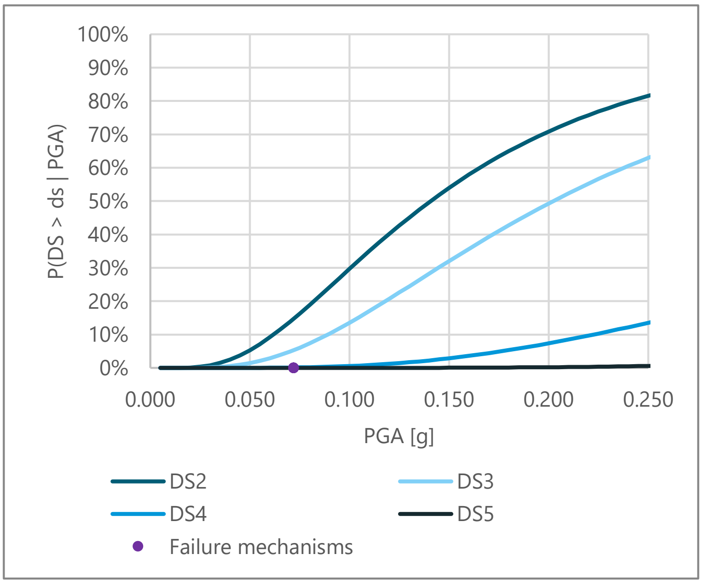
Fragility curves

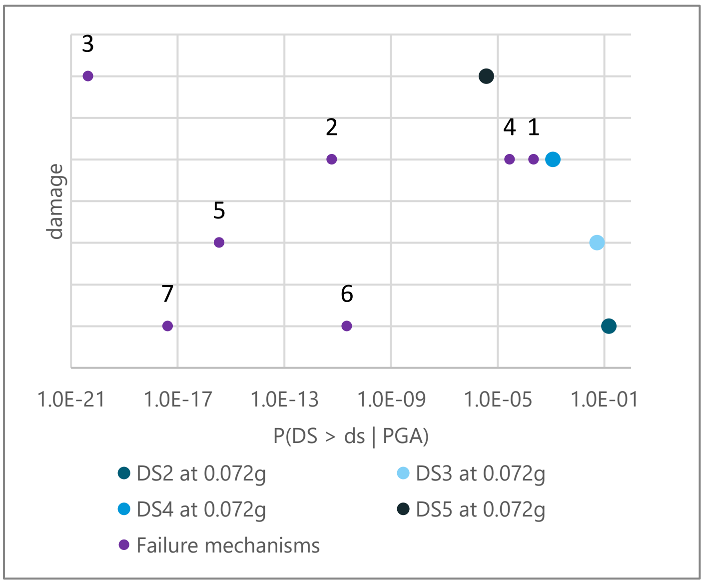
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.14	0.64	1.48E-01	0.10
DS3	0.20	0.64	5.32E-02	0.30
DS4	0.51	0.64	1.16E-03	0.50
DS5	1.26	0.64	3.77E-06	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure bolt connection bracings	0.97	0.10	1.25	DS4	3.51	2.22E-04
2	failure beams	0.72	0.05	1.00	DS4	6.78	5.98E-12
3	failure columns	0.58	0.05	1.00	DS5	9.35	4.33E-21
4	failure of console	0.87	0.05	1.00	DS4	4.03	2.83E-05
5	failure connection columns-foundation	0.65	0.05	1.00	DS3	8.07	3.63E-16
6	failure pile foundation vertical component	0.51	0.10	1.25	DS2	6.59	2.21E-11
7	failure pile foundation horizontal component	0.21	0.10	1.25	DS2	8.60	4.14E-18
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 8
object name: Building N
location: Delfzijl
peak ground acceleration: 0.072 [g]

Typology

label: S2M - Delfzijl
typology: Steel braced frame, medium rise, 4-7 stories (typical height 18.3 m)

CALCULATION

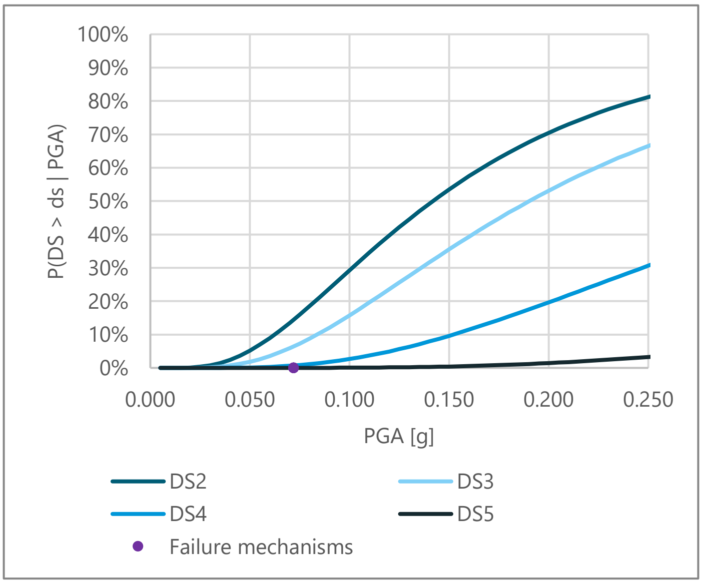
Fragility curves

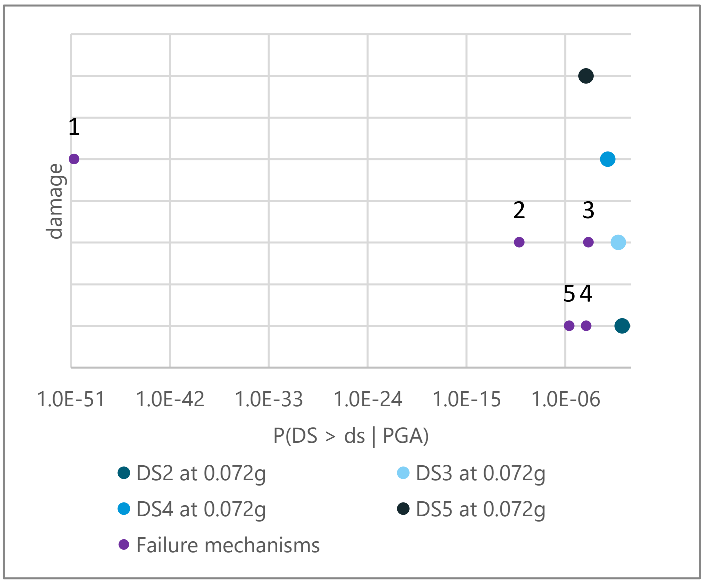
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.14	0.64	1.45E-01	0.10
DS3	0.19	0.64	6.44E-02	0.30
DS4	0.35	0.64	7.13E-03	0.50
DS5	0.81	0.64	7.69E-05	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure building	0.27	0.05	1.00	DS4	15.04	1.92E-51
2	moment failure concrete foundation slab	0.85	0.05	1.15	DS3	6.43	6.40E-11
3	punching failure concrete foundation slab	0.90	0.15	1.50	DS3	3.65	1.31E-04
4	failure pile foundation vertical component	0.93	0.10	1.25	DS2	3.78	7.84E-05
5	failure pile foundation horizontal component	0.81	0.10	1.25	DS2	4.58	2.29E-06
6							
7							
8							
9							
10							

RESULTS





project:	Selectiemethodiek Industrie Stap 2	spreadsheet	version 0.1
projectcode:	124217	FRAGILITY CURVES	
part:	Verification fragility curves	format by:	J. de Bruijn MSc
description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 9	
object name:	Storage rack A	
location:	Delfzijl	
peak ground acceleration:	0.079	[g]

Typology

label:	S2M - Delfzijl
typology:	Steel braced frame, medium rise, 4-7 stories (typical height 18.3 m)

CALCULATION

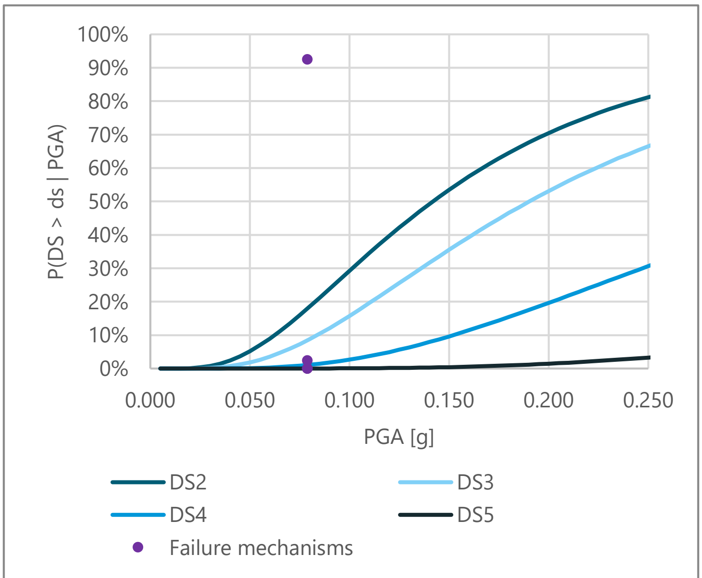
Fragility curves

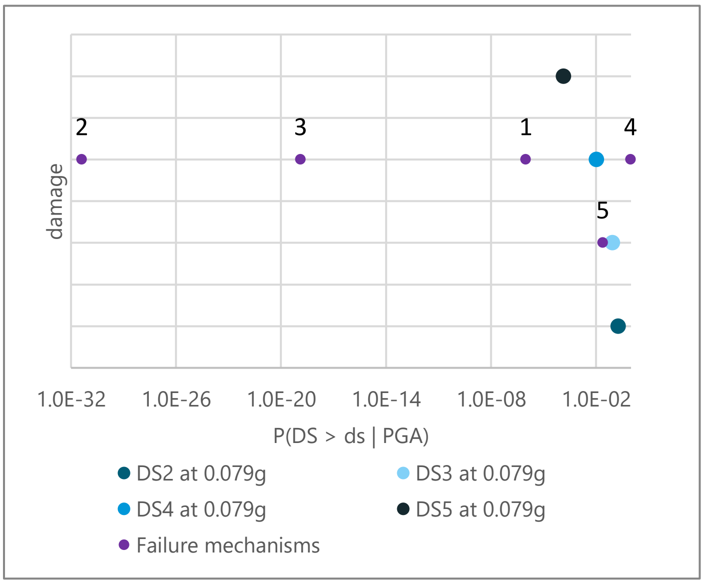
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.14	0.64	1.80E-01	0.10
DS3	0.19	0.64	8.48E-02	0.30
DS4	0.35	0.64	1.06E-02	0.50
DS5	0.81	0.64	1.36E-04	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding columns	0.83	0.05	1.00	DS4	4.76	9.62E-07
2	yielding beams	0.45	0.05	1.00	DS4	11.74	4.07E-32
3	yielding diagonal	0.60	0.05	1.00	DS4	8.98	1.31E-19
4	yielding connection	1.71	0.10	1.25	DS4	-1.44	9.25E-01
5	tensile and shear failure bolted connection	1.20	0.10	1.25	DS3	1.97	2.42E-02
6							
7							
8							
9							
10							

RESULTS





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projectcode:	124217		FRAGILITY CURVES	
part:	Verification fragility curves		format by:	J. de Bruijn MSc
description:			date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 9	
object name:	Building O	
location:	Delfzijl	
peak ground acceleration:	0.079	[g]

Typology

label:	C3L - Delfzijl
typology:	Concrete frame with unreinforced masonry infill walls, low rise, 1-3 stories (typical height 7.3 m)

CALCULATION

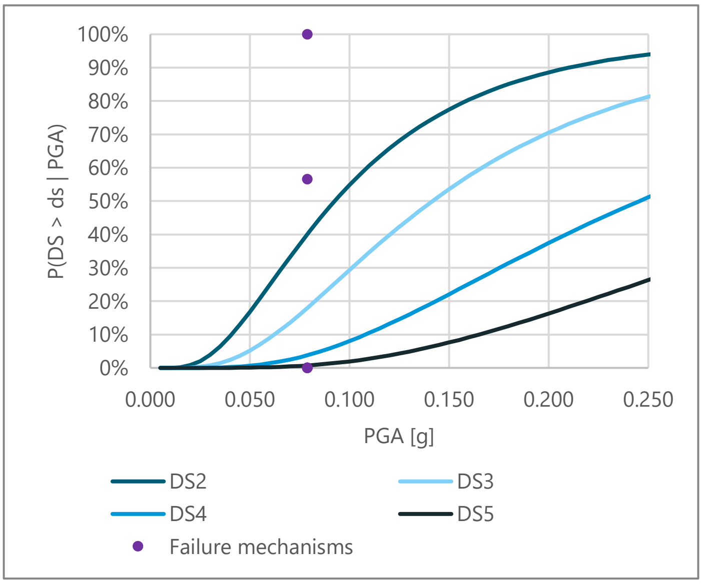
Fragility curves

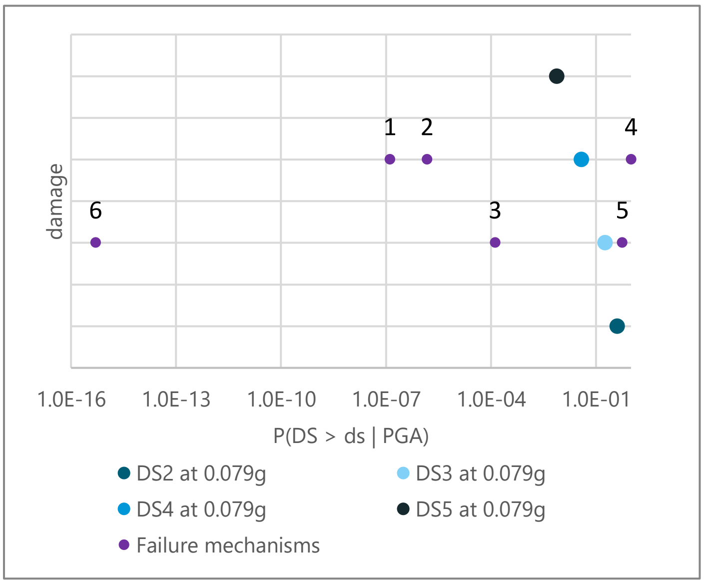
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.09	0.64	4.02E-01	0.10
DS3	0.14	0.64	1.81E-01	0.30
DS4	0.25	0.64	3.82E-02	0.50
DS5	0.37	0.64	7.48E-03	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding reinforcement beams	0.93	0.05	1.15	DS4	5.15	1.29E-07
2	yielding reinforcement columns	0.96	0.05	1.15	DS4	4.67	1.48E-06
3	failure cross-section foundation pile	0.72	0.15	1.20	DS3	3.65	1.31E-04
4	yielding reinforcement floors	1.50	0.05	1.15	DS4	-3.95	1.00E+00
5	in-plane shear failure of masonry walls	3.00	0.25	1.70	DS3	-0.16	5.65E-01
6	yielding reinforcement concrete walls	0.75	0.05	1.15	DS3	8.03	5.03E-16
7							
8							
9							
10							

RESULTS





Witteveen+Bos

project:	Selectiemethodiek Industrie Stap 2	spreadsheet	version 0.1
projectcode:	124217	FRAGILITY CURVES	
part:	Verification fragility curves	format by:	J. de Bruijn MSc
description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 10	
object name:	Building P	
location:	Delfzijl	
peak ground acceleration:	0.065	[g]

Typology

label:	S2M - Delfzijl
typology:	Steel braced frame, medium rise, 4-7 stories (typical height 18.3 m)

CALCULATION

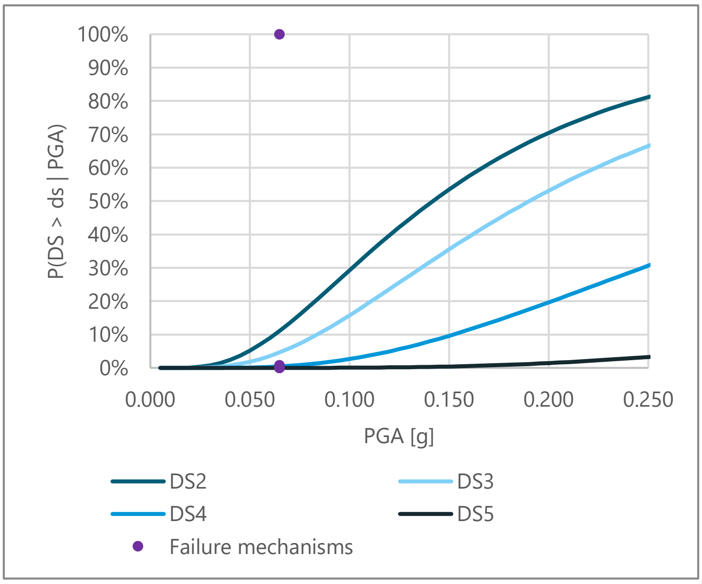
Fragility curves

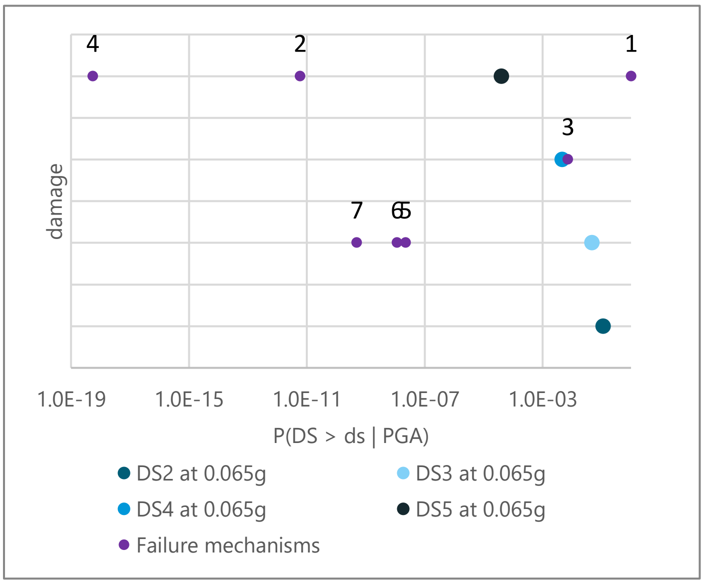
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.14	0.64	1.11E-01	0.10
DS3	0.19	0.64	4.66E-02	0.30
DS4	0.35	0.64	4.52E-03	0.50
DS5	0.81	0.64	4.00E-05	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure of IPE360 columns	1.75	0.05	1.00	DS5	-12.13	1.00E+00
2	failure of HEB360 columns	0.72	0.05	1.00	DS5	6.78	5.98E-12
3	failure connection steel column and concrete column	1.26	0.15	1.50	DS4	2.44	7.26E-03
4	failure concrete columns	0.70	0.05	1.15	DS5	8.82	5.50E-19
5	failure concrete floor and reinforcement	0.91	0.05	1.15	DS3	5.47	2.23E-08
6	failure steel structure above 15600+ (diagonals)	0.66	0.10	1.25	DS3	5.59	1.16E-08
7	failure piles due to bending moment (shaft)	0.87	0.05	1.15	DS3	6.11	4.97E-10
8							
9							
10							

RESULTS





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	part:	Verification fragility curves	format by:	J. de Bruijn MSc
	description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 11
object name: Building Q
location: Delfzijl
peak ground acceleration: 0.071 [g]

Typology

label: S2H - Delfzijl
typology: Steel braced frame, high rise, 8+ stories (typical height 47.5 m)

CALCULATION

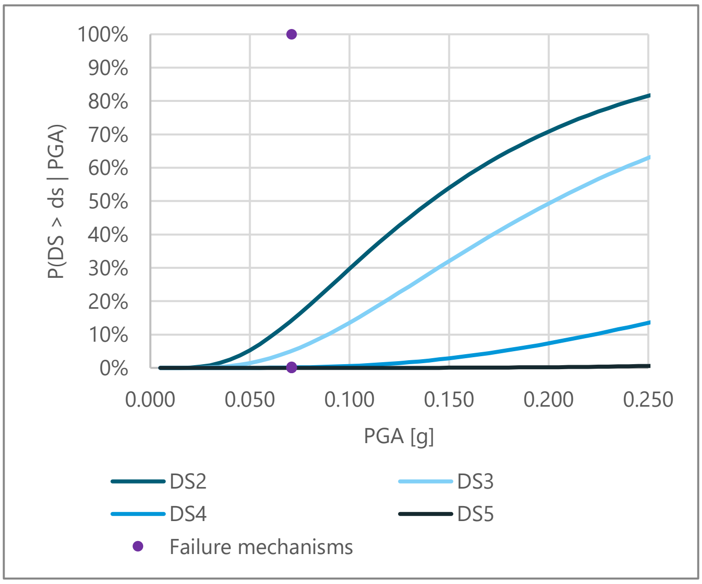
Fragility curves

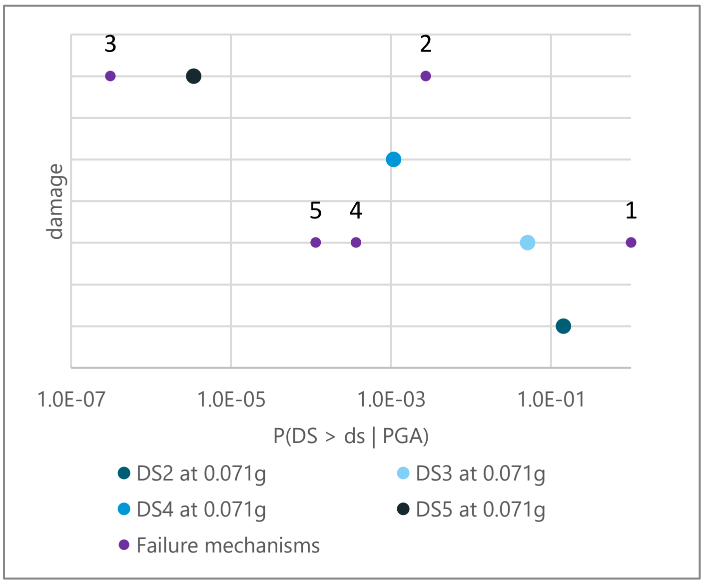
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.14	0.64	1.43E-01	0.10
DS3	0.20	0.64	5.09E-02	0.30
DS4	0.51	0.64	1.08E-03	0.50
DS5	1.26	0.64	3.40E-06	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding steel structure	1.70	0.05	1.00	DS3	-11.21	1.00E+00
2	shear failure concrete column	1.16	0.15	1.50	DS5	2.78	2.72E-03
3	failure connection steel-concrete structure	0.75	0.10	1.25	DS5	4.98	3.11E-07
4	failure piles due to insufficient bearing capacity	0.99	0.10	1.25	DS3	3.38	3.64E-04
5	failure piles due to bending moment (shaft)	0.89	0.15	1.50	DS3	3.68	1.15E-04
6							
7							
8							
9							
10							

RESULTS





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projectcode:	124217	
part:	Verification fragility curves	
description:		

spreadsheet version 0.1
FRAGILITY CURVES

format by: J. de Bruijn MSc
date of format: 6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 12	
object name:	Pipeline bridge C	
location:	Delfzijl	
peak ground acceleration:	0.060	[g]

Typology

label:	S1L - Delfzijl
typology:	Steel moment frame, low rise, 1-3 stories (typical height 7.3 m)

CALCULATION

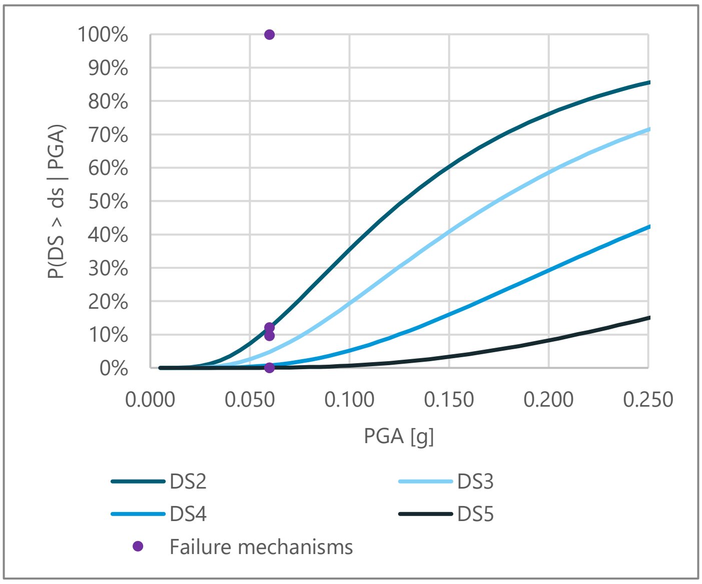
Fragility curves

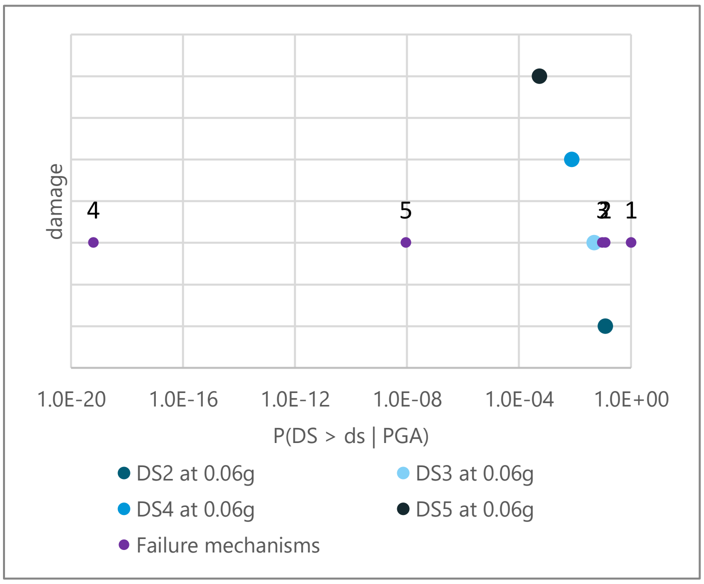
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.13	0.64	1.21E-01	0.10
DS3	0.17	0.64	4.80E-02	0.30
DS4	0.28	0.64	7.59E-03	0.50
DS5	0.49	0.64	5.38E-04	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding steel support structure	1.26	0.05	1.00	DS3	-3.13	9.99E-01
2	failure of connection in steel support structure	1.32	0.10	1.25	DS3	1.17	1.21E-01
3	failure of connection steel structure and concrete footing	1.30	0.10	1.25	DS3	1.31	9.58E-02
4	failure bearing capacity piles (during)	0.14	0.10	1.25	DS3	9.06	6.31E-20
5	failure bending moment piles (shaft)	0.31	0.15	1.50	DS3	5.63	9.12E-09
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 12	
object name:	Building R	
location:	Delfzijl	
peak ground acceleration:	0.064	[g]

Typology

label:	PC2L - Delfzijl
typology:	Precast concrete frames with concrete shear walls, low rise, 1-3 stories (typical height 7.3 m)

CALCULATION

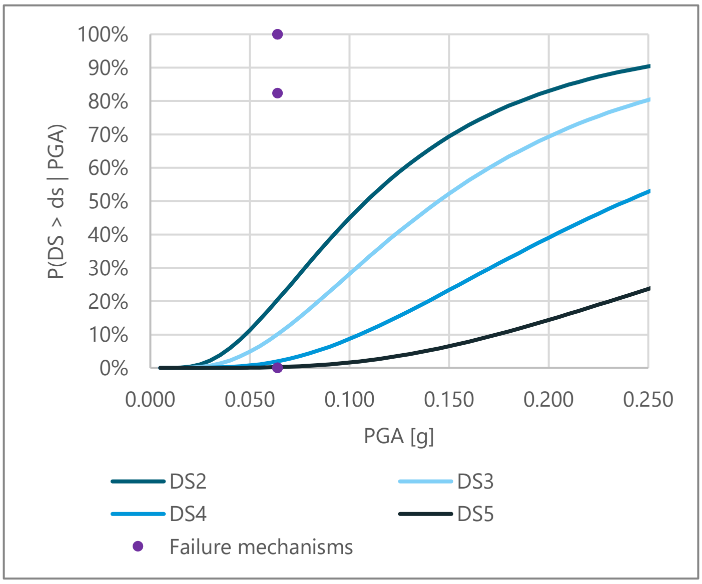
Fragility curves

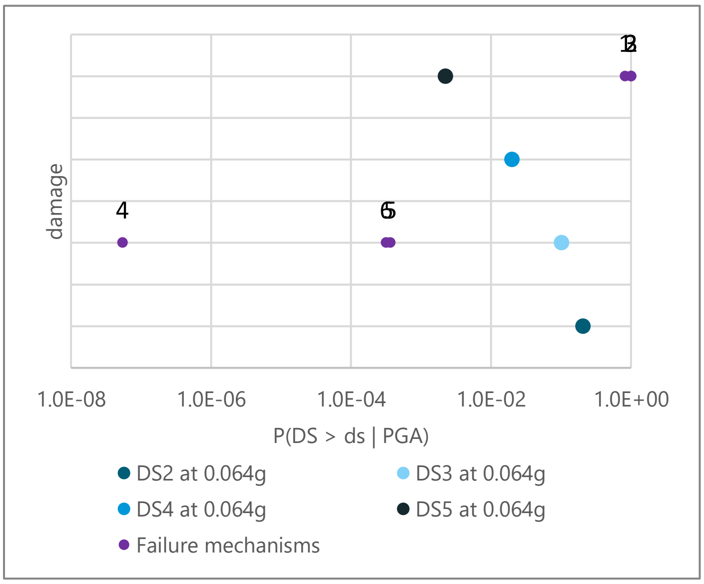
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.11	0.64	2.05E-01	0.10
DS3	0.14	0.64	1.01E-01	0.30
DS4	0.24	0.64	1.98E-02	0.50
DS5	0.40	0.64	2.22E-03	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure roof and connection with roof beams	3.00	0.20	1.70	DS5	-0.93	8.24E-01
2	failure of concrete walls	3.00	0.05	1.15	DS5	-27.90	1.00E+00
3	failure of concrete columns	1.86	0.05	1.15	DS5	-9.70	1.00E+00
4	failure of concrete floors	0.80	0.05	1.00	DS3	5.31	5.42E-08
5	failure piles due to insufficient bearing capacity	0.99	0.10	1.25	DS3	3.38	3.64E-04
6	failure piles due to bending moment (tip)	0.97	0.15	1.50	DS3	3.42	3.18E-04
7							
8							
9							
10							

RESULTS





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	projectcode:	124217	
	part:	Verification fragility curves	format by: J. de Bruijn MSc
	description:		date of format: 6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 12
object name: Storage rack B
location: Delfzijl
peak ground acceleration: 0.064 [g]

Typology

label: S2M - Delfzijl
typology: Steel braced frame, medium rise, 4-7 stories (typical height 18.3 m)

CALCULATION

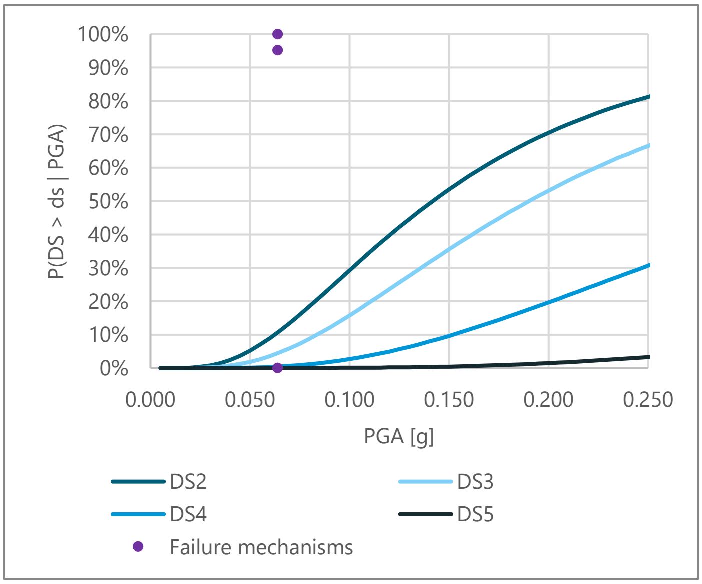
Fragility curves

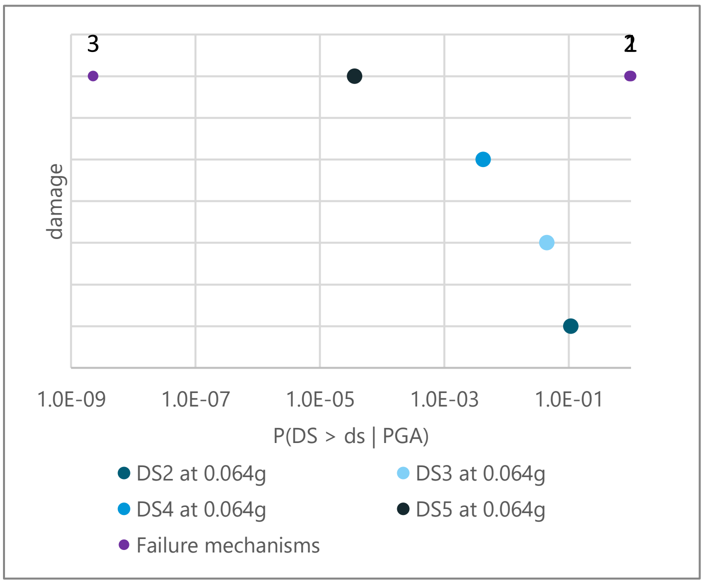
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.14	0.64	1.07E-01	0.10
DS3	0.19	0.64	4.43E-02	0.30
DS4	0.35	0.64	4.21E-03	0.50
DS5	0.81	0.64	3.61E-05	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure of columns	1.35	0.05	1.00	DS5	-4.79	1.00E+00
2	failure of beams	1.18	0.05	1.00	DS5	-1.66	9.52E-01
3	failure of connection steel frame to floor	0.77	0.05	1.00	DS5	5.86	2.28E-09
4							
5							
6							
7							
8							
9							
10							

RESULTS





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projectcode:	124217	FRAGILITY CURVES	
part:	Verification fragility curves	format by:	J. de Bruijn MSc
description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 13
object name: Building S
location: Delfzijl
peak ground acceleration: 0.069 [g]

Typology

label: S2L - Delfzijl
typology: Steel braced frame, low rise, 1-3 stories (typical height 7.3 m)

CALCULATION

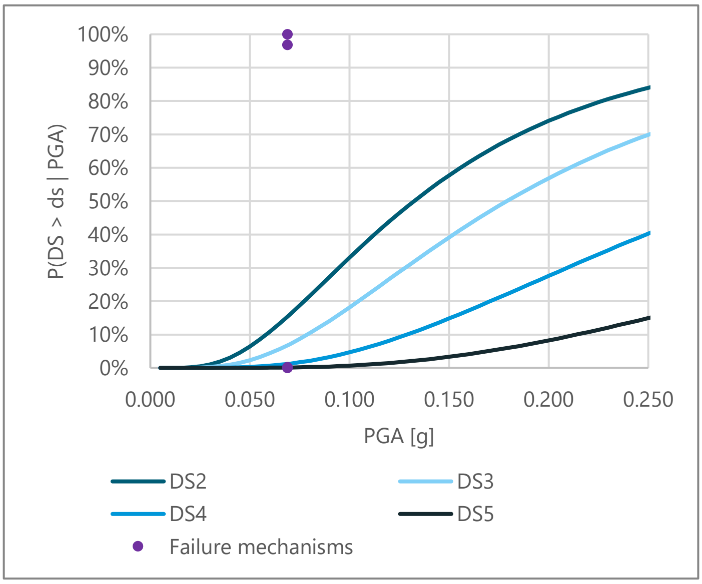
Fragility curves

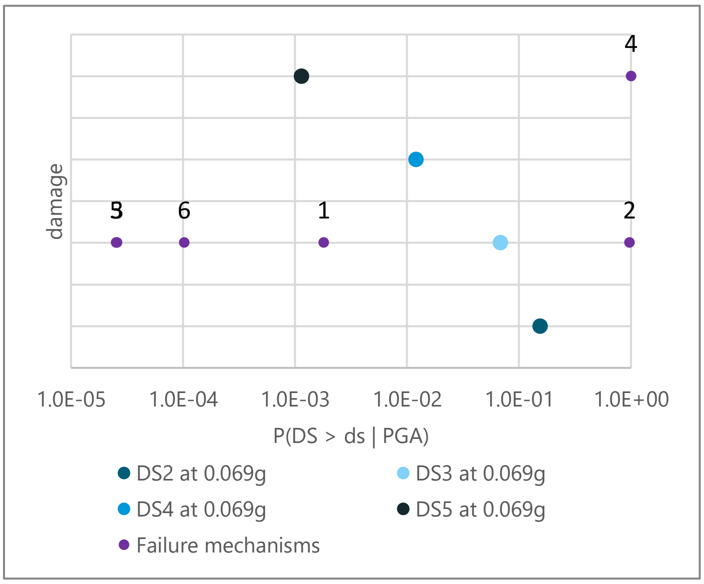
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.13	0.64	1.54E-01	0.10
DS3	0.18	0.64	6.81E-02	0.30
DS4	0.29	0.64	1.20E-02	0.50
DS5	0.49	0.64	1.14E-03	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure connection diagonals	1.06	0.10	1.25	DS3	2.91	1.80E-03
2	failure steel columns	1.19	0.05	1.00	DS3	-1.85	9.68E-01
3	failure connection steel-concrete	0.89	0.10	1.25	DS3	4.05	2.59E-05
4	failure support vertical vessels	1.27	0.05	1.00	DS5	-3.32	1.00E+00
5	failure piles horizontal load	0.78	0.15	1.50	DS3	4.05	2.53E-05
6	failure piles vertical load	0.94	0.10	1.25	DS3	3.71	1.02E-04
7							
8							
9							
10							

RESULTS





Witteveen+Bos

project: Selectiemethodiek Industrie Stap 2
projectcode: 124217
part: Verification fragility curves
description:

spreadsheet FRAGILITY CURVES — version 0.1

format by: J. de Bruijn MSc
date of format: 6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 13
object name: Building T
location: Delfzijl
peak ground acceleration: 0.069 [g]

Typology

label: C2L - Delfzijl
typology: Concrete shear walls, low rise, 1-3 stories (typical height 7.3 m)

CALCULATION

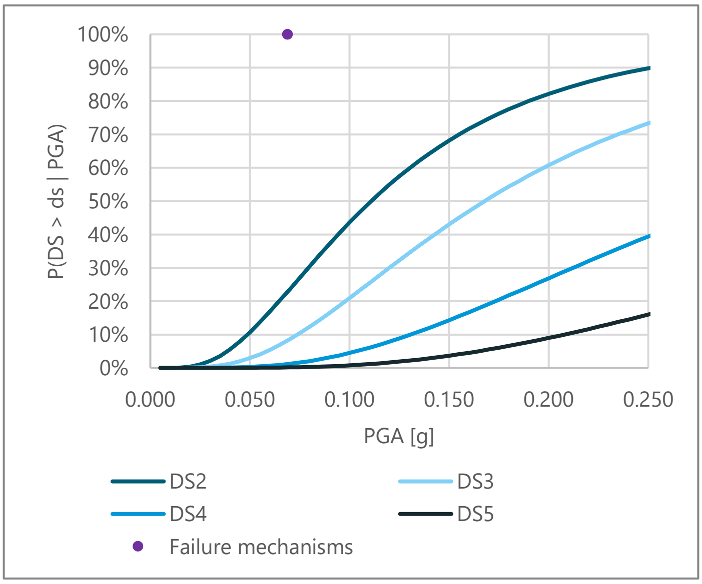
Fragility curves

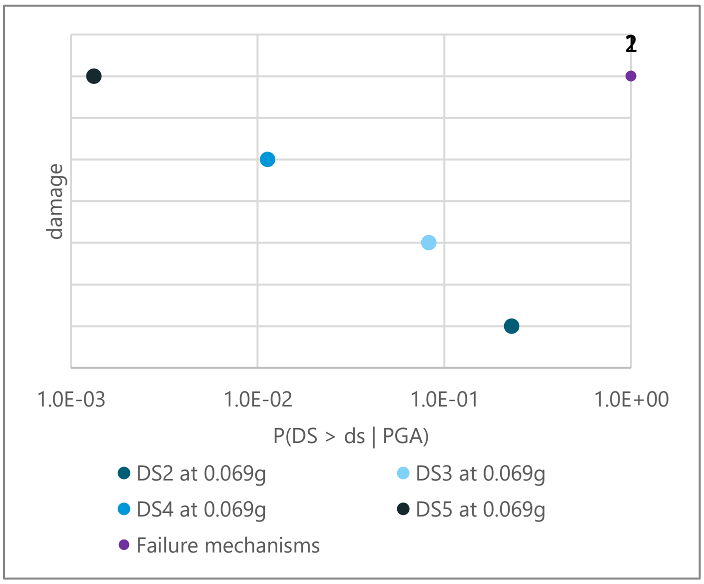
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.11	0.64	2.29E-01	0.10
DS3	0.17	0.64	8.23E-02	0.30
DS4	0.30	0.64	1.13E-02	0.50
DS5	0.47	0.64	1.32E-03	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure concrete structure	3.00	0.15	1.50	DS5	-3.39	1.00E+00
2	failure concrete columns and walls	3.00	0.05	1.15	DS5	-27.90	1.00E+00
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





project:	Selectiemethodiek Industrie Stap 2	spreadsheet	version 0.1
projectcode:	124217	FRAGILITY CURVES	
part:	Verification fragility curves	format by:	J. de Bruijn MSc
description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 14
object name: Building U
location: Eemshaven
peak ground acceleration: 0.032 [g]

Typology

label: S2L - Eemshaven
typology: Steel braced frame, low rise, 1-3 stories (typical height 7.3 m)

CALCULATION

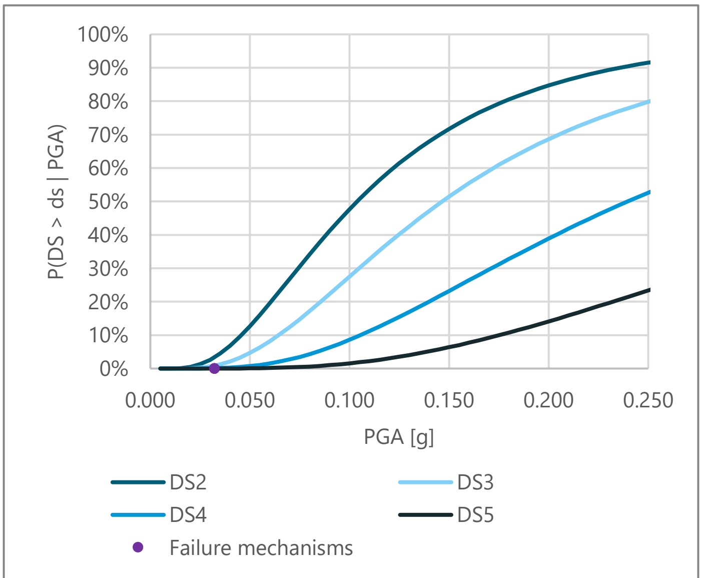
Fragility curves

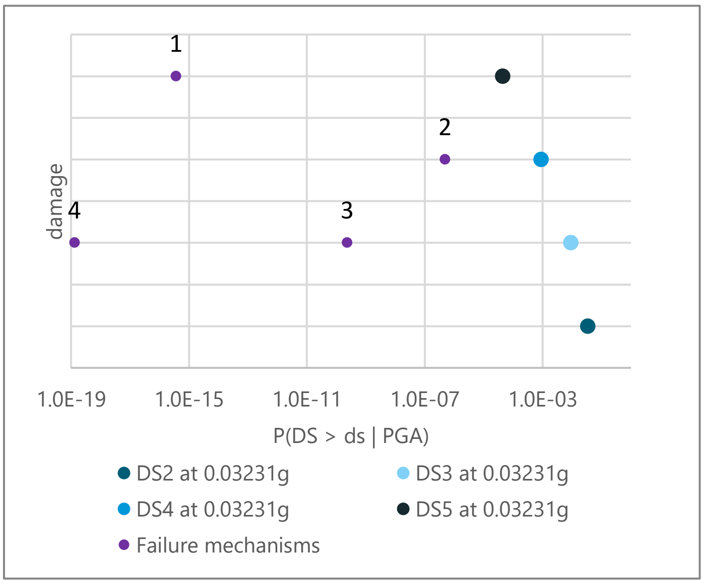
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.10	0.64	3.41E-02	0.10
DS3	0.15	0.64	9.08E-03	0.30
DS4	0.24	0.64	8.72E-04	0.50
DS5	0.40	0.64	4.36E-05	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure of steel members	0.65	0.05	1.00	DS5	8.07	3.63E-16
2	failure of connections	0.76	0.10	1.25	DS4	4.90	4.86E-07
3	failure of piles	0.75	0.05	1.00	DS3	6.23	2.33E-10
4	failure of foundation beam	0.69	0.05	1.15	DS3	8.98	1.31E-19
5							
6							
7							
8							
9							
10							

RESULTS





II.2 Non-structural components

project:	Selectiemethodiek Industrie Stap 2	spreadsheet	version 0.1
projectcode:	124217	FRAGILITY CURVES	
part:	Verification fragility curves	format by:	J. de Bruijn MSc
description:	Non-structural components acc. to HAZUS	date of format:	10-11-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 6
object name: Equipment D
location: Delfzijl
peak ground acceleration: 0.080 [g]

Typology

label: NS-SELF
typology: Non-structural components in structure (100% building height)

CALCULATION

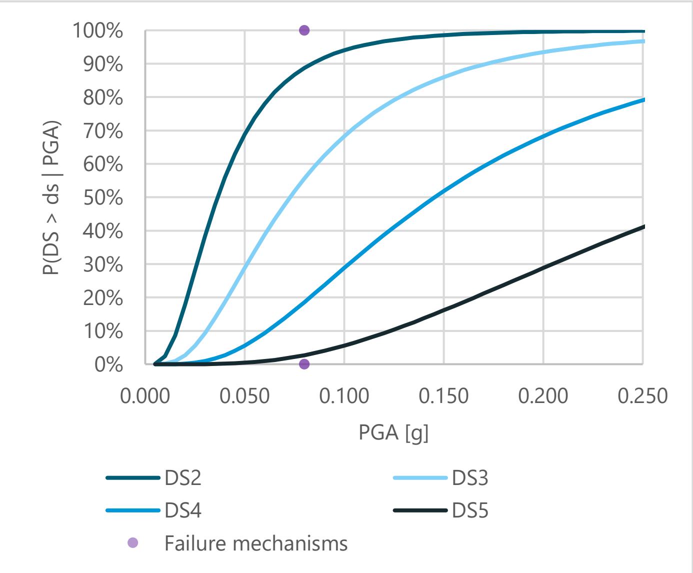
Fragility curves

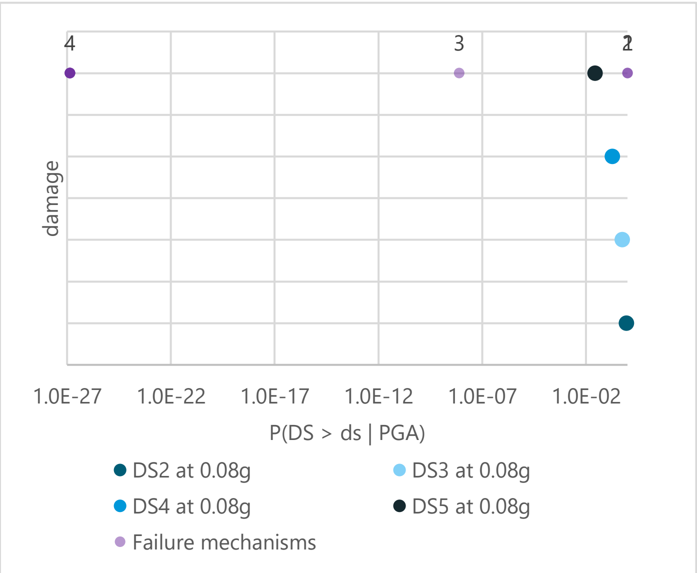
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.04	0.65	8.87E-01	0.10
DS3	0.07	0.67	5.57E-01	0.30
DS4	0.15	0.67	1.86E-01	0.50
DS5	0.29	0.67	2.70E-02	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding consoles installation H-8311	4.00	0.05	1.00	DS5	-53.44	1.00E+00
2	yielding consoles installation H-8312	3.70	0.05	1.00	DS5	-47.93	1.00E+00
3	yielding consoles installation V-8311	0.65	0.10	1.25	DS5	5.65	7.89E-09
4	yielding support installation V-8312	0.50	0.05	1.00	DS5	10.82	1.38E-27
5							
6							
7							
8							
9							
10							

RESULTS





project: Selectiemethodiek Industrie Stap 2
projectcode: 124217
part: Verification fragility curves
description: Non-structural components acc. to HAZUS

spreadsheet
FRAGILITY CURVES
version 0.1

format by: J. de Bruijn MSc
date of format: 10-11-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 6
object name: Equipment E
location: Delfzijl
peak ground acceleration: 0.080 [g]

Typology

label: NS-SELF
typology: Non-structural components in structure (100% building height)

CALCULATION

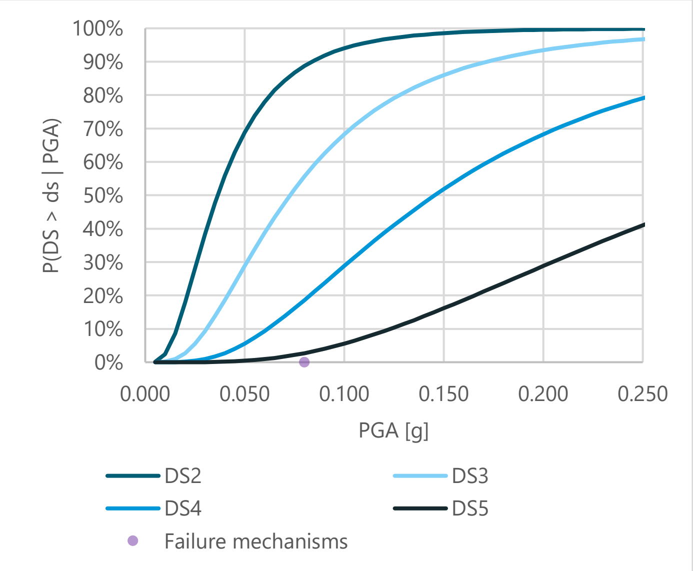
Fragility curves

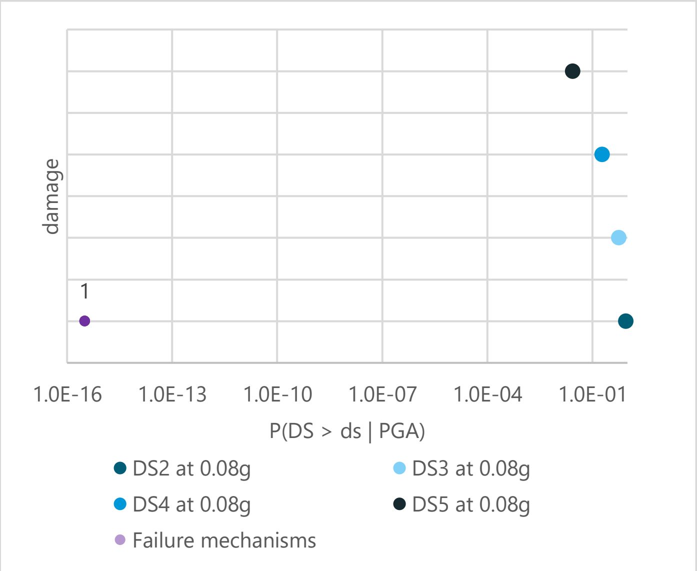
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.04	0.65	8.87E-01	0.10
DS3	0.07	0.67	5.57E-01	0.30
DS4	0.15	0.67	1.86E-01	0.50
DS5	0.29	0.67	2.70E-02	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding steel pipes	0.65	0.05	1.00	DS2	8.08	3.22E-16
2							
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 7
object name: Equipment F
location: Delfzijl
peak ground acceleration: 0.110 [g]

Typology

label: NS-SELF
typology: Non-structural components in structure (100% building height)

CALCULATION

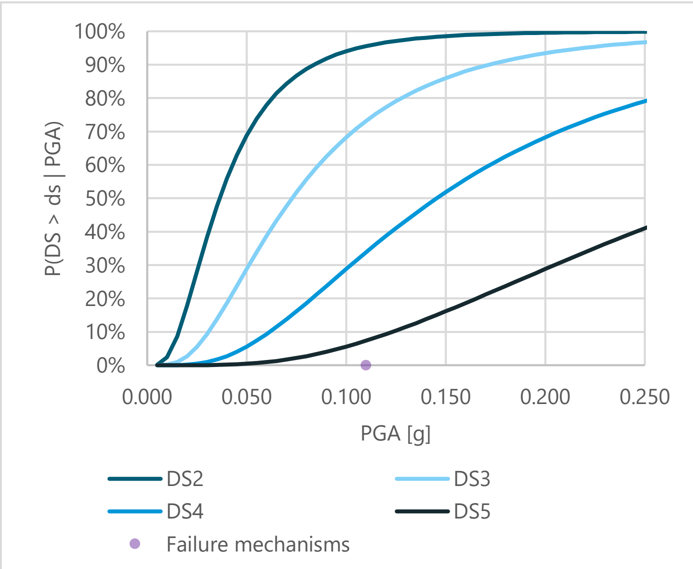
Fragility curves

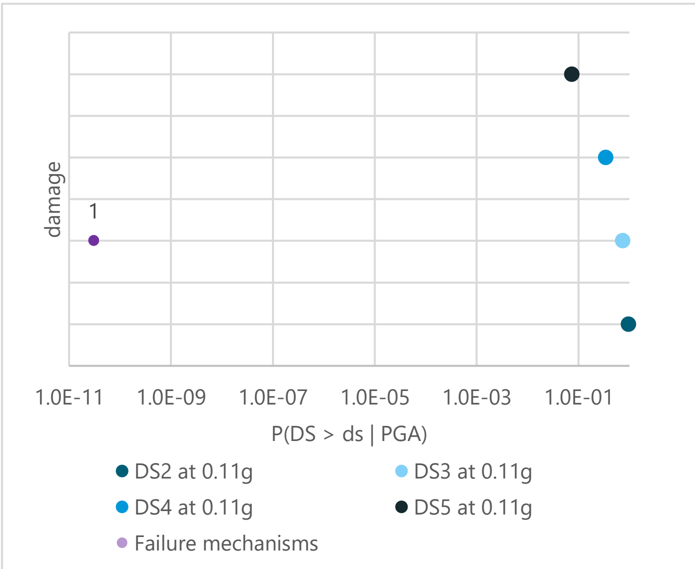
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.04	0.65	9.56E-01	0.10
DS3	0.07	0.67	7.32E-01	0.30
DS4	0.15	0.67	3.38E-01	0.50
DS5	0.29	0.67	7.33E-02	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding/stability steel pipes	0.73	0.05	1.00	DS3	6.54	3.03E-11
2							
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 9
object name: Equipment G
location: Delfzijl
peak ground acceleration: 0.079 [g]

Typology

label: NS-SELF
typology: Non-structural components in structure (100% building height)

CALCULATION

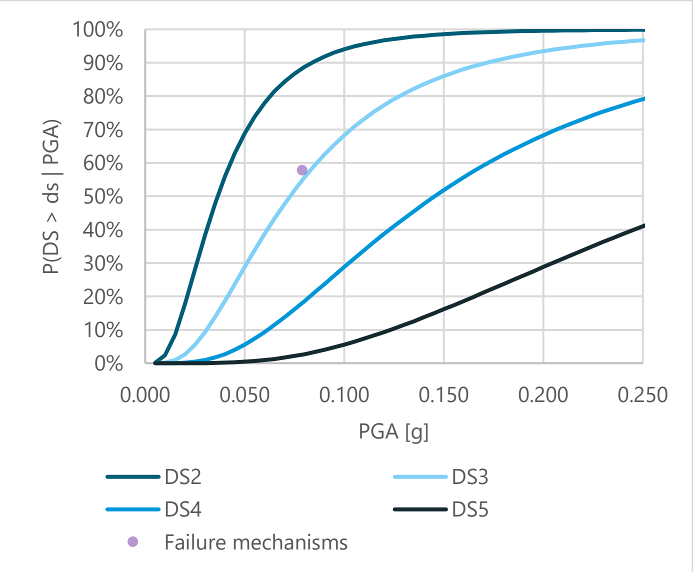
Fragility curves

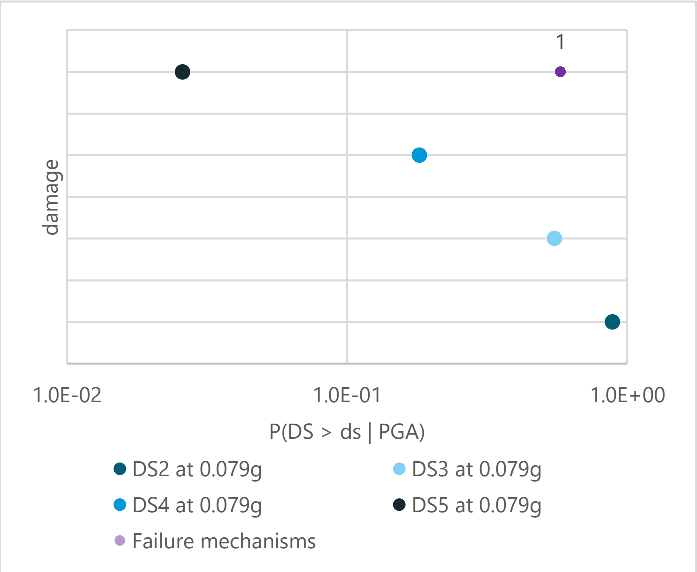
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.04	0.65	8.84E-01	0.10
DS3	0.07	0.67	5.49E-01	0.30
DS4	0.15	0.67	1.81E-01	0.50
DS5	0.29	0.67	2.59E-02	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	stability bigbags	1.10	0.05	1.00	DS5	-0.20	5.78E-01
2							
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 13
object name: Equipment H
location: Delfzijl
peak ground acceleration: 0.069 [g]

Typology

label: NS-SELF
typology: Non-structural components in structure (100% building height)

CALCULATION

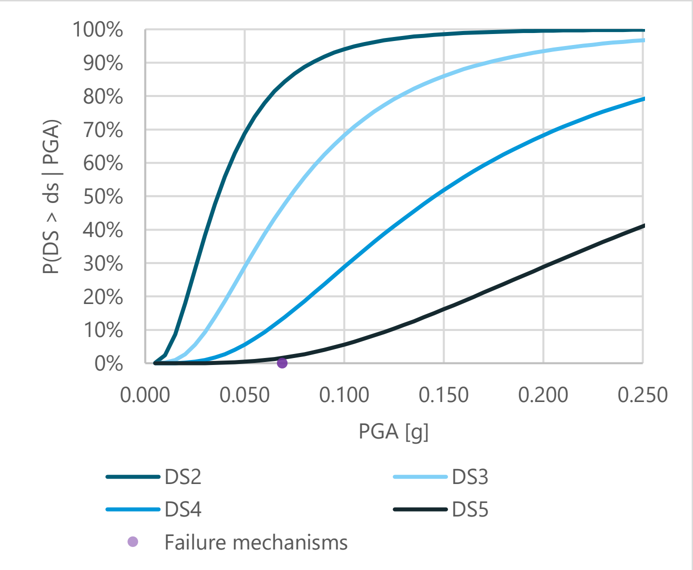
Fragility curves

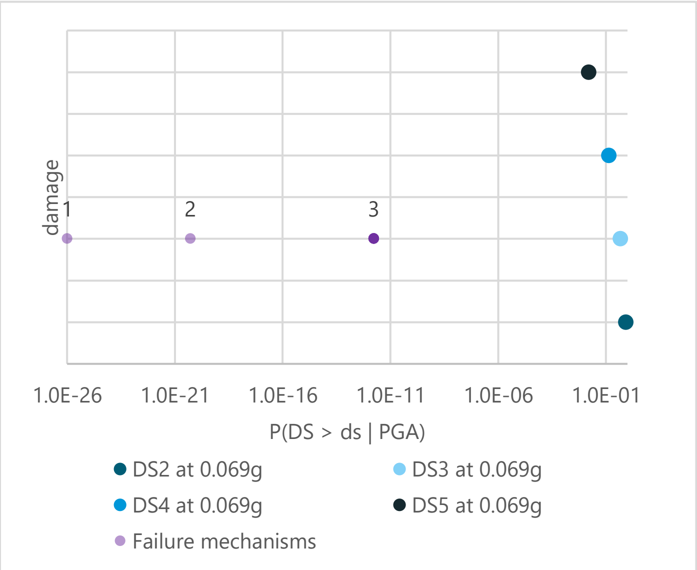
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.04	0.65	8.38E-01	0.10
DS3	0.07	0.67	4.69E-01	0.30
DS4	0.15	0.67	1.33E-01	0.50
DS5	0.29	0.67	1.59E-02	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure of steel structure	0.51	0.05	1.00	DS3	10.64	1.01E-26
2	failure bolted connection tank support-main structure	0.10	0.10	1.25	DS3	9.33	5.23E-21
3	failure connection tank wall-support	0.40	0.10	1.10	DS3	6.96	1.70E-12
4							
5							
6							
7							
8							
9							
10							

RESULTS





Witteveen + Bos

project:	Selectiemethodiek Industrie Stap 2	spreadsheet	version 0.1
projectcode:	124217	FRAGILITY CURVES	
part:	Verification fragility curves	format by:	J. de Bruijn MSc
description:		date of format:	10-11-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 6	
object name:	Equipment D	
location:	Delfzijl	
peak ground acceleration:	0.080	[g]

Typology

label:	NS-WEAK
typology:	Non-structural components in structure (weak supports)

CALCULATION

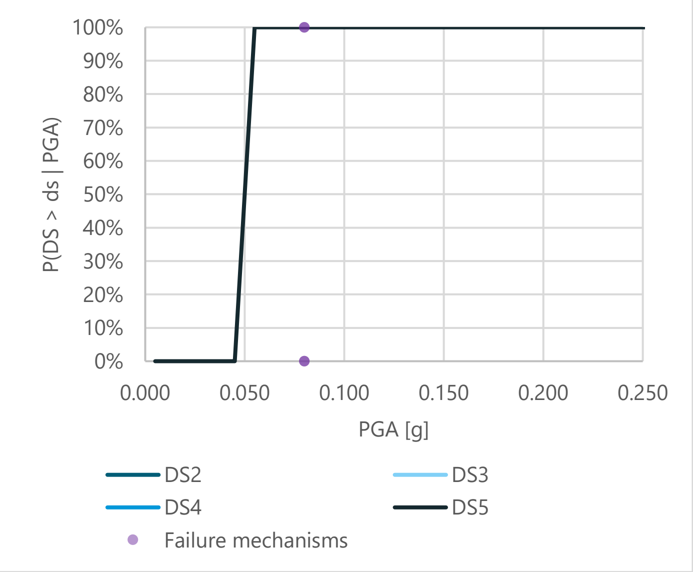
Fragility curves

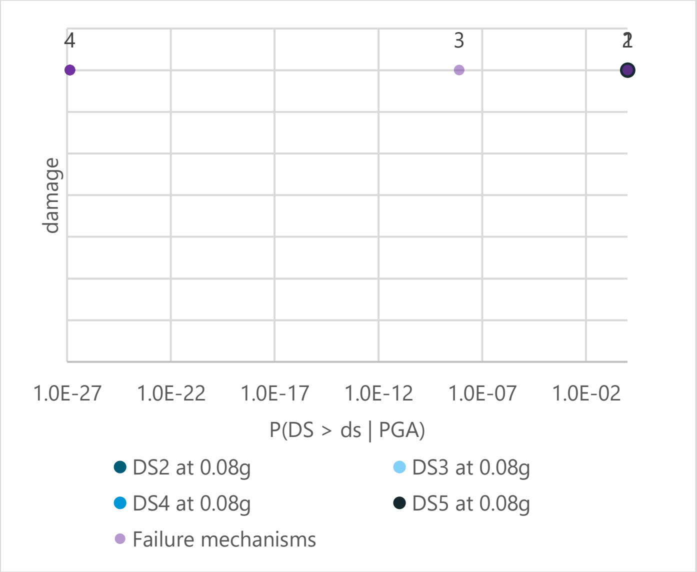
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4				0.50
DS5	0.05	0.00	1.00E+00	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding consoles installation H-8311	4.00	0.05	1.00	DS5	-53.44	1.00E+00
2	yielding consoles installation H-8312	3.70	0.05	1.00	DS5	-47.93	1.00E+00
3	yielding consoles installation V-8311	0.65	0.10	1.25	DS5	5.65	7.89E-09
4	yielding support installation V-8312	0.50	0.05	1.00	DS5	10.82	1.38E-27
5							
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 6
object name:	Equipment E
location:	Delfzijl
peak ground acceleration:	0.080 [g]

Typology

label:	NS-WEAK
typology:	Non-structural components in structure (weak supports)

CALCULATION

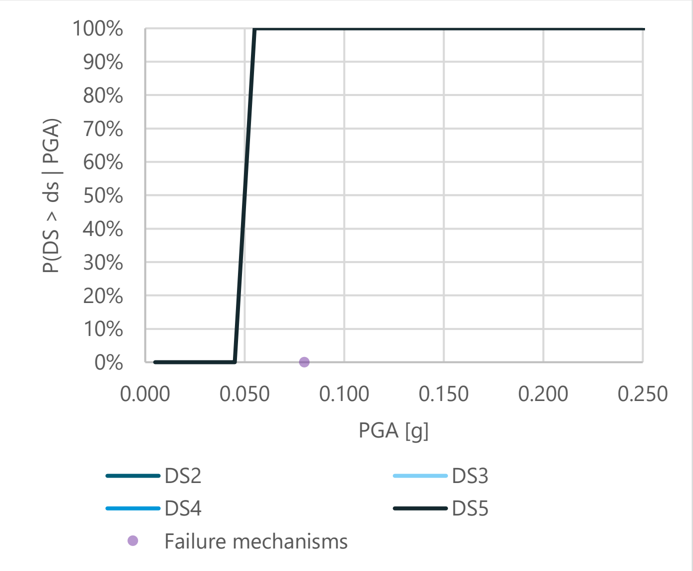
Fragility curves

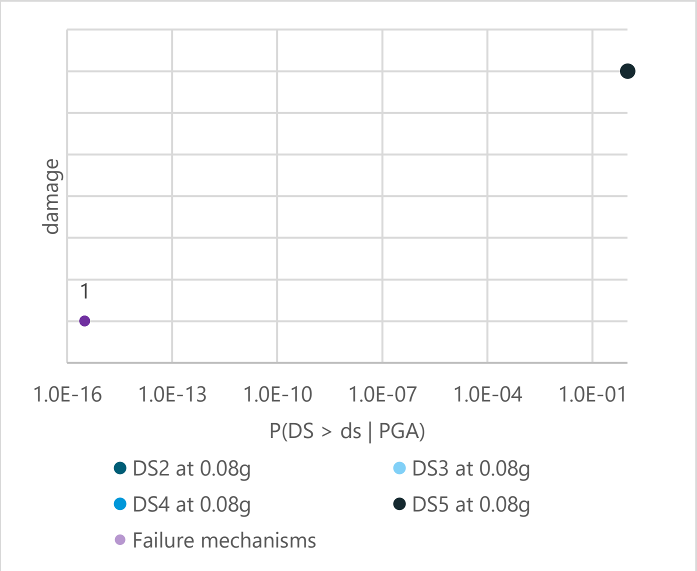
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4				0.50
DS5	0.05	0.00	1.00E+00	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding steel pipes	0.65	0.05	1.00	DS2	8.08	3.22E-16
2							
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





project:	Selectiemethodiek Industrie Stap 2	spreadsheet	version 0.1
projectcode:	124217	FRAGILITY CURVES	
part:	Verification fragility curves	format by:	J. de Bruijn MSc
description:		date of format:	10-11-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 7	
object name:	Equipment F	
location:	Delfzijl	
peak ground acceleration:	0.110	[g]

Typology

label:	NS-WEAK
typology:	Non-structural components in structure (weak supports)

CALCULATION

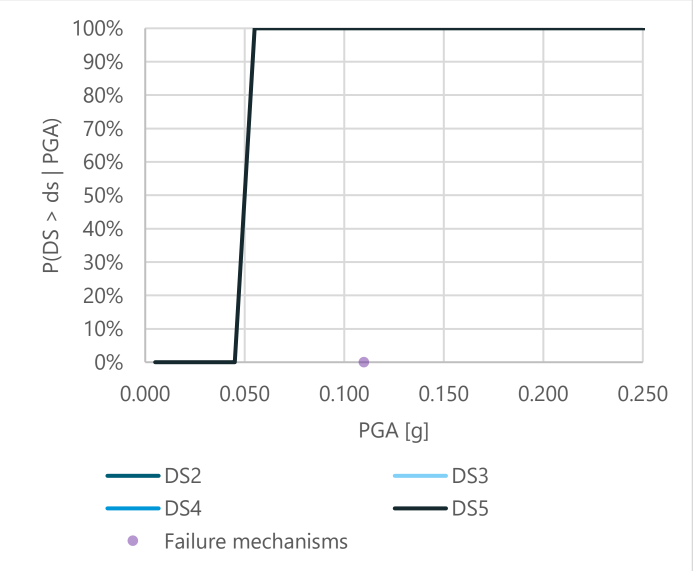
Fragility curves

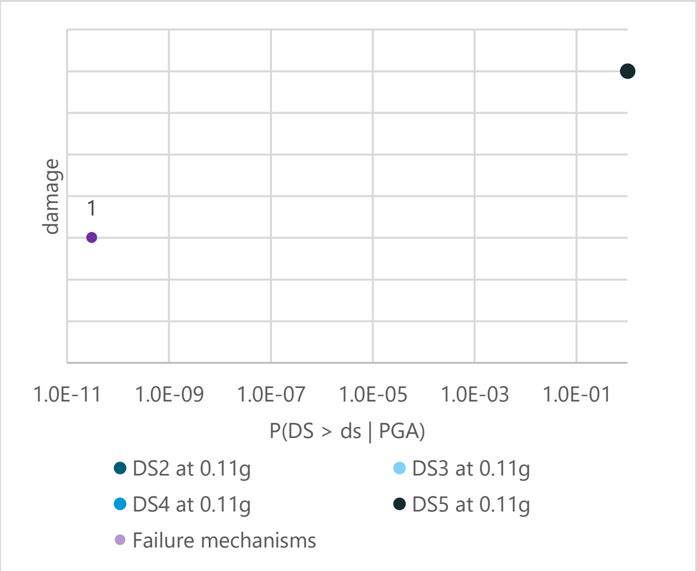
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4				0.50
DS5	0.05	0.00	1.00E+00	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding/stability steel pipes	0.73	0.05	1.00	DS3	6.54	3.03E-11
2							
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





Witteveen+Bos

project: Selectiemethodiek Industrie Stap 2
projectcode: 124217
part: Verification fragility curves
description:

spreadsheet FRAGILITY CURVES — version 0.1

format by: J. de Bruijn MSc
date of format: 10-11-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 9
object name: Equipment G
location: Delfzijl
peak ground acceleration: 0.079 [g]

Typology

label: NS-WEAK
typology: Non-structural components in structure (weak supports)

CALCULATION

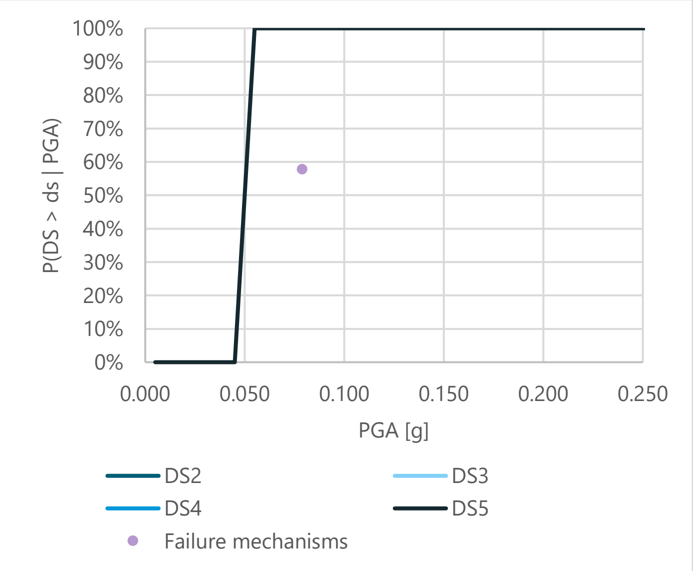
Fragility curves

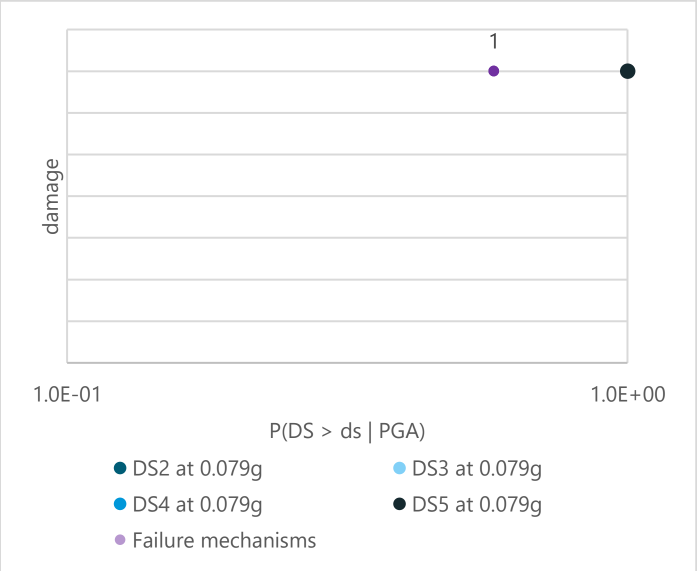
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4				0.50
DS5	0.05	0.00	1.00E+00	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	stability bigbags	1.10	0.05	1.00	DS5	-0.20	5.78E-01
2							
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 13
object name:	Equipment H
location:	Delfzijl
peak ground acceleration:	0.069 [g]

Typology

label:	NS-RIGID
typology:	Non-structural components in structure (rigid supports, 100% building height)

CALCULATION

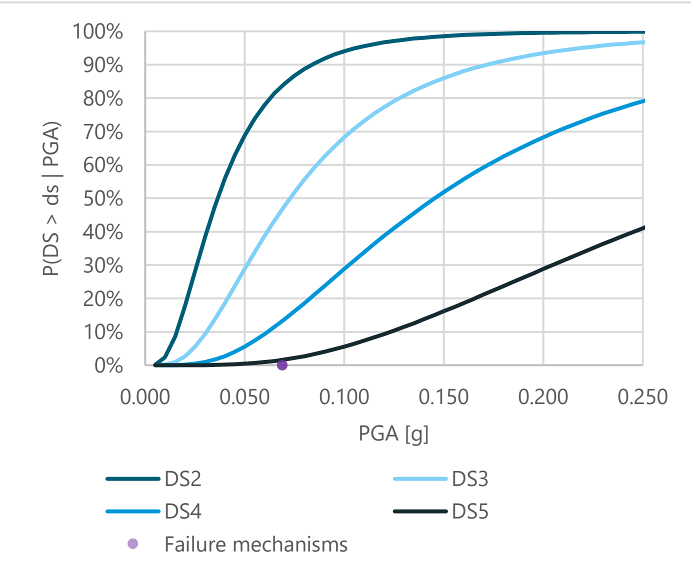
Fragility curves

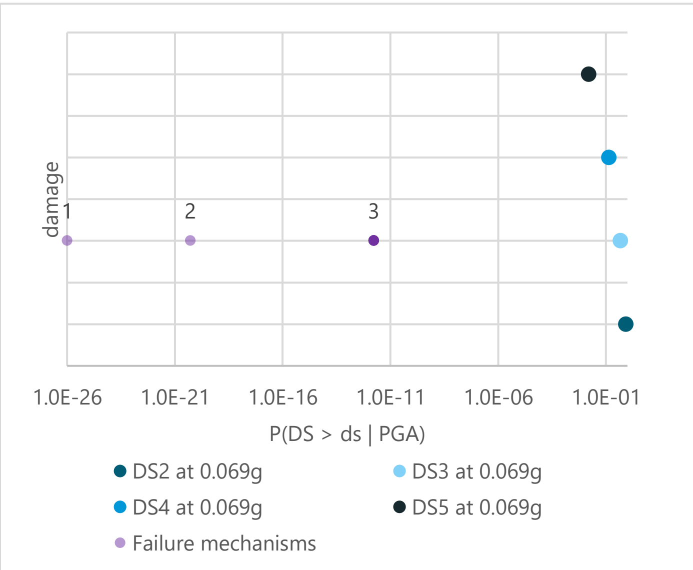
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.04	0.65	8.38E-01	0.10
DS3	0.07	0.67	4.69E-01	0.30
DS4	0.15	0.67	1.33E-01	0.50
DS5	0.29	0.67	1.59E-02	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure of steel structure	0.51	0.05	1.00	DS3	10.64	1.01E-26
2	failure bolted connection tank support-main structure	0.10	0.10	1.25	DS3	9.33	5.23E-21
3	failure connection tank wall-support	0.40	0.10	1.10	DS3	6.96	1.70E-12
4							
5							
6							
7							
8							
9							
10							

RESULTS





II.3 Elevated steel tanks

spreadsheet version 0.1
FRAGILITY CURVES

project: Selectiemethodiek Industrie Stap 2
projectcode: 124217
part: Verification fragility curves
description: Elevated tanks acc. to HAZUS

format by: J. de Bruijn MSc
date of format: 26-9-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 1
object name: Elevated tank A
location: Delfzijl
peak ground acceleration: 0.080 [g]

Typology

label: PSTAS
typology: Elevated Steel Tank

CALCULATION

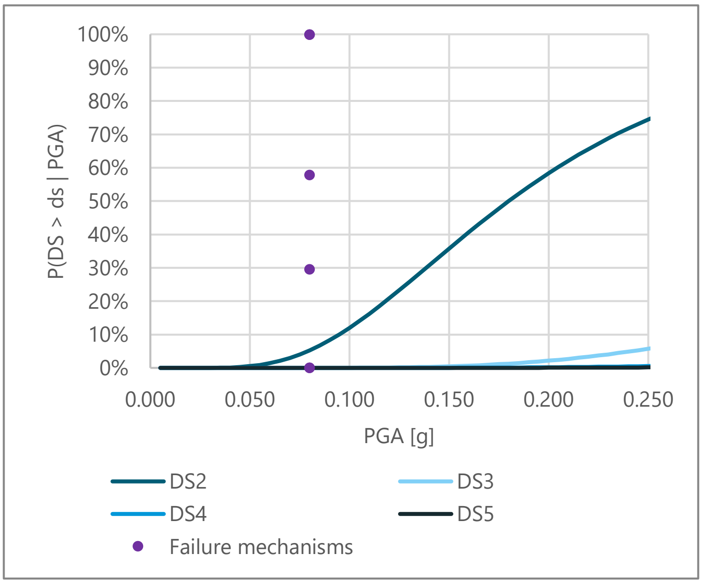
Fragility curves

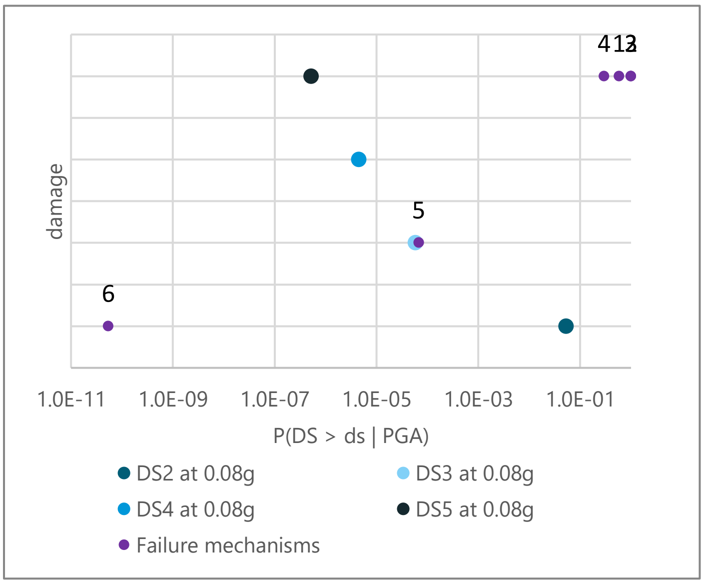
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.18	0.50	5.24E-02	0.10
DS3	0.55	0.50	5.77E-05	0.30
DS4	1.15	0.60	4.45E-06	0.50
DS5	1.50	0.60	5.16E-07	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding structure	1.10	0.05	1.00	DS5	-0.20	5.78E-01
2	welds in connection legs-floor frame	1.25	0.05	1.00	DS5	-2.95	9.98E-01
3	buckling of support columns	1.25	0.05	1.00	DS5	-2.95	9.98E-01
4	buckling of webs of floor frame	1.06	0.05	1.00	DS5	0.54	2.95E-01
5	foundation slab - shear failure	0.68	0.15	1.20	DS3	3.82	6.72E-05
6	geotechnical failure	0.53	0.10	1.25	DS2	6.46	5.40E-11
7							
8							
9							
10							

RESULTS





project: Selectiemethodiek Industrie Stap 2
projectcode: 124217
part: Verification fragility curves
description: Elevated tanks acc. to HAZUS

spreadsheet FRAGILITY CURVES — version 0.1

format by: J. de Bruijn MSc
date of format: 26-9-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 2
object name: Elevated tank B
location: Delfzijl
peak ground acceleration: 0.070 [g]

Typology

label: PSTAS
typology: Elevated Steel Tank

CALCULATION

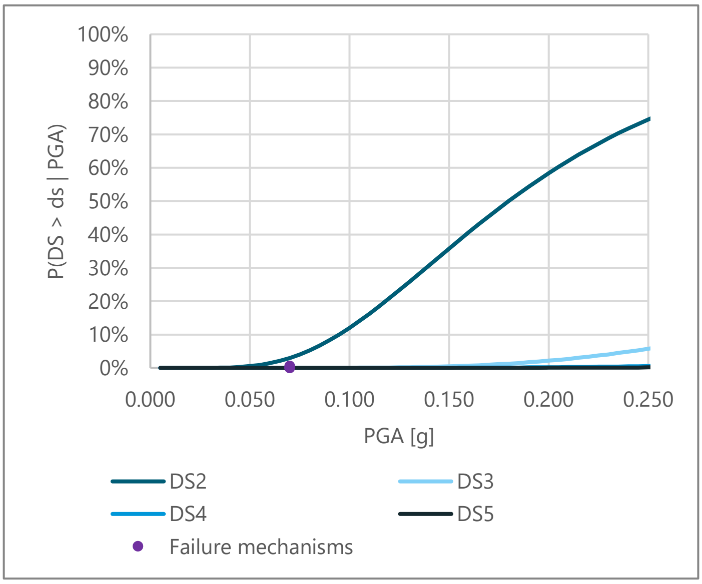
Fragility curves

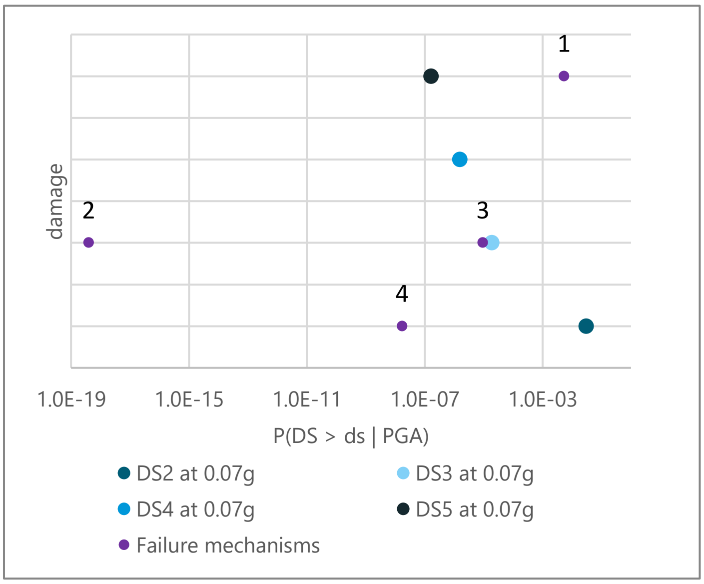
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.18	0.50	2.95E-02	0.10
DS3	0.55	0.50	1.87E-05	0.30
DS4	1.15	0.60	1.54E-06	0.50
DS5	1.50	0.60	1.63E-07	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	buckling of support columns	0.95	0.05	1.00	DS5	2.56	5.26E-03
2	yielding tank shell	0.91	0.05	1.50	DS3	8.86	3.94E-19
3	crushing concrete footing	0.57	0.15	1.20	DS3	4.28	9.39E-06
4	geotechnical failure	0.67	0.10	1.25	DS2	5.52	1.70E-08
5							
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 5
object name: Elevated tank C
location: Delfzijl
peak ground acceleration: 0.060 [g]

Typology

label: PSTAS
typology: Elevated Steel Tank

CALCULATION

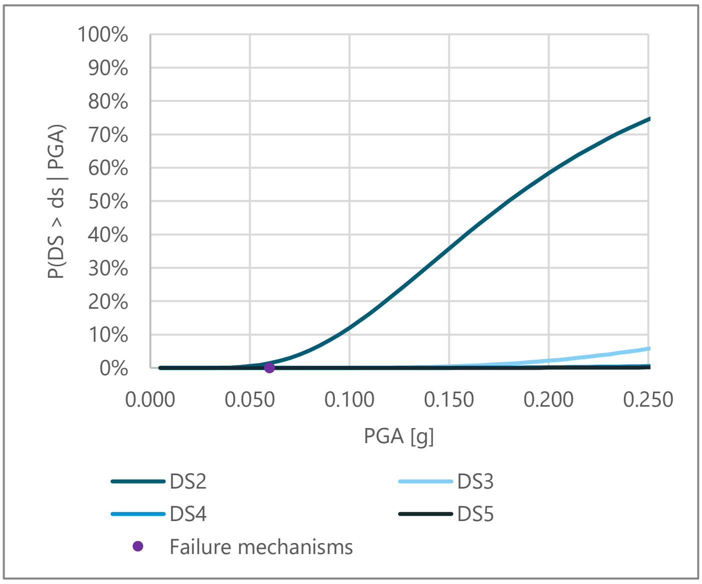
Fragility curves

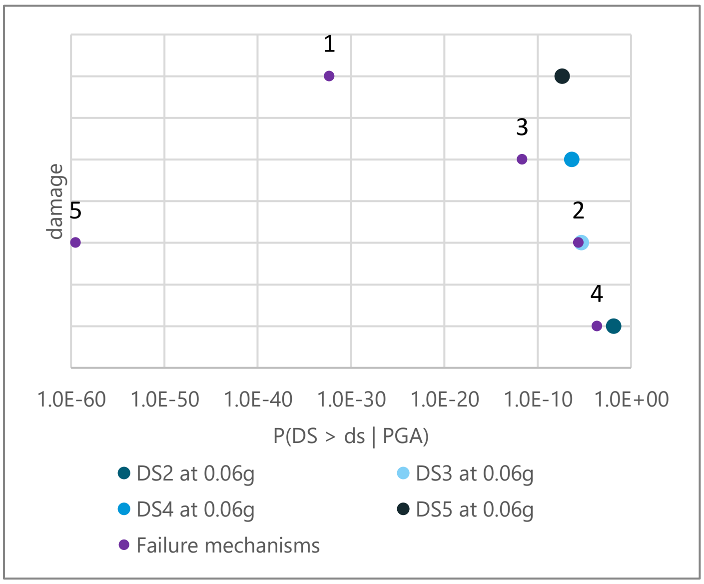
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.18	0.50	1.40E-02	0.10
DS3	0.55	0.50	4.69E-06	0.30
DS4	1.15	0.60	4.28E-07	0.50
DS5	1.50	0.60	4.05E-08	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	buckling support columns	0.44	0.05	1.00	DS5	11.92	4.57E-33
2	yielding support beams	0.84	0.05	1.00	DS3	4.58	2.35E-06
3	bolt failure	0.46	0.10	1.25	DS4	6.92	2.20E-12
4	shear failure pile	0.93	0.10	1.20	DS2	3.52	2.15E-04
5	pounding	0.20	0.05	1.00	DS3	16.33	3.12E-60
6							
7							
8							
9							
10							

RESULTS





project:	Selectiemethodiek Industrie Stap 2	spreadsheet		version 0.1
projectcode:	124217	FRAGILITY CURVES		
part:	Verification fragility curves	format by:	J. de Bruijn MSc	
description:	Elevated tanks acc. to HAZUS	date of format:	26-9-2021	

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 5	
object name:	Elevated tank D	
location:	Delfzijl	
peak ground acceleration:	0.060	[g]

Typology

label:	PSTAS
typology:	Elevated Steel Tank

CALCULATION

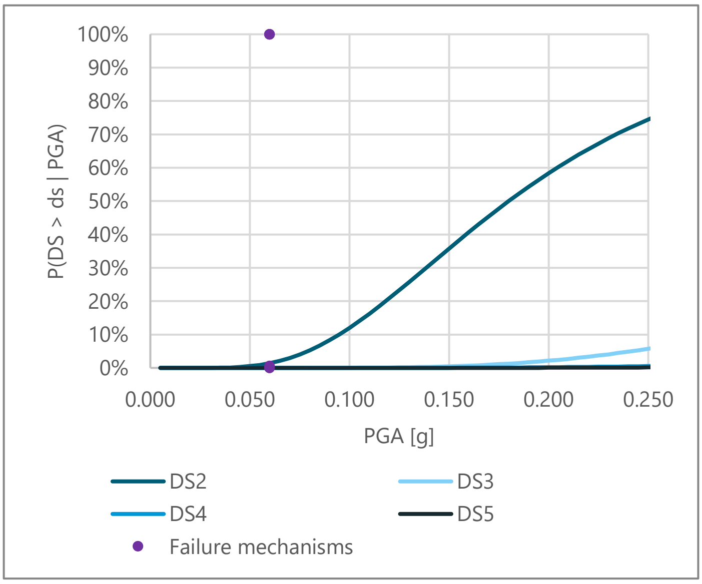
Fragility curves

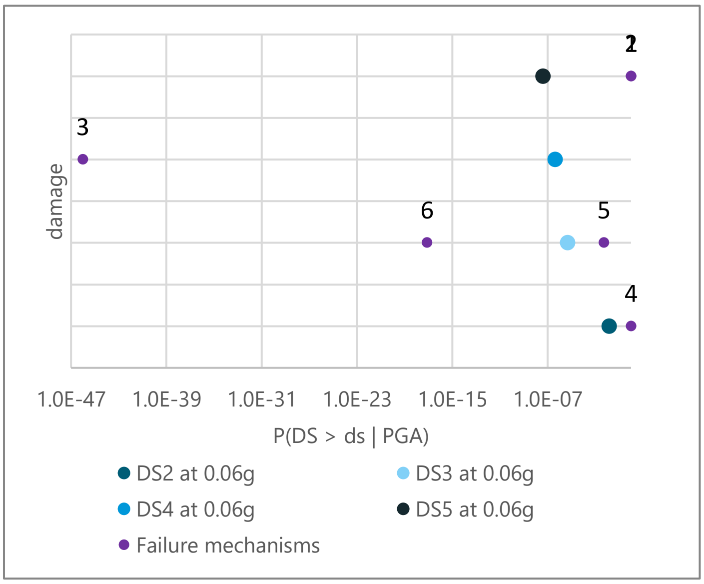
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.18	0.50	1.40E-02	0.10
DS3	0.55	0.50	4.69E-06	0.30
DS4	1.15	0.60	4.28E-07	0.50
DS5	1.50	0.60	4.05E-08	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding support legs	1.39	0.05	1.00	DS5	-5.52	1.00E+00
2	buckling support legs	2.09	0.05	1.00	DS5	-18.37	1.00E+00
3	yielding support frame	0.31	0.05	1.00	DS4	14.31	9.70E-47
4	meridional buckling	2.44	0.05	1.00	DS2	-24.80	1.00E+00
5	shear buckling	0.95	0.05	1.00	DS3	2.56	5.26E-03
6	overflow	0.63	0.05	1.00	DS3	8.53	7.64E-18
7							
8							
9							
10							

RESULTS





project: Selectiemethodiek Industrie Stap 2
projectcode: 124217
part: Verification fragility curves
description: Elevated tanks acc. to HAZUS

spreadsheet FRAGILITY CURVES version 0.1

format by: J. de Bruijn MSc
date of format: 26-9-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 13
object name: Elevated tank E
location: Delfzijl
peak ground acceleration: 0.069 [g]

Typology

label: PSTAS
typology: Elevated Steel Tank

CALCULATION

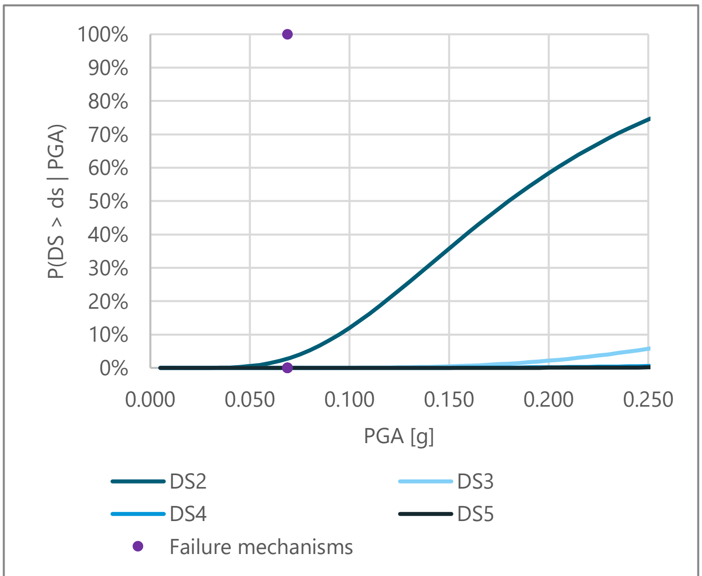
Fragility curves

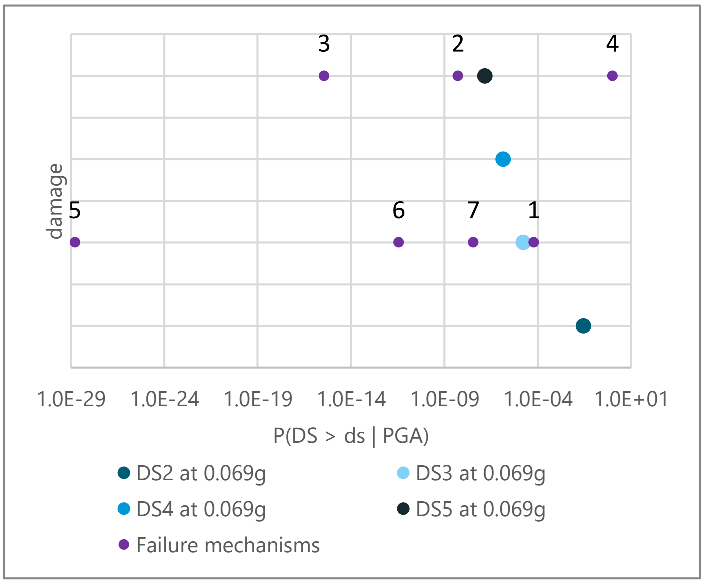
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.18	0.50	2.76E-02	0.10
DS3	0.55	0.50	1.65E-05	0.30
DS4	1.15	0.60	1.37E-06	0.50
DS5	1.50	0.60	1.43E-07	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure of steel shell structure	0.81	0.10	1.10	DS3	3.84	6.05E-05
2	failure of connection between steel shells	0.64	0.10	1.25	DS5	5.72	5.34E-09
3	failure of steel support structure	0.65	0.05	1.00	DS5	8.07	3.63E-16
4	failure connections in support structure	1.39	0.05	1.00	DS5	-5.52	1.00E+00
5	failure concrete foundation beams	0.55	0.05	1.15	DS3	11.22	1.64E-29
6	failure bearing capacity piles (during)	0.47	0.10	1.25	DS3	6.86	3.52E-12
7	failure bending moment piles (shaft)	0.38	0.15	1.50	DS3	5.39	3.46E-08
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 14	
object name:	Elevated tank F	
location:	Eemshaven	
peak ground acceleration:	0.032	[g]

Typology

label:	PSTAS
typology:	Elevated Steel Tank

CALCULATION

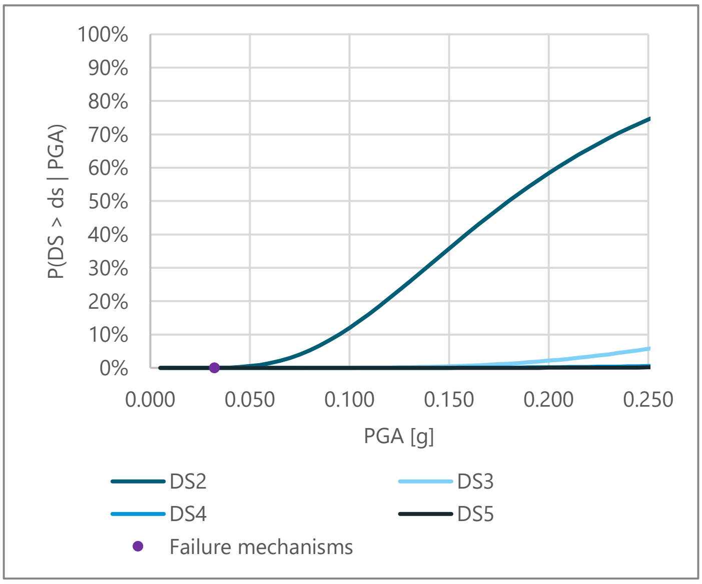
Fragility curves

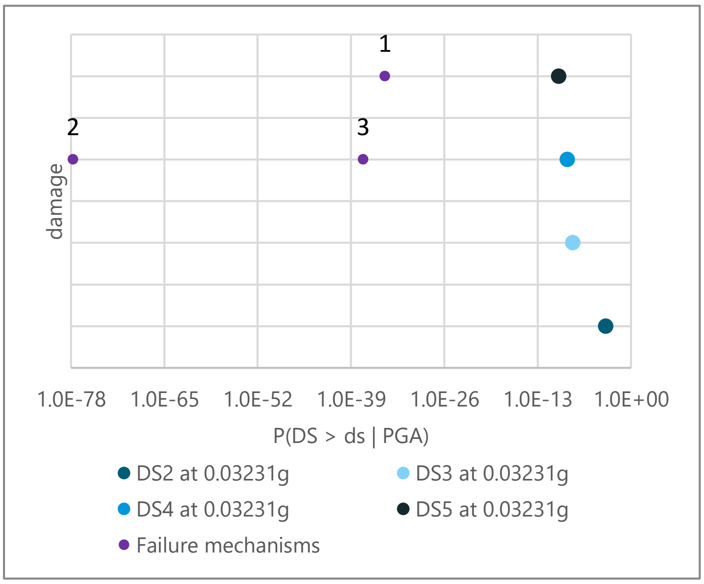
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.18	0.50	2.96E-04	0.10
DS3	0.55	0.50	7.18E-09	0.30
DS4	1.15	0.60	1.31E-09	0.50
DS5	1.50	0.60	7.95E-11	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure member	0.42	0.05	1.00	DS5	12.29	5.20E-35
2	failure connection	0.07	0.05	1.00	DS4	18.71	1.88E-78
3	failure tank structure	0.39	0.05	1.00	DS4	12.84	4.92E-38
4							
5							
6							
7							
8							
9							
10							

RESULTS





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			FRAGILITY CURVES	
	projectcode:	124217		
	part:	Verification fragility curves	format by:	J. de Bruijn MSc
	description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 1
object name: Elevated tank A
location: Delfzijl
peak ground acceleration: 0.080 [g]

Typology

label: PSTAS-NB
typology: Elevated tank (non-braced)

CALCULATION

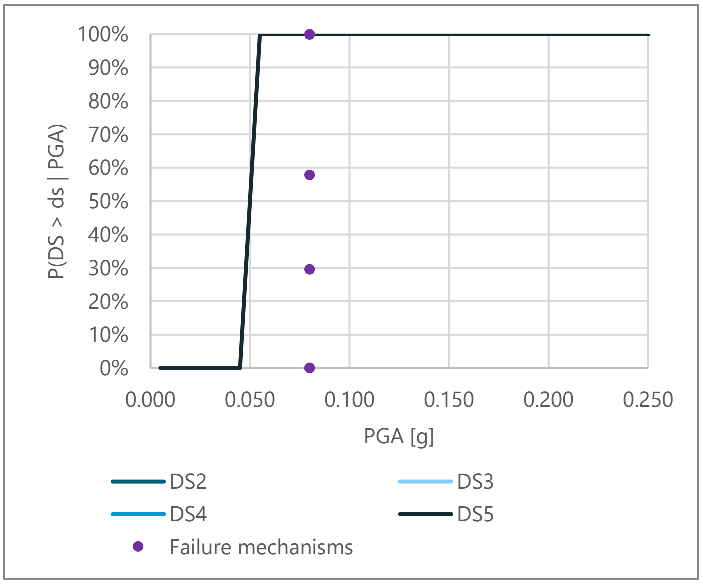
Fragility curves

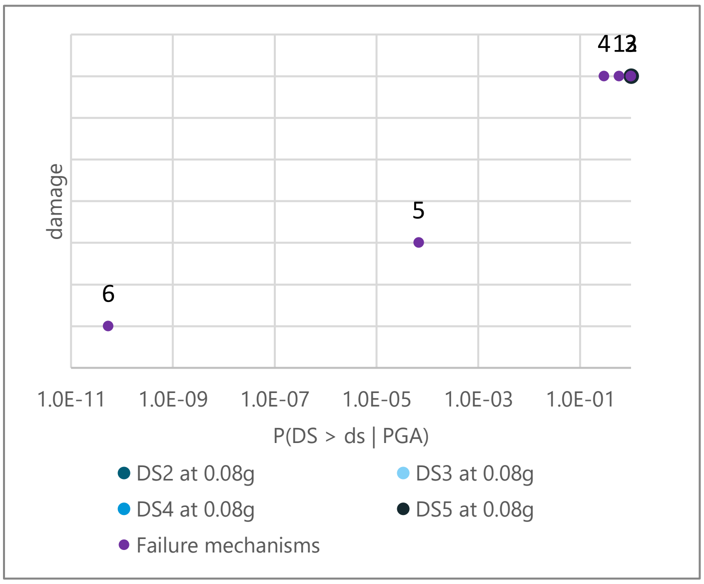
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4				0.50
DS5	0.05	0.00	1.00E+00	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding structure	1.10	0.05	1.00	DS5	-0.20	5.78E-01
2	welds in connection legs-floor frame	1.25	0.05	1.00	DS5	-2.95	9.98E-01
3	buckling of support columns	1.25	0.05	1.00	DS5	-2.95	9.98E-01
4	buckling of webs of floor frame	1.06	0.05	1.00	DS5	0.54	2.95E-01
5	foundation slab - shear failure	0.68	0.15	1.20	DS3	3.82	6.72E-05
6	geotechnical failure	0.53	0.10	1.25	DS2	6.46	5.40E-11
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 2
object name: Elevated tank B
location: Delfzijl
peak ground acceleration: 0.070 [g]

Typology

label: PSTAS-NB
typology: Elevated tank (non-braced)

CALCULATION

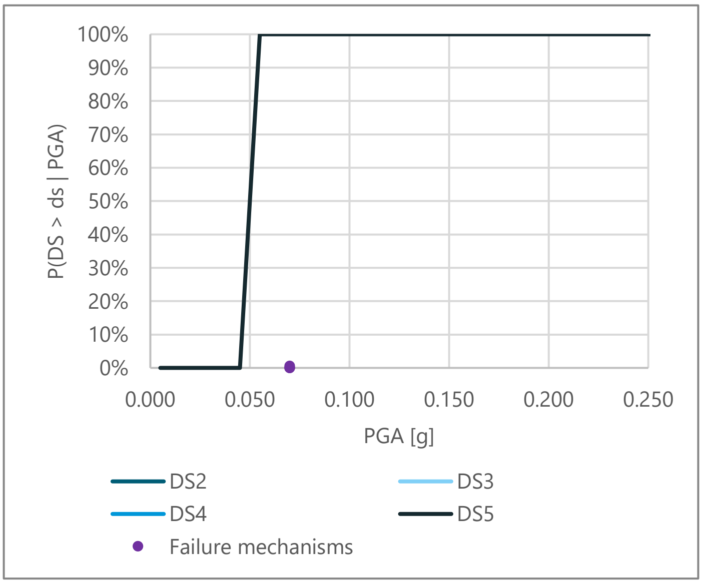
Fragility curves

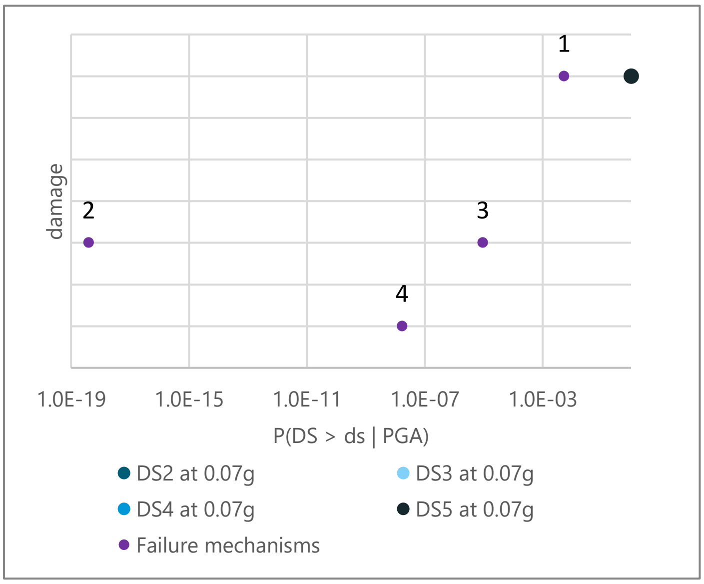
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4				0.50
DS5	0.05	0.00	1.00E+00	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	buckling of support columns	0.95	0.05	1.00	DS5	2.56	5.26E-03
2	yielding tank shell	0.91	0.05	1.50	DS3	8.86	3.94E-19
3	crushing concrete footing	0.57	0.15	1.20	DS3	4.28	9.39E-06
4	geotechnical failure	0.67	0.10	1.25	DS2	5.52	1.70E-08
5							
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 5
object name: Elevated tank C
location: Delfzijl
peak ground acceleration: 0.060 [g]

Typology

label: PSTAS-B
typology: Elevated tank (braced)

CALCULATION

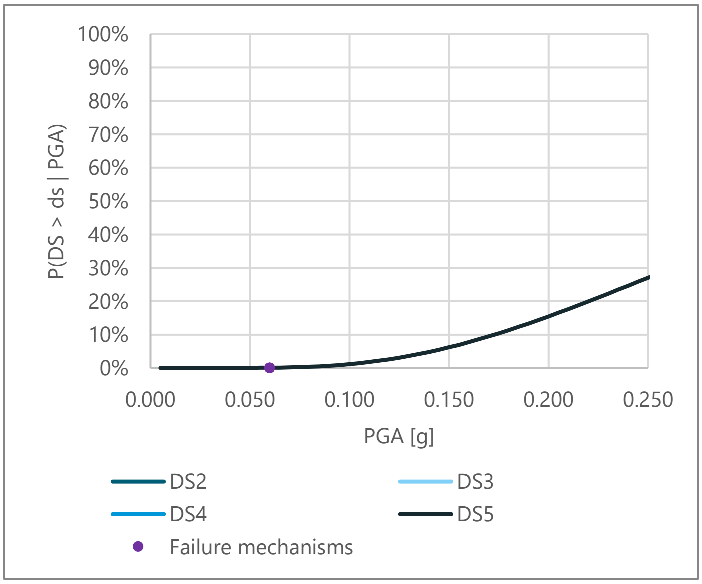
Fragility curves

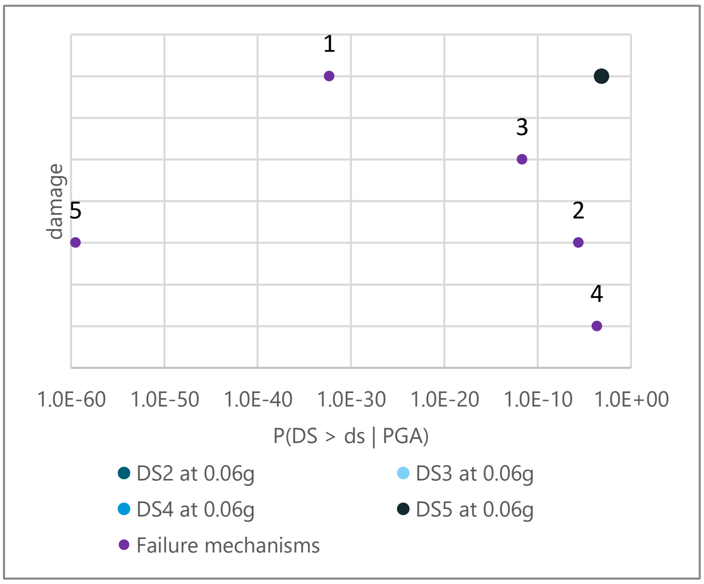
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4				0.50
DS5	0.35	0.55	6.72E-04	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	buckling support columns	0.44	0.05	1.00	DS5	11.92	4.57E-33
2	yielding support beams	0.84	0.05	1.00	DS3	4.58	2.35E-06
3	bolt failure	0.46	0.10	1.25	DS4	6.92	2.20E-12
4	shear failure pile	0.93	0.10	1.20	DS2	3.52	2.15E-04
5	pounding	0.20	0.05	1.00	DS3	16.33	3.12E-60
6							
7							
8							
9							
10							

RESULTS





Witteveen+Bos	project:	Selectiemethodiek Industrie Stap 2	spreadsheet	version 0.1
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	projectcode:	124217		
	part:	Verification fragility curves	format by:	J. de Bruijn MSc
	description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 5
object name: Elevated tank D
location: Delfzijl
peak ground acceleration: 0.060 [g]

Typology

label: PSTAS-NB
typology: Elevated tank (non-braced)

CALCULATION

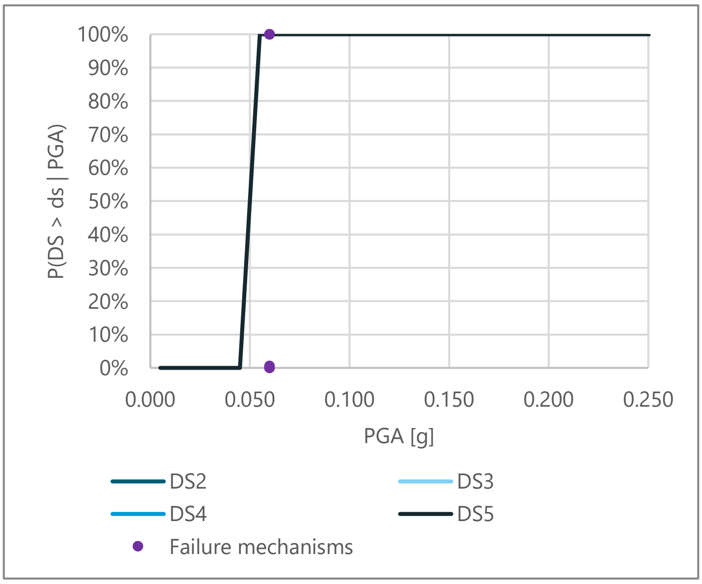
Fragility curves

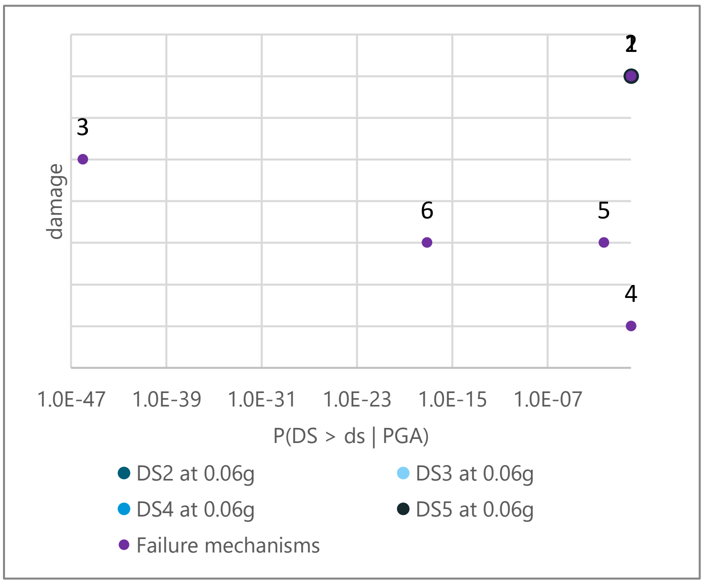
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4				0.50
DS5	0.05	0.00	1.00E+00	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding support legs	1.39	0.05	1.00	DS5	-5.52	1.00E+00
2	buckling support legs	2.09	0.05	1.00	DS5	-18.37	1.00E+00
3	yielding support frame	0.31	0.05	1.00	DS4	14.31	9.70E-47
4	meridional buckling	2.44	0.05	1.00	DS2	-24.80	1.00E+00
5	shear buckling	0.95	0.05	1.00	DS3	2.56	5.26E-03
6	overflow	0.63	0.05	1.00	DS3	8.53	7.64E-18
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 13
object name: Elevated tank E
location: Delfzijl
peak ground acceleration: 0.069 [g]

Typology

label: PSTAS-B
typology: Elevated tank (braced)

CALCULATION

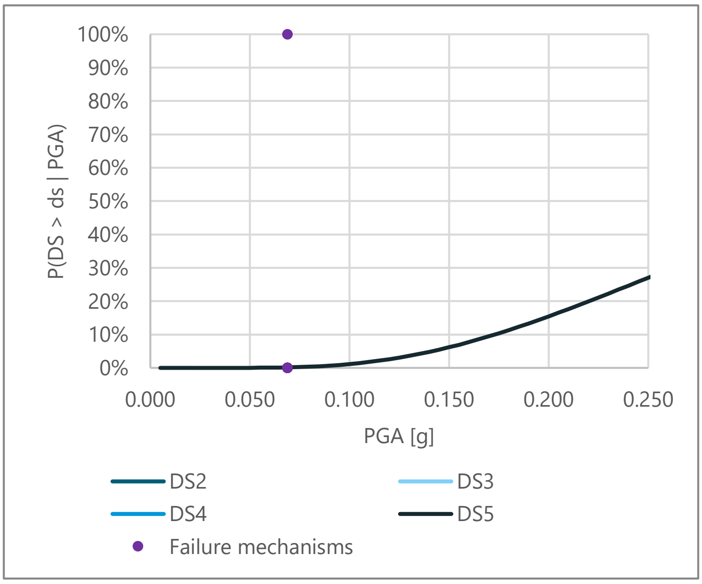
Fragility curves

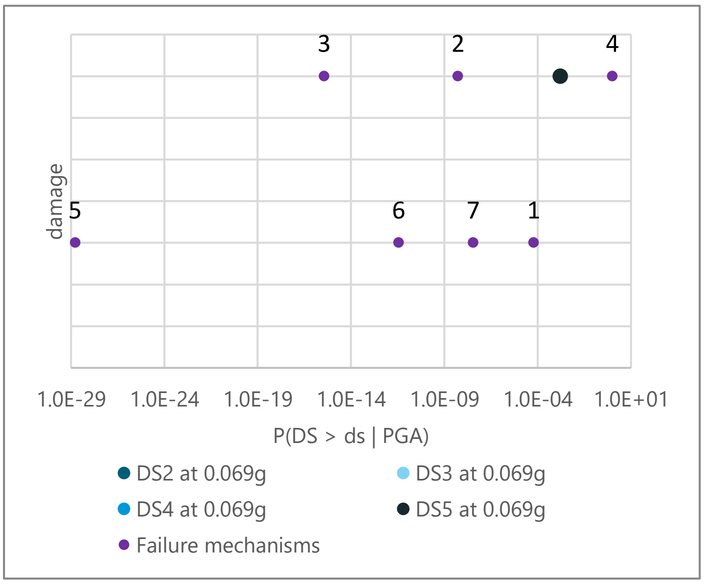
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4				0.50
DS5	0.35	0.55	1.58E-03	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure of steel shell structure	0.81	0.10	1.10	DS3	3.84	6.05E-05
2	failure of connection between steel shells	0.64	0.10	1.25	DS5	5.72	5.34E-09
3	failure of steel support structure	0.65	0.05	1.00	DS5	8.07	3.63E-16
4	failure connections in support structure	1.39	0.05	1.00	DS5	-5.52	1.00E+00
5	failure concrete foundation beams	0.55	0.05	1.15	DS3	11.22	1.64E-29
6	failure bearing capacity piles (during)	0.47	0.10	1.25	DS3	6.86	3.52E-12
7	failure bending moment piles (shaft)	0.38	0.15	1.50	DS3	5.39	3.46E-08
8							
9							
10							

RESULTS





project:	Selectiemethodiek Industrie Stap 2		spreadsheet	version 0.1
projectcode:	124217		FRAGILITY CURVES	
part:	Verification fragility curves		format by:	J. de Bruijn MSc
description:			date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 14	
object name:	Elevated tank F	
location:	Eemshaven	
peak ground acceleration:	0.032	[g]

Typology

label:	PSTAS-B
typology:	Elevated tank (braced)

CALCULATION

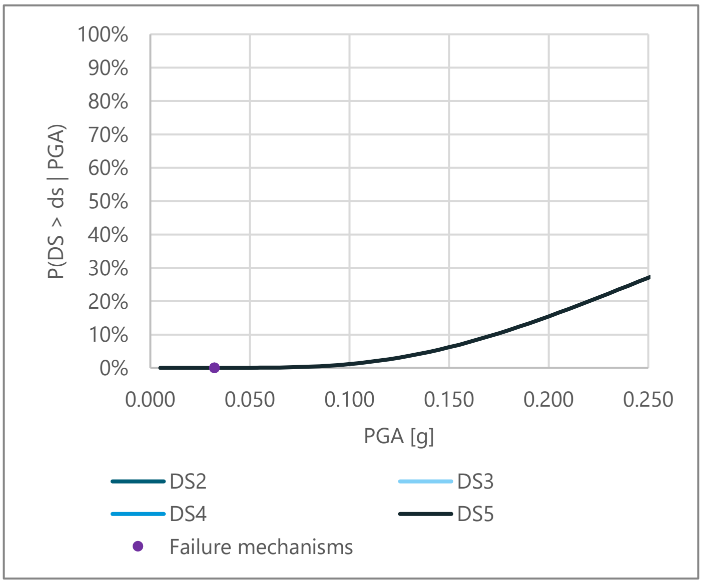
Fragility curves

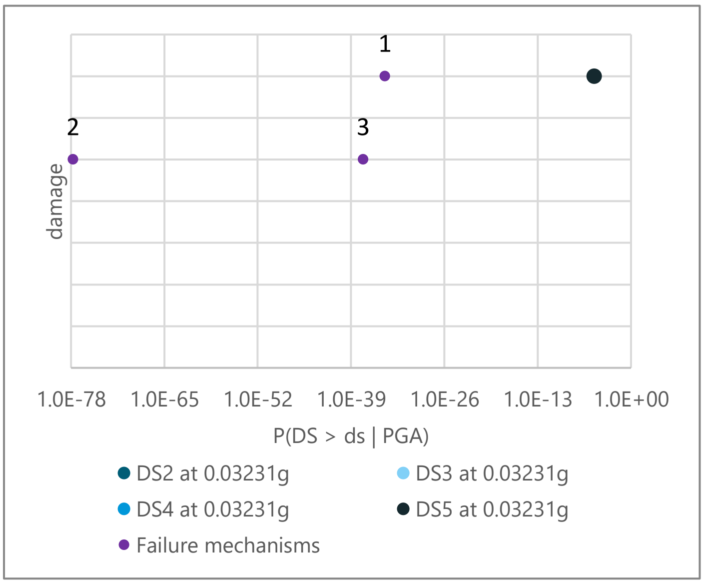
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4				0.50
DS5	0.35	0.55	7.39E-06	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure member	0.42	0.05	1.00	DS5	12.29	5.20E-35
2	failure connection	0.07	0.05	1.00	DS4	18.71	1.88E-78
3	failure tank structure	0.39	0.05	1.00	DS4	12.84	4.92E-38
4							
5							
6							
7							
8							
9							
10							

RESULTS





II.4 On-ground storage tanks

project:	Selectiemethodiek Industrie Stap 2	spreadsheet FRAGILITY CURVES — version 0.1
projectcode:	124217	
part:	Verification fragility curves	format by: J. de Bruijn MSc
description:		date of format: 6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 3	
object name:	Storage tank A	
location:	Eemshaven	
peak ground acceleration:	0.118	[g]

Typology

label:	PSTGS
typology:	On-ground Unanchored Steel Tank

CALCULATION

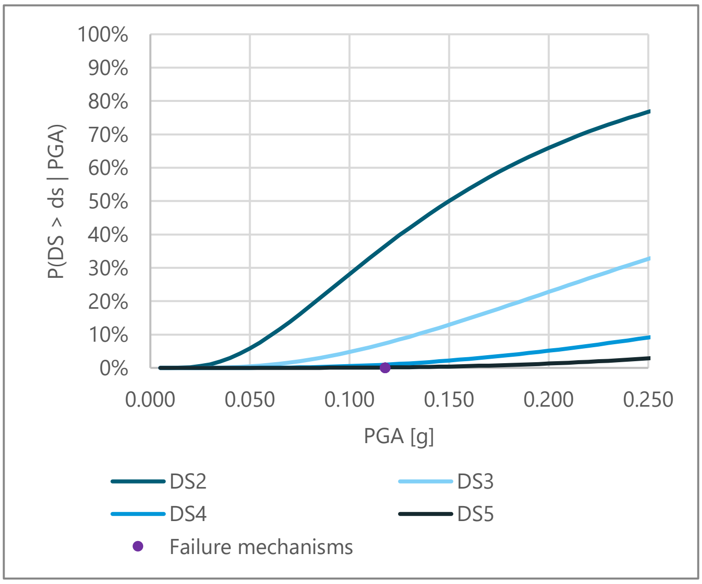
Fragility curves

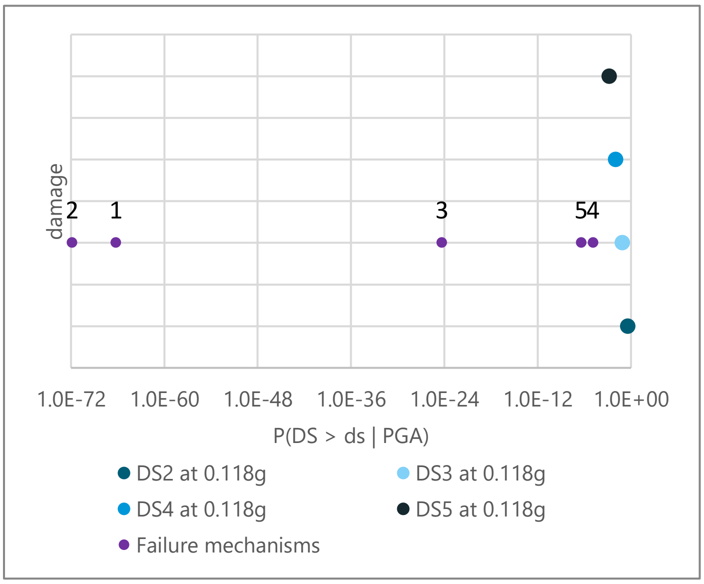
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.15	0.70	3.66E-01	0.10
DS3	0.35	0.75	7.36E-02	0.30
DS4	0.68	0.75	9.77E-03	0.50
DS5	0.95	0.70	1.44E-03	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	shell buckling (meridional)	0.15	0.05	1.00	DS3	17.25	6.00E-67
2	shell buckling (shear)	0.11	0.05	1.00	DS3	17.98	1.39E-72
3	yielding bottom plate	0.53	0.05	1.00	DS3	10.27	4.85E-25
4	yielding annular plate	0.86	0.05	1.00	DS3	4.21	1.27E-05
5	yielding shell	0.82	0.05	1.00	DS3	4.94	3.81E-07
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 1
object name: Storage tank B
location: Delfzijl
peak ground acceleration: 0.175 [g]

Typology

label: PSTGS
typology: On-ground Unanchored Steel Tank

CALCULATION

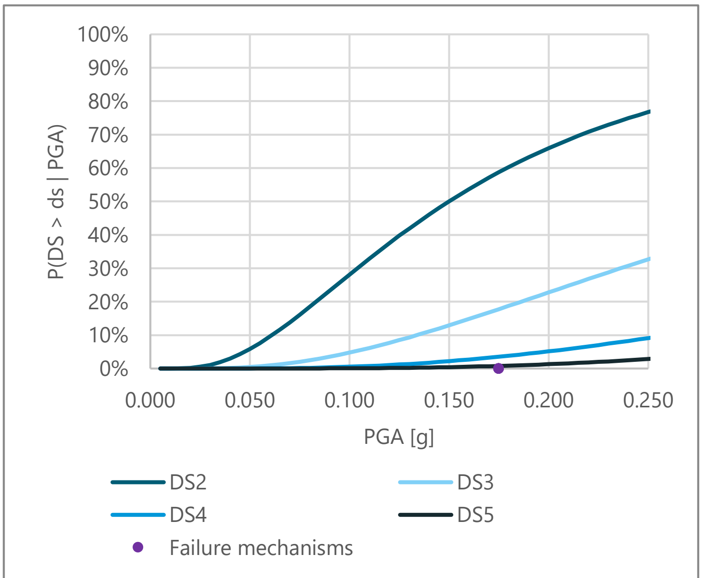
Fragility curves

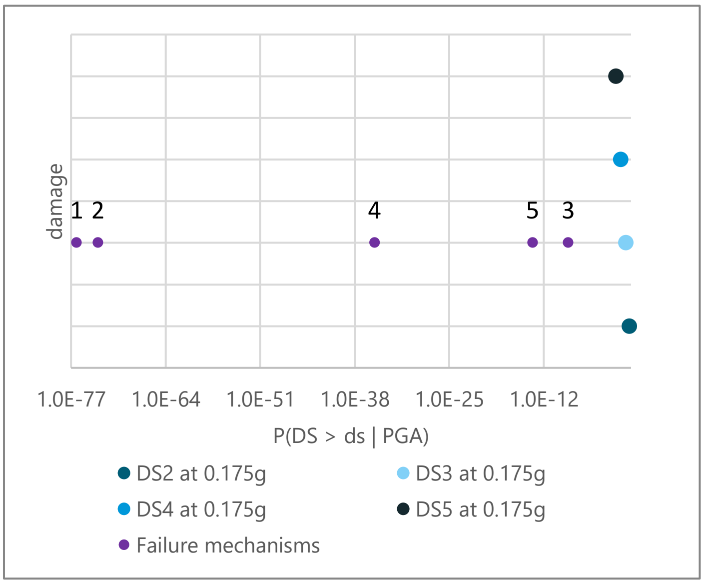
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.15	0.70	5.87E-01	0.10
DS3	0.35	0.75	1.78E-01	0.30
DS4	0.68	0.75	3.52E-02	0.50
DS5	0.95	0.70	7.83E-03	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	shell buckling (meridional)	0.08	0.05	1.00	DS3	18.53	5.78E-77
2	shell buckling (shear)	0.10	0.05	1.00	DS3	18.16	4.98E-74
3	buckling stiffening girders	0.77	0.05	1.00	DS3	5.86	2.28E-09
4	yielding annular plate	0.41	0.05	1.00	DS3	12.47	5.28E-36
5	yielding shell	0.68	0.05	1.00	DS3	7.52	2.84E-14
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 4
object name:	Storage tank C
location:	Veendam
peak ground acceleration:	0.034 [g]

Typology

label:	PSTGS
typology:	On-ground Unanchored Steel Tank

CALCULATION

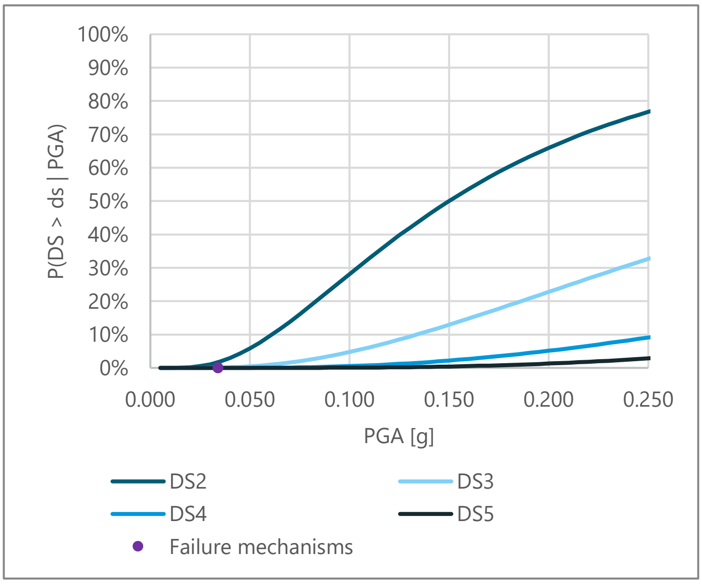
Fragility curves

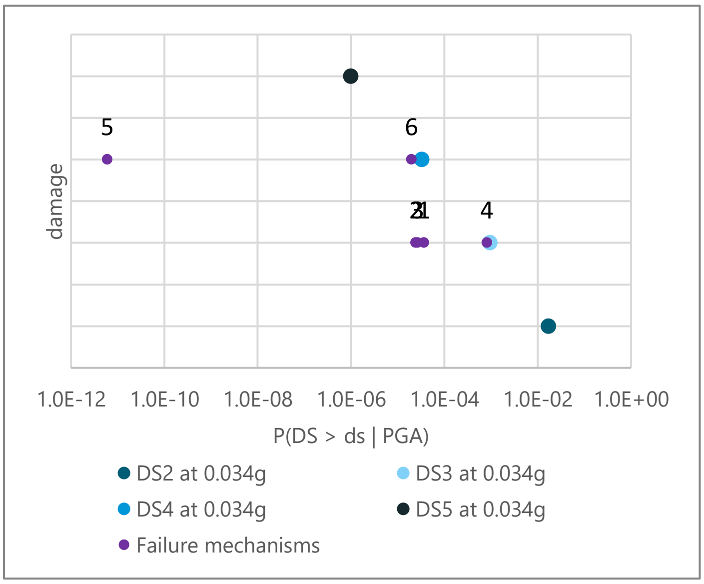
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.15	0.70	1.70E-02	0.10
DS3	0.35	0.75	9.39E-04	0.30
DS4	0.68	0.75	3.24E-05	0.50
DS5	0.95	0.70	9.81E-07	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	delamination shell	0.43	0.20	1.40	DS3	3.97	3.62E-05
2	buckling shell	0.39	0.20	1.40	DS3	4.06	2.41E-05
3	delamination knuckle	0.40	0.20	1.40	DS3	4.04	2.67E-05
4	delamination knuckle	0.77	0.20	1.40	DS3	3.15	8.11E-04
5	yielding anchor	0.72	0.05	1.00	DS4	6.78	5.98E-12
6	pull-out failure of anchor	0.61	0.15	1.20	DS4	4.11	1.97E-05
7							
8							
9							
10							

RESULTS





	project:	Selectiemethodiek Industrie Stap 2	spreadsheet FRAGILITY CURVES	version 0.1
	projectcode:	124217		
	part:	Verification fragility curves	format by:	J. de Bruijn MSc
	description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 11	
object name:	Storage tank E	
location:	Delfzijl	
peak ground acceleration:	0.071	[g]

Typology

label:	PSTGS
typology:	On-ground Unanchored Steel Tank

CALCULATION

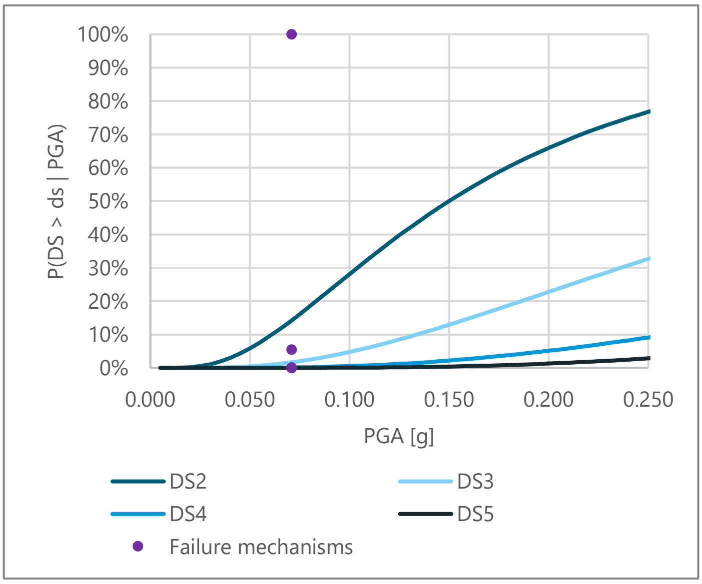
Fragility curves

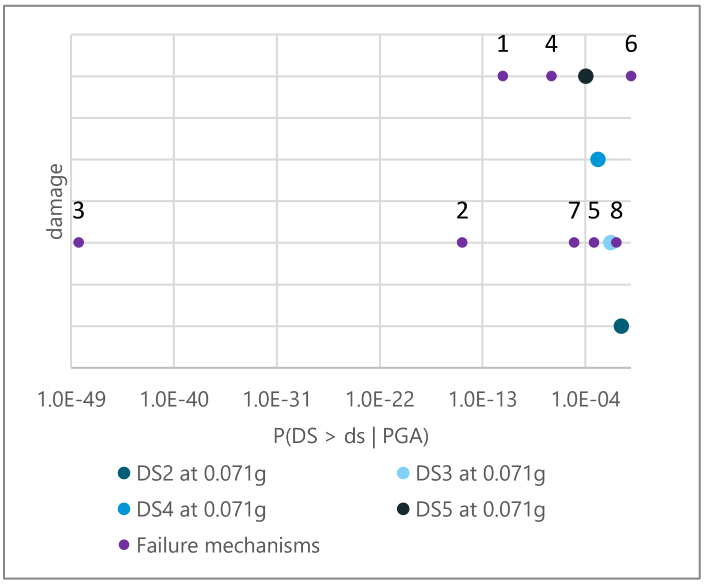
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.15	0.70	1.43E-01	0.10
DS3	0.35	0.75	1.67E-02	0.30
DS4	0.68	0.75	1.30E-03	0.50
DS5	0.95	0.70	1.06E-04	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	global instability (overturning)	0.72	0.05	1.00	DS5	6.78	5.98E-12
2	failure of tank wall (shear buckling)	0.28	0.10	1.10	DS3	7.87	1.75E-15
3	sloshing height	0.29	0.05	1.00	DS3	14.68	4.62E-49
4	failure anchors	0.72	0.10	1.25	DS5	5.18	1.08E-07
5	failure of concrete foundation slab due to punching shear	1.02	0.15	1.50	DS3	3.25	5.80E-04
6	failure of connection pipeline with tanks	5.30	0.05	1.00	DS5	-77.31	1.00E+00
7	failure piles due to insufficient bearing capacity	0.86	0.10	1.25	DS3	4.25	1.08E-05
8	failure piles due to bending moment (shaft)	1.51	0.15	1.50	DS3	1.61	5.41E-02
9							
10							

RESULTS





	project:	Selectiemethodiek Industrie Stap 2	spreadsheet FRAGILITY CURVES	version 0.1
	projectcode:	124217		
	part:	Verification fragility curves	format by:	J. de Bruijn MSc
	description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 12	
object name:	Storage tank F	
location:	Delfzijl	
peak ground acceleration:	0.060	[g]

Typology

label:	PSTGS
typology:	On-ground Unanchored Steel Tank

CALCULATION

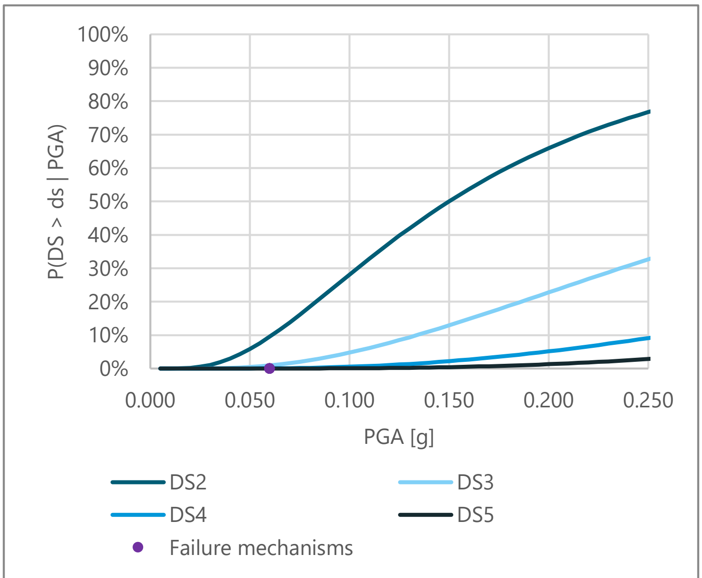
Fragility curves

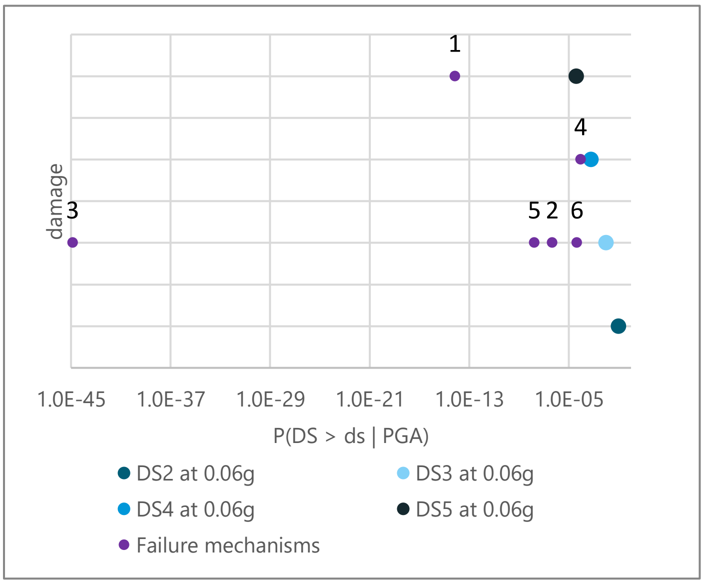
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2	0.15	0.70	9.53E-02	0.10
DS3	0.35	0.75	9.35E-03	0.30
DS4	0.68	0.75	6.04E-04	0.50
DS5	0.95	0.70	3.98E-05	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	global instability (overturning)	0.67	0.05	1.00	DS5	7.70	6.87E-15
2	failure of steel tank wall	0.67	0.10	1.10	DS3	4.91	4.60E-07
3	sliding	0.32	0.05	1.00	DS3	14.12	1.34E-45
4	failure of foundation slab	0.87	0.15	1.50	DS4	3.75	8.80E-05
5	failure bearing capacity piles (during)	0.67	0.10	1.25	DS3	5.52	1.70E-08
6	failure bending moment piles (shaft)	0.82	0.15	1.50	DS3	3.92	4.45E-05
7							
8							
9							
10							

RESULTS





II.5 Horizontal/vertical vessels

	project:	Selectiemethodiek Industrie Stap 2	spreadsheet FRAGILITY CURVES	version 0.1
	projectcode:	124217		
	part:	Verification fragility curves	format by:	J. de Bruijn MSc
	description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 2	
object name:	Vertical vessel A	
location:	Delfzijl	
peak ground acceleration:	0.070	[g]

Typology

label:	VV-SELF
typology:	Large vertical vessels with formed heads, unanchored

CALCULATION

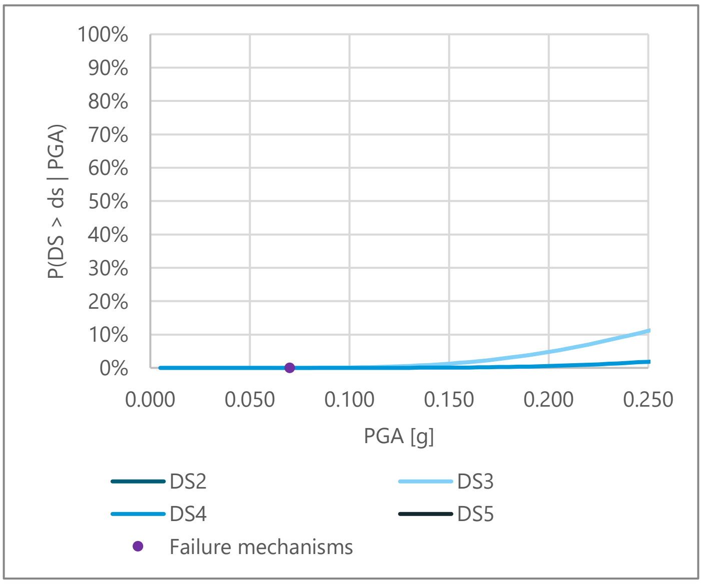
Fragility curves

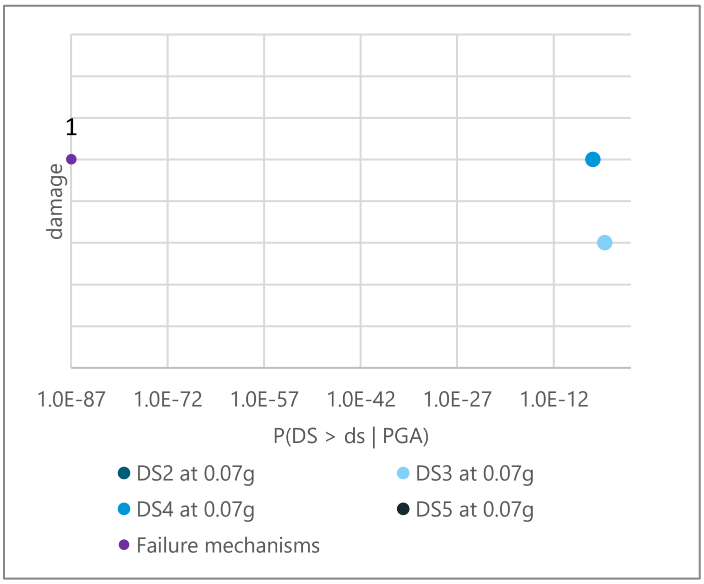
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3	0.46	0.50	8.31E-05	0.30
DS4	0.68	0.48	1.09E-06	0.50
DS5				0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure anchor bolts	0.01	0.05	1.00	DS4	19.82	1.07E-87
2							
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 5
object name: Vertical vessel B
location: Delfzijl
peak ground acceleration: 0.060 [g]

Typology

label: VV-SELF
typology: Large vertical vessels with formed heads, unanchored

CALCULATION

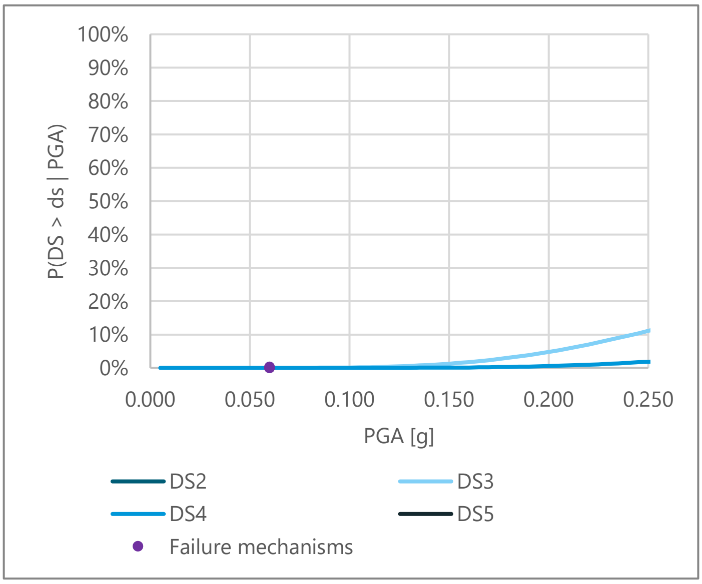
Fragility curves

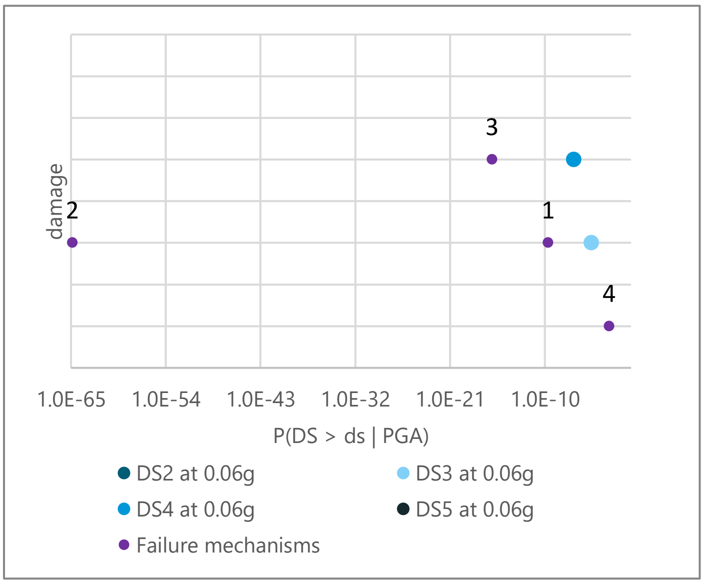
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3	0.46	0.50	2.31E-05	0.30
DS4	0.68	0.48	2.12E-07	0.50
DS5				0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding tank shell	0.75	0.05	1.00	DS3	6.23	2.33E-10
2	buckling skirt	0.16	0.05	1.00	DS3	17.06	1.41E-65
3	anchor bolt failure	0.26	0.10	1.25	DS4	8.26	7.22E-17
4	shear failure pile	0.93	0.15	1.20	DS2	2.77	2.79E-03
5							
6							
7							
8							
9							
10							

RESULTS





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projectcode:	124217	
part:	Verification fragility curves	format by: J. de Bruijn MSc
description:		date of format: 6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 7
object name: Vertical vessel C
location: Delfzijl
peak ground acceleration: 0.080 [g]

Typology

label: VV-SELF
typology: Large vertical vessels with formed heads, unanchored

CALCULATION

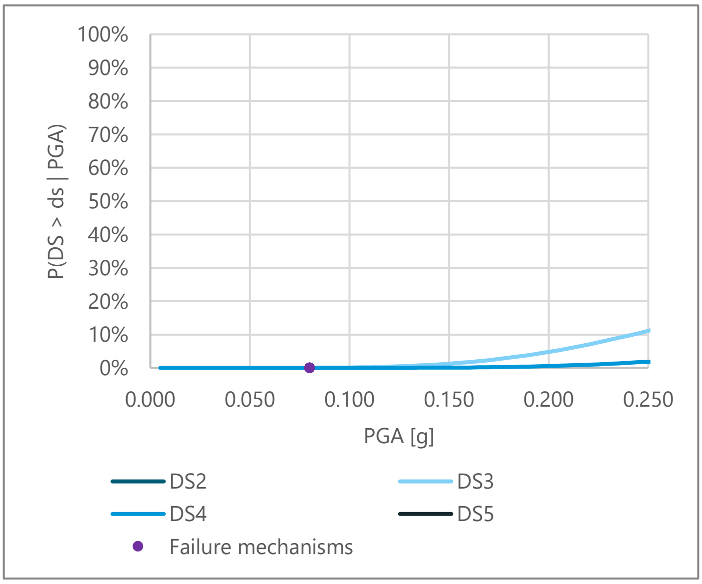
Fragility curves

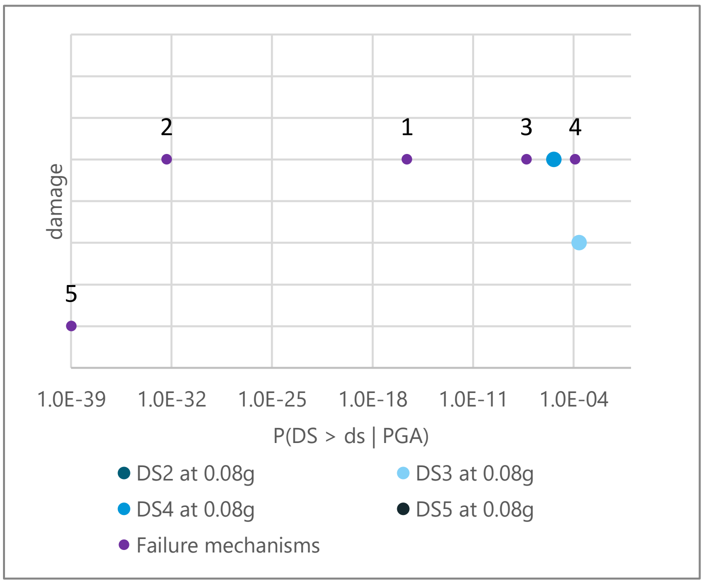
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3	0.46	0.50	2.34E-04	0.30
DS4	0.68	0.48	4.13E-06	0.50
DS5				0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	buckling shell - bottom ring	0.65	0.05	1.00	DS4	8.11	2.51E-16
2	buckling tank shell	0.44	0.05	1.00	DS4	11.92	4.57E-33
3	anchor bolts	0.70	0.10	1.25	DS4	5.32	5.23E-08
4	concrete floor - shear failure	0.90	0.15	1.50	DS4	3.65	1.31E-04
5	pile foundation - shear failure	0.43	0.05	1.15	DS2	13.13	1.04E-39
6							
7							
8							
9							
10							

RESULTS





Witteveen+Bos	project: Selectiemethodiek Industrie Stap 2	spreadsheet FRAGILITY CURVES	version 0.1
	projectcode: 124217		
	part: Verification fragility curves	format by:	J. de Bruijn MSc
	description:	date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 7
object name: Vertical vessel D
location: Delfzijl
peak ground acceleration: 0.080 [g]

Typology

label: VV-SELF
typology: Large vertical vessels with formed heads, unanchored

CALCULATION

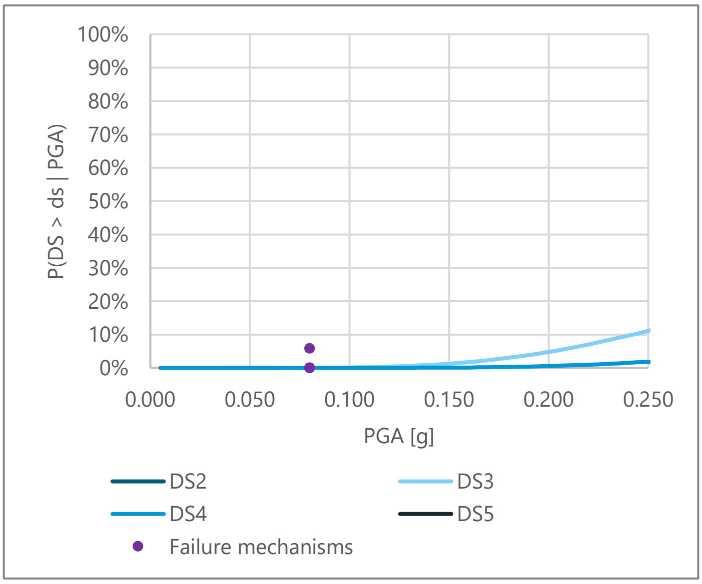
Fragility curves

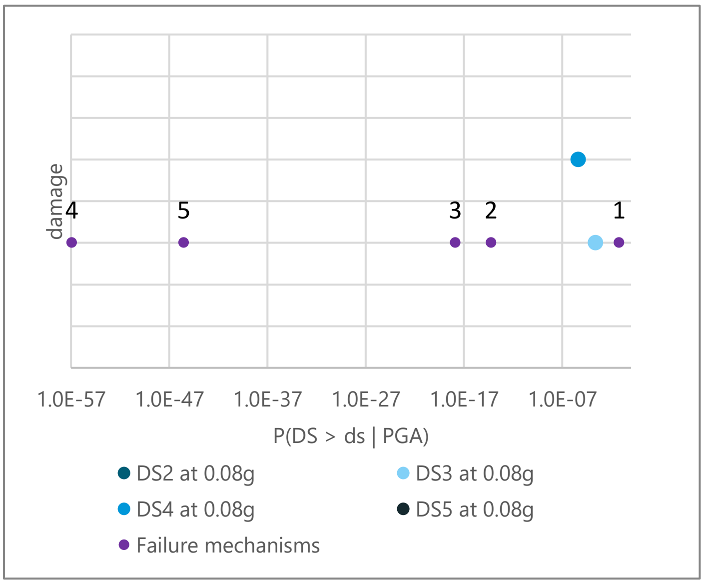
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3	0.46	0.50	2.34E-04	0.30
DS4	0.68	0.48	4.13E-06	0.50
DS5				0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	buckling tank shell	1.00	0.05	1.00	DS3	1.57	5.81E-02
2	anchor bolts - tensile failure	0.34	0.10	1.25	DS3	7.73	5.55E-15
3	anchor bolts - shear failure	0.19	0.10	1.25	DS3	8.73	1.28E-18
4	yielding pipe	0.22	0.05	1.00	DS3	15.96	1.20E-57
5	yielding pipe knuckle	0.31	0.05	1.00	DS3	14.23	3.00E-46
6							
7							
8							
9							
10							

RESULTS





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			FRAGILITY CURVES	
	projectcode:	124217		
	part:	Verification fragility curves	format by:	J. de Bruijn MSc
	description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 7	
object name:	Horizontal vessel A	
location:	Delfzijl	
peak ground acceleration:	0.080	[g]

Typology

label:	HV-SELF
typology:	Large horizontal vessels, unanchored

CALCULATION

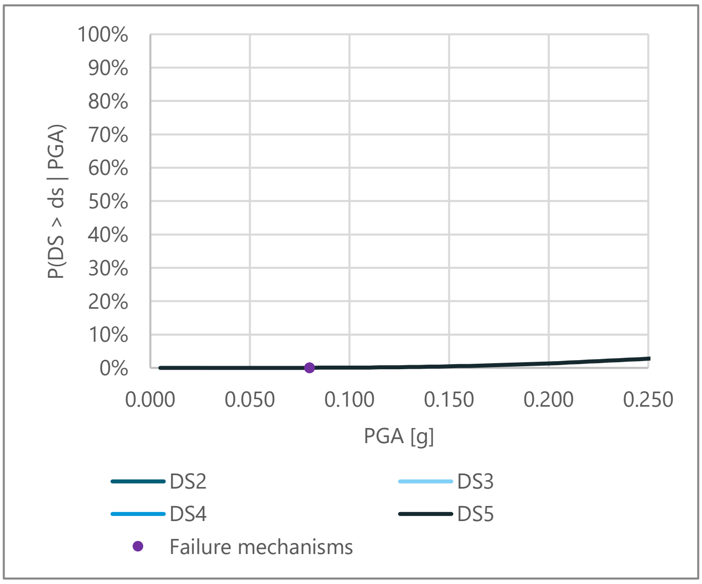
Fragility curves

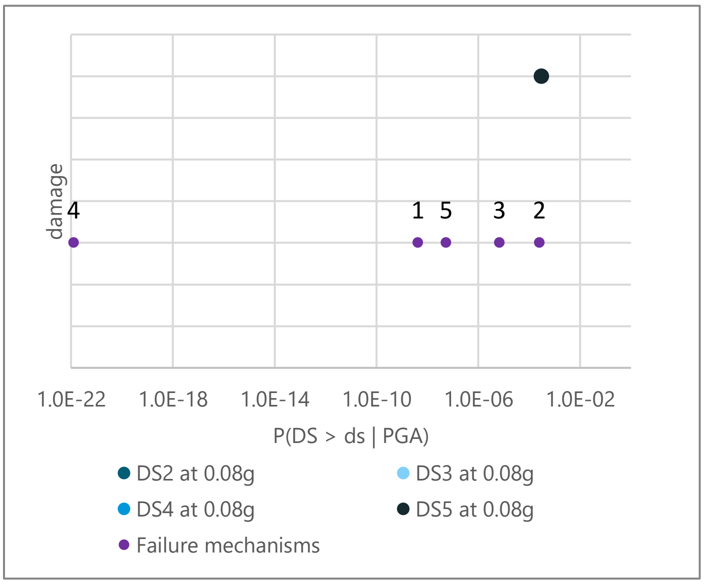
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4				0.50
DS5	1.05	0.75	2.99E-04	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	concrete consoles failure	0.27	0.15	1.50	DS3	5.76	4.20E-09
2	anchorage - bending	0.95	0.15	1.50	DS3	3.48	2.48E-04
3	anchorage - shear	0.69	0.15	1.50	DS3	4.35	6.67E-06
4	yielding pipe	0.56	0.05	1.00	DS3	9.72	1.26E-22
5	yielding pipe knuckle	0.80	0.05	1.00	DS3	5.31	5.42E-08
6							
7							
8							
9							
10							

RESULTS





project:	Selectiemethodiek Industrie Stap 2	spreadsheet	version 0.1
projectcode:	124217	FRAGILITY CURVES	
part:	Verification fragility curves	format by:	J. de Bruijn MSc
description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 13	
object name:	Vertical vessel E	
location:	Delfzijl	
peak ground acceleration:	0.069	[g]

Typology

label:	VV-SELF
typology:	Large vertical vessels with formed heads, unanchored

CALCULATION

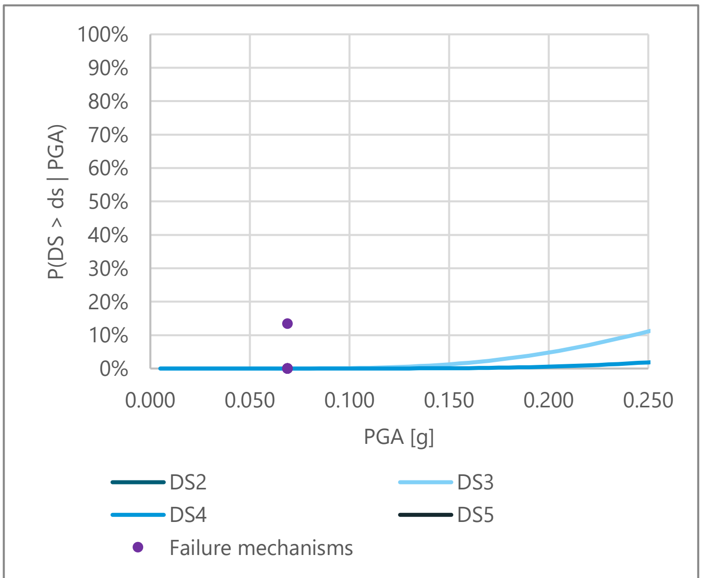
Fragility curves

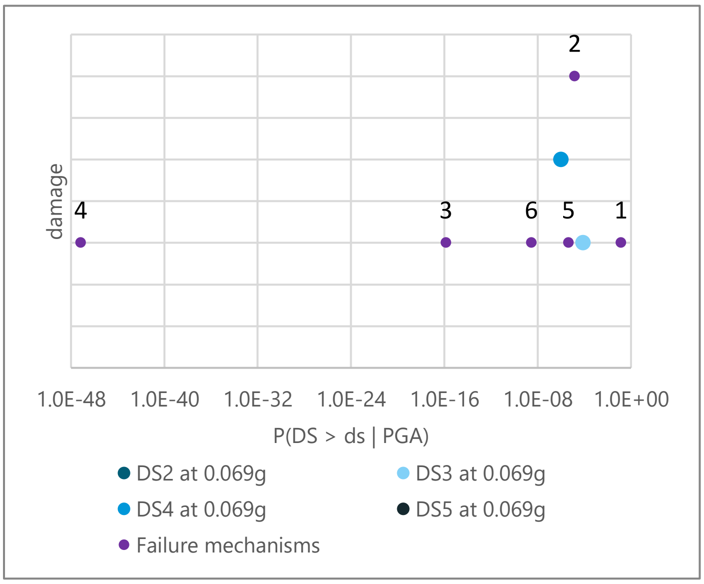
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3	0.46	0.50	7.40E-05	0.30
DS4	0.68	0.48	9.37E-07	0.50
DS5				0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure of steel shell structure	1.17	0.10	1.10	DS3	1.11	1.34E-01
2	failure of connection between steel shells	0.87	0.10	1.25	DS5	4.18	1.45E-05
3	concrete floor with reinforcement	0.74	0.05	1.15	DS3	8.19	1.35E-16
4	connection steel shell-concrete floor	0.30	0.05	1.00	DS3	14.49	6.81E-48
5	failure bearing capacity piles (during)	0.83	0.10	1.25	DS3	4.45	4.31E-06
6	failure bending moment piles (shaft)	0.25	0.15	1.50	DS3	5.83	2.79E-09
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 13
object name: Vertical vessel F
location: Delfzijl
peak ground acceleration: 0.069 [g]

Typology

label: VV-SELF
typology: Large vertical vessels with formed heads, unanchored

CALCULATION

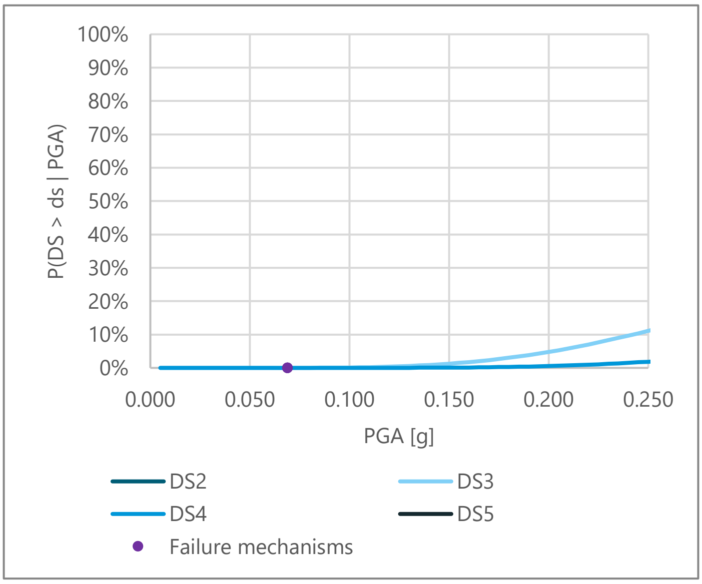
Fragility curves

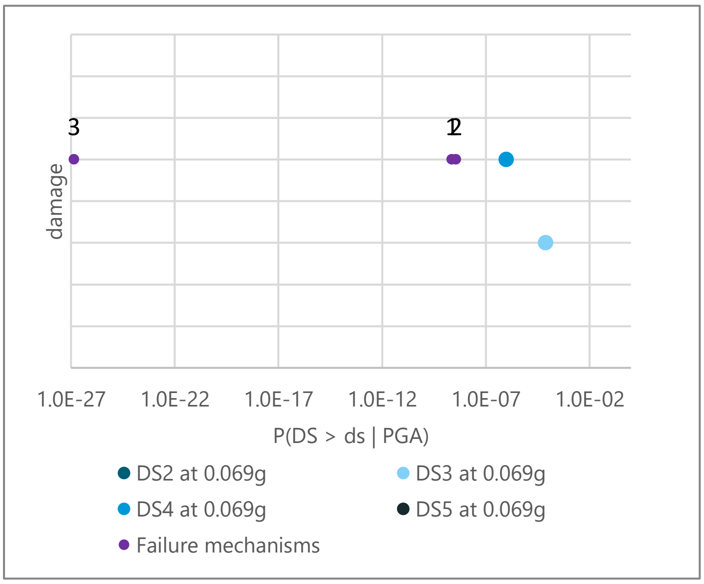
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3	0.46	0.50	7.40E-05	0.30
DS4	0.68	0.48	9.37E-07	0.50
DS5				0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure support plate	0.77	0.05	1.00	DS4	5.86	2.28E-09
2	failure connection support structure-structure building	0.63	0.10	1.25	DS4	5.79	3.59E-09
3	failure connection support structure-tank wall	0.50	0.05	1.00	DS4	10.82	1.38E-27
4							
5							
6							
7							
8							
9							
10							

RESULTS





II.6 Vertical stacks

project:	Selectiemethodiek Industrie Stap 2	spreadsheet	version 0.1
projectcode:	124217	FRAGILITY CURVES	
part:	Verification fragility curves	format by:	J. de Bruijn MSc
description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 4	
object name:	Equipment B / Building C	
location:	Veendam	
peak ground acceleration:	0.034	[g]

Typology

label:	ST-SELF
typology:	Stacks, unanchored

CALCULATION

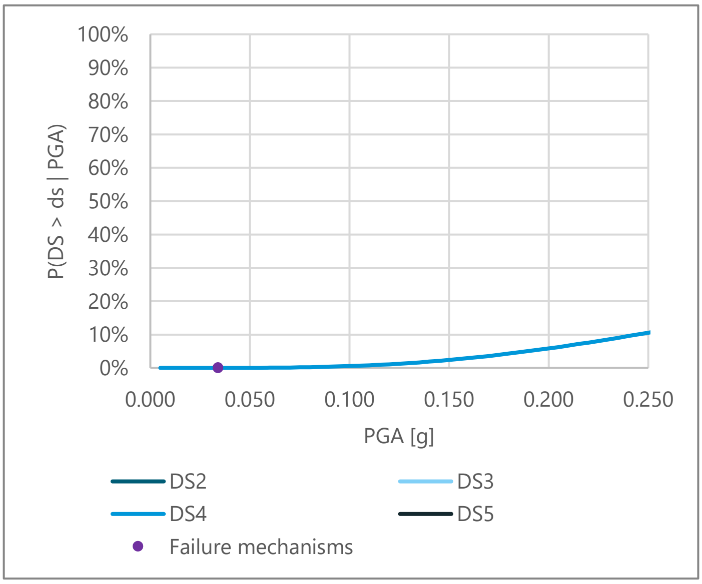
Fragility curves

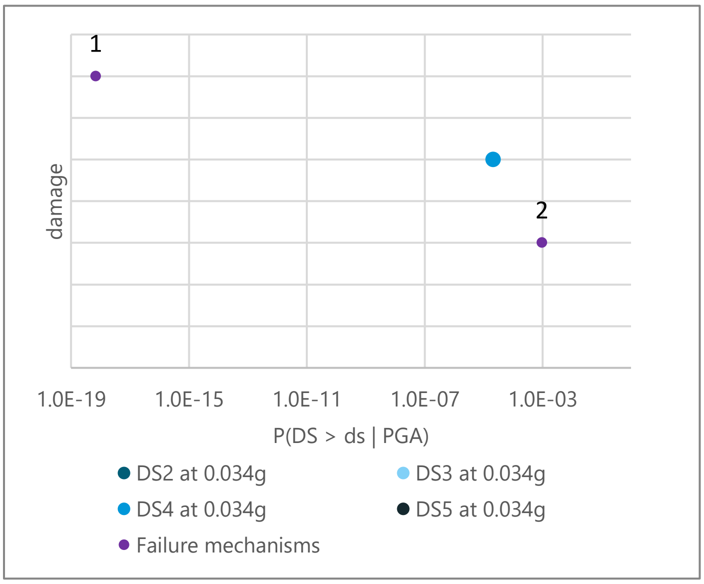
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4	0.60	0.70	2.06E-05	0.50
DS5				0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	buckling support columns	0.61	0.05	1.00	DS5	8.80	6.82E-19
2	yielding	0.92	0.05	1.00	DS3	3.11	9.39E-04
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 7	
object name:	Stack A	
location:	Delfzijl	
peak ground acceleration:	0.080	[g]

Typology

label:	ST-SELF
typology:	Stacks, unanchored

CALCULATION

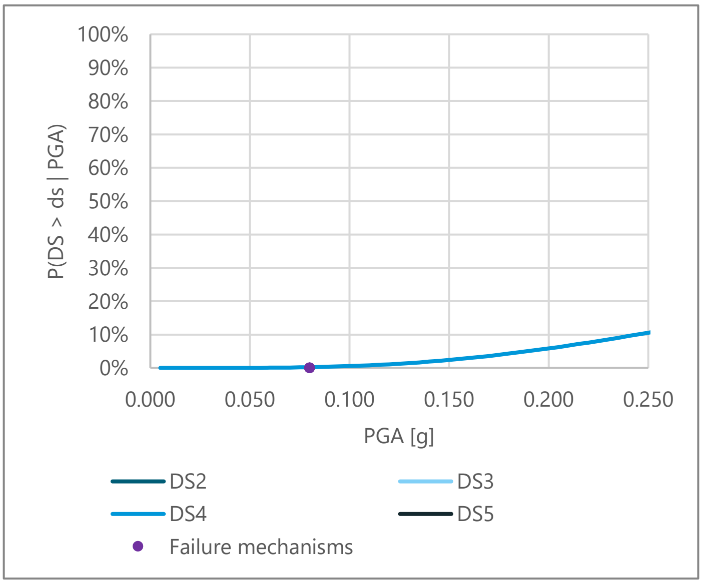
Fragility curves

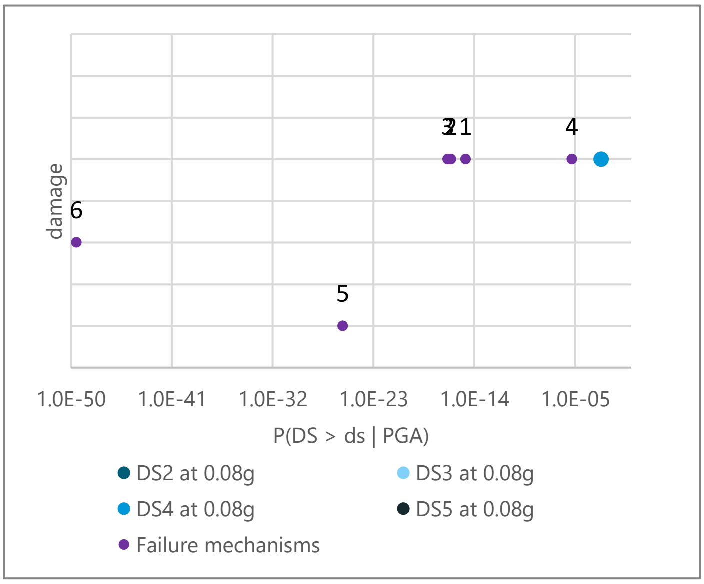
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4	0.60	0.70	2.00E-03	0.50
DS5				0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	buckling tank shell	0.66	0.05	1.00	DS4	7.88	1.61E-15
2	buckling tank - bottom cone	0.64	0.05	1.00	DS4	8.25	7.95E-17
3	anchor bolts	0.25	0.10	1.25	DS4	8.33	4.11E-17
4	concrete floor - shear failure	0.67	0.15	1.50	DS4	4.42	4.90E-06
5	pile foundation	0.59	0.05	1.15	DS2	10.58	1.83E-26
6	yielding pipes	0.28	0.05	1.00	DS3	14.86	3.03E-50
7							
8							
9							
10							

RESULTS





project:	Selectiemethodiek Industrie Stap 2	spreadsheet	version 0.1
projectcode:	124217	FRAGILITY CURVES	
part:	Verification fragility curves	format by:	J. de Bruijn MSc
description:		date of format:	6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 8	
object name:	Stack B	
location:	Delfzijl	
peak ground acceleration:	0.072	[g]

Typology

label:	ST-SELF
typology:	Stacks, unanchored

CALCULATION

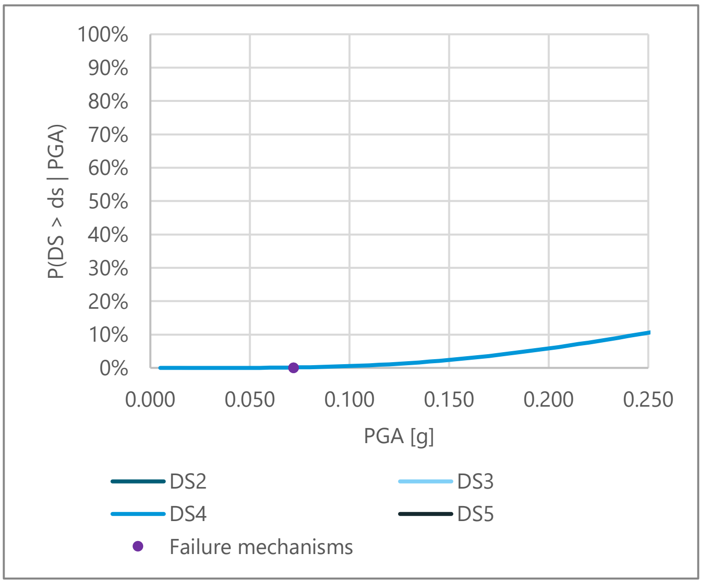
Fragility curves

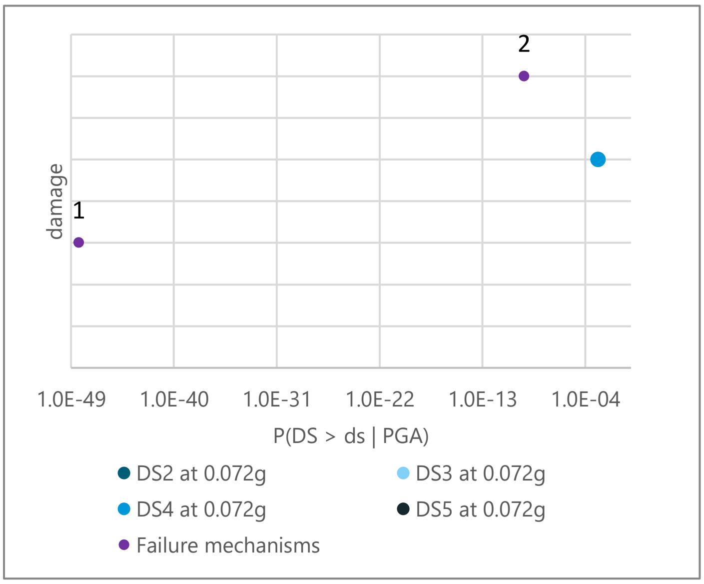
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4	0.60	0.70	1.23E-03	0.50
DS5				0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure steel shell	0.29	0.05	1.00	DS3	14.68	4.62E-49
2	pull-out failure anchor	0.16	0.15	1.50	DS5	6.13	4.38E-10
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





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projectcode:	124217	
part:	Verification fragility curves	format by: J. de Bruijn MSc
description:		date of format: 6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 10	
object name:	Stack C	
location:	Delfzijl	
peak ground acceleration:	0.065	[g]

Typology

label:	ST-SELF
typology:	Stacks, unanchored

CALCULATION

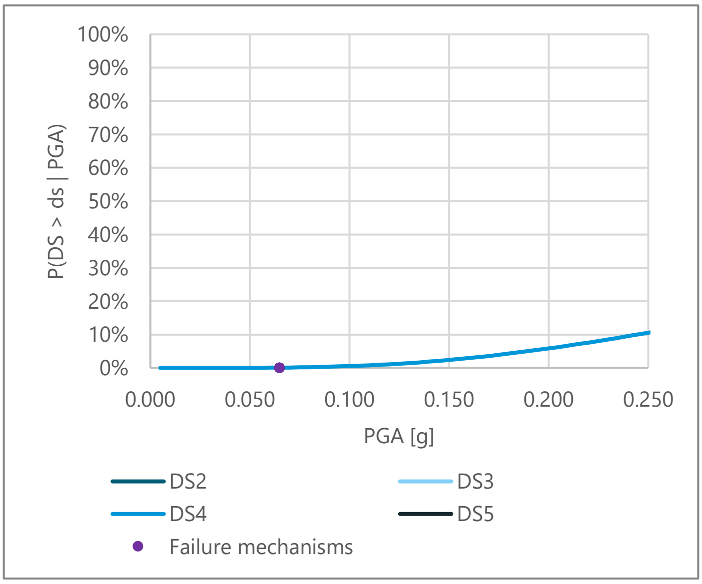
Fragility curves

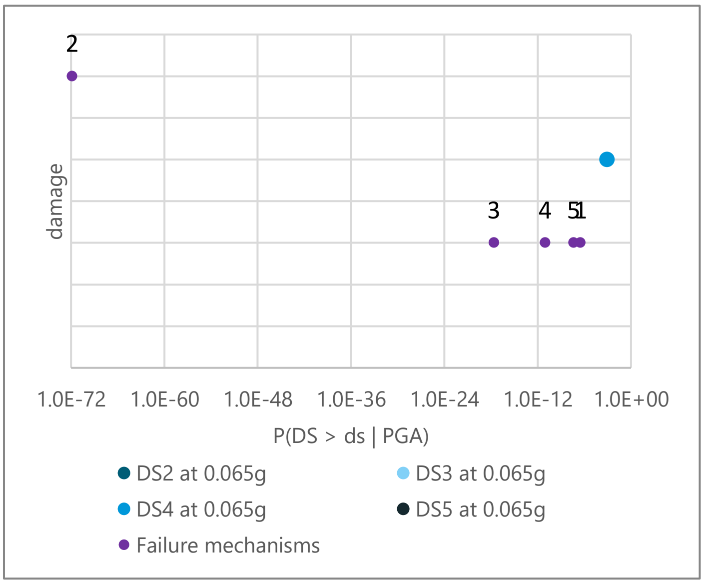
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4	0.60	0.70	7.49E-04	0.50
DS5				0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure vessel wall (pressurised meriodional buckling)	0.66	0.10	1.10	DS3	4.98	3.11E-07
2	failure connection steel and concrete floor	0.11	0.05	1.00	DS5	17.98	1.39E-72
3	failure of concrete floor (yielding reinforcement)	0.71	0.05	1.15	DS3	8.66	2.26E-18
4	failure piles due to insufficient bearing capacity	0.49	0.10	1.25	DS3	6.72	8.91E-12
5	failure piles due to bending moment (shaft)	0.39	0.15	1.50	DS3	5.36	4.17E-08
6							
7							
8							
9							
10							

RESULTS





project: Selectiemethodiek Industrie Stap 2
projectcode: 124217
part: Verification fragility curves
description:

spreadsheet FRAGILITY CURVES
version 0.1
format by: J. de Bruijn MSc
date of format: 6-10-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 11
object name: Stack D
location: Delfzijl
peak ground acceleration: 0.071 [g]

Typology

label: ST-SELF
typology: Stacks, unanchored

CALCULATION

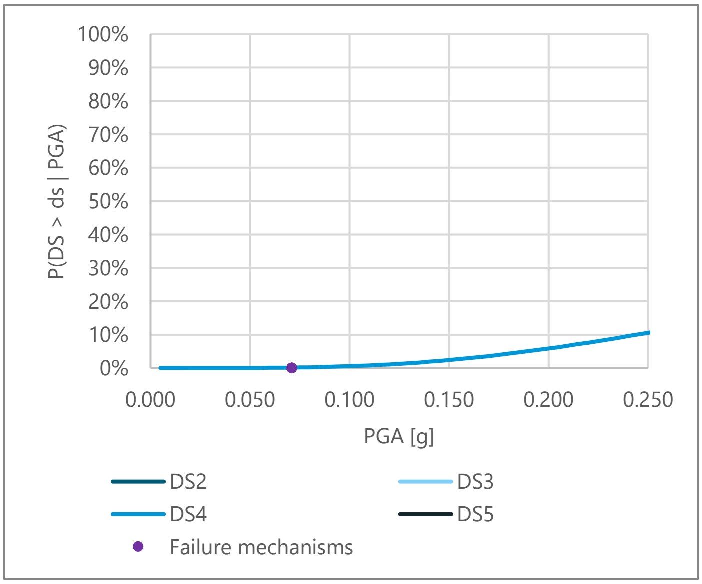
Fragility curves

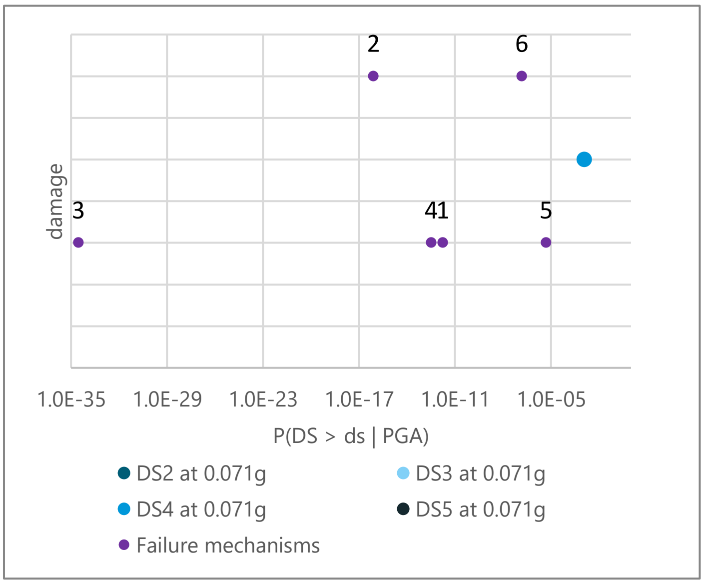
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4	0.60	0.70	1.15E-03	0.50
DS5				0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding/buckling steel shell	0.40	0.10	1.10	DS3	6.96	1.70E-12
2	failure of connection steel structure to concrete floor (fricti	0.64	0.05	1.00	DS5	8.25	7.95E-17
3	yielding reinforcement concrete floor	0.48	0.05	1.15	DS3	12.34	2.87E-35
4	failure piles due to insufficient bearing capacity	0.42	0.10	1.25	DS3	7.19	3.21E-13
5	failure piles due to bending moment (tip)	0.67	0.15	1.50	DS3	4.42	4.90E-06
6	yielding steel pipelines	0.81	0.05	1.00	DS5	5.13	1.46E-07
7							
8							
9							
10							

RESULTS





II.7 Elevated pipes

Witteveen+Bos	project: Selectiemethodiek Industrie Stap 2		spreadsheet FRAGILITY CURVES	version 0.1
	projectcode: 124217			
	part: Verification fragility curves		format by: J. de Bruijn MSc	
	description:		date of format: 10-11-2021	

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 7
object name: Pipeline A
location: Delfzijl
peak ground acceleration: 0.080 [g]

Typology

label: EP-SELF
typology: Elevated pipe, unanchored

CALCULATION

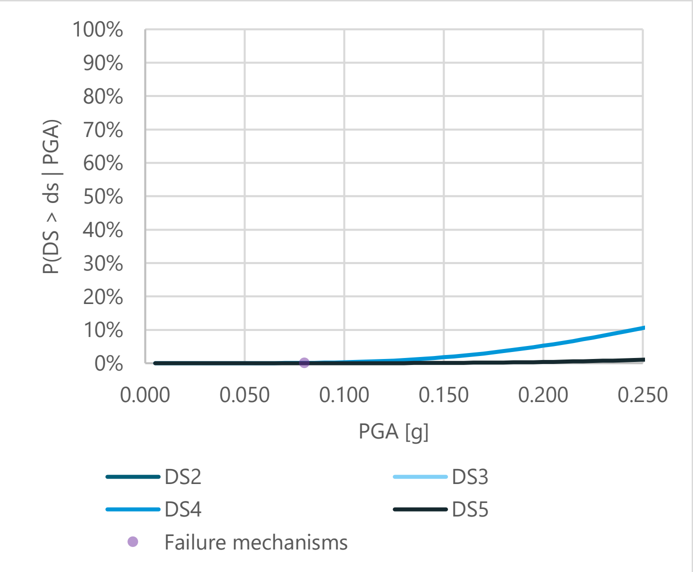
Fragility curves

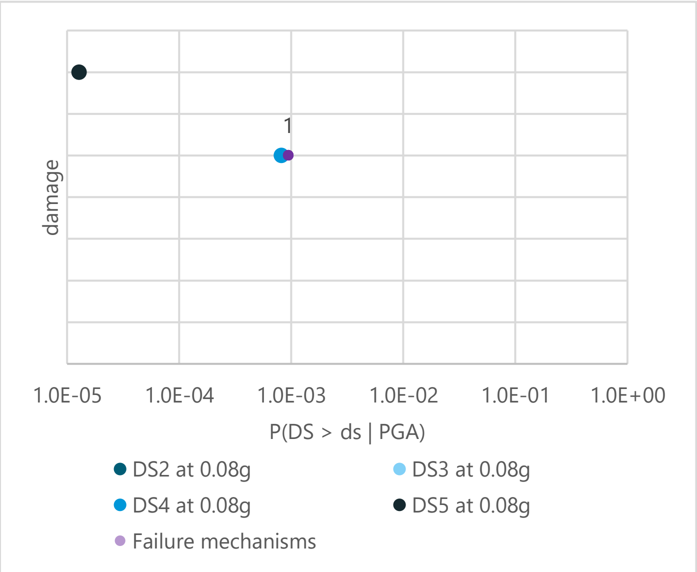
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4	0.53	0.60	8.12E-04	0.50
DS5	1.00	0.60	1.28E-05	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding pipe	0.92	0.05	1.00	DS4	3.11	9.39E-04
2							
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 12	
object name:	Pipeline B	
location:	Delfzijl	
peak ground acceleration:	0.060	[g]

Typology

label:	EP-SELF
typology:	Elevated pipe, unanchored

CALCULATION

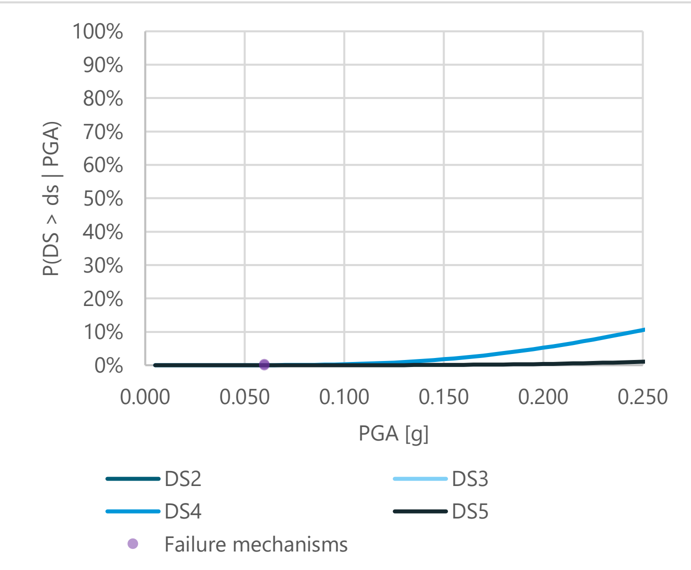
Fragility curves

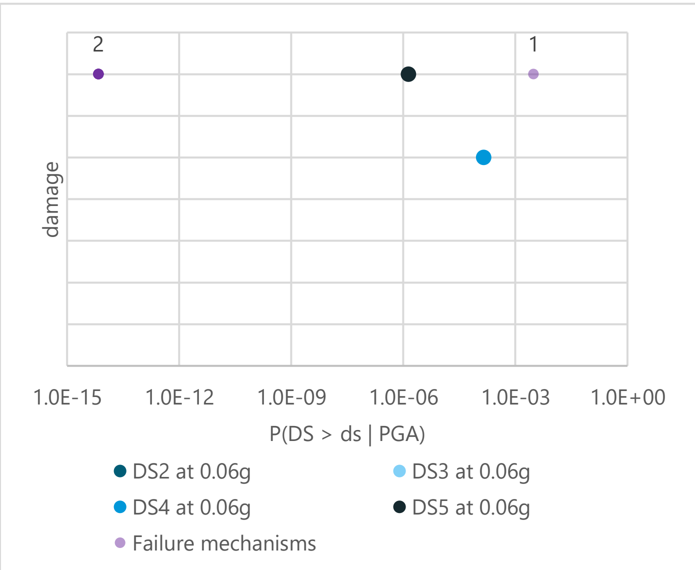
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4	0.53	0.60	1.41E-04	0.50
DS5	1.00	0.60	1.37E-06	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	yielding steel pipeline	0.94	0.05	1.00	DS5	2.74	3.06E-03
2	failure of connection pipeline-tank	0.67	0.05	1.00	DS5	7.70	6.87E-15
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





Witteveen + Bos	project:	Selectiemethodiek Industrie Stap 2	spreadsheet FRAGILITY CURVES	version 0.1
	projectcode:	124217		
	part:	Verification fragility curves	format by:	J. de Bruijn MSc
	description:		date of format:	10-11-2021

VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name:	Company 13	
object name:	Pipeline D	
location:	Delfzijl	
peak ground acceleration:	0.069	[g]

Typology

label:	EP-SELF
typology:	Elevated pipe, unanchored

CALCULATION

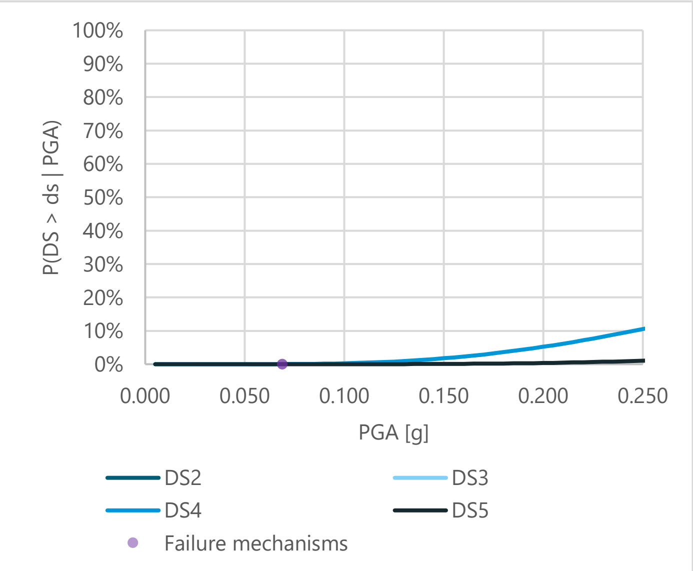
Fragility curves

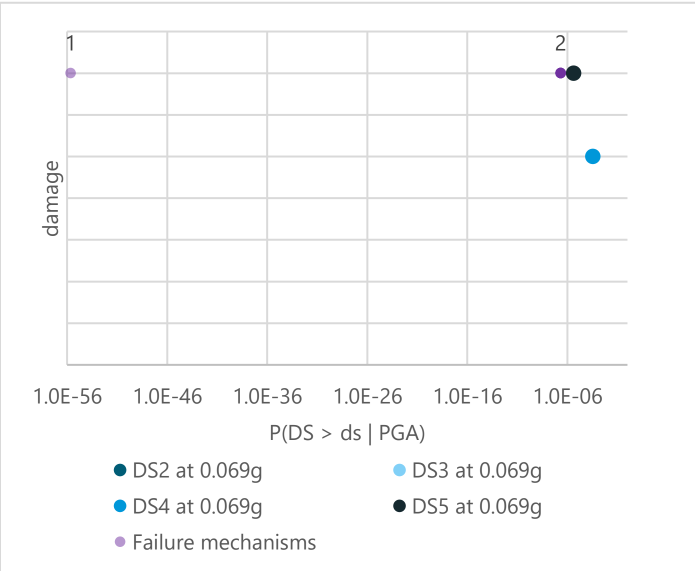
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4	0.53	0.60	3.39E-04	0.50
DS5	1.00	0.60	4.17E-06	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure chloride pipeline	0.23	0.05	1.00	DS5	15.78	2.23E-56
2	failure CPVC pipeline	0.64	0.15	2.00	DS5	5.06	2.12E-07
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 13
object name: Pipeline E
location: Delfzijl
peak ground acceleration: 0.069 [g]

Typology

label: EP-SELF
typology: Elevated pipe, unanchored

CALCULATION

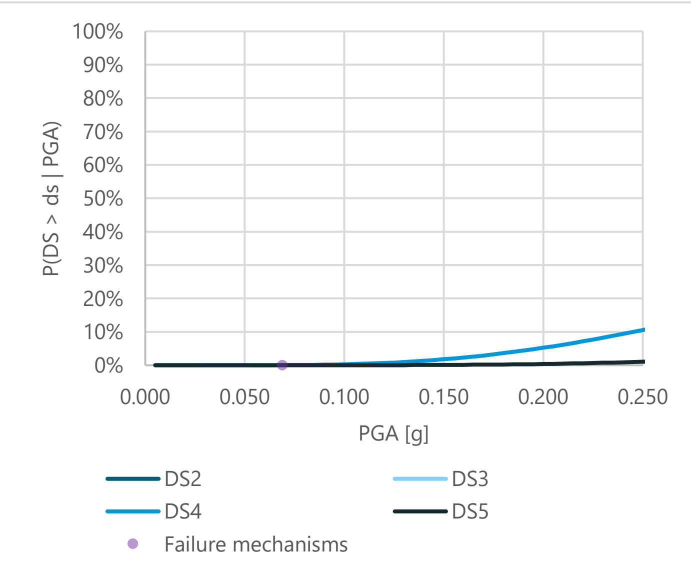
Fragility curves

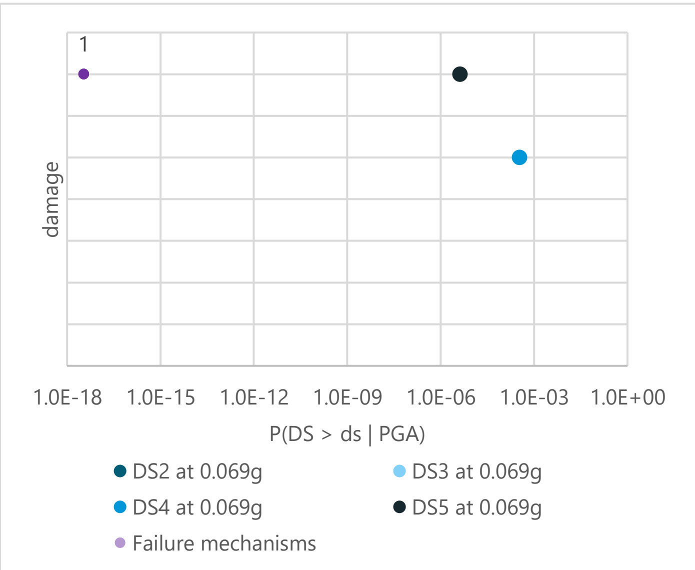
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4	0.53	0.60	3.39E-04	0.50
DS5	1.00	0.60	4.17E-06	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure pipelines	0.62	0.05	1.00	DS5	8.62	3.44E-18
2							
3							
4							
5							
6							
7							
8							
9							
10							

RESULTS





VERIFICATION FRAGILITY CURVES

Verification of fragility curves based on phase 2 calculation reports.

INPUT

General

project name: Company 14
object name: Pipeline F
location: Eemshaven
peak ground acceleration: 0.032 [g]

Typology

label: EP-SELF
typology: Elevated pipe, unanchored

CALCULATION

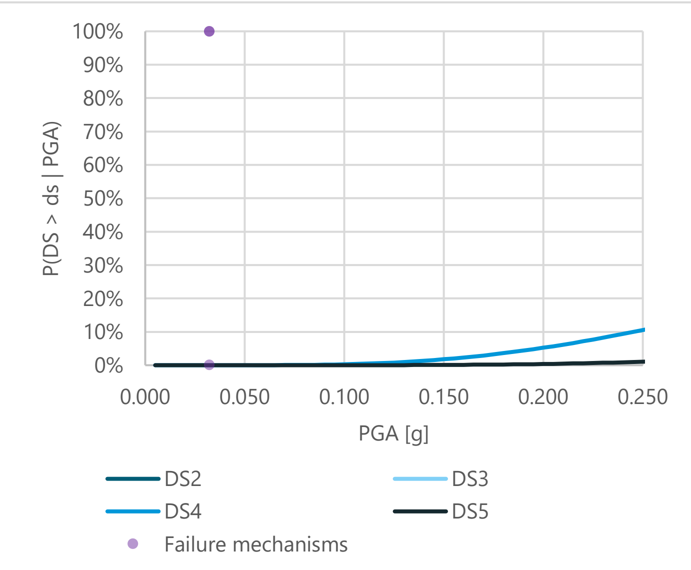
Fragility curves

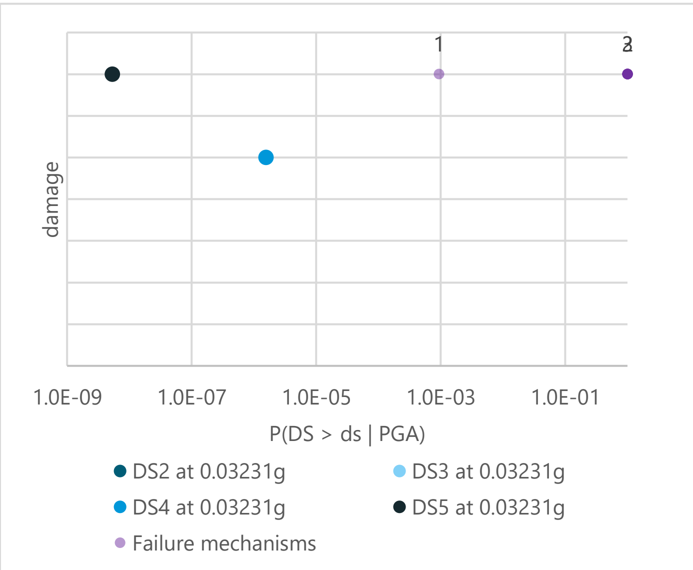
Damage state	Median	Dispersion	P(DS|PGA)	DS value
DS2				0.10
DS3				0.30
DS4	0.53	0.60	1.56E-06	0.50
DS5	1.00	0.60	5.31E-09	0.70

Failure mechanisms

No.	Mechanism	UC	VC	gamma	DS	beta	Pf
1	failure pipeline	0.92	0.05	1.00	DS5	3.11	9.39E-04
2	failure of flanges in pipeline	2.18	0.05	1.00	DS5	-20.02	1.00E+00
3	failure of nozzles	2.96	0.05	1.00	DS5	-34.35	1.00E+00
4							
5							
6							
7							
8							
9							
10							

RESULTS





III

APPENDIX: EXPORT REPORTS FROM TOOL FOR PILOT CALCULATIONS

Selection method Step 2 - based on fragility functions

Analysis results

Company under review (Client):	Company A
Installation(s) under review:	Objects 1, 2 and 3
Engineering consulting company:	Witteveen+Bos
Engineering consultant:	A. Bougioukos
Date:	1-12-2021

Company Logo

CONTENTS

1 ABSTRACT

This report consists the export report of the Selection method Step 2 tool and it has been generated in the context of the pilot calculations. It includes:

- all the information that have been input in the Selection method Step 2 tool and
- the output of the calculations,

for the pilot calculations performed for the industrial company A, for the objects 1, 2 and 3.

The calculations have been performed for two different time windows, from past hazard and future hazard:

- T4 (1-10-2020 t/m 30-09-2021
- T6 (1-10-2023 t/m 30-09-2029

This is done in order to investigate the impact of the seismic hazard on the final outcome.

2 INTRODUCTION

Industrial companies in Groningen conduct engineering reviews on their industrial plants containing hazardous substances to assure earthquake proof designs as a consequence of gas production in Groningen. A specific prescribed assessment framework is in place.

In order to decrease (unnecessary) time consuming calculations for the earthquake resistance of (process) installations with hazardous substances, two selection steps can be performed between the phase 1 qualitative assessment and the phase 2 quantitative assessments.
The selection between these 2 phases consists of the following two steps:

1) With the selection method step 1, process installations identified in phase 1 are uniformly further tested for safety risk
2) For the remaining objects, this selection method step 2 a quickscan with software can be performed to identify whether an installation is globally sufficiently earthquake-resistant for identified scenarios:

- The earthquake load follows from global hazard curves (earthquake threat), which can also include developments such as the phasing out of gas production;
- The probability of exceeding a limit state is tested on the basis of available fragility curves and the probabilistic earthquake threat (the hazard curve).

The selection process ultimately results in a list of objects which no longer require further investigation, and for which objects is to be continued in phase 2 (the quantitative risk analysis). The selection instruments are included in the Groningen earthquake-resistant industry compensation policy rule.

This report provides the output of the so-called 'Selection method Step 2 - based on fragility functions' (NL: 'Selectie methodiek Industrie Stap 2 - op basis van fragility functions') to document the results. The methodology of the tool has been developed by Witteveen+Bos, and has been reviewed by TU Delft. The development has been initiated and facilitated by Nationaal Coördinator Groningen.

Chapter 3 presents an overview of all examined object scenarios. Chapter 4 presents all the input information filled in by the engineering consultant in the tool and the outcome per object scenario. Both chapters are automatically generated, and no action is required from the engineering consultant. In chapters 5 and 6, a summary of the results, and conclusions and recommendations shall be added to this report by the engineering consultant.

3 OVERVIEW OF ALL OBJECT SCENARIOS

This chapter presents an overview of all examined object scenario. All the object scenarios are summarized on the selected risk matrices. In case a custom risk matrix has been selected by the engineering consultant / industrial company, the results are presented not only for the custom risk matrix but also for the SIL risk matrix. This is done in order to maintain consistency among different industrial companies.

Table 1 Overview of all object scenarios

object (tag)	scenario (tag)	severity effect	exposure class
Ob1	Sc1T4	Catastrophic	Public
Ob2	Sc1T4	Catastrophic	Public
Ob3	Sc1T4	Catastrophic	Public
Ob1	Sc1T6	Catastrophic	Public
Ob2	Sc1T6	Catastrophic	Public
Ob3	Sc1T6	Catastrophic	Public

Table 2 Overview descriptions severity effect (labels x-axes risk matrices)

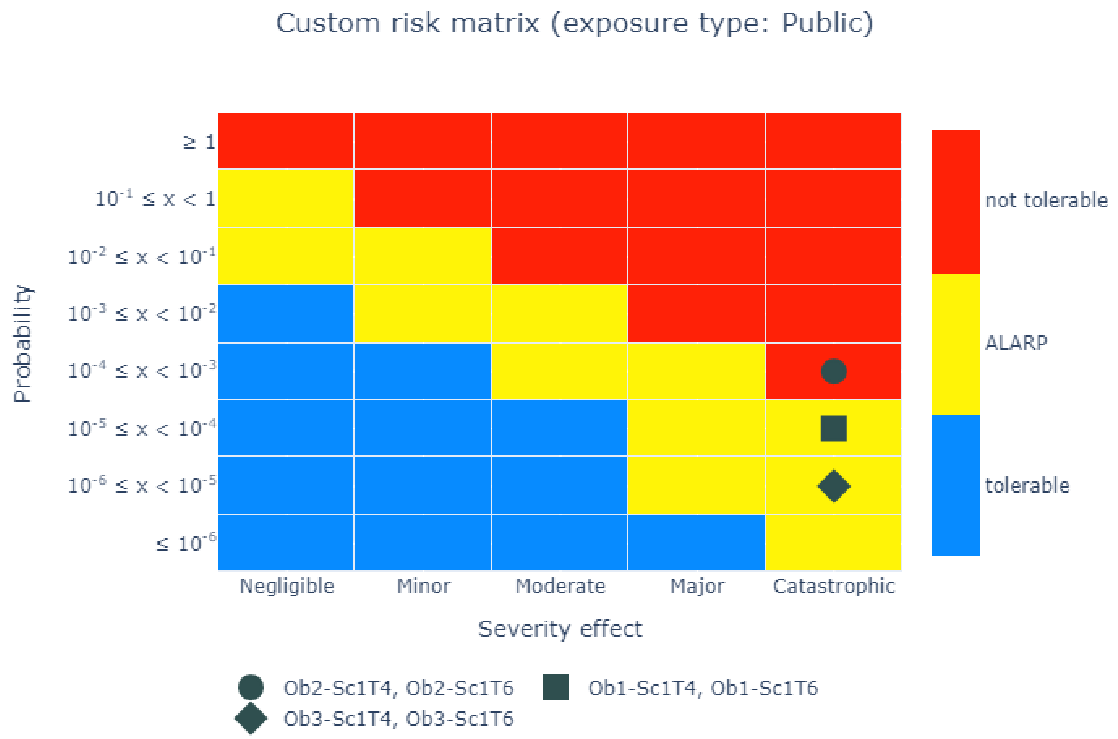
Severity effect	description safety effect	description environmental effect
Negligible	EHBO geval	Morsing
Minor	Rapporteerbaar ongeval (MT, RWC, LTI zonder ziekenhuis opname)	Vrijkomen chemische stof binnen site/eenvoudig op te ruimen
Moderate	Ernstig gewonde (LTI met ziekenhuisopname)	Vrijkomen chemische stof buiten het terrein, dan wel binnen het terrein met langdurige opruimacties, overtreding vergunningsvoorwaarden
Major	1 dode op site / meerdere gewonden	Vrijkomen chemische stof buiten het terrein, langdurige opruimacties
Catastrophic	1 dode buiten de site / meerdere doden op site	Catastrofale schade in de omgeving

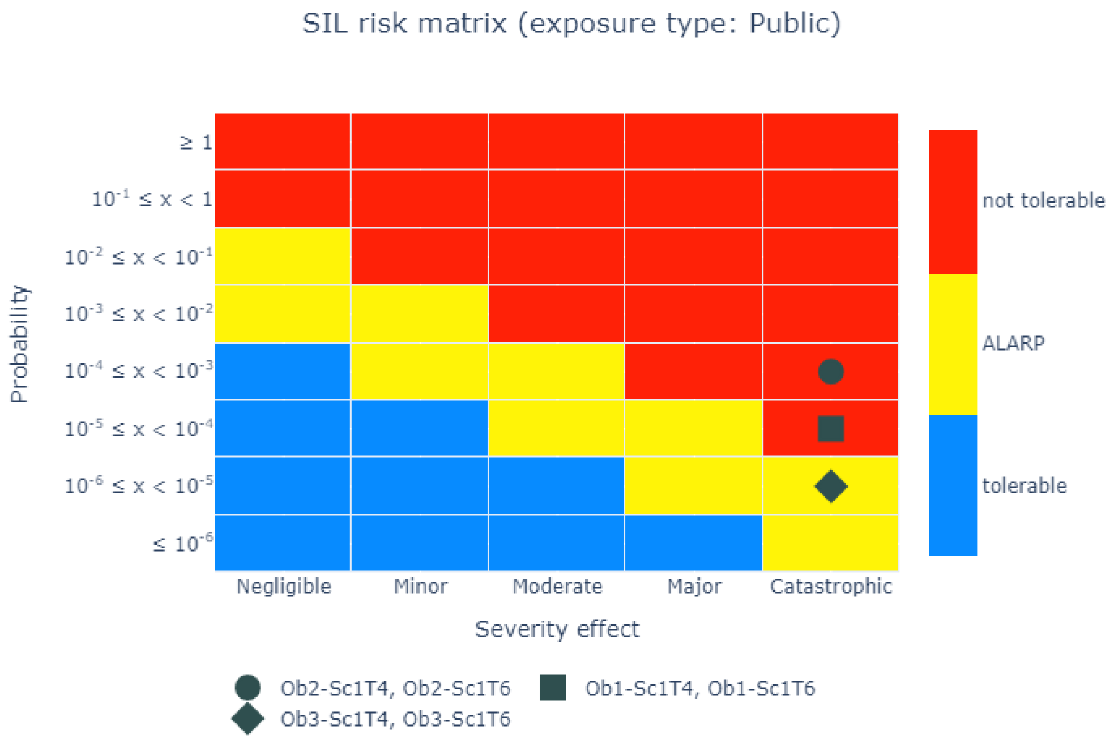
Table 3 Overview SIL descriptions severity effect

Severity effect	description safety effect	description environmental effect
Negligible	Minor injury ("first aid")	Marginal emission and/or damage within site boundary (< 1 ha)
Minor	Serious injury ("staying at home")	Minor emission and/or damage within site boundary (> 1 ha)
Moderate	Major injury ("hospital") or multiple serious injuries	Emission and/or damage within site boundary. No permanent damage to surrounding environment (> 10 ha)
Major	1-2 fatal injuries or permanent disability	Emission and/or damage to surrounding environment (> 100 ha)
Catastrophic	>2 fatal injuries	Major emission and/or damage to surrounding environment (> 1000 ha)

Risk matrices

Public risk matrix





Onsite risk matrix

Risk matrix (exposure type: Onsite) is not available

4 INPUT/OUTPUT PER OBJECT SCENARIO

In this chapter all input values in the tool and choices made by the engineering consultant per object scenario are presented. At the end of each paragraph the outcome is presented on the selected risk matrix and a recommendation regarding further assessment of the foundation is given.

4.1 Object scenario Ob1 - Sc1T4

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T4 (1-10-2020 t/m 30-9-2021)*

Object and scenario input

Object tag: *Ob1*
Object description: *Chloorleidingbrug, Steel braced frame 1-3 stories*

Scenario tag: *Sc1T4*
Scenario description: *LoC: Breuk / instantaan falen, T4, company-specific RM*

Foundation
Type foundation: *pile*

Select severity effect category
Severity effect category: *Catastrophic*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

Exposure class
Exposure class: *Public*

Select object typology from literature
Object typology: *Steel braced frame, low rise, 1-3 stories (typical height 7.3 m)*

Damage state and fragility

Select damage state
Minimum damage state: *DS5*

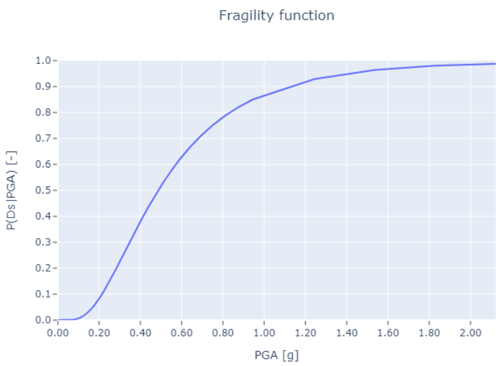
Descriptions damage state

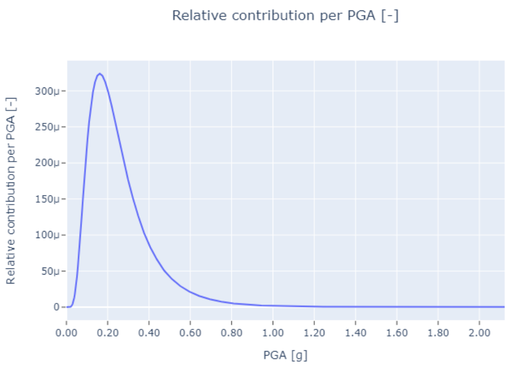
Minimum Damage State	Description
DS2	A few steel braces have yielded, which may be indicated by minor stretching and/or buckling of slender brace members; minor cracks in welded connections; minor deformations in bolted brace connections.
DS3	Some steel braces have yielded, exhibiting observable stretching and/or buckling of braces; a few braces, other members or connections have indications of reaching their ultimate capacity, exhibited by buckled braces, cracked welds, or failed bolted connections.
DS4	Most steel brace and other members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some structural members or connections have exceeded their ultimate capacity, exhibited by buckled or broken braces, flange buckling, broken welds, or failed bolted connections. Anchor bolts at columns may be stretched. Partial collapse of portions of the structure is possible due to failure of critical elements or connections.
DS5	Most of the structural elements have reached their ultimate capacities or some critical members or connections have failed, resulting in dangerous permanent lateral deflection, partial collapse or collapse of the building.

Explanation

Explanation for chosen object typology or threshold (if applicable):
Steel frame around 9 m tall
Explanation for selected damage state in relation to this scenario:
LoC instant failure. Refer to phase 1 report pg.141

Median of fragility function:	*0.486*
Dispersion of fragility function:	*0.64*
Probability of damage state exceedance:	*8.62e-05*





Selection of obligatory conditional factors

Conditional factor person(s) presence: *1*
Label: *Permanent (24/7 people presence)*

Conditional factor safe shutdown LoD: *0.1*
Label: *Safe shutdown*

Explanation for chosen conditional factor safe shutdown LoD: *According to representative(s) of industial company there is safe shut-down system*

Conditional factor construction state: *0.5*
Label: *Good*

Explanation for chosen conditional factor construction state: *According to representative(s) of industial company a good construction state is maintained.*

Optional conditional factors

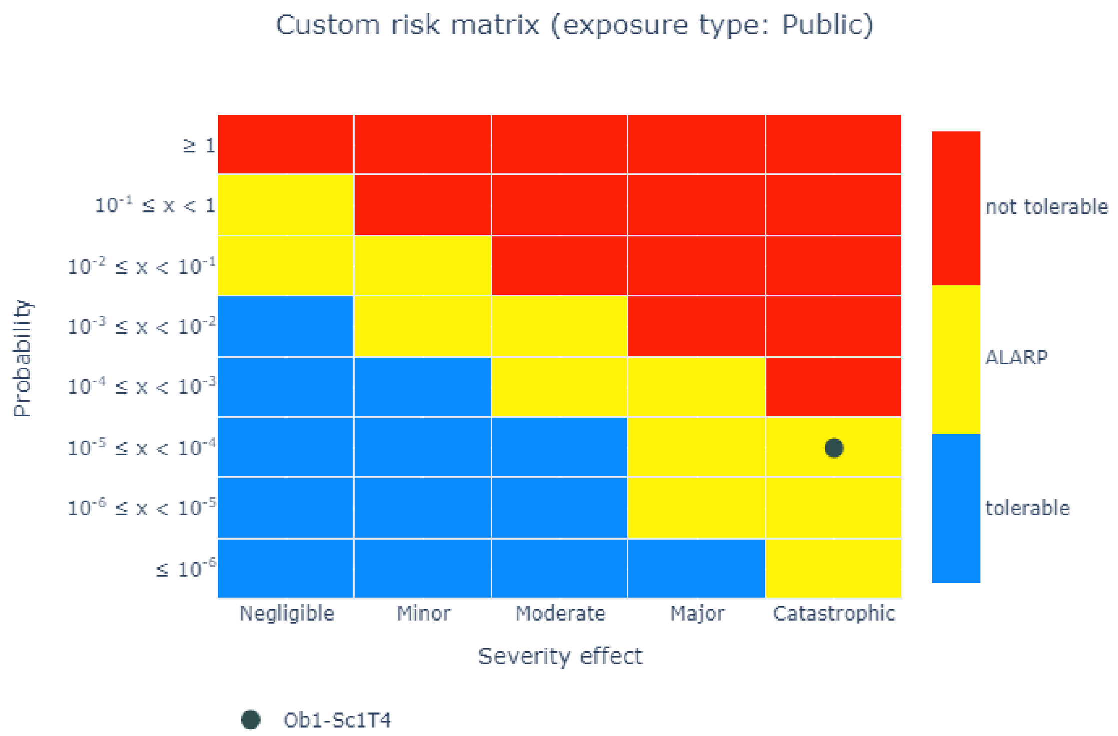
Conditional factor common cause: *22*
Explanation for conditional factor common cause: *According to phase 1 report there is a probability of pounding due to collapse of neighboring section. In this pilot the neighboring section is assessed as non-structural component with a damage state probability of 3.049e-04.The conditional probability of impact due to collapse of neighboring is 0.3 according to phase 1 report. Therefore the total probability of damaging the chloorleiding is 0.3 * 3.049E-04 = 9.147E-5. Therefore the conditional factor that is used here is: (9.147E-5 + 4.311E-06) / 4.311E-06 = 22*

Scenario representation in Risk Matrix

The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object: *Chloorleidingbrug, Steel braced frame 1-3 stories (Ob1)*

Scenario:	*LoC: Breuk / instantaan falen, T4, company-specific RM (Sc1T4)*
Risk matrix selection:	*Public*
The calculated scenario probability is:	*9.484e-05*
The scenario likelihood category is:	*1e-5 ≤ x < 1e-4*
The scenario severity category is:	*Catastrophic*



For the seismic hazard level at the location according to NPR 9998:2020 risks associated with loss of bearing capacity of piles cannot be neglected and both STR and GEO limit state assessment is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

4.2 Object scenario Ob2 - Sc1T4

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T4 (1-10-2020 t/m 30-9-2021)*

Object and scenario input

Object tag: *Ob2*
Object description: *Chloor related installations, Non-structural components in structure*

Scenario tag: *Sc1T4*
Scenario description: *LoC: Breuk / instantaan falen, T4, company specific RM*

Foundation
Type foundation: *pile*

Select severity effect category
Severity effect category: *Catastrophic*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

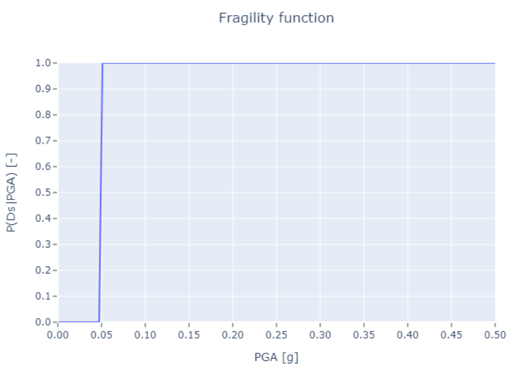
Exposure class
Exposure class: *Public*

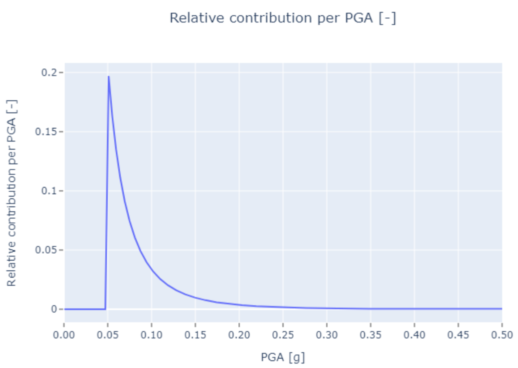
Select object typology from literature
Object typology: *Non-structural components in structure (weak supports)*

Damage state and fragility

Explanation
Explanation for chosen object typology or threshold (if applicable):
Ob2 consists a non-structural component where on support is slip support,. Thus, weak support.
Explanation for selected damage state in relation to this scenario:
There is only one damage state for this fragility curve that leads to total failure

Median of fragility function:	*0.05*
Dispersion of fragility function:	*0.0*
Probability of damage state exceedance:	*6.10e-03*





Selection of obligatory conditional factors

Conditional factor person(s) presence: *1*
Label: *Permanent (24/7 people presence)*

Conditional factor safe shutdown LoD: *0.1*
Label: *Safe shutdown*

Explanation for chosen conditional factor safe shutdown LoD: *According to representative(s) of industrial company there is safe shut-down system*

Conditional factor construction state: *0.5*
Label: *Good*

Explanation for chosen conditional factor construction state: *According to representative(s) of industrial company a good construction state is maintained.*

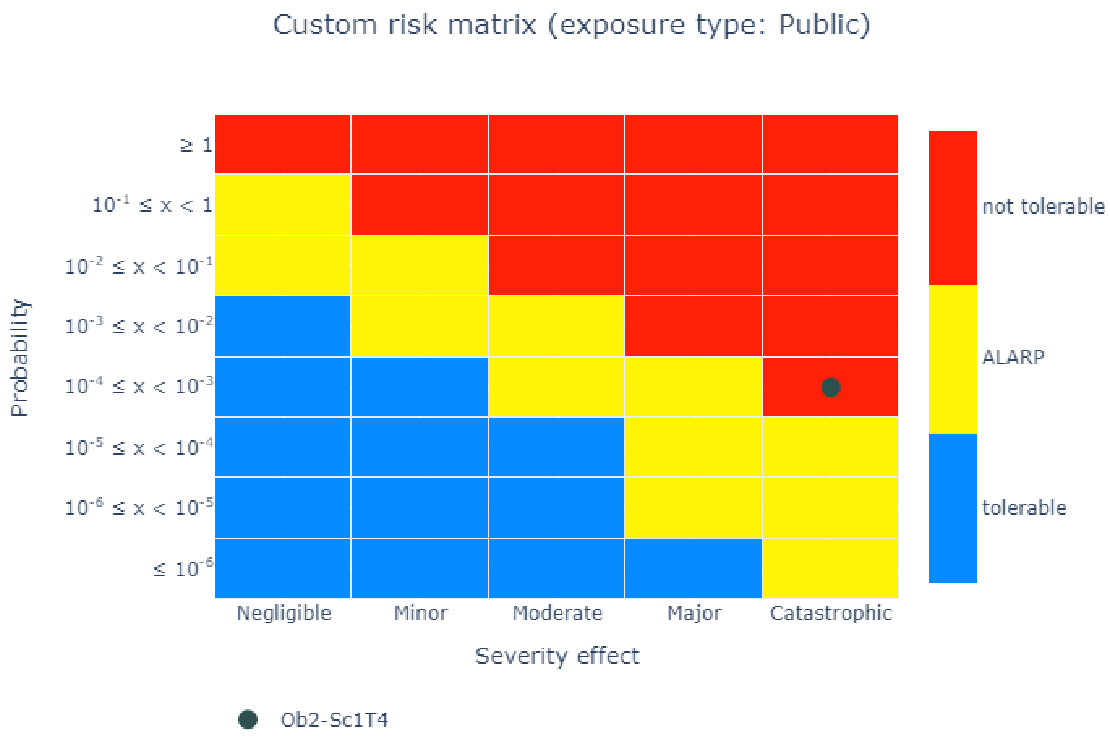
Optional conditional factors

No optional redundancies were specified.

Scenario representation in Risk Matrix

The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object:	*Chloor related instalations, Non-structural components in structure (Ob2)*
Scenario:	*LoC: Breuk / instantaan falen, T4, company specific RM (Sc1T4)*
Risk matrix selection:	*Public*
The calculated scenario probability is:	*3.049e-04*
The scenario likelihood category is:	*1e-4 ≤ x < 1e-3*
The scenario severity category is:	*Catastrophic*



For the seismic hazard level at the location according to NPR 9998:2020 risks associated with loss of bearing capacity of piles cannot be neglected and both STR and GEO limit state assessment is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of

foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

4.3 Object scenario Ob3 - Sc1T4

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T4 (1-10-2020 t/m 30-9-2021)*

Object and scenario input

Object tag: *Ob3*
Object description: *Concrete moment frame, low rise, 1-3 stories*

Scenario tag: *Sc1T4*
Scenario description: *LoC: Breuk / instantaan falen, T4, company specific RM*

Foundation

Type foundation: *pile*

Select severity effect category

Severity effect category: *Catastrophic*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

Exposure class

Exposure class: *Public*

Select object typology from literature

Object typology: *Concrete moment frame, low rise, 1-3 stories (typical height 7.3 m)*

Damage state and fragility

Select damage state

Minimum damage state: *DS5*

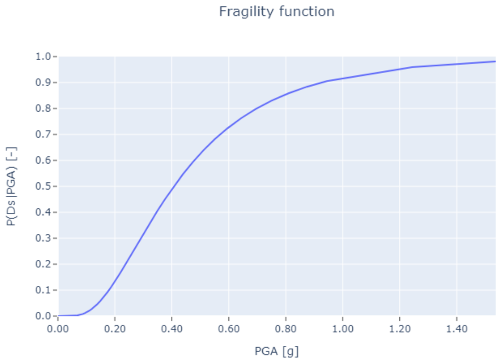
Descriptions damage state

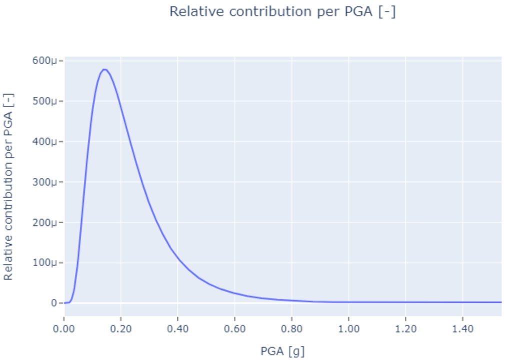
Minimum Damage State	Description
DS2	Flexural or shear type hairline cracks in some beams and columns near joints or within joints.
DS3	Most beams and columns exhibit hairline cracks. In ductile frames, some of the frame elements have reached yield capacity, as indicated by larger flexural cracks and some concrete spalling. Nonductile frames may exhibit larger shear cracks and spalling.
DS4	Some of the frame elements have reached their ultimate capacity, as indicated in ductile frames by large flexural cracks, spalled concrete, and buckled main reinforcement; nonductile frame elements may have suffered shear failures or bond failures at reinforcement splices, broken ties or buckled main reinforcement in columns which may result in partial collapse.
DS5	Structure is collapsed or in imminent danger of collapse due to brittle failure of nonductile frame elements or loss of frame stability.

Explanation

Explanation for chosen object typology or threshold (if applicable):
Concrete moment frame of around 4m tall
Explanation for selected damage state in relation to this scenario:
LoC instant failure. Refer to phase 1 report pg.145

Median of fragility function:	*0.407*
Dispersion of fragility function:	*0.64*
Probability of damage state exceedance:	*1.39e-04*





Selection of obligatory conditional factors

Conditional factor person(s) presence: *1*
Label: *Permanent (24/7 people presence)*

Conditional factor safe shutdown LoD: *0.1*
Label: *Safe shutdown*

Explanation for chosen conditional factor safe shutdown LoD: *According to representative(s) of industrial company there is safe shut-down system*

Conditional factor construction state: *0.5*
Label: *Good*

Explanation for chosen conditional factor construction state: *According to representative(s) of industrial company a good construction state is maintained.*

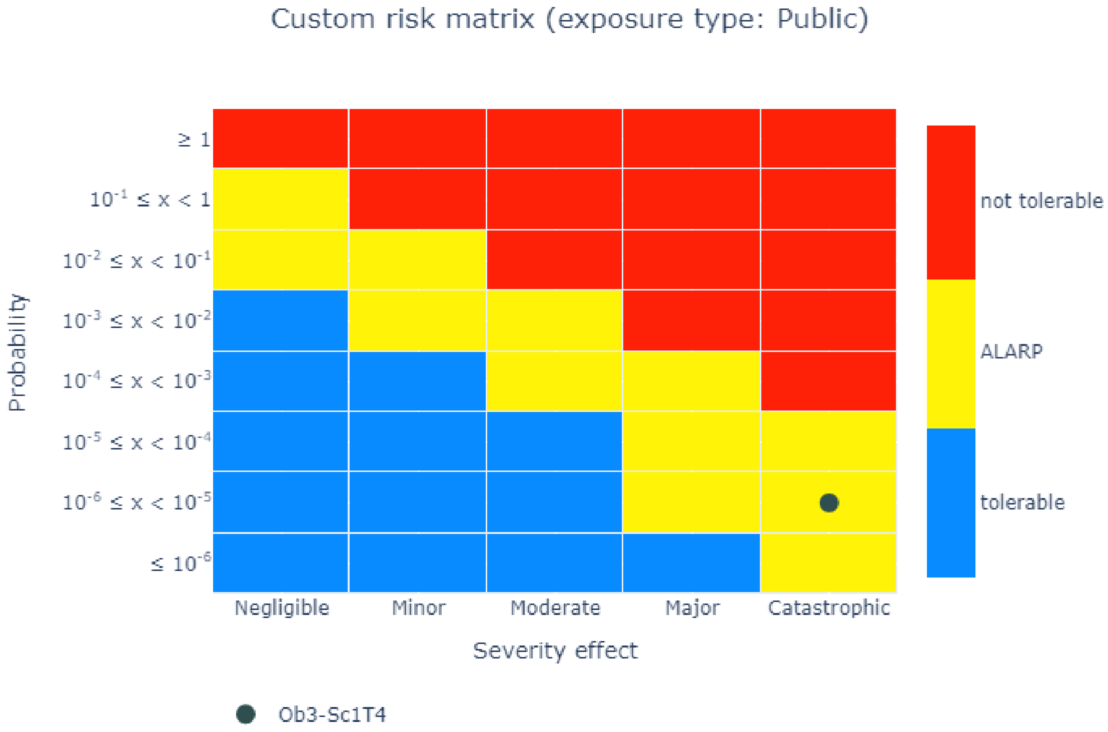
Optional conditional factors

No optional redundancies were specified.

Scenario representation in Risk Matrix

The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object:	*Concrete moment frame, low rise, 1-3 stories (Ob3)*
Scenario:	*LoC: Breuk / instantaan falen, T4, company specific RM (Sc1T4)*
Risk matrix selection:	*Public*
The calculated scenario probability is:	*6.948e-06*
The scenario likelihood category is:	*1e-6 ≤ x < 1e-5*
The scenario severity category is:	*Catastrophic*



For the seismic hazard level at the location according to NPR 9998:2020 risks associated with loss of bearing capacity of piles cannot be neglected and both STR and GEO limit state assessment is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

4.4 Object scenario Ob1 - Sc1T6

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T6 (1-10-2023 t/m 30-9-2029)*

Object and scenario input

Object tag: *Ob1*
Object description: *Chloorleidingbrug, Steel braced frame 1-3 stories*

Scenario tag: *Sc1T6*
Scenario description: *LoC: Breuk / instantaan falen, T6, company specific RM*

Foundation

Type foundation: *pile*

Select severity effect category

Severity effect category: *Catastrophic*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

Exposure class

Exposure class: *Public*

Select object typology from literature

Object typology: *Steel braced frame, low rise, 1-3 stories (typical height 7.3 m)*

Damage state and fragility

Select damage state

Minimum damage state: *DS5*

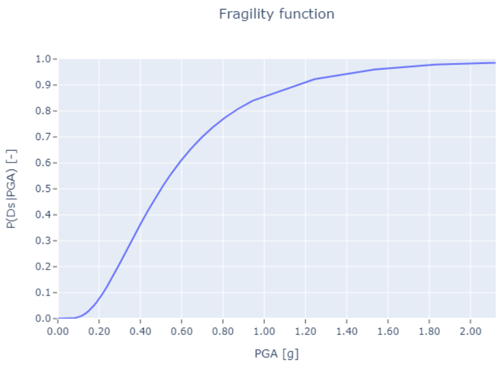
Descriptions damage state

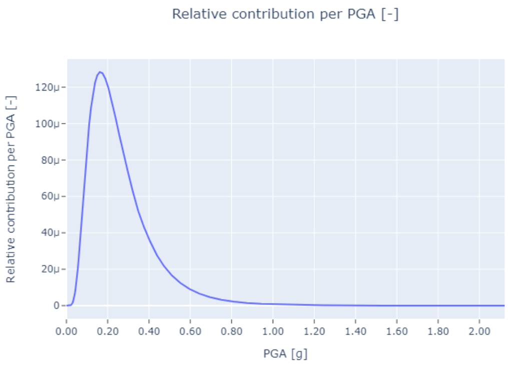
Minimum Damage State	Description
DS2	A few steel braces have yielded, which may be indicated by minor stretching and/or buckling of slender brace members; minor cracks in welded connections; minor deformations in bolted brace connections.
DS3	Some steel braces have yielded, exhibiting observable stretching and/or buckling of braces; a few braces, other members or connections have indications of reaching their ultimate capacity, exhibited by buckled braces, cracked welds, or failed bolted connections.
DS4	Most steel brace and other members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some structural members or connections have exceeded their ultimate capacity, exhibited by buckled or broken braces, flange buckling, broken welds, or failed bolted connections. Anchor bolts at columns may be stretched. Partial collapse of portions of the structure is possible due to failure of critical elements or connections.
DS5	Most of the structural elements have reached their ultimate capacities or some critical members or connections have failed, resulting in dangerous permanent lateral deflection, partial collapse or collapse of the building.

Explanation

Explanation for chosen object typology or threshold (if applicable):
Steel frame around 9 m tall
Explanation for selected damage state in relation to this scenario:
LoC instant failure. Refer to phase 1 report pg.141

Median of fragility function: *0.5*
Dispersion of fragility function: *0.64*
Probability of damage state exceedance: *3.48e-05*





Selection of obligatory conditional factors
Conditional factor person(s) presence: *1*
Label: *Permanent (24/7 people presence)*

Conditional factor safe shutdown LoD: *0.1*
Label: *Safe shutdown*

Explanation for chosen conditional factor safe shutdown LoD: *According to representative(s) of industrial company there is safe shut-down system*

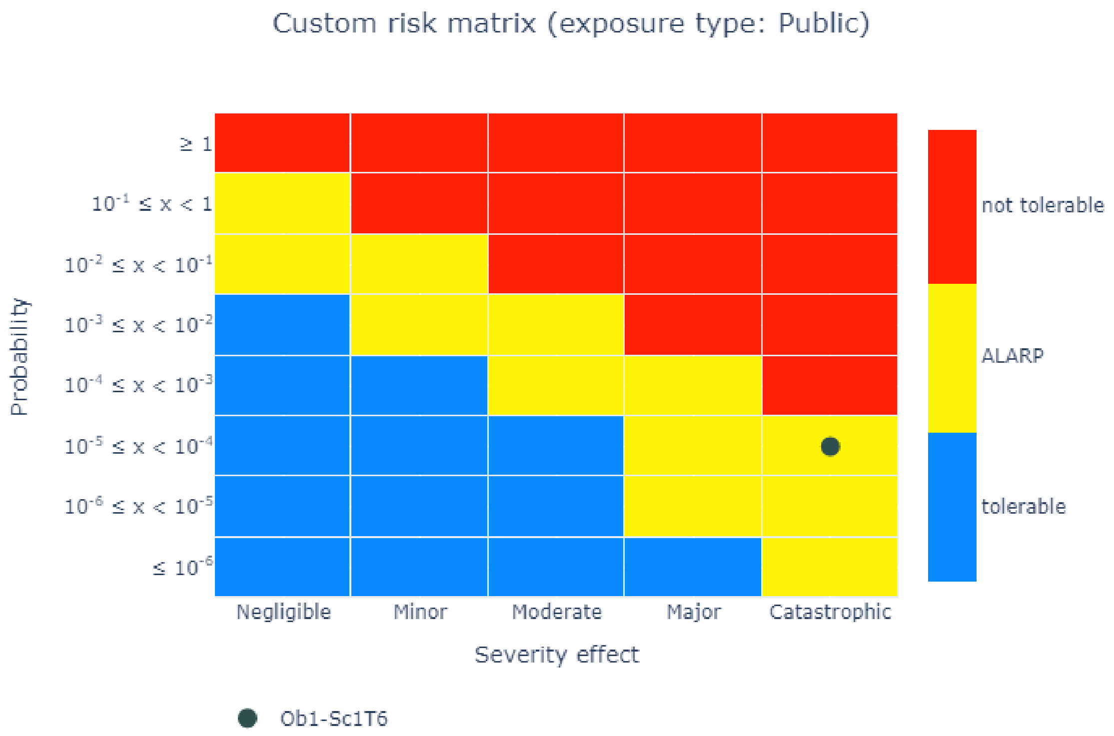
Conditional factor construction state: *0.5*
Label: *Good*

Explanation for chosen conditional factor construction state: *According to representative(s) of industrial company a good construction state is maintained.*

Optional conditional factors
Conditional factor common cause: *22*
Explanation for conditional factor common cause: *According to phase 1 report there is a probability of pounding due to collapse of neighboring section. In this pilot the neighboring section is assessed as non-structural component with a damage state probability of 3.049e-04.The conditional probability of impact due to collapse of neighboring is 0.3 according to phase 1 report. Therefore the total probability of damaging the chloorleiding is 0.3 * 3.049E-04 = 9.147E-5. Therefore the conditional factor that is used here is: (9.147E-5 + 4.311E-06) / 4.311E-06 = 22*

Scenario representation in Risk Matrix
The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object: *Chloorleidingbrug, Steel braced frame 1-3 stories (Ob1)*
Scenario: *LoC: Breuk / instantaan falen, T6, company specific RM (Sc1T6)*
Risk matrix selection: *Public*
The calculated scenario probability is: *3.830e-05*
The scenario likelihood category is: *1e-5 ≤ x < 1e-4*
The scenario severity category is: *Catastrophic*



The risk of loss of bearing capacity due to structural damage of piles is sufficiently low for the seismic hazard level that applies to the location. Only a GEO limit state assessment (liquefaction verification) is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

4.5 Object scenario Ob2 - Sc1T6

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T6 (1-10-2023 t/m 30-9-2029)*

Object and scenario input

Object tag: *Ob2*
Object description: *Chloor related instalations, Non-structural components in structure*

Scenario tag: *Sc1T6*
Scenario description: *LoC: Breuk / instantaan falen, T6, company specific RM*

Foundation
Type foundation: *pile*

Select severity effect category
Severity effect category: *Catastrophic*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

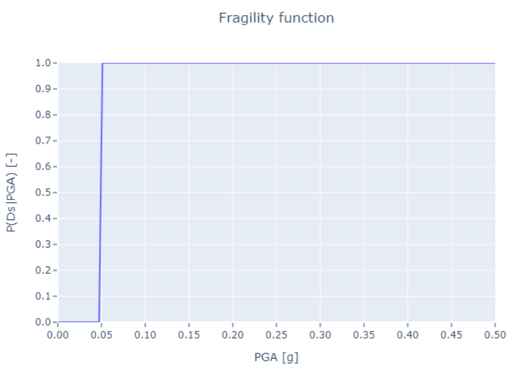
Exposure class
Exposure class: *Public*

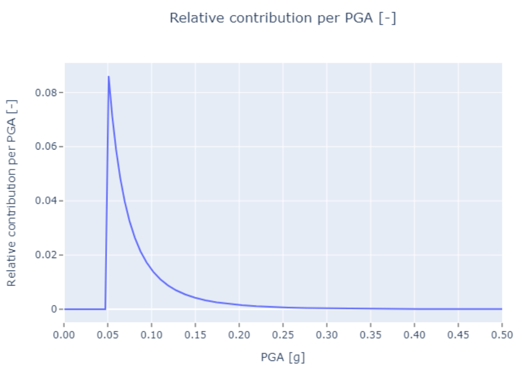
Select object typology from literature
Object typology: *Non-structural components in structure (weak supports)*

Damage state and fragility

Explanation
Explanation for chosen object typology or threshold (if applicable):
Ob2 consists a non-structural component where on support is slip support,. Thus, weak support.
Explanation for selected damage state in relation to this scenario:
There is only one damage state for this fragility curve that leads to total failure

Median of fragility function:	*0.05*
Dispersion of fragility function:	*0.0*
Probability of damage state exceedance:	*2.66e-03*





Selection of obligatory conditional factors

Conditional factor person(s) presence: *1*
Label: *Permanent (24/7 people presence)*

Conditional factor safe shutdown LoD: *0.1*
Label: *Safe shutdown*

Explanation for chosen conditional factor safe shutdown LoD: *According to representative(s) of industrial company there is safe shut-down system*

Conditional factor construction state: *0.5*
Label: *Good*

Explanation for chosen conditional factor construction state: *According to representative(s) of industrial company a good construction state is maintained.*

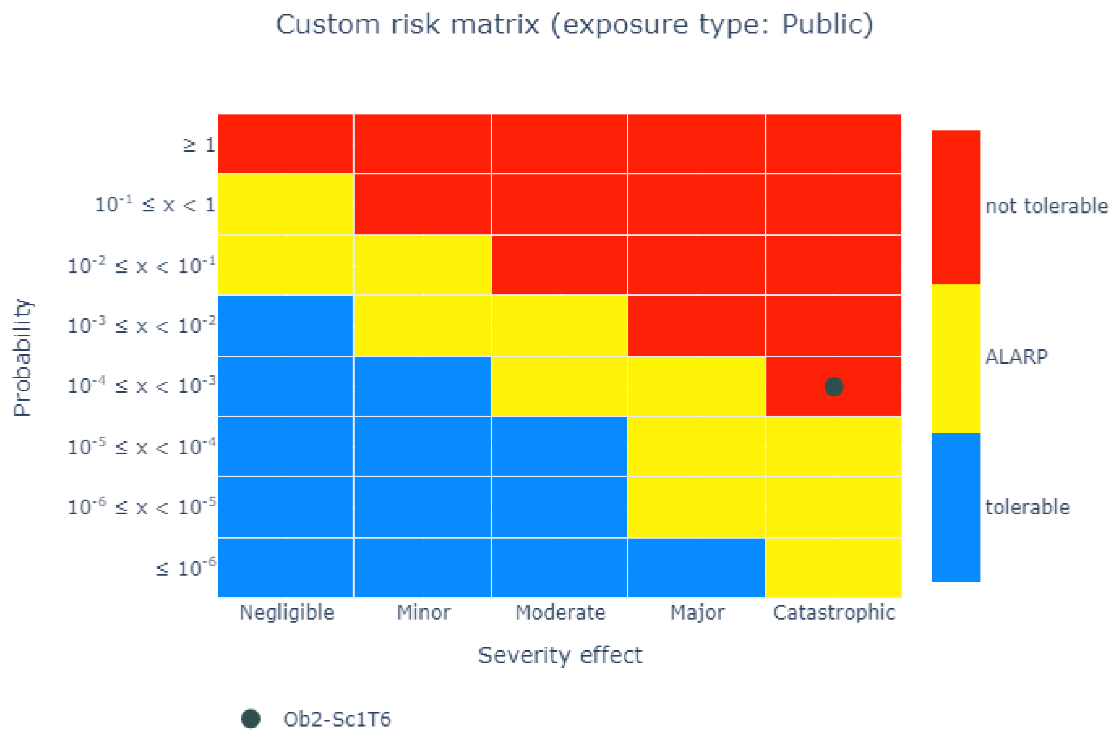
Optional conditional factors

No optional redundancies were specified.

Scenario representation in Risk Matrix

The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object: *Chloor related installations, Non-structural components in structure (Ob2)*
Scenario: *LoC: Breuk / instantaan falen, T6, company specific RM (Sc1T6)*
Risk matrix selection: *Public*
The calculated scenario probability is: *1.328e-04*
The scenario likelihood category is: *1e-4 ≤ x < 1e-3*
The scenario severity category is: *Catastrophic*



The risk of loss of bearing capacity due to structural damage of piles is sufficiently low for the seismic hazard level that applies to the location. Only a GEO limit state assessment (liquefaction verification) is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of

foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

4.6 Object scenario Ob3 - Sc1T6

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T6 (1-10-2023 t/m 30-9-2029)*

Object and scenario input

Object tag: *Ob3*
Object description: *Concrete moment frame, low rise, 1-3 stories*

Scenario tag: *Sc1T6*
Scenario description: *LoC: Breuk / instantaan falen, T6, company specific RM*

Foundation
Type foundation: *pile*

Select severity effect category
Severity effect category: *Catastrophic*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

Exposure class
Exposure class: *Public*

Select object typology from literature
Object typology: *Concrete moment frame, low rise, 1-3 stories (typical height 7.3 m)*

Damage state and fragility

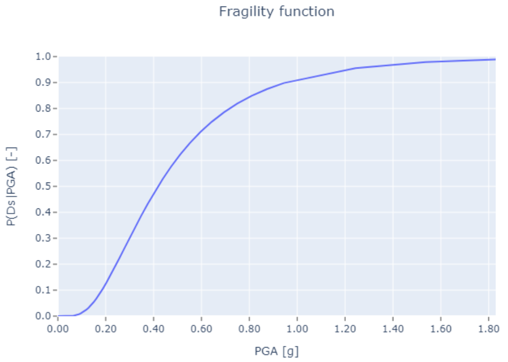
Select damage state
Minimum damage state: *DS5*

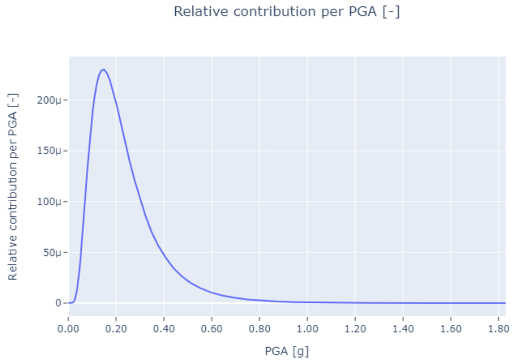
Descriptions damage state

Minimum Damage State	Description
DS2	Flexural or shear type hairline cracks in some beams and columns near joints or within joints.
DS3	Most beams and columns exhibit hairline cracks. In ductile frames, some of the frame elements have reached yield capacity, as indicated by larger flexural cracks and some concrete spalling. Nonductile frames may exhibit larger shear cracks and spalling.
DS4	Some of the frame elements have reached their ultimate capacity, as indicated in ductile frames by large flexural cracks, spalled concrete, and buckled main reinforcement; nonductile frame elements may have suffered shear failures or bond failures at reinforcement splices, broken ties or buckled main reinforcement in columns which may result in partial collapse.
DS5	Structure is collapsed or in imminent danger of collapse due to brittle failure of nonductile frame elements or loss of frame stability.

Explanation
Explanation for chosen object typology or threshold (if applicable):
Concrete moment frame of around 4m tall
Explanation for selected damage state in relation to this scenario:
LoC instant failure. Refer to phase 1 report pg.145

Median of fragility function:	*0.419*
Dispersion of fragility function:	*0.64*
Probability of damage state exceedance:	*5.63e-05*





Selection of obligatory conditional factors

Conditional factor person(s) presence: *1*
Label: *Permanent (24/7 people presence)*

Conditional factor safe shutdown LoD: *0.1*
Label: *Safe shutdown*

Explanation for chosen conditional factor safe shutdown LoD: *According to representative(s) of industrial company there is safe shut-down system*

Conditional factor construction state: *0.5*
Label: *Good*

Explanation for chosen conditional factor construction state: *According to representative(s) of industrial company a good construction state is maintained.*

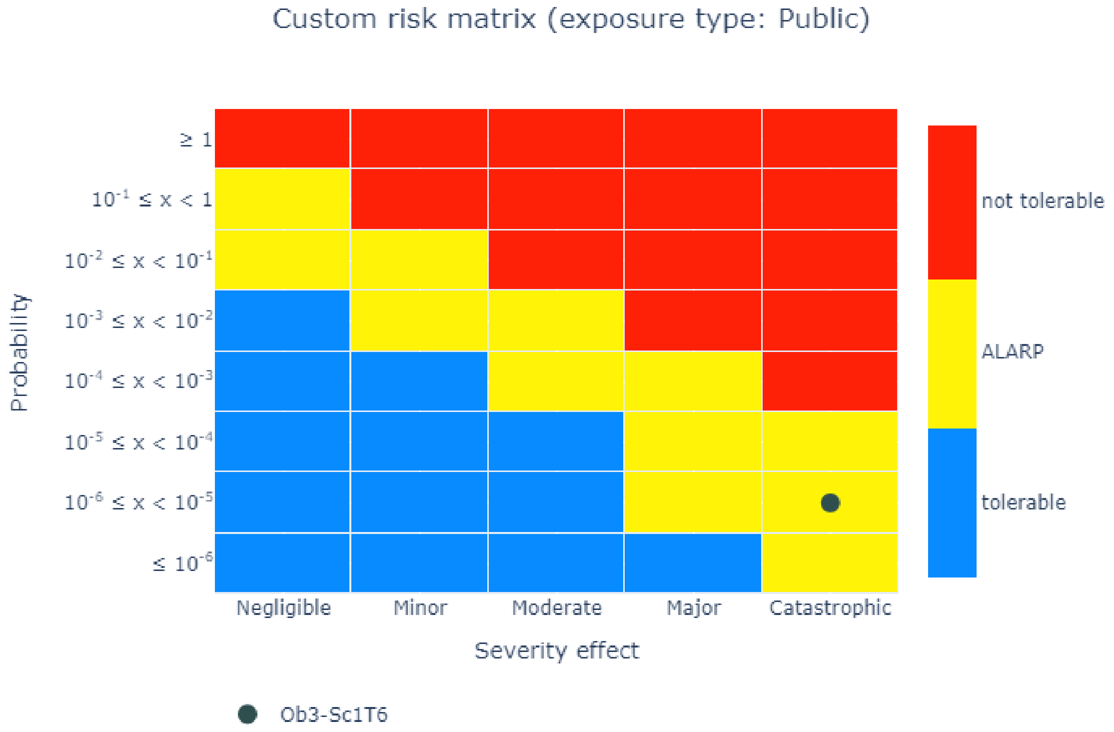
Optional conditional factors

No optional redundancies were specified.

Scenario representation in Risk Matrix

The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object:	*Concrete moment frame, low rise, 1-3 stories (Ob3)*
Scenario:	*LoC: Breuk / instantaan falen, T6, company specific RM (Sc1T6)*
Risk matrix selection:	*Public*
The calculated scenario probability is:	*2.814e-06*
The scenario likelihood category is:	*1e-6 ≤ x < 1e-5*
The scenario severity category is:	*Catastrophic*



The risk of loss of bearing capacity due to structural damage of piles is sufficiently low for the seismic hazard level that applies to the location. Only a GEO limit state assessment (liquefaction verification) is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

5 CONCLUSION

In this report we assess the criticality of 3 objects of the industrial company A with the selection method Step 2 tool, as part of pilot calculations. For all three objects a phase 2 assessment has been performed. The outcome of the phase 2 calculation reports is compared with the outcome of the Selection method Step 2 analysis.

The verdict of the phase 2 studies was that there is no LoC for objects 1 and 3 while there is LoC for object 2 with a maximum U.C. of around 4.0. The Selection method Step 2 analysis classifies object 2 in the red region and the other two objects in the yellow region of the company specific risk matrix. In the SIL risk matrix for public exposure objects 1 and two are classified in the red region while object 3 is classified in the yellow region. The fact that the object 3 is classified in a lower category in the risk matrix, is also in line with the phase 2 studies in which it turns up that object 3 had the lowest maxU.C. compared to the other two objects.

Selection method Step 2 - based on fragility functions

Analysis results

Company under review (Client):	Company B
Installation(s) under review:	Objects 4, 5 and 6
Engineering consulting company:	Witteveen+Bos
Engineering consultant:	A. Bougioukos
Date:	1-12-2021

Company Logo

CONTENTS

1 ABSTRACT

This report consists the export report of the Selection method Step 2 tool and it has been generated in the context of the pilot calculations. It includes:

- all the information that have been input in the Selection method Step 2 tool and
- the output of the calculations,

for the pilot calculations performed for the industrial company B, for the objects 4, 5 and 6.

The calculations have been performed for two different time windows, from past hazard and future hazard:

- T4 (1-10-2020 t/m 30-09-2021
- T6 (1-10-2023 t/m 30-09-2029

This is done in order to investigated the impact of the seismic hazard on the final outcome.

2 INTRODUCTION

Industrial companies in Groningen conduct engineering reviews on their industrial plants containing hazardous substances to assure earthquake proof designs as a consequence of gas production in Groningen. A specific prescribed assessment framework is in place.

In order to decrease (unnecessary) time consuming calculations for the earthquake resistance of (process) installations with hazardous substances, two selection steps can be performed between the phase 1 qualitative assessment and the phase 2 quantitative assessments.
The selection between these 2 phases consists of the following two steps:

1) With the selection method step 1, process installations identified in phase 1 are uniformly further tested for safety risk
2) For the remaining objects, this selection method step 2 a quickscan with software can be performed to identify whether an installation is globally sufficiently earthquake-resistant for identified scenarios:

- The earthquake load follows from global hazard curves (earthquake threat), which can also include developments such as the phasing out of gas production;
- The probability of exceeding a limit state is tested on the basis of available fragility curves and the probabilistic earthquake threat (the hazard curve).

The selection process ultimately results in a list of objects which no longer require further investigation, and for which objects is to be continued in phase 2 (the quantitative risk analysis). The selection instruments are included in the Groningen earthquake-resistant industry compensation policy rule.

This report provides the output of the so-called ‘Selection method Step 2 - based on fragility functions’ (NL: ‘Selectie methodiek Industrie Stap 2 - op basis van fragility functions’) to document the results. The methodology of the tool has been developed by Witteveen+Bos, and has been reviewed by TU Delft. The development has been initiated and facilitated by Nationaal Coördinator Groningen.

Chapter 3 presents an overview of all examined object scenarios. Chapter 4 presents all the input information filled in by the engineering consultant in the tool and the outcome per object scenario. Both chapters are automatically generated, and no action is required from the engineering consultant. In chapters 5 and 6, a summary of the results, and conclusions and recommendations shall be added to this report by the engineering consultant.

3 OVERVIEW OF ALL OBJECT SCENARIOS

This chapter presents an overview of all examined object scenario. All the object scenarios are summarized on the selected risk matrices. In case a custom risk matrix has been selected by the engineering consultant / industrial company, the results are presented not only for the custom risk matrix but also for the SIL risk matrix. This is done in order to maintain consistency among different industrial companies.

Table 1 Overview of all object scenarios

object (tag)	scenario (tag)	severity effect	exposure class
Ob4	Sc1T4	Catastrophic	Public
Ob5	Sc1T4	Catastrophic	Public
Ob6	Sc1T4	Moderate	Public
Ob4	Sc1T6	Catastrophic	Public
Ob5	Sc1T6	Catastrophic	Public
Ob6	Sc1T6	Moderate	Public

Table 2 Overview descriptions severity effect (labels x-axes risk matrices)

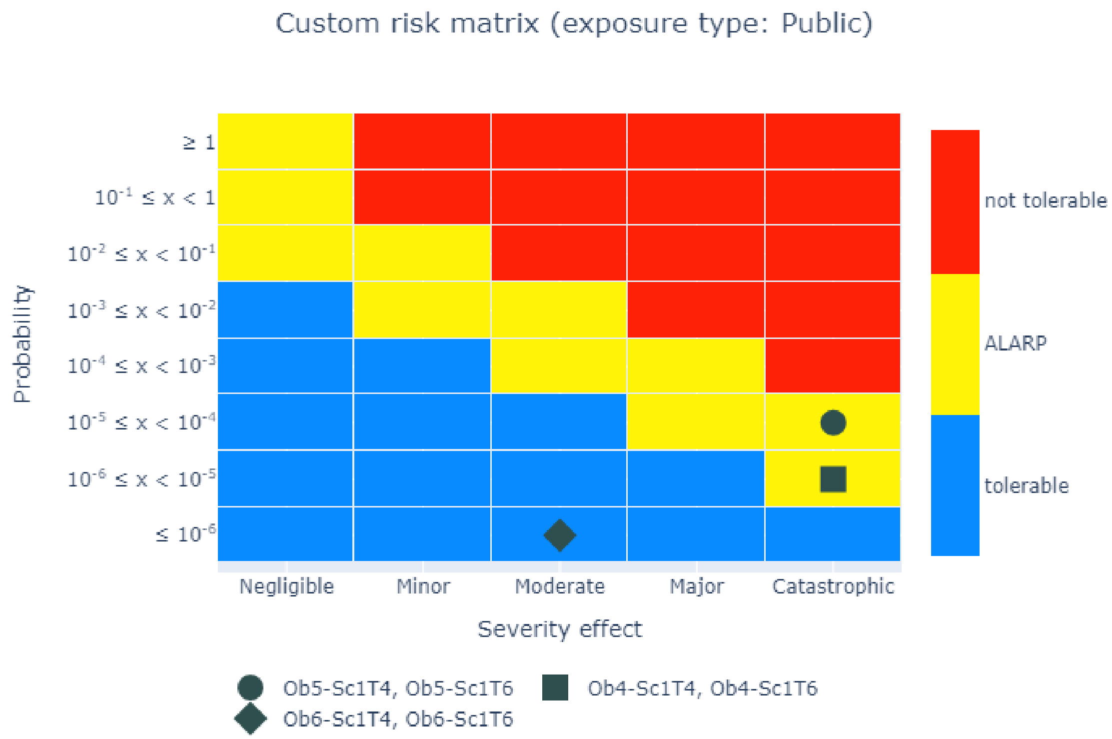
Severity effect	description safety effect	description environmental effect
Negligible	Gering letsel / Gering effect op gezondheid	Lichte schade aan het milieu
Minor	Matig letsel / Matig effect op gezondheid	Beperkte schade aan milieu
Moderate	Ernstig letsel / Ernstig effect op gezondheid	Middelgrote schade aan milieu
Major	1 acuut of door beroepsziekte dodelijk slachtoffer binnen inrichting / meerdere gewonden met ernstig letsel / Permanent verlies centrale functionaliteit	Ernstige schade aan het milieu
Catastrophic	> 1 acute of door beroepsziekte dodelijke slachtoffers binnen inrichting / 1 acuut of door beroepsziekte dodelijk slachtoffer buiten inrichting	Ernstige en blijvende schade aan het milieu

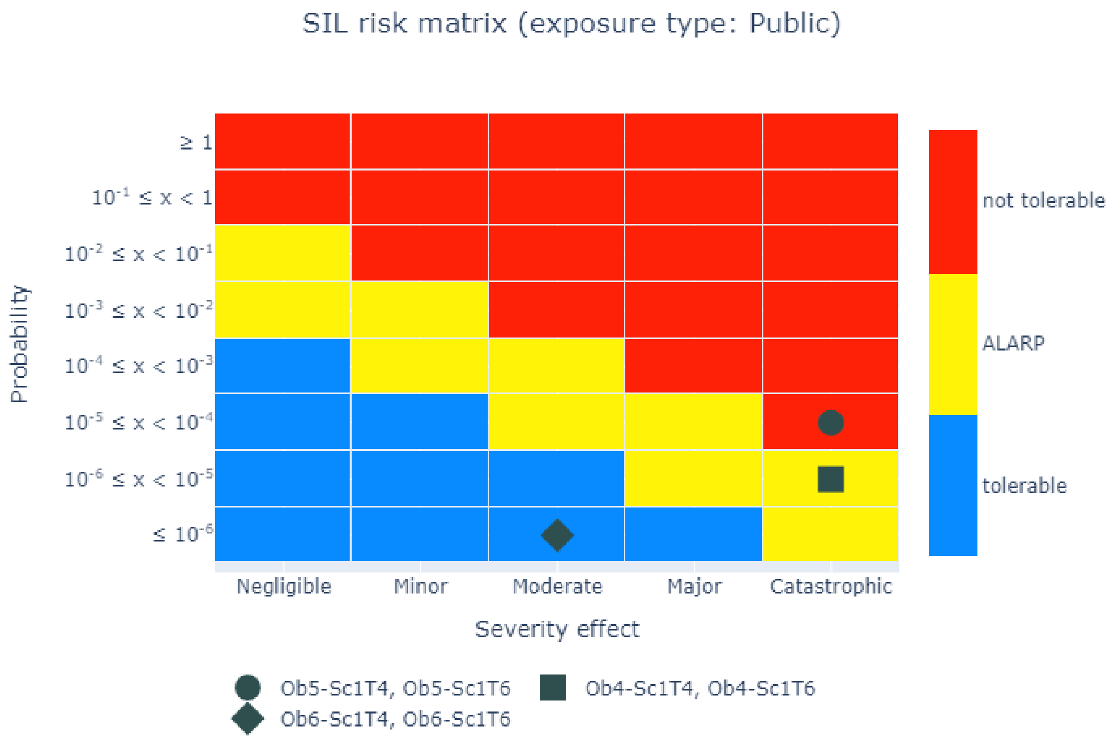
Table 3 Overview SIL descriptions severity effect

Severity effect	description safety effect	description environmental effect
Negligible	Minor injury ("first aid")	Marginal emission and/or damage within site boundary (< 1 ha)
Minor	Serious injury ("staying at home")	Minor emission and/or damage within site boundary (> 1 ha)
Moderate	Major injury ("hospital") or multiple serious injuries	Emission and/or damage within site boundary. No permanent damage to surrounding environment (> 10 ha)
Major	1-2 fatal injuries or permanent disability	Emission and/or damage to surrounding environment (> 100 ha)
Catastrophic	>2 fatal injuries	Major emission and/or damage to surrounding environment (> 1000 ha)

Risk matrices

Public risk matrix





Onsite risk matrix

Risk matrix (exposure type: Onsite) is not available

4 INPUT/OUTPUT PER OBJECT SCENARIO

In this chapter all input values in the tool and choices made by the engineering consultant per object scenario are presented. At the end of each paragraph the outcome is presented on the selected risk matrix and a recommendation regarding further assessment of the foundation is given.

4.1 Object scenario Ob4 - Sc1T4

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T4 (1-10-2020 t/m 30-9-2021)*

Object and scenario input

Object tag: *Ob4*
Object description: *Large horizontal vessels, unanchored*

Scenario tag: *Sc1T4*
Scenario description: *Total failure, T4 Company specific RM*

Foundation

Type foundation: *pile*

Select severity effect category

Severity effect category: *Catastrophic*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

Exposure class

Exposure class: *Public*

Select object typology from literature

Object typology: *Large horizontal vessels, unanchored*

Damage state and fragility

Select damage state

Minimum damage state: *DS5*

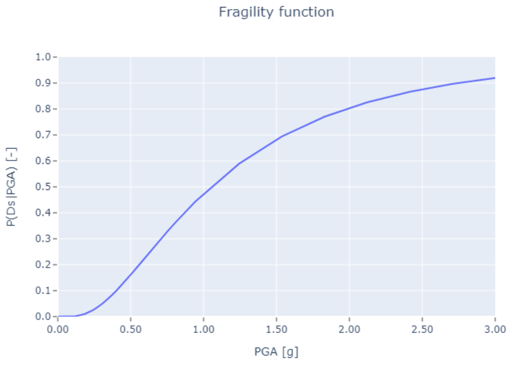
Descriptions damage state

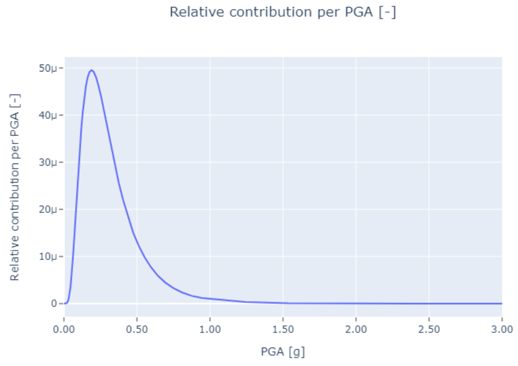
Minimum Damage State	Description
DS5	Extensive damage to horizontal vessels beyond repair

Explanation

Explanation for chosen object typology or threshold (if applicable):
ob4 is a horizontal vessel
Explanation for selected damage state in relation to this scenario:
We assume total failure of the support structure which should imply DS5

Median of fragility function:	*1.05*
Dispersion of fragility function:	*0.75*
Probability of damage state exceedance:	*1.68e-05*





Selection of obligatory conditional factors

Conditional factor person(s) presence: *0.5*
Label: *Partially (regular people presence)Van HAZOP studie 10%-100% (2.5h - 24h / 7)*

Explanation for chosen conditional factor person(s) presence:

Conditional factor safe shutdown LoD: *1*
Label: *No safe shutdown*

Conditional factor construction state: *1*
Label: *Neutral*

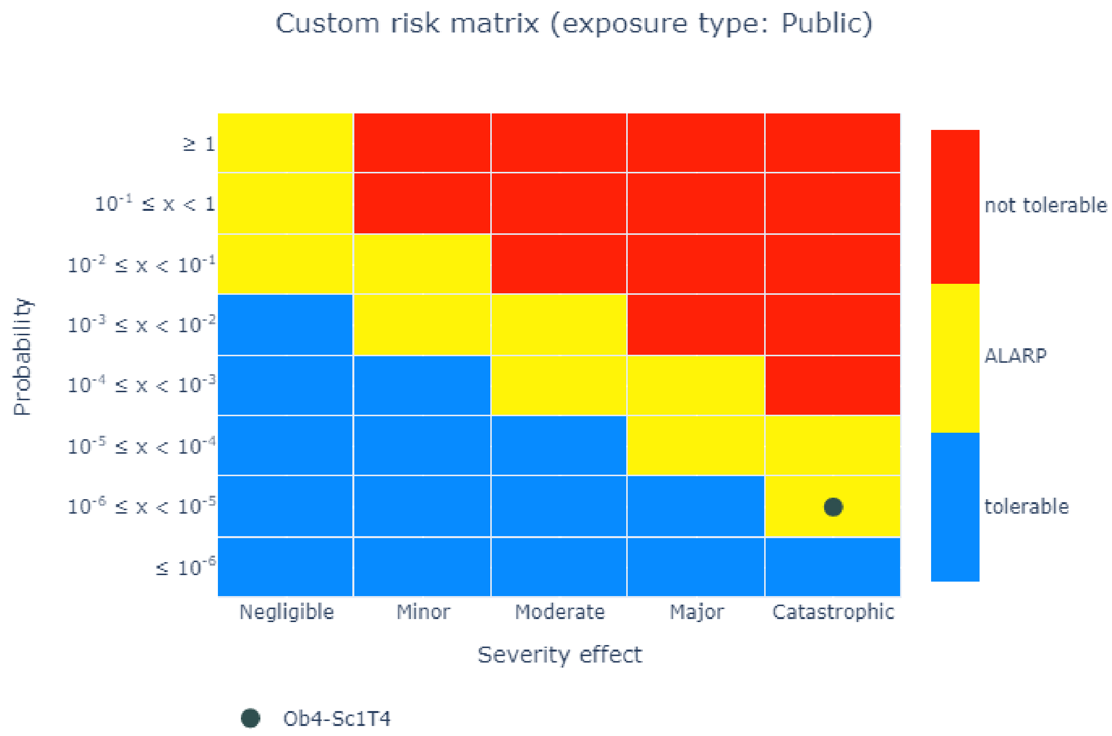
Optional conditional factors

No optional redundancies were specified.

Scenario representation in Risk Matrix

The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object:	*Large horizontal vessels, unanchored (Ob4)*
Scenario:	*Total failure, T4 Company specific RM (Sc1T4)*
Risk matrix selection:	*Public*
The calculated scenario probability is:	*8.421e-06*
The scenario likelihood category is:	*1e-6 ≤ x < 1e-5*
The scenario severity category is:	*Catastrophic*



For the seismic hazard level at the location according to NPR 9998:2020 risks associated with loss of bearing capacity of piles cannot be neglected and both STR and GEO limit state assessment is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

4.2 Object scenario Ob5 - Sc1T4

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T4 (1-10-2020 t/m 30-9-2021)*

Object and scenario input

Object tag: *Ob5*
Object description: *Elevated pipe*

Scenario tag: *Sc1T4*
Scenario description: *Total failure, the probability of the pipeline being damage is also considered here, T4, Company specific RM*

Foundation
Type foundation: *pile*

Select severity effect category
Severity effect category: *Catastrophic*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

Exposure class
Exposure class: *Public*

Select object typology from literature
Object typology: *Elevated pipe, unanchored*

Damage state and fragility

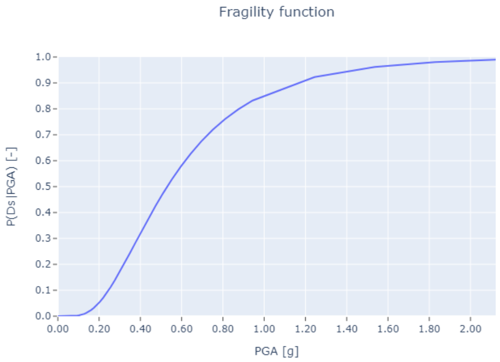
Select damage state
Minimum damage state: *DS4*

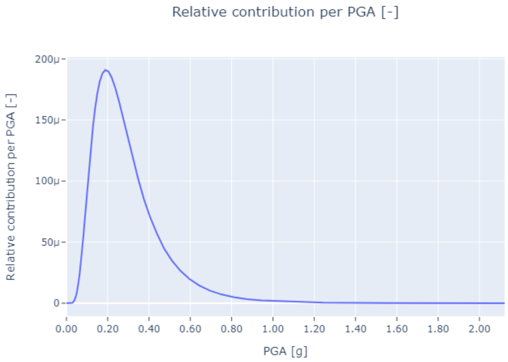
Descriptions damage state

Minimum Damage State	Description
DS4	Extensive damage to elevated pipes (subcomponent of tank farms) or extensive damage to pipes connecting different basins and chemical units (subcomponent of water treatment plants)
DS5	Complete failure of all elevated pipes (subcomponent of tanks farms and refineries) or complete failure of all pipings (subcomponent of water treatment plants)

Explanation
Explanation for chosen object typology or threshold (if applicable):
Ob5 is an elevated pipe
Explanation for selected damage state in relation to this scenario:
We assume externsive damage of the pipe leads to LoC with catastrofic consequences

Median of fragility function:	*0.53*
Dispersion of fragility function:	*0.6*
Probability of damage state exceedance:	*5.65e-05*





Selection of obligatory conditional factors

Conditional factor person(s) presence: *1*
Label: *Permanent (24/7 people presence)*

Conditional factor safe shutdown LoD: *1*
Label: *No safe shutdown*

Conditional factor construction state: *0.5*
Label: *Good*

Explanation for chosen conditional factor construction state: *Pipeline is maintained regularly*

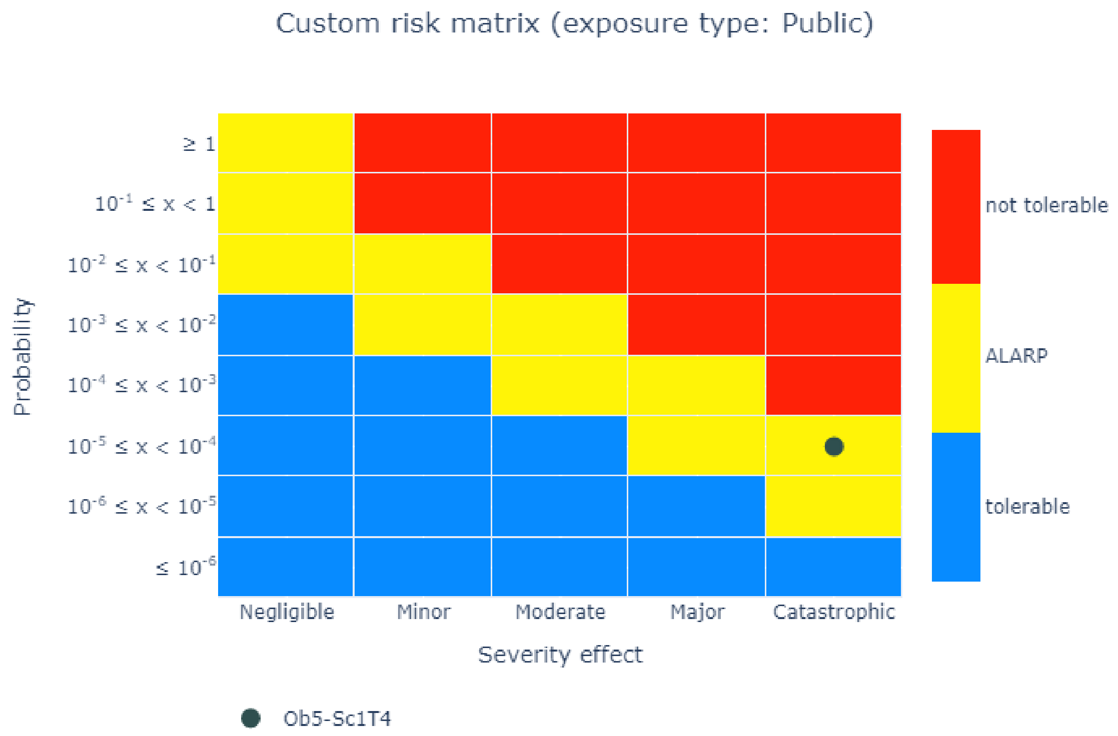
Optional conditional factors

Conditional factor common cause: *1.25*
Explanation for conditional factor common cause: *Due to pounding from neighbouring silotank. The probability of damaging the pipeline due to pounding is calculated as the probability damaging the pipeline given colapse of the neighbouring silotank times the probability of colapse of the neighbouring silotank: P(damage pileline | colapse silotank) * P(colapse silotank) = 0.5 * 1.4e-05 = 7e-06. This is added to the calculated total probability of the catastrophic scenario for the pipeline): 1.68e-05 -> (2.824e-05 + 50% * 1.4e-05) / 2.824e-05 = 1.25*

Scenario representation in Risk Matrix

The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object: *Elevated pipe (Ob5)*
Scenario: *Total failure, the probability of the pipeline being damage is also considered here, T4, Company specific RM (Sc1T4)*
Risk matrix selection: *Public*
The calculated scenario probability is: *3.530e-05*
The scenario likelihood category is: *1e-5 ≤ x < 1e-4*
The scenario severity category is: *Catastrophic*



For the seismic hazard level at the location according to NPR 9998:2020 risks associated with loss of bearing capacity of piles cannot be neglected and both STR and GEO limit state assessment is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

4.3 Object scenario Ob6 - Sc1T4

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T4 (1-10-2020 t/m 30-9-2021)*

Object and scenario input

Object tag: *Ob6*
Object description: *Large vertical vessels with formed heads, unanchored*

Scenario tag: *Sc1T4*
Scenario description: *Total failure, T4, company specific RM*

Foundation
Type foundation: *pile*

Select severity effect category
Severity effect category: *Moderate*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

Exposure class
Exposure class: *Public*

Select object typology from literature
Object typology: *Large vertical vessels with formed heads, unanchored*

Damage state and fragility

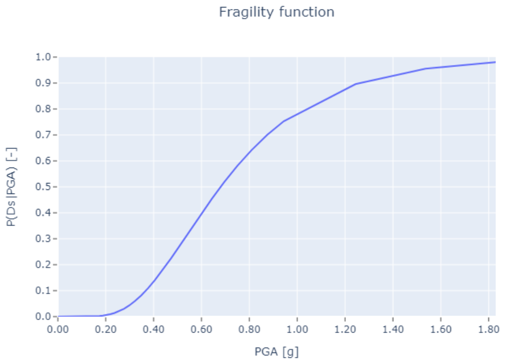
Select damage state
Minimum damage state: *DS4*

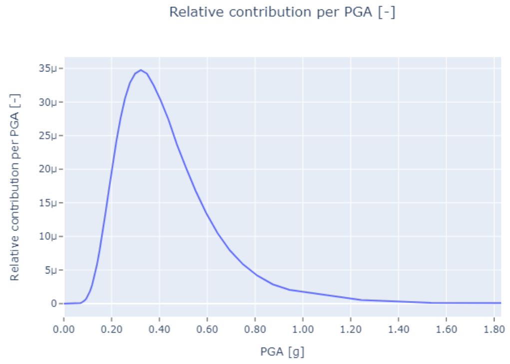
Descriptions damage state

Minimum Damage State	Description
DS3	Not well defined in HAZUS, it is assumed moderate damage state of the vessel
DS4	Not well defined in HAZUS, it is assumed extensive damage state of the vessel

Explanation
Explanation for chosen object typology or threshold (if applicable):
Ob 6 is assumed to be relative large vessel (H = 27 m)
Explanation for selected damage state in relation to this scenario:
We assume total failure of the support structure which should imply DS4

Median of fragility function:	*0.68*
Dispersion of fragility function:	*0.48*
Probability of damage state exceedance:	*1.40e-05*





Selection of obligatory conditional factors

Conditional factor person(s) presence: *0.1*
Label: *Limited (occasional people presence)according to phase 1 report pg. 275*

Explanation for chosen conditional factor person(s) presence:

Conditional factor safe shutdown LoD: *1*
Label: *No safe shutdown*

Explanation for chosen conditional factor safe shutdown LoD: *There is safe shut down but idt does not prevent the entire content from spilling out.*

Conditional factor construction state: *0.5*
Label: *Good*

Explanation for chosen conditional factor construction state: *Robust constructie according to industrial company and consaltant representatives*

Optional conditional factors

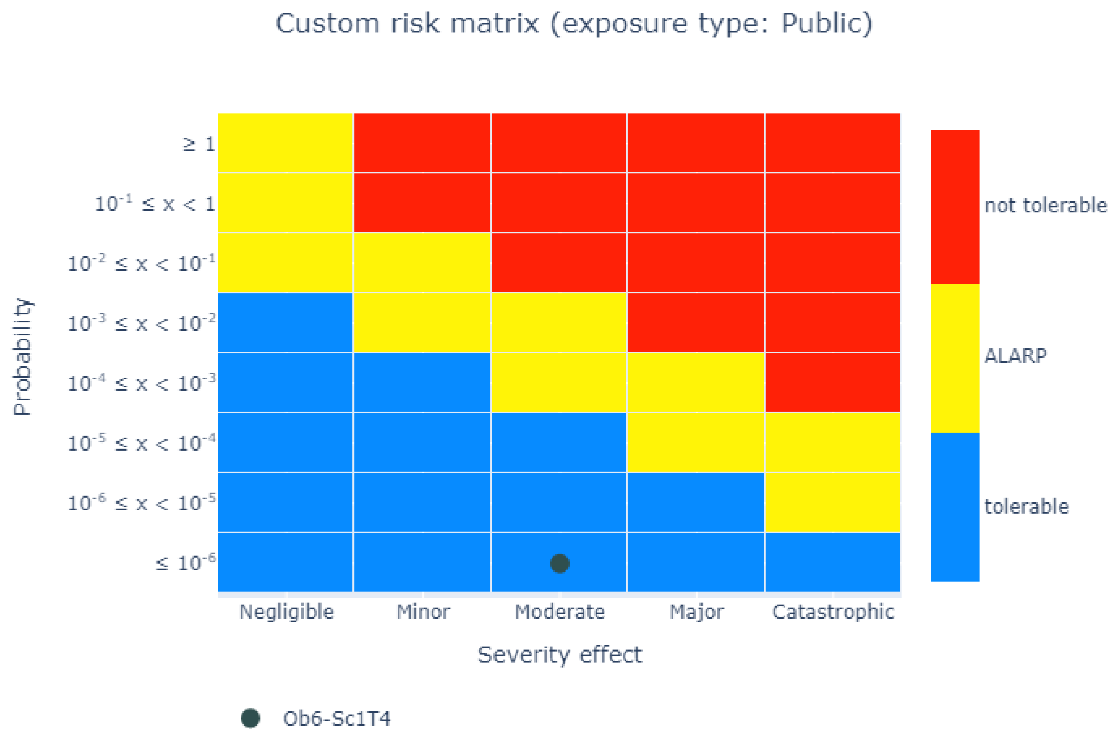
Conditional factor common cause: *1*
Explanation for conditional factor common cause: *pounding scenario, we take this into account in the consequeces because it can lead to collapse of the chloorleiding*

Optional conditional factor 1: *1*
Explanation for optional conditional factor 1: *None*

Scenario representation in Risk Matrix

The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object:	*Large vertical vessels with formed heads, unanchored (Ob6)*
Scenario:	*Total failure, T4, company specific RM (Sc1T4)*
Risk matrix selection:	*Public*
The calculated scenario probability is:	*6.996e-07*
The scenario likelihood category is:	*≤ 1e-6*
The scenario severity category is:	*Moderate*



For the seismic hazard level at the location according to NPR 9998:2020 risks associated with loss of bearing capacity of piles cannot be neglected and both STR and GEO limit state assessment is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

4.4 Object scenario Ob4 - Sc1T6

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T6 (1-10-2023 t/m 30-9-2029)*

Object and scenario input

Object tag: *Ob4*
Object description: *Large horizontal vessels, unanchored*

Scenario tag: *Sc1T6*
Scenario description: *Total failure, T6, company specific RM*

Foundation
Type foundation: *pile*

Select severity effect category
Severity effect category: *Catastrophic*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

Exposure class
Exposure class: *Public*

Select object typology from literature
Object typology: *Large horizontal vessels, unanchored*

Damage state and fragility

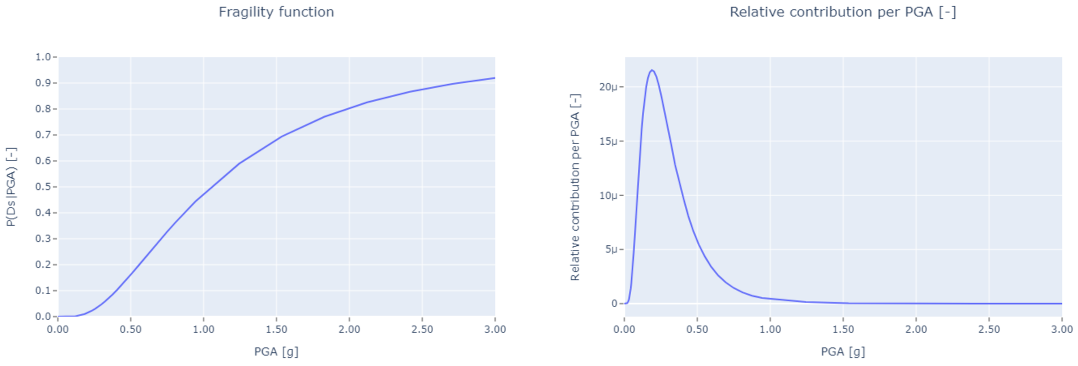
Select damage state
Minimum damage state: *DS5*

Descriptions damage state

Minimum Damage State	Description
DS5	Extensive damage to horizontal vessels beyond repair

Explanation
Explanation for chosen object typology or threshold (if applicable):
Ob4 is a horizontal vessel
Explanation for selected damage state in relation to this scenario:
We assume total failure of the support structure which should imply DS5

Median of fragility function:	*1.05*
Dispersion of fragility function:	*0.75*
Probability of damage state exceedance:	*7.35e-06*



Selection of obligatory conditional factors

Conditional factor person(s) presence: *0.5*
Label: *Partially (regular people presence)Van HAZOP studie 10%-100% (2.5h - 24h / 7)*

Explanation for chosen conditional factor person(s) presence:

Conditional factor safe shutdown LoD: *1*
Label: *No safe shutdown*

Conditional factor construction state: *1*
Label: *Neutral*

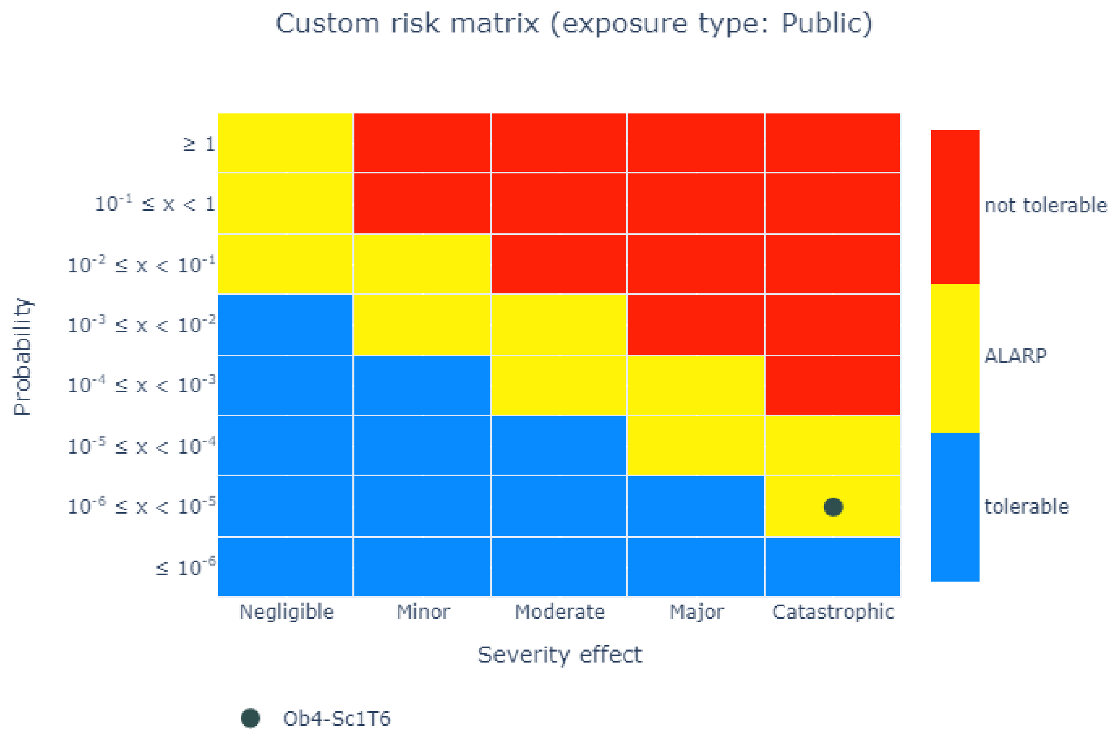
Optional conditional factors

No optional redundancies were specified.

Scenario representation in Risk Matrix

The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object:	*Large horizontal vessels, unanchored (Ob4)*
Scenario:	*Total failure, T6, company specific RM (Sc1T6)*
Risk matrix selection:	*Public*
The calculated scenario probability is:	*3.675e-06*
The scenario likelihood category is:	*1e-6 ≤ x < 1e-5*
The scenario severity category is:	*Catastrophic*



The risk of loss of bearing capacity due to structural damage of piles is sufficiently low for the seismic hazard level that applies to the location. Only a GEO limit state assessment (liquefaction verification) is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

4.5 Object scenario Ob5 - Sc1T6

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T6 (1-10-2023 t/m 30-9-2029)*

Object and scenario input

Object tag: *Ob5*
Object description: *Elevated pipe*

Scenario tag: *Sc1T6*
Scenario description: *Total failure, the probability of the pipeline being damage is also considered here, T6, copmany specific RM*

Foundation

Type foundation: *pile*

Select severity effect category

Severity effect category: *Catastrophic*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

Exposure class

Exposure class: *Public*

Select object typology from literature

Object typology: *Elevated pipe, unanchored*

Damage state and fragility

Select damage state

Minimum damage state: *DS4*

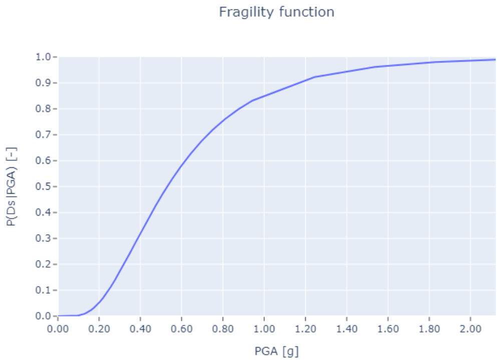
Descriptions damage state

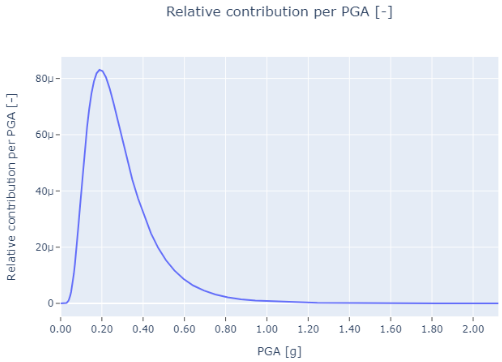
Minimum Damage State	Description
DS4	Extensive damage to elevated pipes (subcomponent of tank farms) or extensive damage to pipes connecting different basins and chemical units (subcomponent of water treatment plants)
DS5	Complete failure of all elevated pipes (subcomponent of tanks farms and refineries) or complete failure of all pipings (subcomponent of water treatment plants)

Explanation

Explanation for chosen object typology or threshold (if applicable):
Ob5 is an elevated pipe
Explanation for selected damage state in relation to this scenario:
We assume externsive damage of the pipe leads to LoC with catastrofic consequences

Median of fragility function:	*0.53*
Dispersion of fragility function:	*0.6*
Probability of damage state exceedance:	*2.46e-05*





Selection of obligatory conditional factors

Conditional factor person(s) presence: *1*
Label: *Permanent (24/7 people presence)*

Conditional factor safe shutdown LoD: *1*
Label: *No safe shutdown*

Conditional factor construction state: *0.5*
Label: *Good*

Explanation for chosen conditional factor construction state: *Pipeline is maintained regularily*

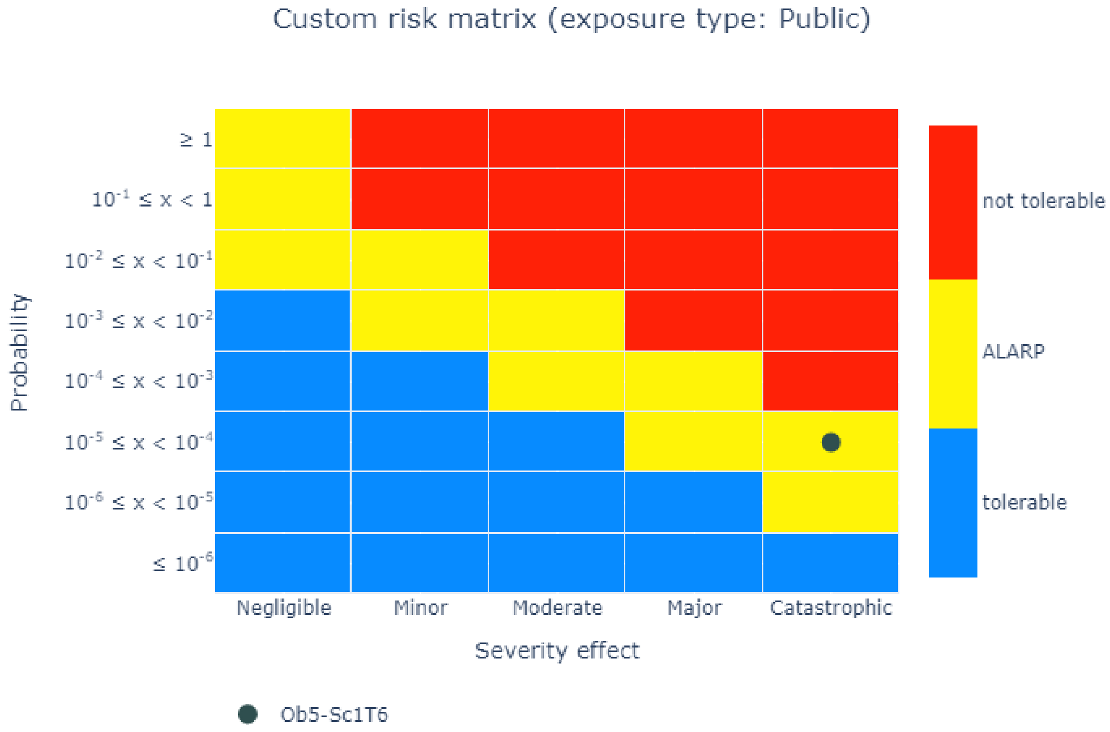
Optional conditional factors

Conditional factor common cause: *1.25*
Explanation for conditional factor common cause: *Due to pounding from neighbouring silotank. The probability of damaging the pipeline due to pounding is calculated as the probability damaging the pipeline given colapse of the neighbouring silotank times the probability of colapse of the neighbouring silotank: P(damage pileline | colapse silotank) * P(colapse silotank) = 0.5 * 1.4e-05 = 7e-06. This is added to the calculated total probability of the catastrophic scenario for the pipeline): 1.68e-05 -> (2.824e-05 + 50% * 1.4e-05) / 2.824e-05 = 1.25*

Scenario representation in Risk Matrix

The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object: *Elevated pipe (Ob5)*
Scenario: *Total failure, the probability of the pipeline being damage is also considered here, T6, copmany specific RM (Sc1T6)*
Risk matrix selection: *Public*
The calculated scenario probability is: *1.540e-05*
The scenario likelihood category is: *1e-5 ≤ x < 1e-4*
The scenario severity category is: *Catastrophic*



The risk of loss of bearing capacity due to structural damage of piles is sufficiently low for the seismic hazard level that applies to the location. Only a GEO limit state assessment (liquefaction verification) is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

4.6 Object scenario Ob6 - Sc1T6

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T6 (1-10-2023 t/m 30-9-2029)*

Object and scenario input

Object tag: *Ob6*
Object description: *Large vertical vessels with formed heads, unanchored*

Scenario tag: *Sc1T6*
Scenario description: *Total failure, T6, company specific RM*

Foundation
Type foundation: *pile*

Select severity effect category
Severity effect category: *Moderate*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

Exposure class
Exposure class: *Public*

Select object typology from literature
Object typology: *Large vertical vessels with formed heads, unanchored*

Damage state and fragility

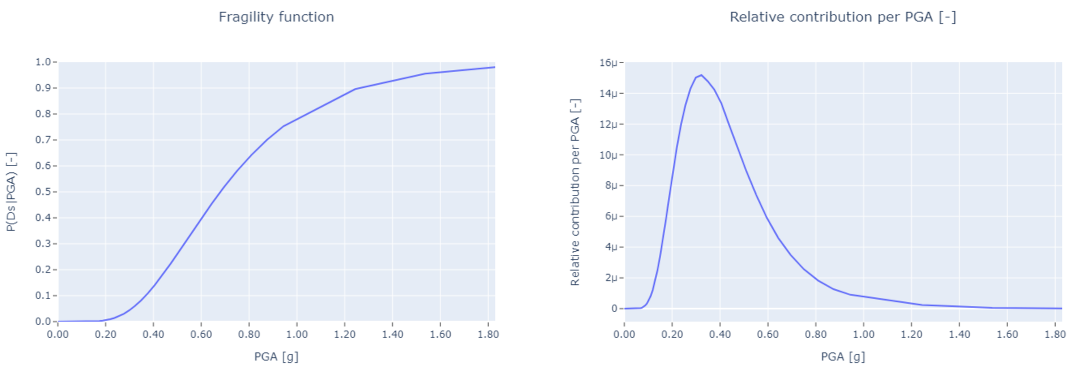
Select damage state
Minimum damage state: *DS4*

Descriptions damage state

Minimum Damage State	Description
DS3	Not well defined in HAZUS, it is assumed moderate damage state of the vessel
DS4	Not well defined in HAZUS, it is assumed extensive damage state of the vessel

Explanation
Explanation for chosen object typology or threshold (if applicable):
Ob 6 is assumed to be relative large vessel (H = 27 m)
Explanation for selected damage state in relation to this scenario:
We assume total failure of the support structure which should imply DS4

Median of fragility function:	*0.68*
Dispersion of fragility function:	*0.48*
Probability of damage state exceedance:	*6.12e-06*



Selection of obligatory conditional factors

Conditional factor person(s) presence: *0.1*
Label: *Limited (occasional people presence)according to phase 1 report pg. 275*

Explanation for chosen conditional factor person(s) presence:

Conditional factor safe shutdown LoD: *1*
Label: *No safe shutdown*

Explanation for chosen conditional factor safe shutdown LoD: *There is safe shut down but idt does not prevent the entire content from spilling out.*

Conditional factor construction state: *0.5*
Label: *Good*

Explanation for chosen conditional factor construction state: *Robust constructie according to industrial company and consultant representatives*

Optional conditional factors

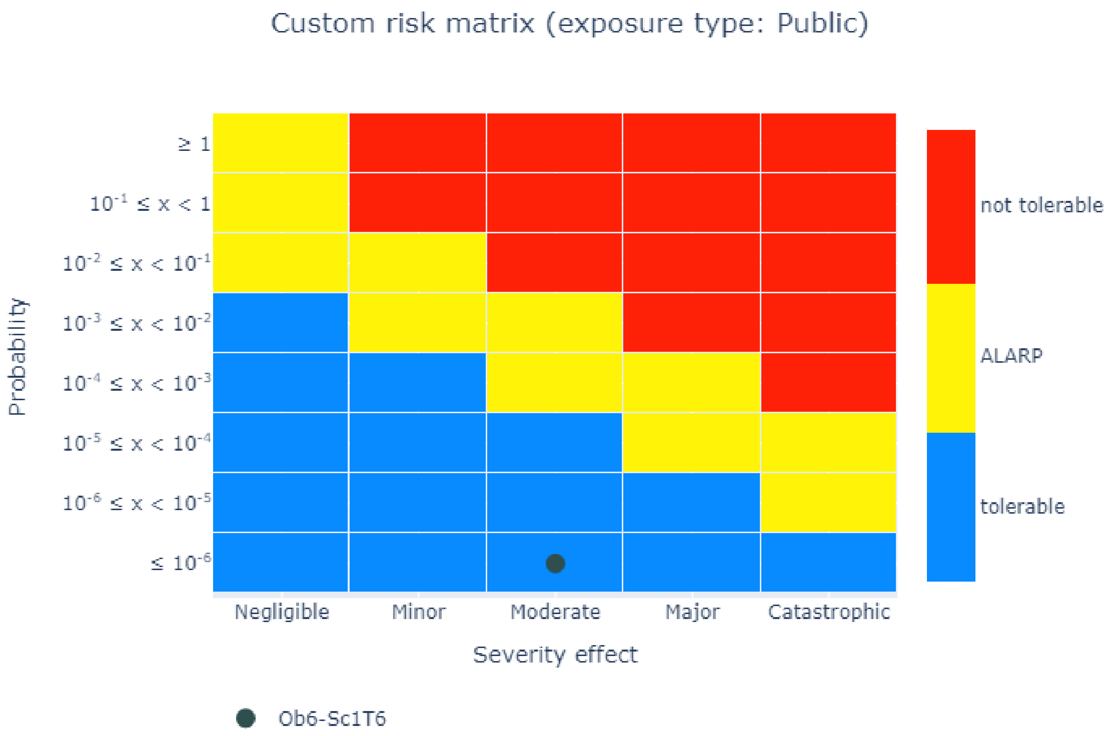
Conditional factor common cause: *1*
Explanation for conditional factor common cause: *pounding scenario, we take this into account in the consequeces because it can lead to collapse of the chloorleiding*

Optional conditional factor 1: *1*
Explanation for optional conditional factor 1: *None*

Scenario representation in Risk Matrix

The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object:	*Large vertical vessels with formed heads, unanchored (Ob6)*
Scenario:	*Total failure, T6, company specific RM (Sc1T6)*
Risk matrix selection:	*Public*
The calculated scenario probability is:	*3.062e-07*
The scenario likelihood category is:	*≤ 1e-6*
The scenario severity category is:	*Moderate*



The risk of loss of bearing capacity due to structural damage of piles is sufficiently low for the seismic hazard level that applies to the location. Only a GEO limit state assessment (liquefaction verification) is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

5 CONCLUSION

In this report we assess the criticality of 3 objects of the industrial company B with the selection method Step 2 tool, as part of pilot calculations. For all three objects a phase 2 assessment has been performed. The outcome of the phase 2 calculation reports is compared with the outcome of the Selection method Step 2 analysis.

For all the objects the verdict of the phase 2 studies was that there is no LoC with a maximum U.C. of around 0.9 for all the objects. The Selection method Step 2 analysis classifies these three objects in the blue and yellow region of the company specific risk matrix and in the blue, yellow and red region in the SIL risk matrix for public exposure.

Selection method Step 2 - based on fragility functions

Analysis results

Company under review (Client):	Company C
Installation(s) under review:	Object 7
Engineering consulting company:	Witteveen+Bos
Engineering consultant:	A. Bougioukos
Date:	1-12-2021

Company Logo

CONTENTS

1 ABSTRACT

This report consists the export report of the Selection method Step 2 tool and it has been generated in the context of the pilot calculations. It includes:

- all the information that have been input in the Selection method Step 2 tool and
- the output of the calculations,

for the pilot calculations performed for the industrial company C, for the object 7.

The calculations have been performed for two different time windows, from past hazard and future hazard:

- T4 (1-10-2020 t/m 30-09-2021
- T6 (1-10-2023 t/m 30-09-2029

This is done in order to investigate the impact of the seismic hazard on the final outcome.

2 INTRODUCTION

Industrial companies in Groningen conduct engineering reviews on their industrial plants containing hazardous substances to assure earthquake proof designs as a consequence of gas production in Groningen. A specific prescribed assessment framework is in place.

In order to decrease (unnecessary) time consuming calculations for the earthquake resistance of (process) installations with hazardous substances, two selection steps can be performed between the phase 1 qualitative assessment and the phase 2 quantitative assessments.
The selection between these 2 phases consists of the following two steps:

1) With the selection method step 1, process installations identified in phase 1 are uniformly further tested for safety risk
2) For the remaining objects, this selection method step 2 a quickscan with software can be performed to identify whether an installation is globally sufficiently earthquake-resistant for identified scenarios:

- The earthquake load follows from global hazard curves (earthquake threat), which can also include developments such as the phasing out of gas production;
- The probability of exceeding a limit state is tested on the basis of available fragility curves and the probabilistic earthquake threat (the hazard curve).

The selection process ultimately results in a list of objects which no longer require further investigation, and for which objects is to be continued in phase 2 (the quantitative risk analysis). The selection instruments are included in the Groningen earthquake-resistant industry compensation policy rule.

This report provides the output of the so-called 'Selection method Step 2 - based on fragility functions' (NL: 'Selectie methodiek Industrie Stap 2 - op basis van fragility functions') to document the results. The methodology of the tool has been developed by Witteveen+Bos, and has been reviewed by TU Delft. The development has been initiated and facilitated by Nationaal Coördinator Groningen.

Chapter 3 presents an overview of all examined object scenarios. Chapter 4 presents all the input information filled in by the engineering consultant in the tool and the outcome per object scenario. Both chapters are automatically generated, and no action is required from the engineering consultant. In chapters 5 and 6, a summary of the results, and conclusions and recommendations shall be added to this report by the engineering consultant.

3 OVERVIEW OF ALL OBJECT SCENARIOS

This chapter presents an overview of all examined object scenario. All the object scenarios are summarized on the selected risk matrices. In case a custom risk matrix has been selected by the engineering consultant / industrial company, the results are presented not only for the custom risk matrix but also for the SIL risk matrix. This is done in order to maintain consistency among different industrial companies.

Table 1 Overview of all object scenarios

object (tag)	scenario (tag)	severity effect	exposure class
Ob8	Sc1T4	Moderate	Public
Ob8	Sc1T6	Moderate	Public

Table 2 Overview descriptions severity effect (labels x-axes risk matrices)

Severity effect	description safety effect	description environmental effect
Negligible	Slight injury or health effect	Slight effect
Minor	Minor injury or health effect	Minor effect
Moderate	Major injury or health effect	Moderate effect
Major	Permanent total disability or up to three fatalities	Major effect
Catastrophic	More than three fatalities	Massive effect

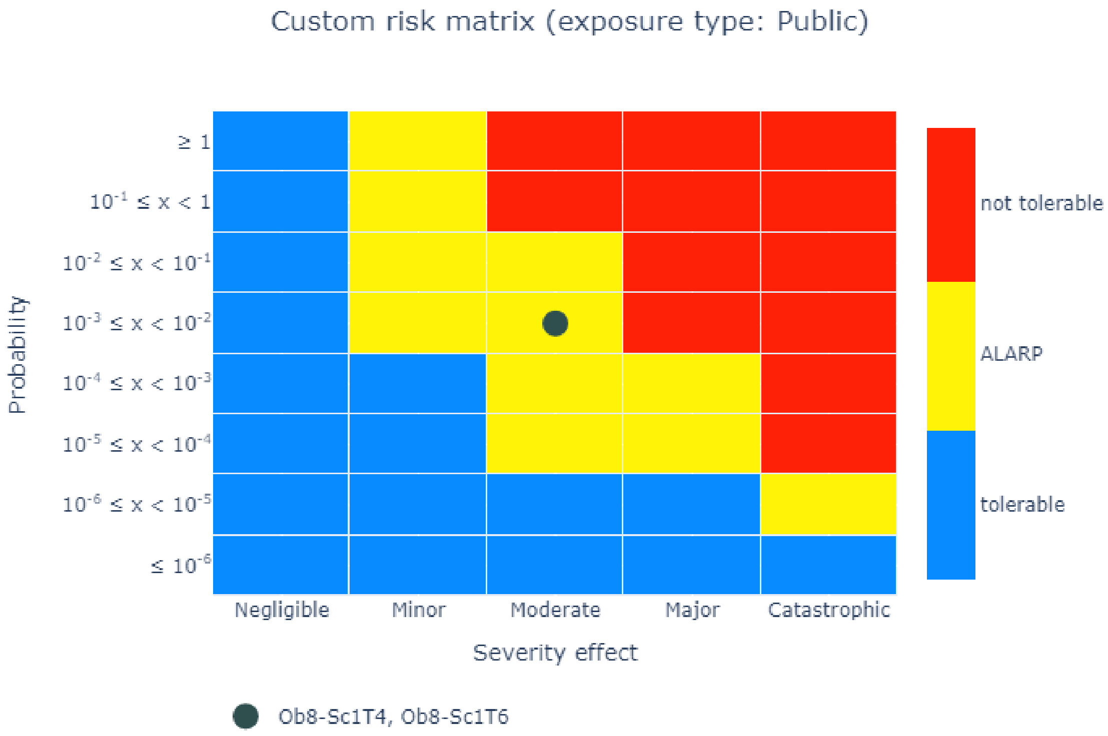
Table 3 Overview SIL descriptions severity effect

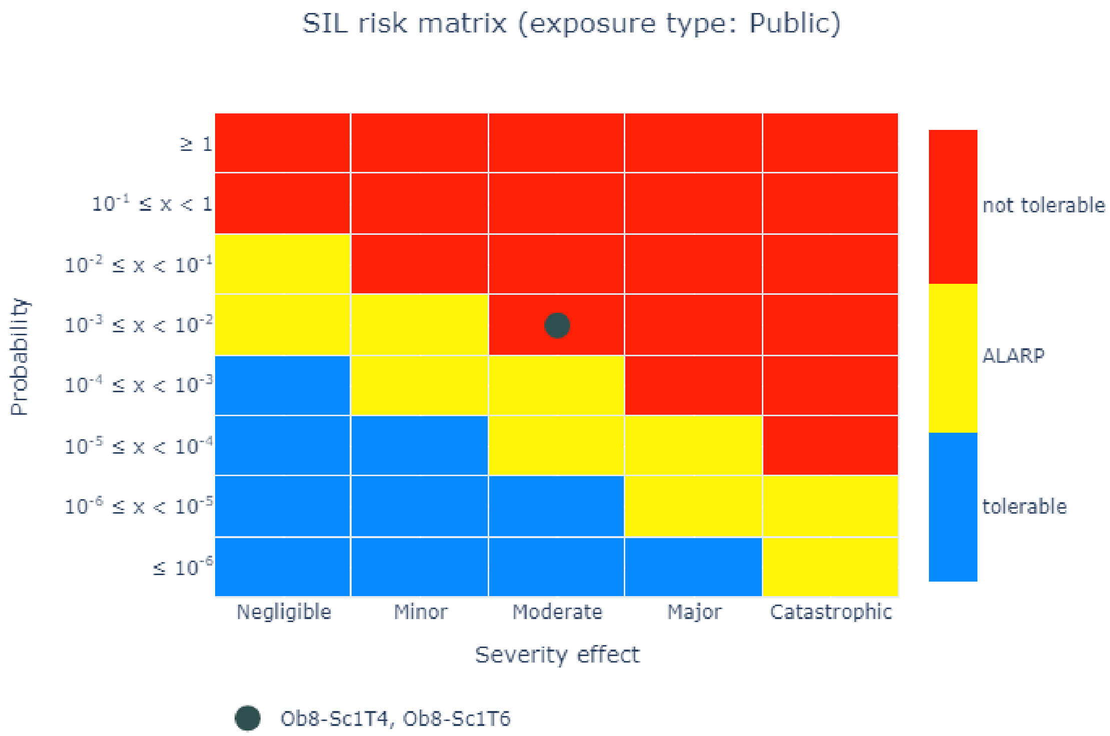
Severity effect	description safety effect	description environmental effect
Negligible	Minor injury ("first aid")	Marginal emission and/or damage within site boundary (< 1 ha)
Minor	Serious injury ("staying at home")	Minor emission and/or damage within site boundary (> 1 ha)
Moderate	Major injury ("hospital") or multiple serious injuries	Emission and/or damage within site boundary. No permanent damage to surrounding environment (> 10 ha)
Major	1-2 fatal injuries or permanent disability	Emission and/or damage to surrounding environment (> 100 ha)

Severity effect	description safety effect	description environmental effect
Catastrophic	>2 fatal injuries	Major emission and/or damage to surrounding environment (> 1000 ha)

Risk matrices

Public risk matrix





Onsite risk matrix

Risk matrix (exposure type: Onsite) is not available

4 INPUT/OUTPUT PER OBJECT SCENARIO

In this chapter all input values in the tool and choices made by the engineering consultant per object scenario are presented. At the end of each paragraph the outcome is presented on the selected risk matrix and a recommendation regarding further assessment of the foundation is given.

4.1 Object scenario Ob8 - Sc1T4

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T4 (1-10-2020 t/m 30-9-2021)*

Object and scenario input

Object tag: *Ob8*
Object description: *Elevated tanks without any lateral support*

Scenario tag: *Sc1T4*
Scenario description: *LoC for total collapse of the tanks is considered for T4*

Foundation
Type foundation: *pile*

Select severity effect category
Severity effect category: *Moderate*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

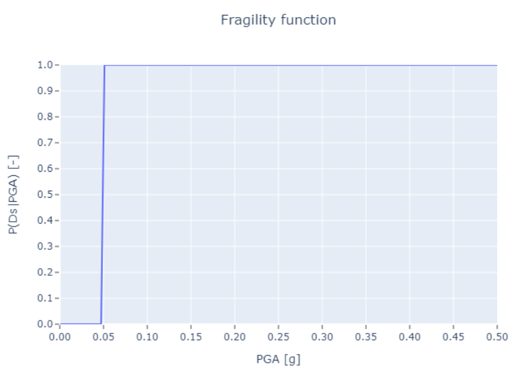
Exposure class
Exposure class: *Public*

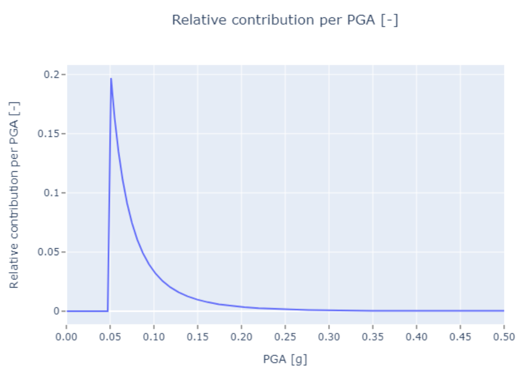
Select object typology from literature
Object typology: *Elevated tank (non-braced)*

Damage state and fragility

Explanation
Explanation for chosen object typology or threshold (if applicable):
The support structure seems strong in one direction but it is not braced at any of the two directions
Explanation for selected damage state in relation to this scenario:
There is not option for damage state for this fragility function. total colapse is considered

Median of fragility function:	*0.05*
Dispersion of fragility function:	*0.0*
Probability of damage state exceedance:	*6.10e-03*





Selection of obligatory conditional factors

Conditional factor person(s) presence: *1*
Label: *Permanent (24/7 people presence)*

Conditional factor safe shutdown LoD: *1*
Label: *No safe shutdown*

Conditional factor construction state: *1*
Label: *Neutral*

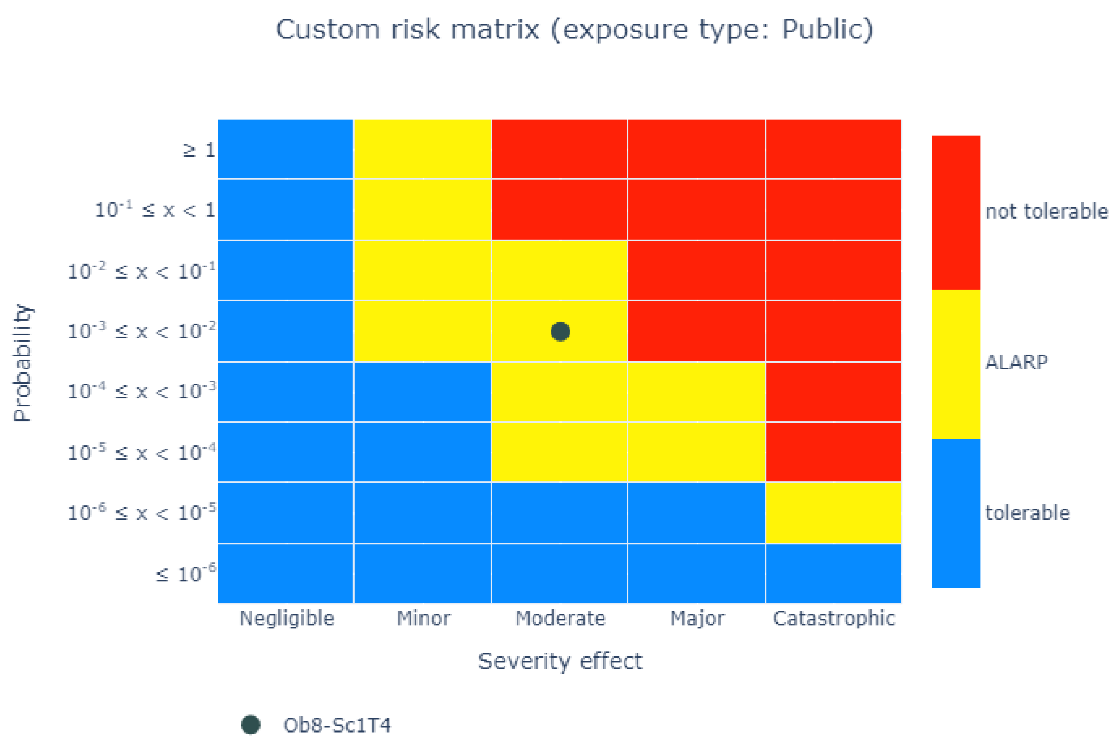
Optional conditional factors

No optional redundancies were specified.

Scenario representation in Risk Matrix

The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object:	*Elevated tanks without any lateral support (Ob8)*
Scenario:	*LoC for total collapse of the tanks is considered for T4 (Sc1T4)*
Risk matrix selection:	*Public*
The calculated scenario probability is:	*6.099e-03*
The scenario likelihood category is:	*1e-3 ≤ x < 1e-2*
The scenario severity category is:	*Moderate*



For the seismic hazard level at the location according to NPR 9998:2020 risks associated with loss of bearing capacity of piles cannot be neglected and both STR and GEO limit state assessment is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of

foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

4.2 Object scenario Ob8 - Sc1T6

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T6 (1-10-2023 t/m 30-9-2029)*

Object and scenario input

Object tag: *Ob8*
Object description: *Elevated tanks without any lateral support*

Scenario tag: *Sc1T6*
Scenario description: *LoC for total collapse of the tanks is considered for T6*

Foundation
Type foundation: *pile*

Select severity effect category
Severity effect category: *Moderate*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

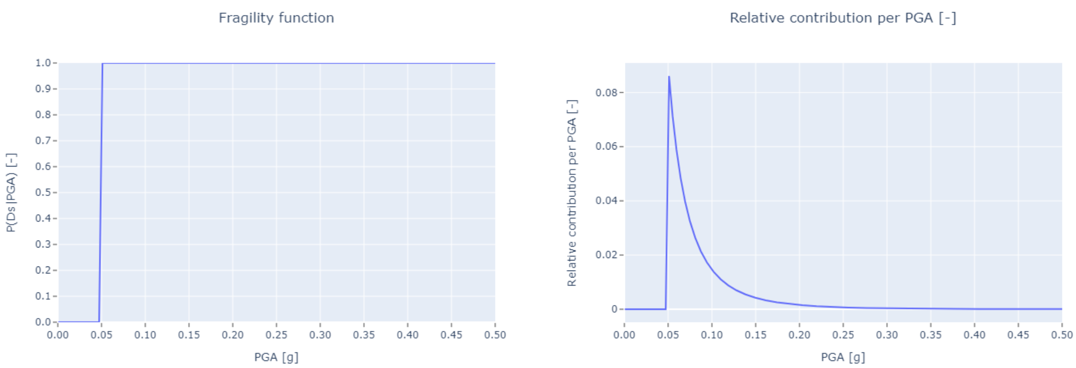
Exposure class
Exposure class: *Public*

Select object typology from literature
Object typology: *Elevated tank (non-braced)*

Damage state and fragility

Explanation
Explanation for chosen object typology or threshold (if applicable):
The support structure seems strong in one direction but it is not braced at any of the two directions
Explanation for selected damage state in relation to this scenario:
There is not option for daage state for this fragility function. total colapse is considered

Median of fragility function: *0.05*
Dispersion of fragility function: *0.0*
Probability of damage state exceedance: *2.66e-03*



Selection of obligatory conditional factors

Conditional factor person(s) presence: *1*
Label: *Permanent (24/7 people presence)*

Conditional factor safe shutdown LoD: *1*
Label: *No safe shutdown*

Conditional factor construction state: *1*
Label: *Neutral*

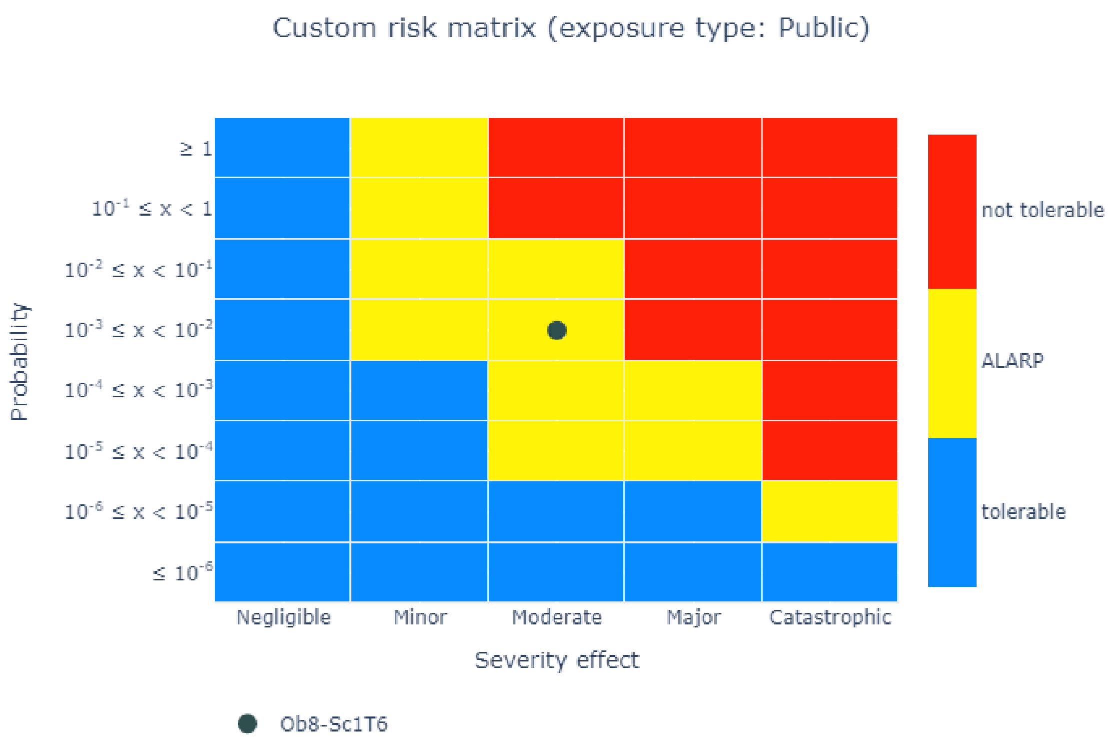
Optional conditional factors

No optional redundancies were specified.

Scenario representation in Risk Matrix

The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object:	*Elevated tanks without any lateral support (Ob8)*
Scenario:	*LoC for total collapse of the tanks is considered for T6 (Sc1T6)*
Risk matrix selection:	*Public*
The calculated scenario probability is:	*2.657e-03*
The scenario likelihood category is:	*1e-3 ≤ x < 1e-2*
The scenario severity category is:	*Moderate*



The risk of loss of bearing capacity due to structural damage of piles is sufficiently low for the seismic hazard level that applies to the location. Only a GEO limit state assessment (liquefaction verification) is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

5 CONCLUSION

In this report we assess the criticality of 1 object of the industrial company C with the selection method Step 2 tool, as part of pilot calculations. For this object a phase 2 assessment has been performed. The outcome of the phase 2 calculation reports is compared with the outcome of the Selection method Step 2 analysis.

The verdict of the phase 2 study was that there is LoC for object 2 with a maximum U.C. of around 1.25. The Selection method Step 2 analysis classifies this object in the yellow region of the company specific risk matrix. In the SIL risk matrix for public exposure this object is classified in the red region.

Selection method Step 2 - based on fragility functions

Analysis results

Company under review (Client):	Company D
Installation(s) under review:	Object 8
Engineering consulting company:	Witteveen+Bos
Engineering consultant:	A. Bougioukos
Date:	1-12-2021

Company Logo

CONTENTS

1 ABSTRACT

This report consists the export report of the Selection method Step 2 tool and it has been generated in the context of the pilot calculations. It includes:

- all the information that have been input in the Selection method Step 2 tool and
- the output of the calculations,

for the pilot calculations performed for the industrial company D, for the object 8.

The calculations have been performed for two different time windows, from past hazard and future hazard:

- T4 (1-10-2020 t/m 30-09-2021
- T6 (1-10-2023 t/m 30-09-2029

This is done in order to investigate the impact of the seismic hazard on the final outcome.

2 INTRODUCTION

Industrial companies in Groningen conduct engineering reviews on their industrial plants containing hazardous substances to assure earthquake proof designs as a consequence of gas production in Groningen. A specific prescribed assessment framework is in place.

In order to decrease (unnecessary) time consuming calculations for the earthquake resistance of (process) installations with hazardous substances, two selection steps can be performed between the phase 1 qualitative assessment and the phase 2 quantitative assessments.
The selection between these 2 phases consists of the following two steps:

1) With the selection method step 1, process installations identified in phase 1 are uniformly further tested for safety risk
2) For the remaining objects, this selection method step 2 a quickscan with software can be performed to identify whether an installation is globally sufficiently earthquake-resistant for identified scenarios:

- The earthquake load follows from global hazard curves (earthquake threat), which can also include developments such as the phasing out of gas production;
- The probability of exceeding a limit state is tested on the basis of available fragility curves and the probabilistic earthquake threat (the hazard curve).

The selection process ultimately results in a list of objects which no longer require further investigation, and for which objects is to be continued in phase 2 (the quantitative risk analysis). The selection instruments are included in the Groningen earthquake-resistant industry compensation policy rule.

This report provides the output of the so-called ‘Selection method Step 2 - based on fragility functions’ (NL: ‘Selectie methodiek Industrie Stap 2 - op basis van fragility functions’) to document the results. The methodology of the tool has been developed by Witteveen+Bos, and has been reviewed by TU Delft. The development has been initiated and facilitated by Nationaal Coördinator Groningen.

Chapter 3 presents an overview of all examined object scenarios. Chapter 4 presents all the input information filled in by the engineering consultant in the tool and the outcome per object scenario. Both chapters are automatically generated, and no action is required from the engineering consultant. In chapters 5 and 6, a summary of the results, and conclusions and recommendations shall be added to this report by the engineering consultant.

3 OVERVIEW OF ALL OBJECT SCENARIOS

This chapter presents an overview of all examined object scenario. All the object scenarios are summarized on the selected risk matrices. In case a custom risk matrix has been selected by the engineering consultant / industrial company, the results are presented not only for the custom risk matrix but also for the SIL risk matrix. This is done in order to maintain consistency among different industrial companies.

Table 1 Overview of all object scenarios

object (tag)	scenario (tag)	severity effect	exposure class
Ob7	Sc1T4	Major	Public
Ob7	Sc1T6	Major	Public

Table 2 Overview descriptions severity effect (labels x-axes risk matrices)

Severity effect	description safety effect	description environmental effect
Negligible	small injury, no LTA	Major LOC to environment. damage (large area)
Minor	njury or ill-health requiring first aid only	Significant LOC to environment, National support required
Moderate	Injury requiring medical treatment or ill-health leading to disability	Serious effects, medium LOC to environment, assistance 3rd parties required
Major	Serious injuryes of life threatening occupational disease	Major effect
Catastrophic	One or multiple Fatalities, or one permanent disability	Massive effect

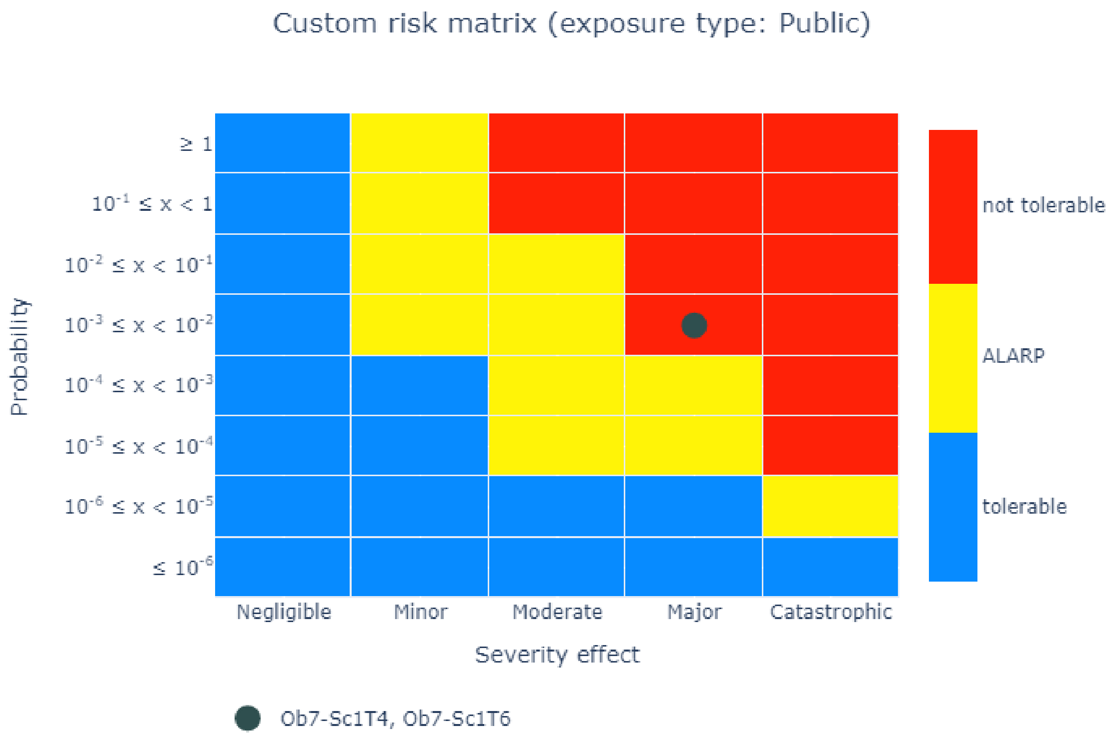
Table 3 Overview SIL descriptions severity effect

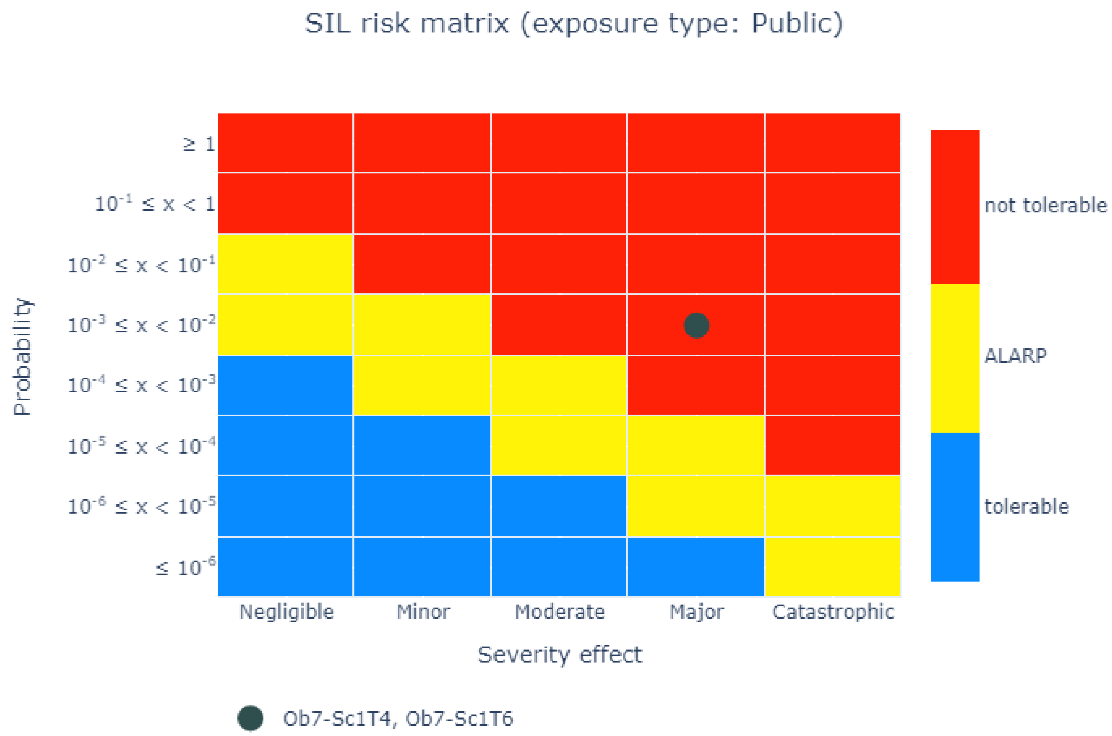
Severity effect	description safety effect	description environmental effect
Negligible	Minor injury ("first aid")	Marginal emission and/or damage within site boundary (< 1 ha)
Minor	Serious injury ("staying at home")	Minor emission and/or damage within site boundary (> 1 ha)
Moderate	Major injury (“hospital”) or multiple serious injuries	Emission and/or damage within site boundary. No permanent damage to surrounding environment (> 10 ha)

Severity effect	description safety effect	description environmental effect
Major	1-2 fatal injuries or permanent disability	Emission and/or damage to surrounding environment (> 100 ha)
Catastrophic	>2 fatal injuries	Major emission and/or damage to surrounding environment (> 1000 ha)

Risk matrices

Public risk matrix





Onsite risk matrix

Risk matrix (exposure type: Onsite) is not available

4 INPUT/OUTPUT PER OBJECT SCENARIO

In this chapter all input values in the tool and choices made by the engineering consultant per object scenario are presented. At the end of each paragraph the outcome is presented on the selected risk matrix and a recommendation regarding further assessment of the foundation is given.

4.1 Object scenario Ob7 - Sc1T4

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T4 (1-10-2020 t/m 30-9-2021)*

Object and scenario input

Object tag: *Ob7*
Object description: *Elevated without bracings*

Scenario tag: *Sc1T4*
Scenario description: *Scenario LoC total collapse is considered*

Foundation
Type foundation: *pile*

Select severity effect category
Severity effect category: *Major*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

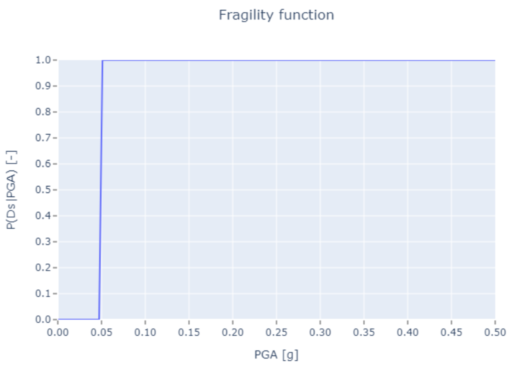
Exposure class
Exposure class: *Public*

Select object typology from literature
Object typology: *Elevated tank (non-braced)*

Damage state and fragility

Explanation
Explanation for chosen object typology or threshold (if applicable):
The elevated tank is supported by very thin legs which povide limited lateral support
Explanation for selected damage state in relation to this scenario:
There is not option for damage state for this fragility function. total colapse is considered

Median of fragility function:	*0.05*
Dispersion of fragility function:	*0.0*
Probability of damage state exceedance:	*6.10e-03*



Selection of obligatory conditional factors
Conditional factor person(s) presence: *1*
Label: *Permanent (24/7 people presence)*

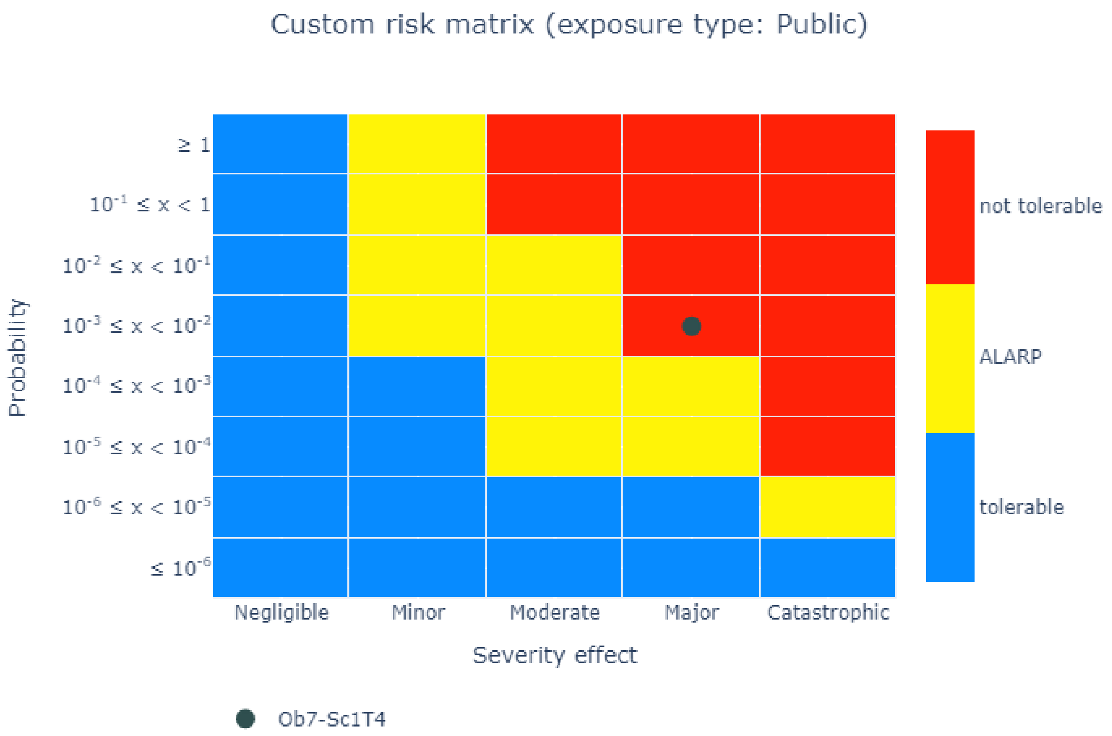
Conditional factor safe shutdown LoD: *1*
Label: *No safe shutdown*

Conditional factor construction state: *1*
Label: *Neutral*

Optional conditional factors
No optional redundancies were specified.

Scenario representation in Risk Matrix
The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object:	*Elevated without bracings (Ob7)*
Scenario:	*Scenario LoC total collapse is considered (Sc1T4)*
Risk matrix selection:	*Public*
The calculated scenario probability is:	*6.099e-03*
The scenario likelihood category is:	*1e-3 ≤ x < 1e-2*
The scenario severity category is:	*Major*



For the seismic hazard level at the location according to NPR 9998:2020 risks associated with loss of bearing capacity of piles cannot be neglected and both STR and GEO limit state assessment is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of

foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

4.2 Object scenario Ob7 - Sc1T6

Location and time window input

The selected location and time window: *Industriegebied Delfzijl, time window T6 (1-10-2023 t/m 30-9-2029)*

Object and scenario input

Object tag: *Ob7*
Object description: *Elevated without bracings*

Scenario tag: *Sc1T6*
Scenario description: *Scenario LoC total collapse is considered*

Foundation
Type foundation: *pile*

Select severity effect category
Severity effect category: *Major*
Reasoning for choosing this severity effect category: *Based on phase 1 study*

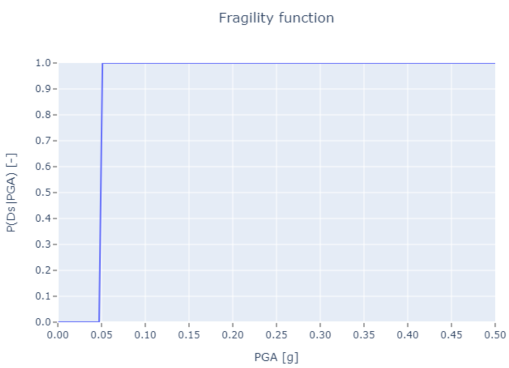
Exposure class
Exposure class: *Public*

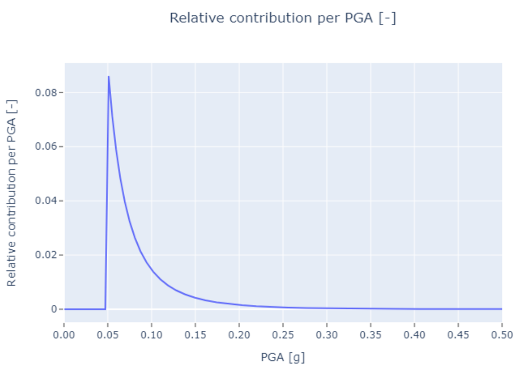
Select object typology from literature
Object typology: *Elevated tank (non-braced)*

Damage state and fragility

Explanation
Explanation for chosen object typology or threshold (if applicable):
The elevated tank is supported by very thin legs which povide limited lateral support
Explanation for selected damage state in relation to this scenario:
There is not option for damage state for this fragility function. total colapse is considered

Median of fragility function:	*0.05*
Dispersion of fragility function:	*0.0*
Probability of damage state exceedance:	*2.66e-03*





Selection of obligatory conditional factors

Conditional factor person(s) presence: *1*
Label: *Permanent (24/7 people presence)*

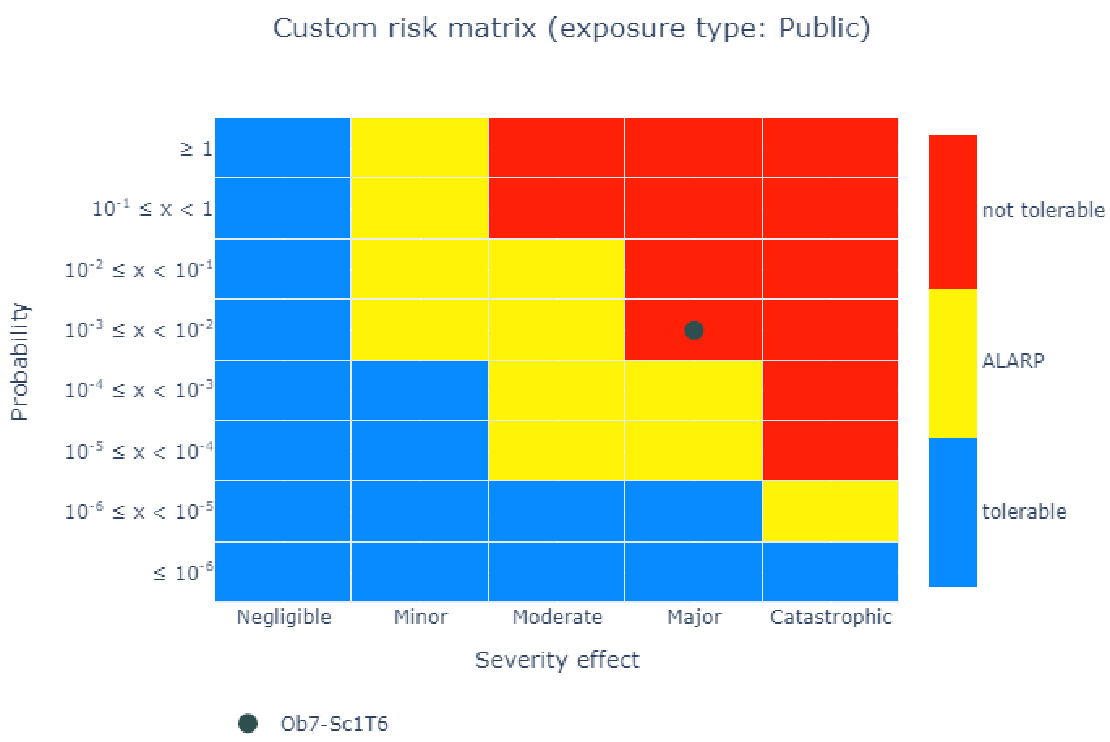
Conditional factor safe shutdown LoD: *1*
Label: *No safe shutdown*

Conditional factor construction state: *1*
Label: *Neutral*

Optional conditional factors
No optional redundancies were specified.

Scenario representation in Risk Matrix
The presented risk matrix below is in accordance with the Ducth SIL Platform publication "A concise best practice guide on Risk Management", October 2018. For public exposure the acceptance criteria are reduced by one likelihood category:

Object:	*Elevated without bracings (Ob7)*
Scenario:	*Scenario LoC total collapse is considered (Sc1T6)*
Risk matrix selection:	*Public*
The calculated scenario probability is:	*2.657e-03*
The scenario likelihood category is:	*1e-3 ≤ x < 1e-2*
The scenario severity category is:	*Major*



The risk of loss of bearing capacity due to structural damage of piles is sufficiently low for the seismic hazard level that applies to the location. Only a GEO limit state assessment (liquefaction verification) is required for the pile foundation (refer to Handreiking Fase 2 (Deltares/TNO), Handreiking LoC and Seismic verification of foundations of industrial assets in Groningen (Witteveen en Bos)). Reference also to NPR 9998:2020 par. 10.4.1.

5 CONCLUSION

In this report we assess the criticality of 1 object of the industrial company D with the selection method Step 2 tool, as part of pilot calculations. For this object a phase 2 assessment has been performed. The outcome of the phase 2 calculation reports is compared with the outcome of the Selection method Step 2 analysis.

The verdict of the phase 2 study was that there is LoC for object 2 with a maximum U.C. of around 2.4. The Selection method Step 2 analysis classifies this object in the red region on both the company specific risk matrix and the SIL risk matrix for public exposure.