Methodology Prognosis of Building Damage

and

Study and Data Acquisition Plan for Building Damage

NAM: [redacted] 5.1.2e

Contents

1 Samenvatting

Eind 2016 heeft het Kabinet ingestemd met het Winningsplan 2016 voor het Groninger gasveld, onder de voorwaarden en beperkingen die de Mijnbouwwet mogelijk maakt. Ten aanzien van schade aan gebouwen als gevolg van de toegestane productie heeft de overheid bij de instemming bepaald dat NAM:

i. per 1 februari 2017 een **methodiek** heeft onwikkeld om schades vast te stellen en te voorspellen
ii. de methodiek aansluitend toepast en per 1 november 2017 een **voorspelling** doet op basis van de toegestane productie(verdeling)

Het navolgende rapport bevat de voorgestelde **methodiek** om te komen tot een voorspelling van toekomstige schades. De NAM stelt een aanpak voor op basis van een samengestelde methodiek, bestaande uit:

1. **historische trends**: deze aanpak bouwt voort op de historisch waargenomen schades. Het aantal schade-rapporten is aanzienlijk toegenomen en heeft inmiddels de kwaliteit om daarop gedegen analyses te baseren en met enige zeggingskracht een projectie op de toekomst te geven. Een aantal trends is reeds aangereikt in het Winningsplan 2016. Dit deel van de methodiek zal daarop een verdere diepgang geven.
2. **gebouwrespons**: dit deel van de methodiek is gelijk aan de aanpak binnen de dreigings- en risico-analyse tot nu toe. Op basis van de EMS-systematiek omvat het de toepassing van experimentele onderzoeken om verschillende schadeniveaus bij verschillende grondbewegingen te voorspellen. Daartoe zullen additionele onderzoeken worden verricht gedurende 2017, waaronder nieuwe testen op de schudtafel.
3. **schadeprogressie**: deze stroom modelleert het ontstaan en de eventuele groei van scheurvorming en schades bij verschillende niveaus van grondbeweging. Daarbij zal specifieke aandacht worden geschonken aan het effect van reeds bestaande spanningsverhoudingen binnen een gebouw.

Deze drie methoden zijn aanvullend aan elkaar om de toekomstige schade door aardbevingen te kunnen voorspellen. Waarbij elke methode ziet op een specifiek deel van de 'schadeladder' die loopt van DS1 naar DS5. Naar verwachting dragen zij elk afzonderlijk bij aan de ontwikkeling van de 'kwetsbaarheidscurves' die aan de basis liggen van de voorspelling.

Het gezamenlijke resultaat en overkoepelende voorspelling van de toekomstige schades in de Groninger regio zal **voor 1 november 2017** aan de minister van Economische Zaken worden aangeboden.

1.1 Summary

At the end of 2016, the Dutch government approved the Winningsplan 2016 for the Groningen gasfield, based on the requirements of the Mining Act. With regard to damage to buildings, the government stipulated that NAM shall:

i. Provide a **methodology** to forecast damage by February 1, 2017;
ii. Provide the **actual forecast** (given production of 24 bcm/year) by November 1, 2017.

The current report lays out the proposed methodology to arrive at a prognosis for future damage. NAM proposes a three-pronged approach:

1. **Historical Trends Method.** This approach builds on the historical record of damage in Groningen to date. The volume of damage assessments has increased significantly over the past years – and so has the quality of damage assessments. This allows for meaningful projections into the future. NAM has already shared a number of trends in the 2016 Winningsplan. This approach will deepen that effort.
2. **Building Response Method.** This approach is similar to the earlier Hazard and Risk studies. Following the EMS-98 convention, it employs experimental findings to predict different levels of damage at different levels of ground motion. Supplementary experiments will be conducted throughout 2017. This also includes additional shake-table tests.
3. **Damage Development Method.** This approach will model the initiation and development of cracks and damage for different levels of ground motion. This approach will specifically focus on the effects of pre-existing stress in a building.

These three methods are supplementary in their ability to forecast future earthquake damage. Each method is particularly suited for a specific range of the spectrum of damage states, which runs from DS1 to DS5. It is therefore anticipated that each of these three methods will in one way or another contribute to the development of the required fragility curves, which lie at the base of forecasting of future earthquake damage.

The joint results of these three methods, providing an overall estimate of future earthquake damage in the Groningen region, will be submitted to the Minister of Economic Affairs **before November 1, 2017**.

1.2 Readers Guide

The current chapter serves as a summary of the overall report.

Chapters 2 provides a general introduction (section 2.1), describes the motivation for this report (section 2.3) and gives an overview of the important concept of building damage states (section 2.4). Furthermore, the studies relevant to building damage already included in the "Study and Data Acquisition Plan Induced Seismicity in Groningen - Update Post-Winningsplan 2016" (issued April 2016) (Ref. 3) are summarized (section 2.2).

In chapter 3, the methodology for forecasting building damage is presented. This will be implemented as an extension of the probabilistic methodology for the assessment of seismic hazard and risk, used for Winningsplan 2016.

Although the assessment of hazard has already been developed over the last years, this needs to be extended to cover hazard metrics more appropriate for the forecasting of building damage. The additional hazard studies are described in chapter 4.

As part of the studies supporting the assessment of seismic risk, fragility curves for a large set of different building typologies have been developed for the higher building damage states including full and partial collapse (DS4 and DS5). Essential for the prognosis of building damage, is to supplement these fragility curves with fragility curves for lower damage states (DS1 to DS3). The following three chapters, 5 to 7, describe the proposed studies, laboratory experiments and projects to develop these additional fragility curves. Each chapter describes a separate work stream. These three chapters, serve as a "Study and Data Acquisition Plan for Building Damage".

These three work streams are brought together in chapter 8, in a work plan for the development of the fragility curves covering the full range of damage states. A schedule for the delivery of a building damage prognosis is provided in chapter in chapter 9. These two section together are a plan of approach for the "Study and Data Acquisition Plan for Building Damage".

2 Introduction

2.1 Studies into Forecasting and Mitigation of Damage

Following the Huizinge earthquake of 16th August 2012, NAM has intensified the study effort and undertaken a research program. This was based on the Study and Data Acquisition Plan prepared for the first time in October 2012 (Ref. 1) and since then updated in 2014 (following Winningsplan 2013) (Ref. 2) and 2016 (submitted with Winningsplan 2016) (Ref. 3).

The prime objectives of this plan are:

1. To improve understanding of the impact of the earthquake hazard on buildings and other structures and the subsequent impact on safety of the community;
2. To perform a fully integrated Hazard and Risk Assessment for the Groningen region, with all known uncertainties fully and consistently recognised and quantified;
3. To identify, evaluate and develop mitigation options to reduce safety risk:
   - Production measures, i.e. changes in the production from the field
   - An optimised Structural Safety Upgrading program:
     - Identify buildings and/or building elements that pose a safety risk
     - Establish optimal structural upgrading methodologies
   - Measures for industry and infrastructure.

Other important objectives are to:

4. To discuss the merits of alternative scientific views, and initiate additional studies and/or data acquisition to promote consensus amongst the knowledge institutes;
5. To monitor compaction, subsidence and seismicity;
6. To improve continuously our understanding of the physical mechanisms leading to induced seismicity and the resulting hazard;
7. To reduce the uncertainty in the hazard and risk assessment.

Up until now, this study program focused primarily on **personal safety** and **understanding and forecasting of hazard and risk.** The Hazard and Risk Assessment of November 2015 provided for first time a calibrated probabilistic assessment of risk. Since then, studies focussing on building damage have been accelerated.

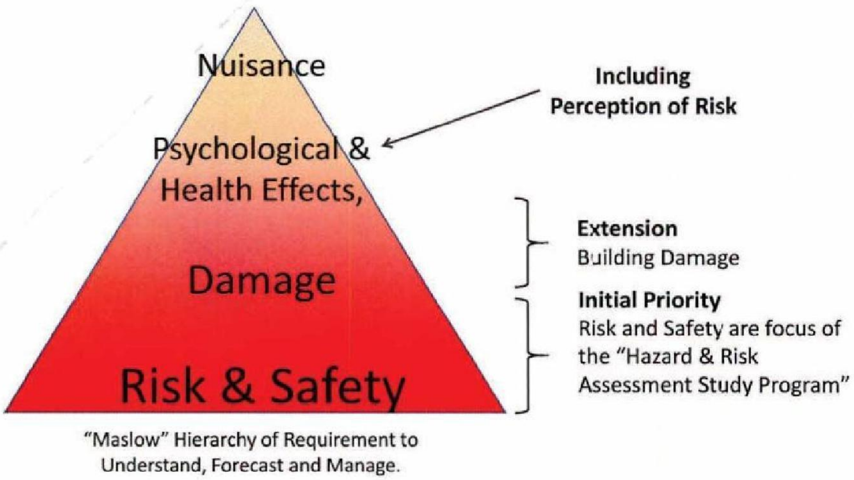

Figure 2.1 Prioritisation of the study focus. Initially, Risk was the prime focus of the studies program.

Damage has been one of the 'strands' in NAM's bow-tie as of December 2013 (Ref. 4). The initiating study into a comprehensive methodology for building damage commenced in January 2016 for inclusion into the Winningsplan (Ref. 7), which was submitted on 1st April 2016. The study is further documented in Chapter 9 of the Technical Addendum of the Winningsplan and mainly consisted of an analysis of damage claim data and showed results of the damage forecasting method developed by TNO in 2009 for more recent earthquakes. The relationship between seismic activity and damage claims appears to be complex.

Further research is required into:

- The area where earthquakes could release sufficient energy to cause damage
- the precise relationship between damage claim reports and actual damage,
- The assessment of claimed damages as A-, B- or C-damage, or combinations thereof

There appears a growing trend in the content of C-damage (damage which cannot be attributed to earthquakes) in damage claims from mid-2015 onwards.

2.2 Studies into Building Damage in the "Study and Data Acquisition Plan Induced Seismicity in Groningen - Update Post-Winningsplan 2016"

The research activities with regard to building damage included in the "Study and Data Acquisition Plan into effects of Induced Seismicity in Groningen - Update Post-Winningsplan 2016" focus on: 1) monitoring; and 2) damage data collection. This section offers a brief recap of the most important damage-related study activities in that plan (Ref. 3).

2.2.1 Hazard Description for Damage Prediction

The assessment of risk initially focussed on the collapse of buildings and failure of building elements. The choice of hazard metrics focussed on this overall objective. The assessment of building damage requires the forecasting of additional hazard metrics. The forecasting of these metrics is included in the "Study and Data Acquisition Plan – Update Post-Winningsplan 2016".

2.2.1.1 Ground Shaking

The focus on building collapse required the forecasting of response spectral acceleration and duration of the ground movement. One of the metrics for ground acceleration that is often used is PGA.

For the prediction of building damage, ground velocity and and repeated seismic loading from a number of events may also play an important role.

2.2.1.2 Liquefaction

The hazard resulting from liquefaction of loose sand due to an earthquake will be incorporated in the hazard assessments.

While less important for risk, liquefaction can result in uneven settlement and damage to buildings and especially to underground infrastructure like sewers.

2.2.1.3 Uneven Settlement

Building damage can be the result of uneven settlement. This is an alternative cause of earthquake building damage, but can also exacerbate earthquake damage. Swelling clays near the foundation of buildings can potentially cause stresses on foundations lowering the threshold for damage due to earthquake vibrations.

2.2.2 Monitoring Network for Building Damage

2.2.2.1 Monitoring Network

To monitor the movement of the foundations at buildings, TNO has installed **accelerometers** in the foundations of selected buildings in the Groningen area. Initially, close to 200 buildings were selected. Some 20 of these were public buildings such as town halls of municipalities. In the course of 2015, additional accelerometers have been placed by TNO and currently the total number of sensors installed exceeds 300. Buildings were inspected for damage prior to installation of the sensors and have been re-inspected after each earthquake near the building.

2.2.2.2 Building Inspections of buildings with Monitoring Sensors

Building inspections are carried out frequently in the Groningen. These inspections help us to deepen our understanding of the causal link between earthquake vibrations and damage to buildings. As part of the sensor installation, an initial inspection of damage on the outside of the building (e.g. cracks in exterior walls) is carried out. During this initial inspection, any characteristic properties of the building are logged that may be relevant for damage analysis at a later stage.

After each sizable earthquake, **another inspection** is carried out for buildings subjected to a maximum vibration velocity exceeding 1 mm/s to establish potential additional damage caused by the earthquake. The nature and degree of that damage is then classified in a damage category. By plotting inspection results for all the buildings in the monitoring network against the peak vibration velocity (or other hazard metric for the earthquake), relationships can be established between these two variables.

2.2.3 Use of High Resolution InSar to monitor Building Movement

The geodetic work plan will be coupled to currently available geodetic data and will provide a long-term complementary monitoring solution. The high resolution **InSar** acquisition, processing and reporting will offer important support to damage analysis and documentation of building movements without the need for dedicated interventions.

2.2.4 Flexible Seismic Monitoring System

The **Flexible Seismic Monitoring System** will allow monitoring of movements in individual buildings. Several accelerometers can be placed for a limited duration at various locations in the building under investigation; e.g. different floor levels. This will allow assessing the response of the building to small vibrations to establish the resonance frequency of the building.

2.2.5 In-situ Dynamic Testing of Structural Systems

The shake-table tests in the laboratory will be further analysed and extended to better analyse the damage patterns and development of the lower damage states. The feasibility of performing **in-situ shake-table tests** on existing buildings will be investigated.

2.3 Damage in Instemmingsbesluit winningsplan Groningenveld (30th September 2016)

Building damage played a central role in the comments from SodM and other advisory committees (Tcbb and SAC) on Winningsplan 2016. In his "Instemmingsbesluit Winningsplan Groningenveld" (30th September 2016), the Minister summarised the comments by SodM as follows[1]:

> *Verder geeft SodM aan dat het de beoordeling van NAM dat schade van niveau DS1 en zeker DS2 voor inwoners van Groningen acceptabel zou zijn, niet deelt. DS2-schade (scheuren in meerdere muren) is naar de mening van SodM meer dan slechts "hinder". Het voorkomen en beperken van schade zouden volgens SodM uitgangspunt moeten zijn bij het bepalen van het niveau van de gasproductie. NAM geeft er volgens SodM onvoldoende blijk van dat dit ook voor haar een leidend criterium is.*

[1] Translation from Dutch: SodM further indicates that the assessment of NAM that damage levels DS1 and DS2 would be acceptable for certain residents of Groningen, is not shared. DS2 damage (cracks in several walls) is in the opinion of SodM more than a mere "nuisance." Preventing and minimizing damage should be the starting point according to SodM in determining the level of gas production. NAM gives in the view of SodM sufficiently recognition that this is for NAM a guiding criterion.

The section "overige besluiten" of the "Instemmingsbesluit winningsplan Groningenveld" (30th September 2016) contains the following statements concerning damage.

8.5 Schade[2]

Met de adviseurs ben ik van mening dat er, naast berekening van het veiligheidsrisico, een goed inzicht nodig is in de schade die door de gaswinning uit het Groningenveld ontstaat. Daartoe dient een rekenmethodiek ontwikkeld te worden die inzicht geeft in de te verwachten schades die niet zo groot zijn dat het de veiligheid in gevaar brengt, maar die op grond van de Mijnbouwwet wel zoveel mogelijk moeten worden voorkomen. Het gaat daarbij om de schadeniveaus DS1, DS2 en DS3 van de EMS schaal EMS-98 van de European Seismological Commission.

Vervolgens dient NAM op basis van deze rekenmethodiek berekeningen uit te voeren die aan mij wordt gerapporteerd. In dat rapport moet ook inzicht gegeven worden in het schadedeel van de berekening van het maatschappelijk risico.

NAM addresses this issue in the response (*zienswijze*) to the "Instemmingsbesluit Winningsplan Groningenveld" (30th September 2016)[3]:

De indruk dat NAM DS1- en DS2-schade ongekwalificeerd acceptabel zou vinden, is mogelijk ontstaan op basis van het bewuste onderscheid dat in het Winningsplan is gemaakt tussen de (levens)veiligheidsoverweging (waaraan kleinere schades alleen niet bijdragen) en de overweging van schade als bron van zorg en hinder voor de bevolking. In het Winningsplan wordt in de hoofdstukken 6.3.2.1 en 7.2.1 ook toegelicht dat eerst naar veiligheid wordt gekeken en daarna naar schade en de voorkoming van hinder daarvan. Daarbij moet worden bedacht dat maatregelen die vanuit veiligheidsperspectief worden genomen óók een positieve invloed hebben op het voorkomen en beperken van schade, hoewel de huidige stand van de techniek deze nog niet kan kwantificeren.

The "Instemmingsbesluit Winningsplan Groningenveld" (30th September 2016) imposes the following on NAM:

Besluit[4]:

Artikel 7

1. *De Nederlandse Aardolie Maatschappij B.V. dient uiterlijk op 1 februari 2017 een rapport in bij de Minister van Economische Zaken waarin een methodiek is opgenomen voor het berekenen van de mate van schade – als gevolg van geïnduceerde bevingen - voor de schadegrenstoestanden DS1, DS2 en DS3 uit het EMS-98, European Seismological Commission, 1998.*

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[2] Translation from Dutch:
8.5 Damage
With my advisers, I am of the opinion that, in addition to calculating the safety risk, a good understanding of the damage caused by the gas from the Groningen field is required. For this purpose, a calculation method needs to be developed that gives insight into the expected damage that are not so large as to cause a safety at risk, but which should be avoided as much as possible under the Mining Act. It concerns the damage levels DS1, DS2 and DS3 of the EMS scale EMS-98 of the European Seismological Commission.
Subsequently, NAM should perform based on this calculation method calculations and report these to me. That report should also provide insight into the damage part of the calculation of the societal risk.

[3] Translation from Dutch:
The impression that NAM would find DS1- and DS2 damage unqualified acceptable, may arise because a conscious distinction was made in the Winningsplan 2016 between the (life) safety considerations (in which minor damage only do not contribute) and the consideration of damage as a source of concern and nuisance to the public. In the Winningsplan 2016 this is also explained in sections 6.3.2.1 and 7.2.1 which first look at safety and then to injury and the prevention of nuisances thereof. It should be noted that measures taken from the safety perspective also have a positive impact on preventing and minimizing damage, although the current state of technology cannot quantify it yet.

[4] Translation from Dutch:
Article 7
1. The NAM B.V. has to submit a report no later than February 1, 2017 to the Minister of Economic Affairs in which a methodology has been included for the calculation of the level of damage - due to induced earthquakes - for the damage limit states DS1, DS2 and DS3 of the EMS-98, European Seismological Commission, 1998.
2. The NAM B.V. has to submit a report no later than November 1, 2017 to the Minister of Economic Affairs, in which the methodology referred to in the first paragraph, worked out for the level of production under Article 2, paragraph 1. It also included an estimate in the report of the factor MR (S), which is the loss section of the definition of social risk.

2. *De Nederlandse Aardolie Maatschappij dient uiterlijk 1 november 2017 een rapport in bij de Minister van Economische Zaken, waarin de methodiek, als bedoeld onder het eerste lid, is uitgewerkt voor het productieniveau uit artikel 2, eerste lid. Tevens wordt in het rapport een raming opgenomen van de factor MR(S), zijnde het schadedeel van de definitie van maatschappelijk risico.*

Artikel 7

1. De Nederlandse Aardolie Maatschappij B.V. dient uiterlijk op 1 februari 2017 een rapport in bij de Minister van Economische Zaken waarin een methodiek is opgenomen voor het berekenen van de mate van schade – als gevolg van geïnduceerde bevingen - voor de schadegrenstoestanden DS1, DS2 en DS3 uit het EMS-98, European Seismological Commission, 1998.

2. De Nederlandse Aardolie Maatschappij dient uiterlijk 1 november 2017 een rapport in bij de Minister van Economische Zaken, waarin de methodiek, als bedoeld onder het eerste lid, is uitgewerkt voor het productieniveau uit artikel 2, eerste lid. Tevens wordt in het rapport een raming opgenomen van de factor MR(S), zijnde het schadedeel van de definitie van maatschappelijk risico.

Figure 2.2 Excerpt from the "Instemmingsbesluit Winningsplan Groningenveld" issued 30th September 2016.

The current document also describes a proposal for an additional study effort aimed at developing the knowledge and capability to fulfil the requirement of article 7 in the instemmingsbesluit.

2.4 Building Damage States

2.4.1 European Seismological Commission, EMS-1998

The *severity* of an earthquake is described by both magnitude and intensity. These refer to different, but related, characteristics of an earthquake.

The Winningplan 2016, article 7 of the instemmingsbesluit and many of the studies available refer to EMS-98, European Seismological Commission, 1998 (Ref. 8). The EMS-98 document provides the guidelines for estimation of the *intensity* of an earthquake.

Magnitude of earthquakes

The **magnitude** of an earthquake reflects the energy released. An earthquake has one single magnitude.

Intensity of earthquakes

The **intensity** of an earthquake represents the shaking resulting from an earthquake and captures the local impact on humans and buildings and the potential to cause damage. The earthquake intensity depends for example on distance from the epicenter and local soil conditions.

The Winningplan 2016, article 7 of the instemmingsbesluit and many of the studies available refer to EMS-98, European Seismological Commission, 1998 (Ref. 8). The EMS-98 document provides the guidelines for estimation of the intensity of an earthquake.

Damage of buildings is assessed on the basis of a damage classification. This is provided for two main categories: unreinforced masonry buildings (URM) and reinforced concrete (RC) buildings. Figures 2.4 and 2.5 describe each of the 5 distinguished damage grades for both main categories. The description of the damage states in these figures is purely qualitative. For instance, "negligible to slight damage" is termed DS1, "moderate damage" DS2, "substantial to heavy damage" DS3". The EMS scale relates DS1 to "hairline cracks in very few walls", DS2 to "cracks in many walls" and DS3 to "large and extensive cracks in most walls". The qualitative descriptions of the building damage states form a very useful, practical and generally accepted and applied classification system for building damage. However, there remains a subjective element to the assessment, leaving (some) room for different interpretations, making it difficult to unequivocally ascertain the damage state of a building.

Figure 2.3 *Cover of the "European Macroseismic Scale 1998, EMS-98"by the European Seismological Commission (G. Grünthal), 1998 and the "Field Manual for post-earthquake damage and safety assessment and short term counter measures (AeDEA)" by the European Commission Joint Research Centre (JRC), 2007*

2.4.2 Field Manual for post-earthquake damage and safety assessment (AeDEA)

The European Commission Joint Research Centre (JRC) has prepared a field manual for post-earthquakes evaluation of buildings (Ref. 9). Using a standard form, buildings can be classified and damage of buildings can be graded in a consistent manner. The JRC field manual also contains a section with examples of damaged buildings and their damage ratings. The manual focusses mainly on the higher damage states. For instance, it does not offer an example of a building with DS1.

Unfortunately, this highly practical manual still leaves us with remaining ambiguity in the classification of simulation results and laboratory experimental results. A more precise definition of damage states, therefore, would be very useful. The proposed research aims to establish a consistent definition of the damage states to reduce ambiguity in the interpretation of these results.

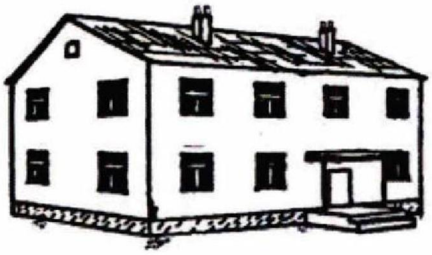
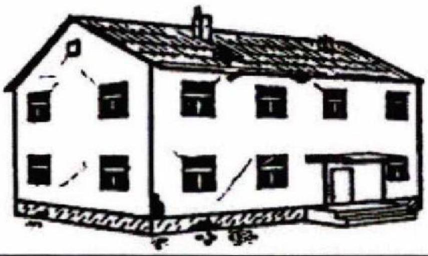
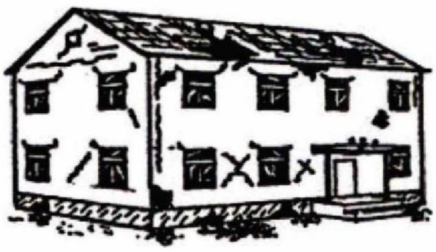
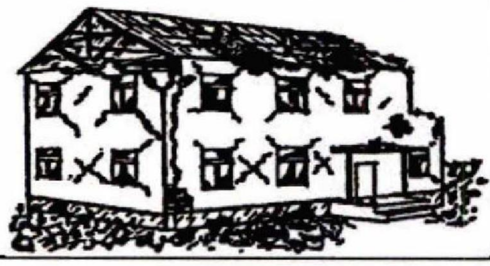
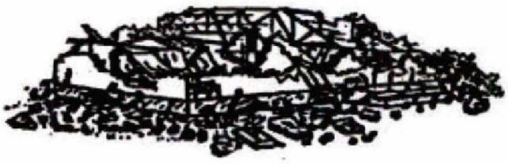
Classification of damage to masonry buildings	
	**Grade 1: Negligible to slight damage** **(no structural damage,** **slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage** **(slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage** **(moderate structural damage,** **heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	**Grade 4: Very heavy damage** **(heavy structural damage,** **very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.
	**Grade 5: Destruction** **(very heavy structural damage)** Total or near total collapse.

Figure 2.4 Classification of damage to masonry buildings. Illustration taken from EMS-98, European Seismological Commission, 1998 (Ref. 8).

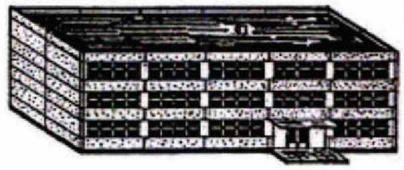
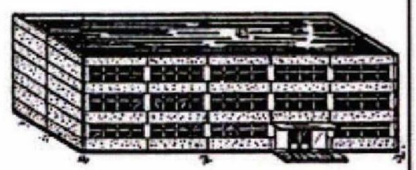
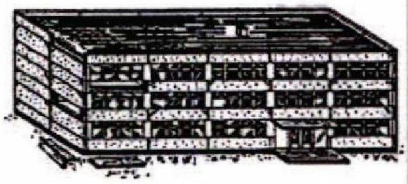
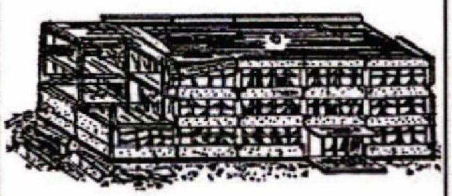
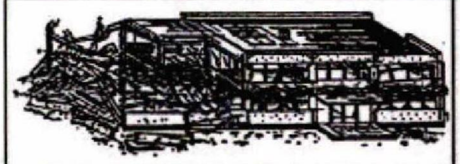
Classification of damage to buildings of reinforced concrete	
	**Grade 1: Negligible to slight damage** **(no structural damage,** **slight non-structural damage)** Fine cracks in plaster over frame members or in walls at the base. Fine cracks in partitions and infills.
	**Grade 2: Moderate damage** **(slight structural damage,** **moderate non-structural damage)** Cracks in columns and beams of frames and in structural walls. Cracks in partition and infill walls; fall of brittle cladding and plaster. Falling mortar from the joints of wall panels.
	**Grade 3: Substantial to heavy damage** **(moderate structural damage,** **heavy non-structural damage)** Cracks in columns and beam column joints of frames at the base and at joints of coupled walls. Spalling of conrete cover, buckling of reinforced rods. Large cracks in partition and infill walls, failure of individual infill panels.
	**Grade 4: Very heavy damage** **(heavy structural damage,** **very heavy non-structural damage)** Large cracks in structural elements with compression failure of concrete and fracture of rebars; bond failure of beam reinforced bars; tilting of columns. Collapse of a few columns or of a single upper floor.
	**Grade 5: Destruction** **(very heavy structural damage)** Collapse of ground floor or parts (e. g. wings) of buildings.

Figure 2.5 *Classification of damage to reinforced concrete buildings. Illustration taken from EMS-98, European Seismological Commission, 1998 (Ref. 8), also used in Winningsplan 2016.*

2.4.3 Definition of Damage States for Experimental Studies

The descriptive definition of the Damage States in EMS-98 (Ref. 8) and the further clarification in "Field Manual for post-earthquake damage" (Ref. 9) provides a very useful and practical guide for expeditious assessment of building damage due to earthquakes. This section discusses a more quantitative description and classification of building damage to masonry structures for experimental and theoretical investigations.

2.4.3.1 Pre-requisite for experimental and theoretical investigations into building damage: How do we define 'damage' and how do we quantitatively define the damage states?

Before discussing any measurement instruments, we need to define damage. Somewhat surprisingly, such a definition is not readily available from previous international earthquake research. In the European Macro-seismic Scale 1998, EMS-98, "negligible to slight damage" is termed DS1, "moderate damage" DS2, "substantial to heavy damage" DS3. These notions are purely descriptive and therefore leave room for interpretation. For example, the EMS scale relates DS1 to "hairline cracks in very few walls", DS2 to "cracks in many walls" and DS3 to "large and extensive cracks in most walls". Such qualitative descriptions are rather subjective; they are only a partial guide to measuring building damage.

We will start with a review of these criteria and then come up with proposals to quantify the descriptions. First, 'damage' can be associated with the visible state of *deformation*: the walls and bed joints not being level anymore, not being plumb anymore, tilting, bowing visibly out-of-plane, sagging visibly in-plane, hogging visibly in-plane. Such damage can be identified by the naked eye, by bed joint levelling ("lintvoeg waterpassing") or simply by experiencing that doors or windows "stick". Second, 'damage' can emerge in visible degradation of the masonry material, mainly in the form of *mode-I tensile cracks*. Though other forms of degradation occur, like mode-II shear slip, compression spalling or crushing, these become relevant only for higher earthquake loads with excessive shearing in bed joints or toe crushing in piers. For *light earthquake vibrations* however, we assume that only mode-I tensile cracks occur as by far the weakest point of unreinforced masonry is its low tensile stress capacity, and consequently, this weakness drives to tensile cracking for small vibrations. The focus in this study is thus on mode-I tensile cracks, featuring in the Groningen damage cases.

The above limit states will be elaborated and quantified mainly in terms of crack width. This task will be carried out as part of the research. This study will rely on the framework employed in tunnelling-induced settlement damage to masonry houses (Giardina et al. 2015), which states:

- negligible damage is crack width < 0.1 mm,
- very slight damage is crack width < 1 mm,
- slight damage is crack width < 5 mm,
- moderate damage is crack width between 5 and 15 mm,
- severe damage is crack width between 15 and 25 mm,
- very severe damage is crack width > 25 mm.

Figure 2.6 shows an example of such damage state quantification in terms of crack width, both as continuous and discrete function.

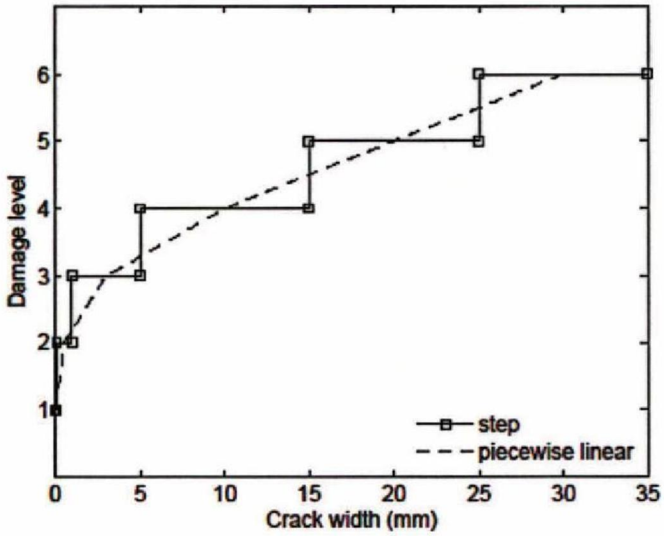


Figure 2.6 Example of damage state quantification in terms of crack width, both as continuous and discretized function.

In addition to crack width, the experiments and computations in this study will also pay attention to the following aspects of building damage:

1. Crack density;
2. Crack spacing;
3. Number of cracks;
4. Crack direction (horizontal, vertical, stair-case diagonal), crack tapering (tapering of crack width, e.g. is the maximum crack width at the top or at the bottom of the façade - an interesting indicator for understanding damage);
5. Appearance of cracks (it makes a difference whether cracks run along brick-joint interfaces in clean brickwork "schoon metselwerk", or whether we have through-brick cracks in clean brickwork, or cladding cracks in plastered brickwork);
6. Deformation measures like displacement profiles, un-level, tilts, distortions.
7. Implicit damage criteria in terms of e.g. drift limits, as assumed in e.g. the Italian codes (also for the definition of damage criteria for non-URM structures).

3 Methodology for assessing Building Damage

3.1 Introduction

The probabilistic assessment of seismic hazard associated with the induced earthquakes in the Groningen field was performed using the Monte Carlo simulation method as of Winningsplan 2013. In November 2015, an integrated probabilistic assessment of seismic hazard and risk in the Groningen area was prepared using an extension of the Monte Carlo software. For Winningsplan 2016 this methodology was further refined to cover the full causal chain from the withdrawal of gas from the reservoir to the life safety impact on people in buildings (Fig. 3.1).

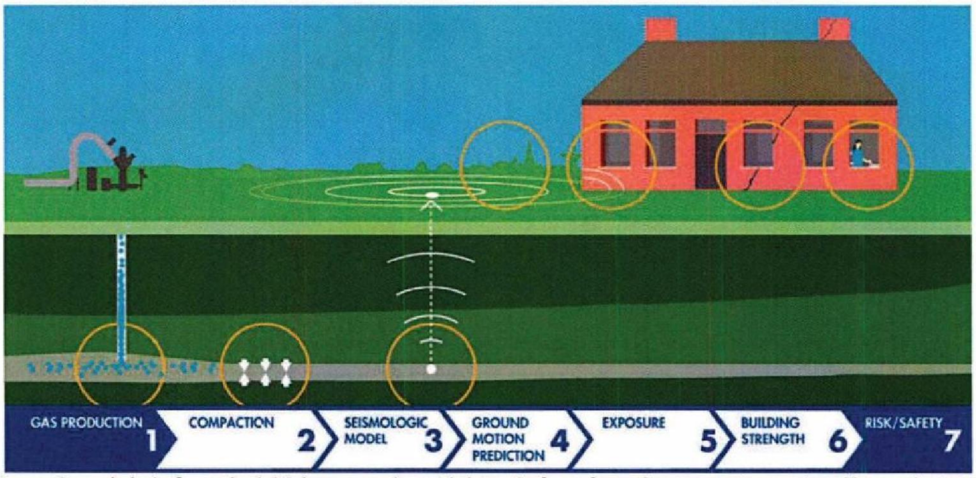


Figure 3.1 *Causal chain from the initial cause - the withdrawal of gas from the reservoir - to the effect - the impact on the life safety risk for people in buildings.*

3.2 Monte Carlo Simulation

A typical Monte Carlo simulation repeats the model calculations many thousands of times, each time using different randomly selected input values, such that the stochastic variability of the output is small enough to ensure stability of the accumulated results at the probability levels required. The Monte Carlo methodology used for the seismic hazard and risk assessment is summarised in Figure 3.2. Full details of the method can be found in references 5, 6 and 10.

Underlying model

- The underlying **seismological model** is an empirical relationship between reservoir compaction and structure and the number of earthquakes induced by the gas production over a given time. This model considers the occurrence of earthquakes to be a (Poisson) random process, driven by the reservoir compaction due to production. Compaction is modelled for a range of gas production scenarios.
- The effects of spatial and temporal clustering of earthquakes were found to be statistically significant and have been incorporated in the model using the Epidemic Type After-shock Sequence (ETAS) formalism.
- The consequences of the individual synthetic earthquakes are calculated using probabilistic models for earthquake ground motion, building damage and risk of death or injury of the exposed population.
- The seismological model and ground motion prediction equations have been repeatedly calibrated using the earthquake catalogue (locations and magnitudes) and ground motion data available to date. The compaction model is calibrated with a wealth of geodetic data.

Input parameters

- ***Synthetic earthquake catalogues***. In the Monte Carlo simulation process for the induced seismic hazard and risk assessment, repeated random sampling of a set of input distributions is used to build up a probabilistic output. So-called 'synthetic earthquake catalogues' (i.e., event locations and magnitudes for a specified time period) are generated from the input probability distributions of total seismic moment, number of events and event epicentres.

- ***Aleatory uncertainties.*** The inherently stochastic nature of earthquakes and the statistical variability of key properties determining earthquake ground motion, building damage and consequences of damage for inhabitants are captured by the properties of the input distributions sampled. In this way the so-called aleatory uncertainties are modelled. Examples of such aleatory uncertainties in our simulation process are numbers of earthquakes in a catalogue and their locations, orientations and magnitudes, subsurface rock properties and small-scale near surface soil properties, strength and condition of buildings and the locations of inhabitants in relation to occurrences of building collapse.
- ***Epistemic uncertainties.*** Systematic uncertainties associated with a lack of knowledge of key pieces of information, the so called epistemic uncertainties, are addressed by running separate simulations with different sets of input parameter values. The key epistemic uncertainties are identified and likely ranges of values for these parameters with associated probabilities are estimated. Examples of key epistemic uncertainties identified are: i) the earthquake stress drops; ii) the maximum possible earthquake magnitude; iii) the set of medians and standards deviations defining the fragility curves; iv) and the values of the coefficients determining the probabilities of death if building collapse occurs.

Design

- ***Logic tree.*** With a manageable set of epistemic uncertainties identified and quantified, a logic tree is built up by running a separate simulation for each distinct path through the set of all possible parameter choices. For example, if four key uncertain parameters have been identified, each with 3 possible values (low, mid and high cases) then a logic tree with 3^4=81 distinct paths must be simulated. The final result is a set of output distributions from which summary statistics (mean, median, P10, P90 etc) can be calculated by combining results from the individual logic tree branches weighted by their input probabilities.
- Fragility curves are used to characterise the probabilities of building damage. A fragility curve gives the probability of a given building type exceeding a given damage state as a function of the seismic ground motion (ideally spectral displacement at a given frequency). It is a cumulative distribution function characterising the capacity of buildings of a certain typology to withstand seismic loading (demand) and therefore reflects the spread of building properties within the defined typology class. Fragility curves have so far been developed only for the higher damage states characterising partial collapse (Damage State 4, DS4) and full collapse (Damage State 5, DS5), for the assessment of life safety risk. The assessment of lower states of building damage requires the development of fragility curves for the damage states DS1, DS2 and DS3 as shown schematically in Fig. 3.3. The activities to develop these fragility curves are described in sections 5, 6 and 7.

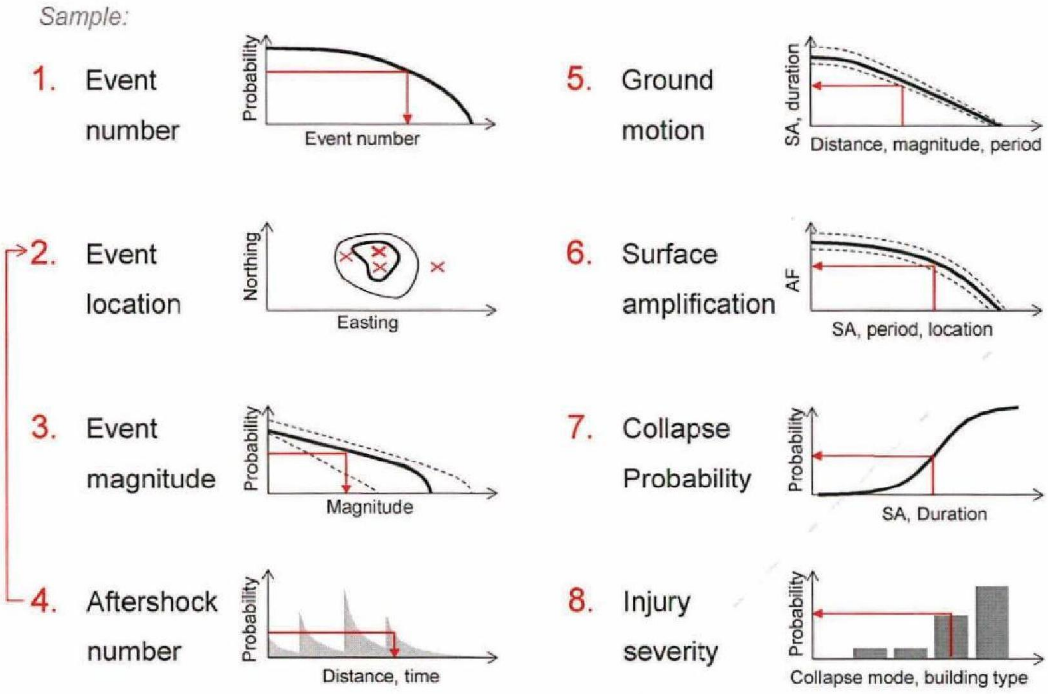


Figure 3.2 Monte Carlo simulation of the seismic hazard and risk model.

The extension of the method to encompass the lower damage states will make significant additional demands on computation (CPU time). Efforts to speed up the code for the Monte Carlo simulation have progressed in 2016. However, whether these have kept pace with the anticipated growth in CPU demand for the prognosis of the lower states of building damage needs to be tested.

The procedure entails the following. Earthquake magnitudes are sampled from the frequency-magnitude distribution (usually assumed to follow a Gutenberg-Richter relationship). This distribution, then, will be truncated at the high end by the maximum magnitude, M_{max}, and at the low end by M_{min}. A value of M_{min} must be chosen such that it is low enough to ensure that all significant contributions to the ground motion hazard and risk are captured, but high enough to allow sufficiently fast simulations. For the evaluation of lower building damage, states M_{min} will need to be set much lower than for the building collapse fatality risk assessment resulting in increased simulation run times.

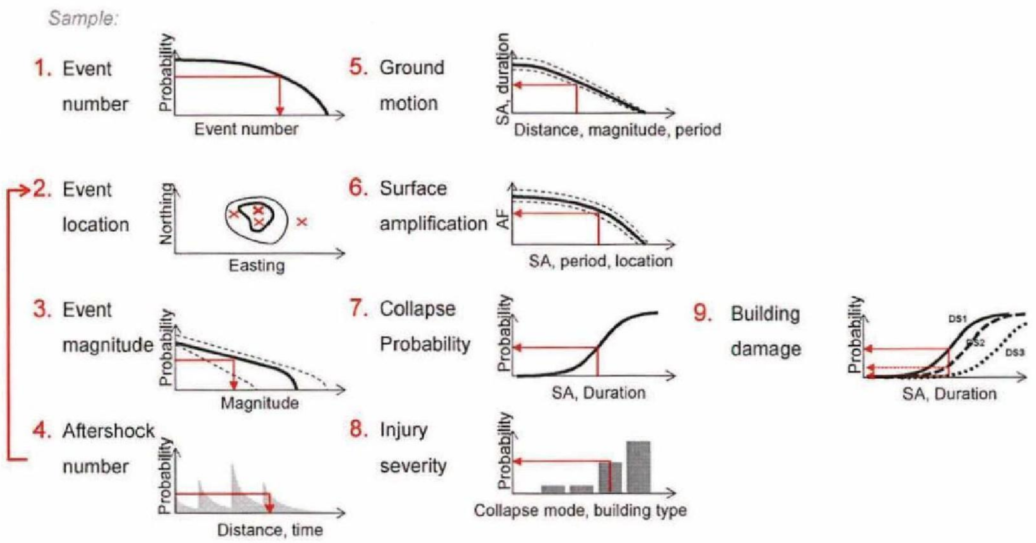


Figure 3.3 Monte Carlo simulation of the seismic hazard and risk model, extended for the prognosis for building damage.

3.3 Fragility Curves for buildings in Groningen

Forecasting building damage (as well as life safety risk) requires fragility curves for the established set of building typologies covering lower damage states (DS1, 2 and 3) as well as the building collapse states (DS4 and 5). The remainder of this document will focus on the activities to develop this extended set of fragility curves.

Fragility curves are typically constructed by considering building capacity within a population of buildings of a given typology class. They take the form of a log-normally distributed random variable. Capacity, A, of a building to withstand seismic ground motion demand, a, can be expressed in terms of a median capacity, A_m, and a log-normally distributed random variable, ε, with logarithmic standard deviation, β:

$$A = \varepsilon A_m$$

The fragility function gives the probability of failure – that is, the probability of experiencing a given level of damage – for demand, a, as

$$P_f(\mathrm{a}) = \Phi\left[\frac{lna - lnA_m}{\beta}\right]$$

where Φ is the cumulative normal distribution function. In other words, the fragility curve gives the probability that the building's capacity is *less* than the seismic demand for a specific damage state.

Figure 3.4 shows an example of a generic set of fragility curves. This set of curves belongs to a single building typology. Each curve allows us to derive the probability that a certain damage state is exceeded, given the (measured) ground motion. In some applications, peak ground acceleration (PGA) is used as the seismic ground motion demand metric.

For an exposure to a ground motion, the probability that a house of this typology would transition to fall within each of the five buildings damage states can be read of extracted. Given that the fragility functions are applied to aggregations of buildings of a given typology within each zone at which the hazard is calculated, this probability can be interpreted as a proportion of those buildings that fall in each damage state.

Figure 3.5 shows a generic example for building exposed to peak ground acceleration of 0.15 g.

In the implementation for the prognosis of building damage in Groningen, it is probable that the same metrics as the collapse fragility functions (i.e. spectral acceleration and 5-75% significant duration) will be used as the ground motion metrics, but other metrics (including PGV) will also be considered.

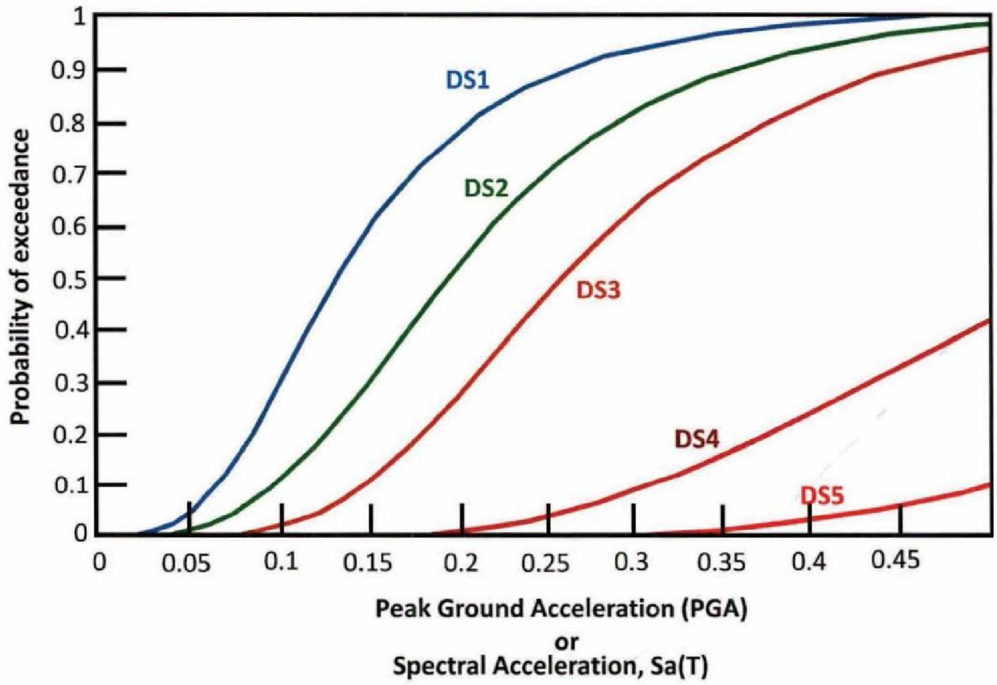


Figure 3.4 *Generic example of fragility curves for the damage states DS1 – DS5, for a single building typology.*

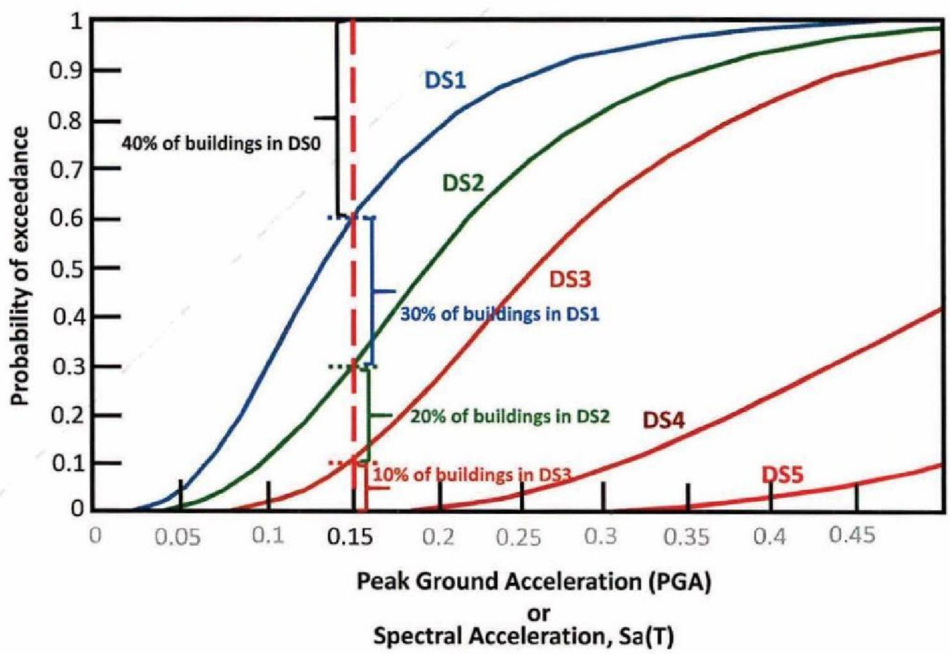


Figure 3.5 *Generic example of a fragility curve for a building typology. The impact of an earthquake with a PGA (in this case of 0.15 g) on buildings of the relevant typology has been indicated. The damage state DS0 is used to indicate "no building damage".*

The lower damage states are much more likely to occur than partial or full building collapse (DS4 and DS5 respectively), which were the only damage state estimated in the risk assessment for the Winningsplan. It is therefore important that repeat damage (of DS1 or DS2) is accounted for in the forecasting methodology.

To account for *repeated* damage it is necessary to first assign a damage state to each building (of a given typology in a given hazard zone) by sampling from the aforementioned damage distribution and then the history of the damage states that a building is subjected to during each simulated evaluation period can be stored, from which various statistics can be extracted. This will allow investigation of the response of immediate repair of the building and potential importance of accumulation of damage for no repair.

The building code Eurocode 8 recommends using a reference return period for the "damage limitation requirement", T_{DLR}, of 95 years equivalent to a reference exceedance probability, P_{DLR} of 10% in 10 years. This is analogous to the recommendation of Eurocode 8 of a reference return period for the "No-collapse requirement", T_{NCR}, of 475 years, which has been used in the assessment of building collapse risk.

The development of fragility curves for lower damage states will be based on the studies and experiments of the three work streams described in the sections 5, 6 and 7. Broadly speaking there are three approaches to the assessment of building fragility:

Empirical: After an earthquake the building damage is assessed and recorded. From this field data, fragility curves can be constructed. This method is valuable but also suffers from some drawbacks. The first drawback is uncertainty in the local ground motion. Often the level of ground motion is not recorded and therefore has a large uncertainty. The focus is on the damaged buildings and the undamaged buildings are often not counted or recorded, making it difficult to assess the *relative* level of damage. The quality and consistency of the damage assessments in the field often also limits their usefulness. In recent years, attempts have been made to improve the quality and consistency of the recorded damage assessments in the field (Ref. 9), but historical damage assessments have not had the benefit of this work, while priorities after an earthquake are not focussed on damage assessment in support of studies.

The second drawback stems from the unique characteristics of the Groningen building stock compared with those of actively studied areas. In the case of Groningen, use of empirical fragility curves derived in other areas is fraught with difficulties because of the unique characteristics of the Groningen building stock compared to those of actively studied areas (e.g. areas with tectonic seismicity in southern Europe, Ref. 11).

A third and final drawback is that this empirical method is restricted to experience domain of earthquakes smaller than magnitude 3.6 and primarily damage level DS1 and possibly very limited data for DS2. The method does not allow extrapolation of the observed building damage to larger earthquakes.

Finally, for lower damage states, the cause of the damage is very difficult to establish. Damage at these levels due to an earthquake is difficult to distinguish from damage due to other causes (e.g. vibration from heavy road traffic, rail transport or construction work).

Analytical: For the generation of the set of fragility curves covering the different building typologies for the Groningen area, used in the risk assessment, an analytical approach combining computer modelling with laboratory experiments was used. The analytical method has the following main advantages:

(1) Versatile approach fully supporting the probabilistic hazard, risk and building damage assessment methodology,
(2) Allows uncertainties to be evaluated, incorporated and aggregated in the probabilistic hazard, risk and building damage assessment methodology,
(3) Allows for assessment of building response to ground motions outside the historical experience base,
(4) Allows for tailoring of the fragility curves to the historical and current building methodologies and local building typologies.

Studies into fragility using analytical methods so far have only been carried out for building stock in the countries in southern Europe bordering the Mediterranean (Fig 3.6). The building methods and typologies in these areas are substantially different from those in Groningen. These fragility curves can therefore not be used directly. That said, these studies do provide useful insights into how fragility curves may be developed for the Groningen building stock.

Hybrid approach: Consists of a combination of the above two approaches.

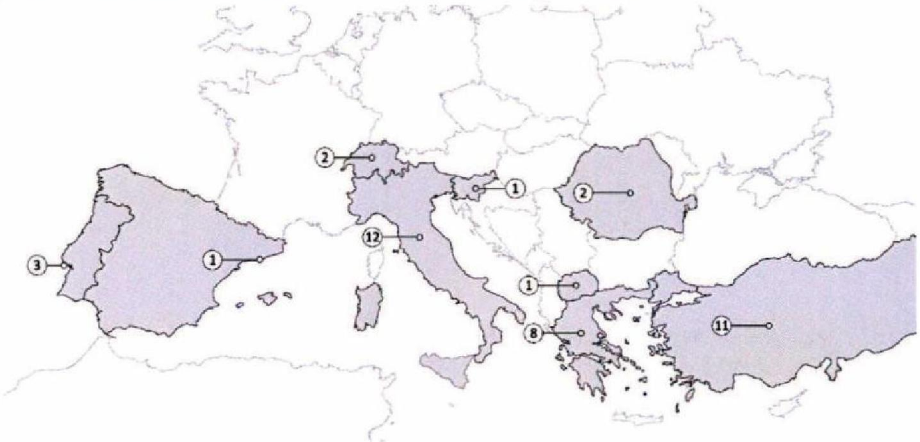


Figure 3.6 *Distribution of the examined analytical fragility assessment methodologies by country: Italy (12); Turkey (11); Greece (8); Portugal (3); Romania (2); Switzerland (2); Former Yugoslav Republic of Macedonia (1); Slovenia (1) and Spain (1). (Taken from Ref. 11; Figure 6.)*

Sections 5, 6 and 7 will describe the three work streams of the work program for the development of fragility curves. This is essentially a hybrid approach consisting mainly of analytical approaches and empirical methods where appropriate. The study plan in these three sections does not only try to develop fragility curves for the prognosis of future building damage, but also aims to gain a deeper understanding of damage patterns. The latter is key to developing damage reduction measures and design of damage repairs, which also avoid reoccurrence of building damage. Section 8 contains a synthesis of the results of these three work streams.

4 Metrics and Description of Hazard for Damage Forecasting

4.1 Introduction

The research into the effects of induced earthquakes in Groningen focussed primarily on the collapse of buildings and impact on persons and the subsequent life safety risk. The metrics used to describe the hazard were selected for this purpose. In this section, we will introduce additional metrics and research to describe the metrics of hazard appropriate for the forecasting of building damage. These hazard metrics will cover both ground movement (section 3.2.1) and liquefaction (section 3.2.2).

Additionally there is a number of complicating and contributing factors that may affect the forecast. These include (1) existing building damage; (2) pre-existing stresses in buildings that impact on the damage caused by the induced earthquakes and (3) impact of exposure to multiple earthquakes. The impact of these will also need to be understood.

The Study and Data Acquisition Plan for Winningsplan 2016 (Ref. 3), already contained studies into these ground motion hazard metrics, liquefaction and uneven settlement. These studies need to be extended and expedited, with extra emphasis on building damage.

4.2 Earthquake Hazard

4.2.1 Ground Movement

Ground Motion Prediction methods have focussed on prediction of PGA (Peak Ground Acceleration), spectral acceleration at several periods and significant ground shaking duration. These are the most important hazard metrics for the prediction of building collapse, failure of building elements and hence for personal risk. For the assessment of the potential to cause building damage, the velocity-based hazard metrics such as PGV (Peak Ground Velocity) and V_{TOP} are also important. Empirical evidence elsewhere has shown that building damage (DS1 and DS2) correlates more strongly with PGV and V_{TOP}.

The official Dutch guidelines for assessing the impact of vibration on buildings, as mentioned in Winningsplan 2016 and presented in the document Building Damage: Measurement and Assessment (SBR, 2002) (Ref. 13) is based on ground velocity. This is an extra impetus for developing a Ground Motion Prediction method for PGV and V_{TOP}.

NAM will develop a Groningen-specific (induced) Ground Motion Prediction method to estimate the value of PGV at specific locations. The assessment of PGV will initially primarily be in support of assessment of building damage due to historical earthquakes and expected future damage. Furthermore, to ensure consistency with the SBR Guidelines (Ref. 14), apart from the geometric mean velocity also a Ground Motion Prediction method for the V_{TOP} parameter (the 'maximum' value of PGV) will be developed.

4.2.2 Liquefaction

The Groningen area contains widespread deposits of saturated sands. This makes it necessary to consider the possibility of earthquake-induced liquefaction. This element was largely absent from the Hazard and Risk Model, because its prime focus is on the estimation of casualties due to earthquake-induced damage in buildings, and liquefaction-induced damage in buildings almost never leads to loss of life.

The development of a model for the assessment of liquefaction hazard started in 2014. However, because of the high profile that has been given to this hazard and also because of the potential impact on key infrastructure—dikes in particular— and lifelines. The model for the assessment of the liquefaction hazard in the Groningen field is being developed by a joint collaboration between the Hazard & Risk Team established by NAM and independent knowledge institute Deltares; this work is supported by expert guidance from Professor Russell Green of Virginia Tech.

The workflow for liquefaction assessment in the Groningen field is shown in Figure 4.1. The elements within the dashed line constitute the core components of the approach to calculating whether or not liquefaction is likely to be triggered, given the characteristics of the subsurface and the earthquake-induced ground shaking. The other two boxes in the upper half of the figure simply place these calculations within the framework of the Monte Carlo-based probabilistic hazard calculations. The lower part of the figure relates to the extension of the calculations from the likelihood of liquefaction occurring to estimates of the resulting displacements and settlements of the ground.

The ultimate objective of the model is to estimate, in a probabilistic framework, the possible ranges of vertical settlements and horizontal displacements that could result from liquefaction and excess pore water pressures, even if liquefaction is not triggered. However, current approaches to liquefaction hazard assessment are largely deterministic and not calibrated to the small-to-moderate earthquake magnitudes that will predominate in Groningen. Moreover, methods for estimating the resulting ground deformations are not very well developed and also require detailed information about the surface and subsurface conditions. Therefore, the development of an assessment model to provide probabilistic estimates of liquefaction-induced ground deformations that is calibrated both to the seismic hazard and the local geotechnical conditions in the Groningen field is a very major undertaking. The development of a model for estimating liquefaction-induced deformations is planned in stages, starting with the likelihood of liquefaction triggering. If the assessment of the potential for liquefaction triggering indicates that this is an unlikely outcome, further work will be adjusted accordingly.

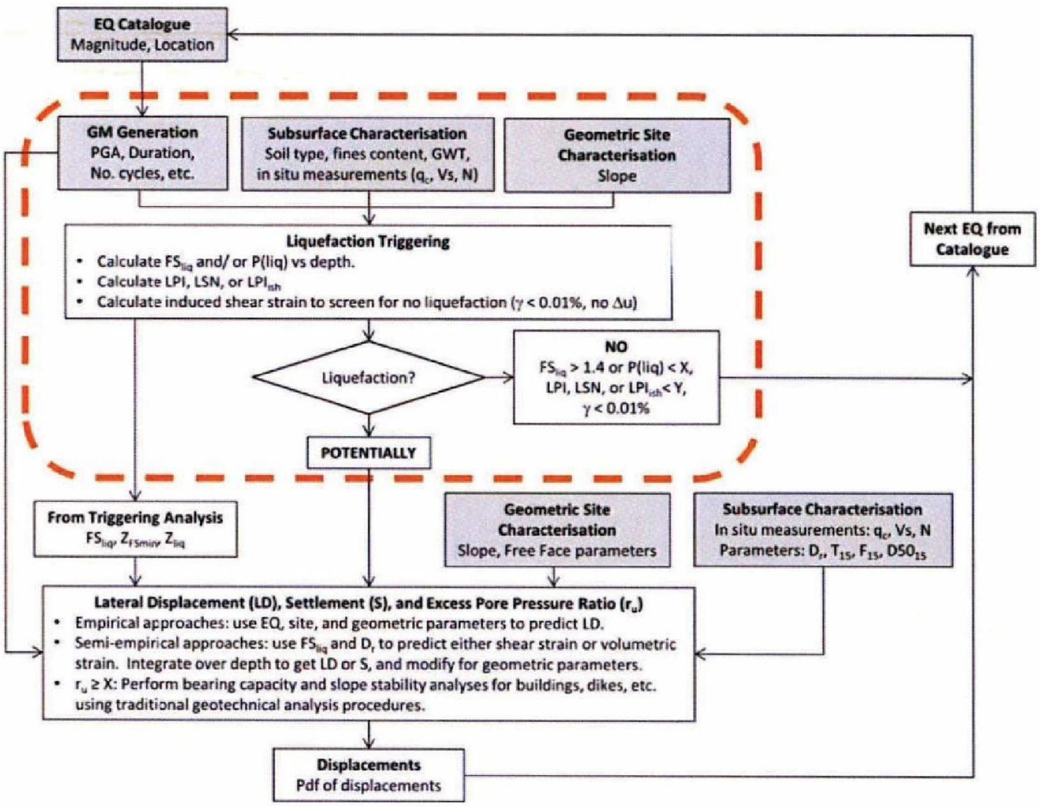


Figure 4.1 *Workflow for the liquefaction hazard assessment in the Groningen field.*

The objective and efforts are currently focused on developing a model for assessing the potential for liquefaction triggering in the field—indicated by the dashed line in Figure 3.1 — but executed within the frame of probabilistic calculations. This would be the result of this probabilistic assessment together with an initial evaluation of the potential impact of the liquefaction potential, possibly even including initial estimates—based on existing models—

of resulting ground deformations. More details on the studies into liquefaction can be found in the Study and Data Acquisition Plan submitted with Winningsplan 2016 (Ref. 3).

4.3 Contributing factors to earthquake-related Building Damage

Several factors can aggravate the impact of the earthquake motion on the building. These need to be better understood. These are:

- The building is mechanically pre-stressed due to ground deformation and uneven settlement.
- The building has pre-existing building damage.
- The buildings have been exposed to the impact of multiple earthquakes.

4.3.1 Ground Deformation and Uneven Settlement

4.3.1.1 Use of ground deformation for Building Damage monitoring and assessment

Ground deformation may cause building damage depending on its magnitude, spatial extent and timespan. Ground deformation in Groningen is complicated not only by the gas production that varies in volume from year to year but also by the ground level variation due to expansion or compaction of the shallow subsurface typically between ground level and 50m in depth.

Ground deformation is the resultant of two forms of deformation. We will use the term 'deep compaction' to refer to deformation caused by gas production and we will use the term 'shallow settlement' to refer to the deformation in the shallow subsurface .The causes and spatial distribution of shallow compaction are not well understood. Possible causes include ground water table variation, types and responses of shallow subsurface to the weight of man-made structures (e.g., given the same weight of structure peat layer settles more than sand layer).

In the mining industry building damages caused by ground deformation are often assessed by three variables:

1. **Horizontal strain** (see Fig.3.2), resulting from differential movement between two points causing a change in length of the surface between the two points. If the length of the surface increases, a tensile strain is induced and if the length of the surface reduces a compressive strain is created.
2. **Curvature,** resulting from differential settlement across the ground surface. .
3. **Tilt,** caused by a differential vertical subsidence between two points that changes the slope of the surface between the two points.

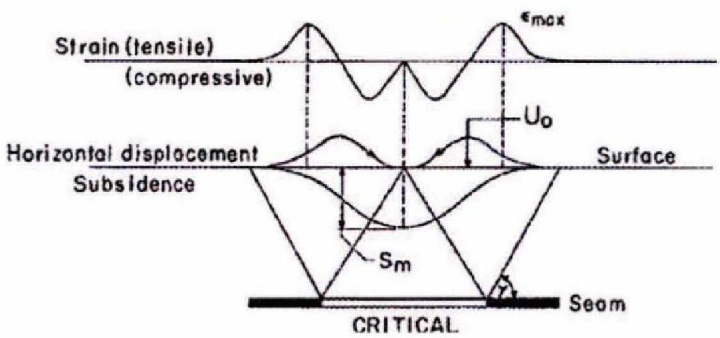


Fig.4.2: Horizontal displacement, subsidence and strains (tensile, compressive) as result of a single source of deep compaction.

Finally, not all ground deformation causes building damages. Arcadis, for example, uses the following critical values to screen ground deformation induced building damages.

- 1 mm over 10 meters in horizontal strain (Krazsch, 1974),
- 20 km radius of sphere in curvature (Krazsch, 1974),
- 25 mm over 10 meters in tilt (Sambeek, 2000).

Techniques for ground deformation monitoring are discussed in section 3.1.3.3: Monitoring Ground Deformation and Uneven Settlement.

4.3.1.2 Causes of Ground Deformation and Uneven Settlement

4.3.1.2.1 Swelling Clays (Knip- and Zwelklei)

Swelling clay (also known as expansive clay) is a type of clay or soil that is prone to large volume changes (swelling and shrinking) that are directly related to changes in water content. Soils with a high content of expansive minerals can swell during a wet season and form deep cracks in drier seasons. Soils with smectite clay minerals, including montmorillonite and bentonite, have the most dramatic shrink-swell capacity. The mineral make-up of this type of soil is responsible for the moisture retaining capabilities.

The changes in the volume of these clays could potentially have important consequences for the foundations of structures built on these clays. Mitigation of the effects of expansive clay on structures built in areas with expansive clays is a major challenge in geotechnical engineering. In areas of Groningen where swelling clays are present, changes in the groundwater level can potentially result in stresses on the foundation of buildings and as a result cause or contribute to damage to these foundations. More details on the studies into swelling clays can be found in the Study and Data Acquisition Plan submitted with Winningsplan 2016 (Ref. 3).

4.3.1.2.2 Anthropogenic Soils

Additional data acquisition is recommended for terp/wierden (local dwelling mounts) composition assessment. Previous research (Ref. 15) indicates intra-regional variability in the composition of terps as well as variability within the individual terps themselves. Although we are confident that our current models provide a good first assessment of the lithology, the need for more detailed information on lithoclass variability at both scales is considered. In this section, we provide suggestions for improvements to the models for the terps, in order to get a better understanding of the spatial heterogeneities.

We suggest obtaining shear-wave velocity profiles combined with hand soil coring on a representative number of terps. The aim of this exercise is twofold. First, it will provide insight into the within-terp lithoclass variability. Second, the obtained data will assist us in extrapolating lithoclass classification to other terps. More details on the studies into anthropogenic soils can be found in the Study and Data Acquisition Plan submitted with Winningsplan 2016 (Ref. 3).

4.3.1.2.3 Proximity to Sloping Surfaces

Wierden/terps are not the only pieces of land with sloping surfaces. Other examples are sloping surfaces near ditches, trenches or drains. We will study the impact of these surfaces on ground movement due to earthquakes. The seismic monitoring network and – potentially – tilt meters can be used to study lateral spreading. The data gathered can be compared to models of the ground movement in the direct proximity of these sloping surfaces.

Some of the quarried dwelling mounds have steep sloping surfaces. They experience soil creep and the stability of the slopes is not guaranteed. These slopes should be investigated; installation of additional tilt meters and field measurements at these sites should be considered.

Embankments and banks may generate a number of threats:

- Directly due to the presence of water.
- Directly due to the possible collapse.
- Indirectly due to the "wave guide" effect.

These effects will be investigated and their impact quantified. This will be done through a series of (active and/or monitoring) experiments in the direct vicinity of these features and in (control) areas with similar geology, which do not have these structures. This should inform the decision on whether or not to pay extra attention to embankment and banks and if so, then determine the area of influence of these features.

4.3.1.3 Monitoring Ground Deformation and Uneven Settlement

The primary tool for measuring ground deformation-induced building damage will be the so-called InSAR technique. This technique uses radar images acquired by satellites. Millions of measurements can be acquired simultaneously by satellite in a single pass. InSAR is the only aerial monitoring technique that can map ground deformation along line-of-sight and cover the whole Groningen field with very high point density (see Fig. 3.3). Spirit levelling and GPS data may be used for calibration and cross validation. To be able to measure both horizontal and vertical deformation by InSAR it is planned to use both ascending and descending geometries.

Fig. 4.3 InSAR (TSX 3 m resolution) measurements over Groningen.

The following tasks will be carried out:

1. Classification of buildings by their subsidence rate;
2. Examining potential building damages by tilt and strain analysis;
3. Mapping shallow compaction and assessing its impact on building damages.

4.3.1.3.1 1. Classify buildings by their subsidence rate

The very high resolution (< 3m) satellite images acquired through inSAR will enable us to measure the deformation of each individual building and its surroundings. This, in turn, will enable us to make a classification of buildings in terms of subsidence rate, allowing for faster identification of buildings that experience faster subsidence than their neighbours (see Fig.3.4 as an example). A faster than average subsidence can be an indication of foundation or structural issues of the buildings, which could then lead to a ground-based inspection.

Fig. 4.4 *Subsidence rate per building derived from InSAR measurements. A faster subsidence (highlighted in the dashed circle) than its neighbours suggests the building may have foundation or structural issues.*

4.3.1.3.2 2 Examine potential building damages by tilt and strain analysis

Figure 3.5 shows the locations (targets) of InSAR measurements acquired over a freestanding building in Groningen. At each of these locations, InSAR provides a *time series* of deformation as measured at that location. The density of the measurement depends on the image resolution and relative orientation of the house with respect to the satellite. Given sufficient density, InSAR can be used to assess building damages in terms of horizontal strain and tilt as discussed in section 2: use ground deformation for building damage monitoring and assessment.

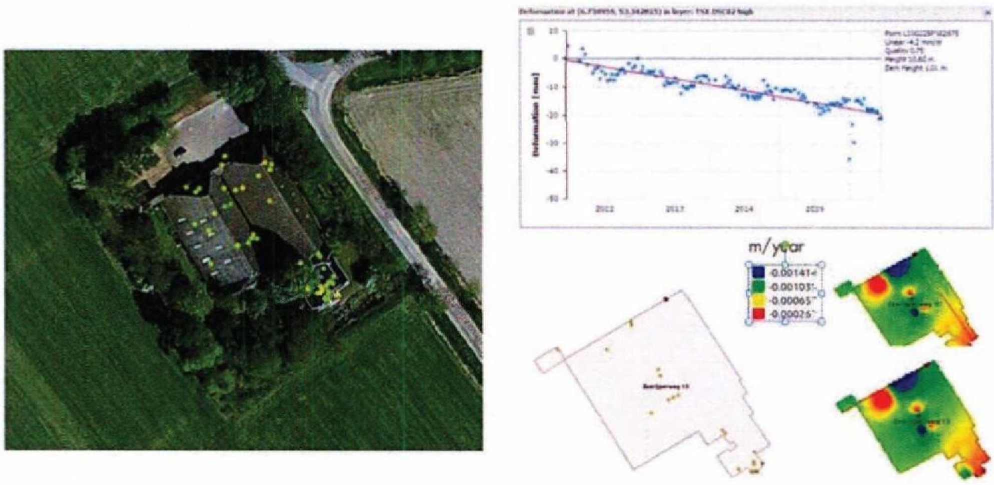


Fig. 4.5 *InSAR measurements over a building (left) and deformation time series derived from one of the InSAR measurements (top right). Differential subsidence of the building can also be derived (low right).*

4.3.1.3.3 3. Map shallow compaction and assess its impact on building damages

Fig. 4.6 InSAR measurements; Left: from ground (< 3 m in height). Right from top of buildings (> 3m)

As discussed in section 2 building damage due to ground deformation is usually related to an increase in strain on the structure. An increase in strain requires a non-homogeneous (i.e., differential) deformation, within length scales similar to the size of the structure. Such differential motion is rarely due to deep sources of subsidence, such as a volume change in a gas reservoir (Ref. 16), as these volume changes would 'translate' buildings as a whole, rather than increasing the strain on them. Therefore, differential motion on typical length scales of buildings is thought to be more likely the result of shallow driving mechanisms. Whereas subsidence due to deep driving mechanisms has been studied extensively, and infrastructure has been established (levelling benchmarks, GPS stations, PS-interferometry), the influence of differential motion originating from shallow driving mechanisms is much less known. These mechanisms include the compaction of soil, peat oxidation and consolidation and can be variable over small spatial scales. Moreover, shallow processes are expected to have more temporal variability, e.g. a seasonal signal with amplitude in the order of a centimetre. Given these characteristics, traditional geodetic techniques are not suited to detect, measure and monitor shallow deformation over e.g. pasture areas.

Very high-resolution InSAR data has the potential to successfully distinguish shallow settlement from deep compaction. This is made possible by comparing deformation rates between measurements from the roof of buildings that have solid foundation and measurements from ground surface, see Fig. 3.6.

Alternatively, a multi-sensor InSAR approach has also been identified as a promising technique for measuring shallow compaction. InSAR works best over urban areas where the signal-to-noise ratio of its measurements is highest. However, shallow compaction is expected to take place more likely in pasture type of land surface where the signal to noise ratio drops substantially. To overcome this challenge studies have been done in the scientific community by optimal combination of multiple InSAR datasets with advanced stochastic models of various noise components to obtain best estimate of shallow compaction [17, 18]. These studies show that given suitable datasets (X, C and L bands), an adequate deformation model and processing settings; shallow compaction is measurable with good repeatability at relatively low cost comparing to field measurements. Studies to monitor shallow compaction will initially be carried out for areas where these are most likely to occur.

The activities described in this section, aim to better understand the processes that can potentially cause stresses in the walls of a building. Experiments and simulations to assess the response of a building with pre-stressed walls to an earthquake are discussed in section 6 of this report.

4.3.2 Pre-existing Damage

As we have seen in the previous sections, building damage may occur for a number of reasons: vibrations due to piling and construction operations in the vicinity of the building, uneven settling due to tunnelling operations or oxidation of peat layers due to lowering of ground water levels beneath the building. Lack of maintenance of the building can further deteriorate the state of the building and cause damage. In such situations, vibrations due to an earthquake can aggravate pre-existing building damage. This makes it often difficult to determine unequivocally how much of the damage is due to earthquakes and what part of the damage should be attributed to other causes (Ref. 17).

Unfortunately, poor maintenance of houses is not just theory, but does occur in practice – and the northern part of the Netherlands is no exception. The Ministry of VROM (Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer) notes in April 2007 (Ref. 18) that there are many dilapidated buildings in the three northern provinces of the Netherlands:

> *In the north of the Netherlands a remarkably large number of dilapidated buildings have been found, buildings that show clear structural defects. In the inspection week nearly one hundred cases of serious disrepair have been reported. Fifteen percent of this is found in Drenthe, a quarter in Friesland and the rest in the province of Groningen.*
>
> *In about half the cases reported these are dilapidated farmhouses, the remainder is equally split between residential and commercial properties. Among the dilapidated buildings are numerous national monuments.*
>
> *Derelict characteristic and historic farms were also the subject of a seminar by Libau "repurposing farms" in March 2006.*
>
> *Municipalities undertake little action against the decay. Initial contacts on this subject shows that many municipalities hardly pay attention anyway to the quality of the existing building stock.*[5]

An inventory of pre-existing damage due to causes other than earthquakes is important for forecasting earthquake damage for a number of reasons:

- The cause of damage may not have been established unequivocally and earthquakes may have been a potential cause.
- The pre-existing damage might have been exacerbated by the earthquakes (e.g. existing cracks might have further opened up);
- A building may have been damaged due to multiple causes, earthquakes being one of them. The building could show damage patters typical for two different damage inducing processes (e.g. a combination of uneven settlement and vibrations),

In all these three cases the reoccurrence of damage after a repair will depend on different factors.

[5] Original Dutch text: 'In het noorden zijn een opvallend groot aantal vervallen panden aangetroffen, panden die duidelijke constructieve gebreken vertonen. In de schouwweek zijn bijna honderd gevallen van ernstig verval gesignaleerd. Zo'n vijftien procent hiervan is te vinden in Drenthe, een kwart in Friesland en de rest in de provincie Groningen.Het gaat in ongeveer de helft van de gesignaleerde gevallen om boerderijen, verder in ongeveer gelijke mate om woningen en bedrijfspanden. Onder de vervallen panden bevinden zich tal van rijksmonumenten.Vervallen karakteristieke en monumentale boerderijen waren ook het onderwerp van een studiemiddag 'herbestemming boerderijen' in maart 2006 van Libau.Gemeenten doen weinig tegen het verval. Uit de eerste contacten hierover blijkt dat veel gemeenten sowieso nauwelijks aandacht schenken aan de kwaliteit van de bestaande gebouwenvoorraad.'

Figure 4.7 Example of a dilapidated building. Illustration taken from "VROM-Inspectie, Handreiking aanpak vervallen panden", April 2007 (Ref. 18).

The buildings assessed during that study are not known to NAM. Many of buildings in poor condition have been addressed as part of the "Bijzondere Gevallen". These might therefore have become less important for forecasting of future building damage, but are important for analysis of building damage reported resulting from historical earthquakes.

4.3.3 Impact of Multiple Earthquakes

The methodology for assessment of the hazard in support of building damage will record the number of small earthquakes with the potential to cause building damage during the evaluation period. This gives an insight into the repeated exposure of a building to earthquakes.

The study plan includes an experimental and modelling campaign are included to investigate the impact of this repeated exposure (chapter 8). This includes the accumulation of damage over multiple earthquakes and the potential weakening of building materials due to repeated loading or degradation.

5 Historical Trends Method: Damage Assessment based on Analysis of Observed Damage

5.1 Damage Assessment based on Damage Claims and Observed Damage

5.1.1 Existing Method

An analysis of building damage resulting from past earthquakes can be used as input for a forecasting method for future building damage resulting from a seismic hazard. This method, however, will be limited to the range of ground movement historically experienced. This is a limitation of any method based on previous experience.

A study of past building damage was carried out by TNO in the "Kalibratiestudie schade door aardbevingen" published in November 2009 (Ref. 20). This research into building damage started in 2006 and was commissioned by five oil and gas companies (NAM BV, BP Nederland Energy BV (later TAQA), Vermillion Oil & Gas Netherlands BV and Wintershall Noordzee BV). The objective of this study was to establish the maximum distance from the epicentre where damage could be expected, given the earthquake's magnitude on the Richter Scale.

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TNO-034-DTM-2009-04435
Kalibratiestudie schade door aardbevingen

Datum 11 november 2009

Figure 5.1 Cover of "Kalibratiestudie schade door aardbevingen" published by TNO in 2009 (Ref. 20).

In part 5 of the Technical Addendum to the Winningsplan Groningen 2016 addressing building damage, the TNO methodology is used to estimate the number of damaged buildings after the Huizinge (August 16, 2012) and Hellum (September 30, 2015) earthquakes, respectively. These expectations were then compared with the number of damage claims received within 10 weeks after each seismic event. In this comparison, we should keep in mind that, in terms of energy release, the Huizinge earthquake was roughly 5.5 times stronger than the earthquake in Hellum.

For the Huizinge earthquake, the analysis showed a strong correlation between predicted impact on building damage and observed building damage (awarded on supported damage claims). That correlation is much weaker for the Hellum earthquake, where the number of damage claims is much higher than the predicted building damage.

This comparison suggests that the total number of buildings expected using this method to have been damaged because of the historical earthquakes is between 5,000 and 10,000. This is a considerably smaller number than the total number of awarded damage claims.

Conceivably, a more refined methodology might be developed based on the damage claims and information about which claims have been awarded and which were not. However, the currently available data quality severely limits the capability to do this.

5.1.2 Damage Claims and Damage Inspections

Trying to minimize the consequences of the earthquakes on her license to operate, NAM decided to set up an easy and accessible claim procedure in 2012. This approach led to a large number of inhabitants claiming incurred damage resulting from induced earthquakes. Especially early 2014, many claims were submitted because of the higher number of earthquakes M>2 and claimants becoming familiar with the process and related arrangements.

NAM had to establish an organisation able to handle the vast amount of damage claims. With limited knowledge regarding earthquakes, experts started assessing damage on a large scale.

During the following years, knowledge on the effect of the earthquakes in Groningen increased significantly, also because of the extensive research program supported by NAM. In January 2015 CVW, a dedicated organisation operationally separate from NAM, took over the damage claim handling process. Although much progress was made in the professionalization of the operational process, application of knowledge gains progressed slowly over time. In recent months, CVW has initiated several efforts to improve the reporting of damage assessments.

To be able to establish an accurate forecast of the damage to buildings caused by earthquakes, historical assessment data can in principle be used. In order to do so, the quality of the historical data must be sufficient. As the knowledge on earthquakes was limited in the past, the data must be verified prior to be used as input. Due to varying extensiveness of the explanations regarding the cause of damage in the historical reports, assessing the quality of the data can be a challenge. This can result in a forecast based on historical assessment data, which significantly deviates from a future actual outcome based on current and progressing knowledge.

In the Technical Addendum of the Winningsplan 2016 (Ref. 7), an analysis was presented of the damage claim data. This showed for the earthquakes in 2013 and later no clear correlation between the volume and location of the damage claims and recorded earthquakes (Fig. 5.2). The rate damage claims were made seems to consist of three distinct periods with a different average claim rates.

The potential for establishing an accurate forecast of different damage states based on the building damage records is therefore limited;

- Most of the building damage is for damage state 1, DS1,
- The explanation of the cause of assessed damages in the damage data base is relatively poor, especially for the earlier building damage report,
- An inspection of the damage claims data shows no clear relation with the occurrence of earthquakes,
- More work is needed to determine the cause of DS1 damage and be able attribute the damage to earthquakes or assess the contribution of earthquakes to the overall damage.

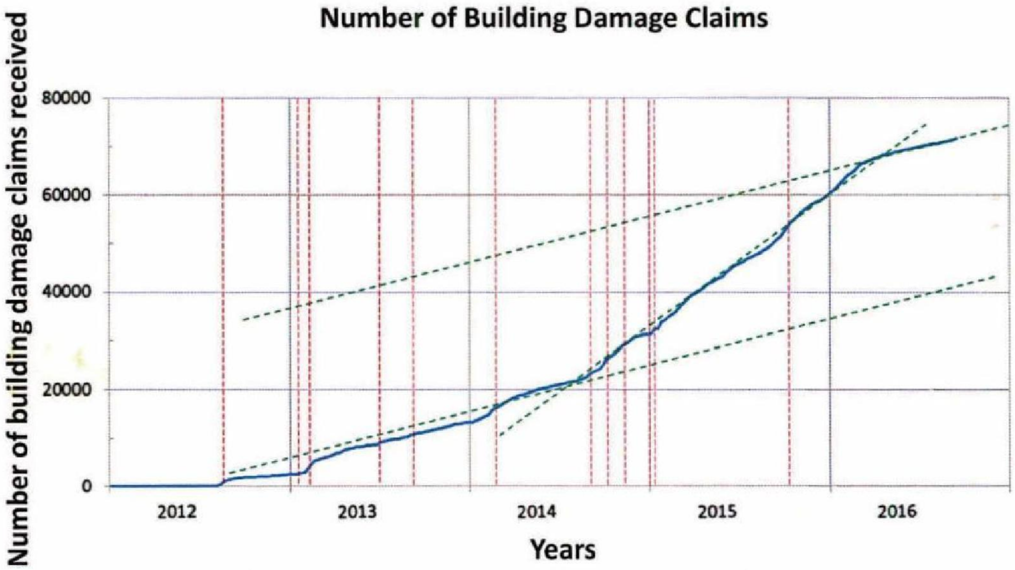


Figure 5.2 *Number of building damage claims received by NAM and CVW since the Huizinge earthquake of August 2012. The red vertical line indicate timing of earthquakes with magnitude larger than M=2.0.*

5.1.3 Database of Damage Claims and Damage Assessments

Advanced data analytics may conceivably be used to evaluate contributing factors to damage claims rate. If clear trends are evaluated, a predictive tool might be developed. This plan will describe the data inputs and analytic tools that may be used to further our damage claims analysis. The data analysis and can be used but will not be limited to:

- Compare theoretical damages estimates (scientific) vs the assessed damage results (perceived), flow chart attached to describe further
- Derive additional lessons learned in the damage assessment quality and can be leveraged to develop a quality control tool
- Evaluate damage assessment trends within similar groups of buildings (typology, location, etc.) and can be improved in the future with the data-driven assessment process
- Forecast cost of building damage repairs
- Identify other contributing factors for claims, assessed damaged, and repair cost

Advanced analytic tools will be used to integrate, transform, visualize and model the data.

Several data inputs will be evaluated to determine contributing factors for damage claims, assessed damage results, and damage repair costs. The data set will include a variety of potential factors to consider further:

- Damage claim data including building location and repair cost
- Damage assessment result including type of assessed damage (i.e., earthquake-related or not earthquake-related damage)
- Building database including most likely building typology
- KNMI earthquake database including magnitude and location of earthquakes >2.0
- Ground motion prediction equation to develop an "earthquake intensity" measure to compare ground motions for all buildings and all earthquakes >2.0
- Media events including the monthly rate of media events and key events
- Protocol and process changes including the value-additional program and Damage Assessor Handbook rollout

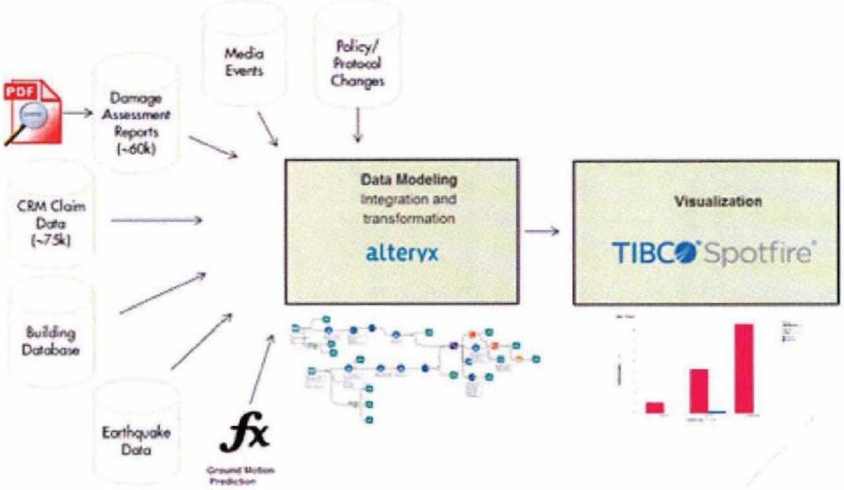


Figure 5.3 *Potential structure of the advanced analytic tool used to integrate, transform and visualize the data.*

We envisage a two-step process to developing the advanced analytics tool.

1. Data integration (using Alteryx)
2. Trend evaluation (using Spotfire)

Alteryx will provide a structured and stable platform for the large data set and Spotfire will assist the user to visualize trends used in the prediction tool. For example, the monthly rate of damage claims can be evaluated based on assessed damage result as a function of time and earthquake activities as seen in Figure 5.4.

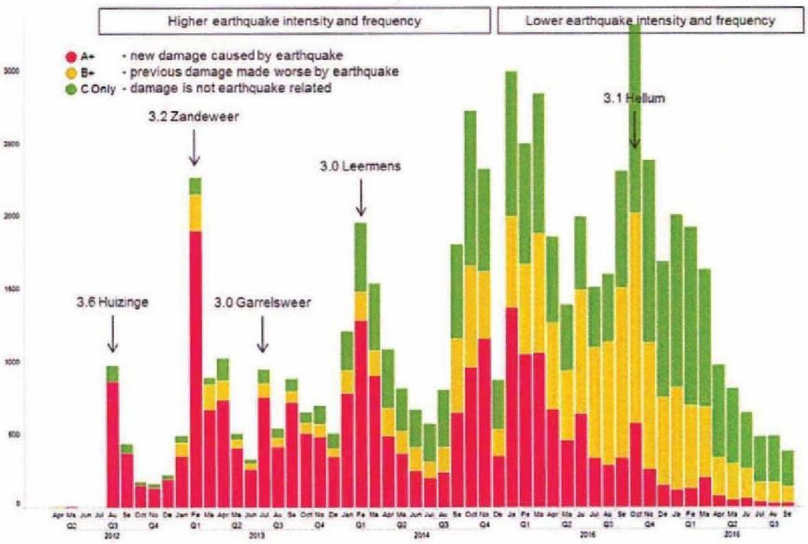


Figure 5.4 *Example of the output of the advanced analytics tool to demonstrate the capability of such an approach and tool. This graph shows the Potential Assessed Damage Trends over time. Further studies are required to assure the trend.*

Other visualization features can be used to evaluate geographic relationship of claims over time and the assessed damage result in a map view and can be coupled with a time-history of earthquake characteristics (i.e., frequency, intensity, etc.). A simplified view is seen in Figure 5.5 and a deeper dive can be performed by municipality.

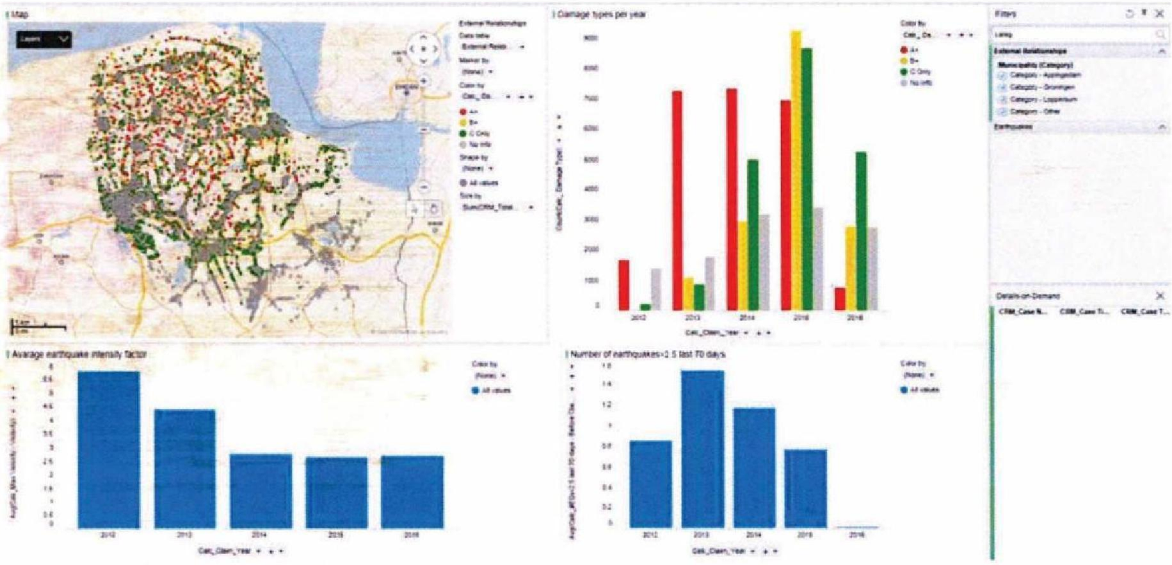


Figure 5.5 Example of the output of the advanced analytics tool to demonstrate the capability of such an approach and tool. This graph shows the Potential Claim Activity Map and Earthquake Activity. Further studies are required to assure the trend.

External factors (i.e., non-earthquake events) can also be added to the evaluation and visualization process. For example, claims involved in the *Waarde Vermeerderings Regeling* (Value Addition Program) can be analyzed separately by identification of municipalities eligible in the program. These claims are highlighted in green in the upper left chart of Figure 5.6 and other factors can be simultaneously evaluated to visualize trends (i.e., assessed damage result, media event intensity, ground motion intensity).

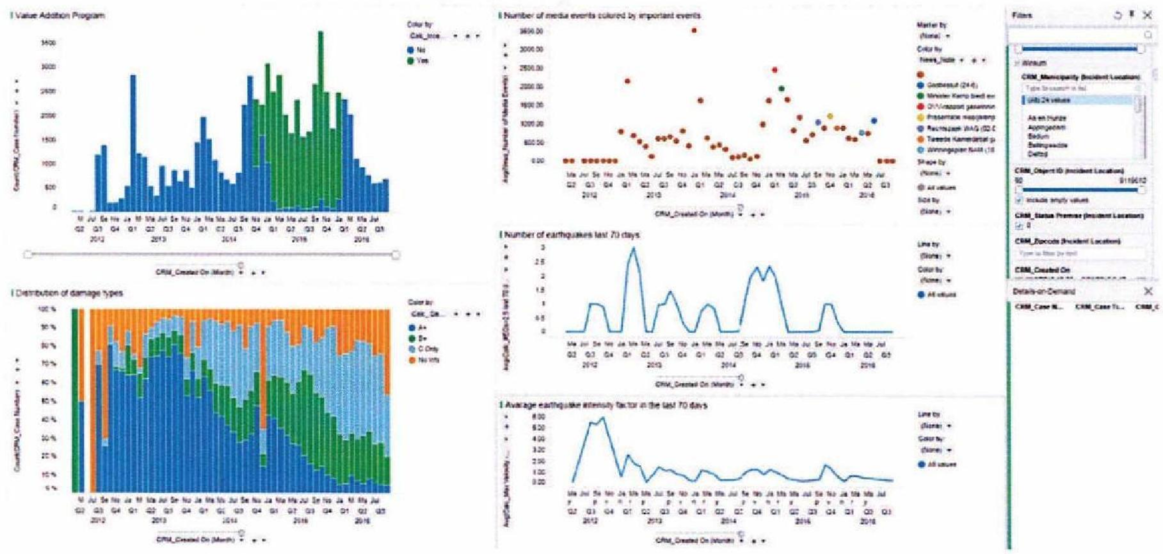


Figure 5.6 Example of the output of the advanced analytics tool to demonstrate the capability of such an approach and tool. This graph shows the *Potential Value Addition and Media Event Evaluation*. Further studies are required to assure the trend.

Repair costs over time can be evaluated. As seen in Figure 5.7, any range of repair costs can be evaluated to determine trends of building damage costs for either total quantity of buildings or percent of total claims.

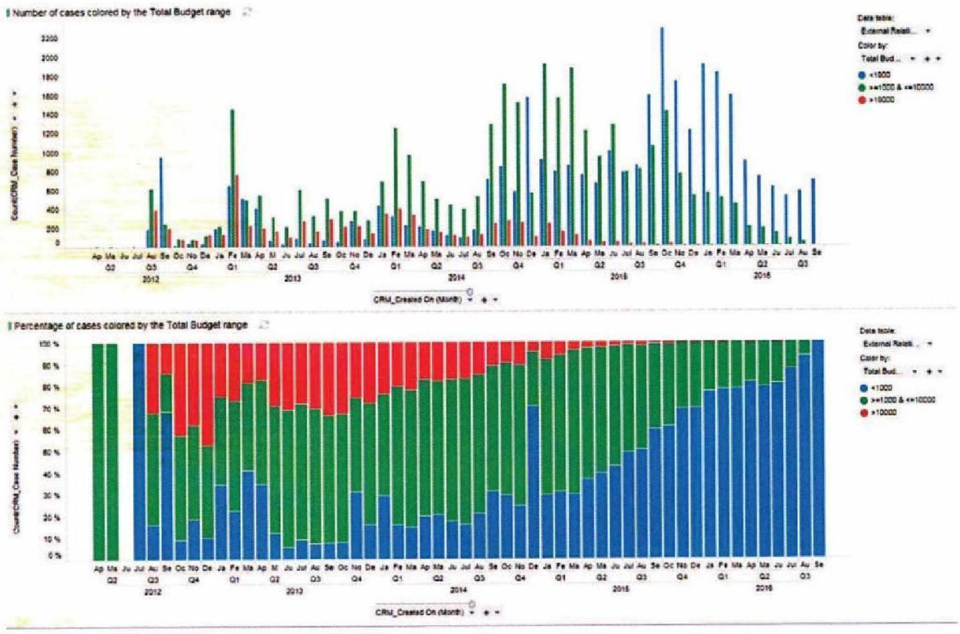


Figure 5.7 *Example of the output of the advanced analytics tool to demonstrate the capability of such an approach and tool. This graph shows the Potential Repair Cost Evaluation. Further studies are required to assure the trend.*

5.2 Damage Assessment using the Monitoring Network for Building Damage with TNO Sensors

NAM has installed accelerometers in the foundations of buildings in the Groningen field area. Initially, close to 200 buildings were selected, some 20 of which being public buildings such as town halls of municipalities. In the course of 2015, TNO has placed more than one hundred additional accelerometers. The total number of sensors installed now exceeds 300.

5.2.1 Building Selection

Through www.namplatform.nl home owners could request to have a sensor installed in their building. A selection of buildings was made using the following criteria:

1. Geographical criteria to
    a. Achieve a good coverage of the seismically active area.
    b. High likelihood of measuring the highest accelerations based on the hazard map
    c. Proximity to geophone stations
    d. Distribution to cover different soil conditions
2. Building criteria:
    a. Achieve a good coverage of the building typologies
    b. Cover different foundations (piles versus no piles)

During the registration, additional data on the buildings was collected, including the state of the building.

5.2.2 Building Sensors

The vibration measurement system consists of a tri-axial vibration sensor and a central unit. The central unit is for signal conditioning (sensor conditioning, filtering) and transfer of the data to the TNO remote data center. Based on detailed specifications, NAM has selected GeoSig as the supplier for the vibration measurement systems. Their system consists of a separate recorder and sensor (Figure 5.8) with the following specifications:

- Recorder: GMSplus Measuring System
- Sensor: AC-73 Force Balance Accelerometer

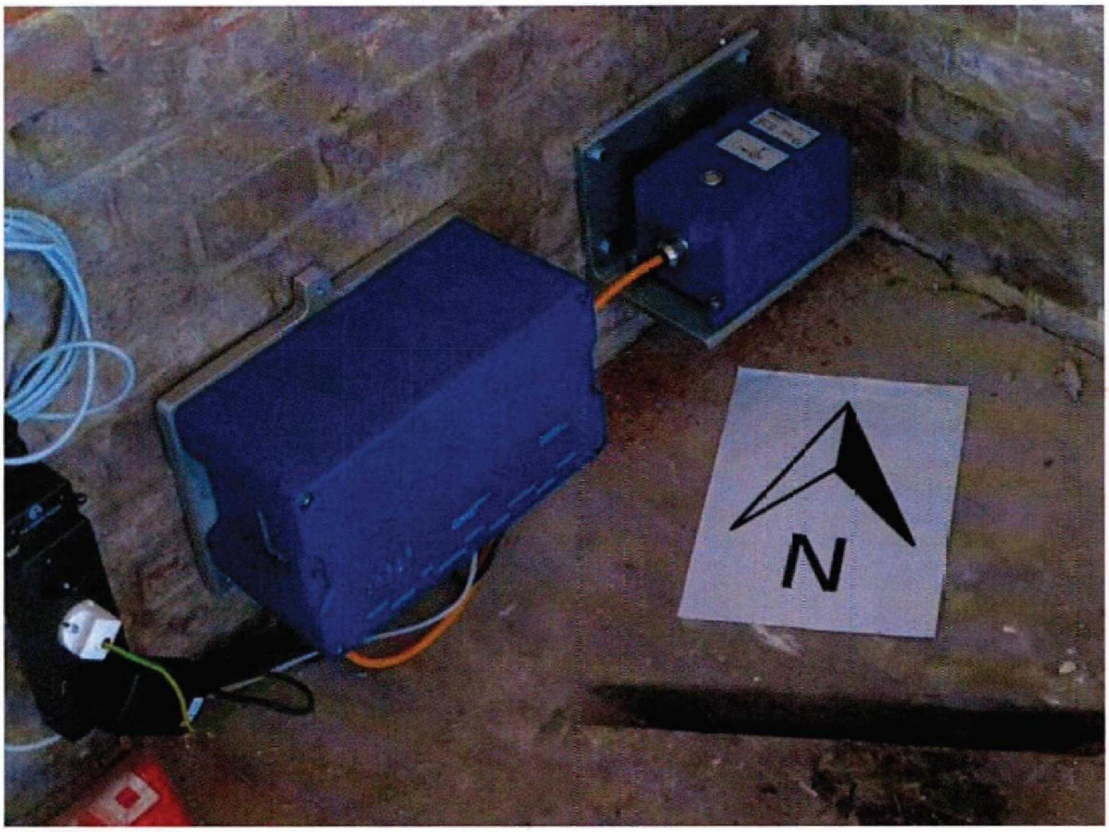


Figure 5.8 Vibration monitoring system – recorder (left) and sensor (right)

Vibration is sampled continuously at 250Hz and stored in an internal buffer. When vibration exceeds a certain threshold level (set at velocity of 1 mm/s)[6] the Data Centre is notified by sending the time of triggering. At that time logging of the event starts with a pre-trigger duration of 10 seconds. After collecting data for 20 seconds (at 250 Hz) the time traces (one per channel) are instantaneously sent to the TNO Vibration Data Centre (Fig. 5.9). In addition to the communication of measurements during the events, the vibration measurement system also sends a regular 'heartbeat' containing the peak vibration velocity and acceleration over the last minute. Examples of the heartbeat signal and a recording of a seismic event are shown in figures 5.10 and 5.11.

[6] The trigger level of 1 mm/s is in the order of the strictest limits of the SBR directive (Ref. 13 and 14) for vibration damage. Other vibration sources like traffic may cause such, or higher, levels. These levels tend not to occur often but when they do, they may be relevant.

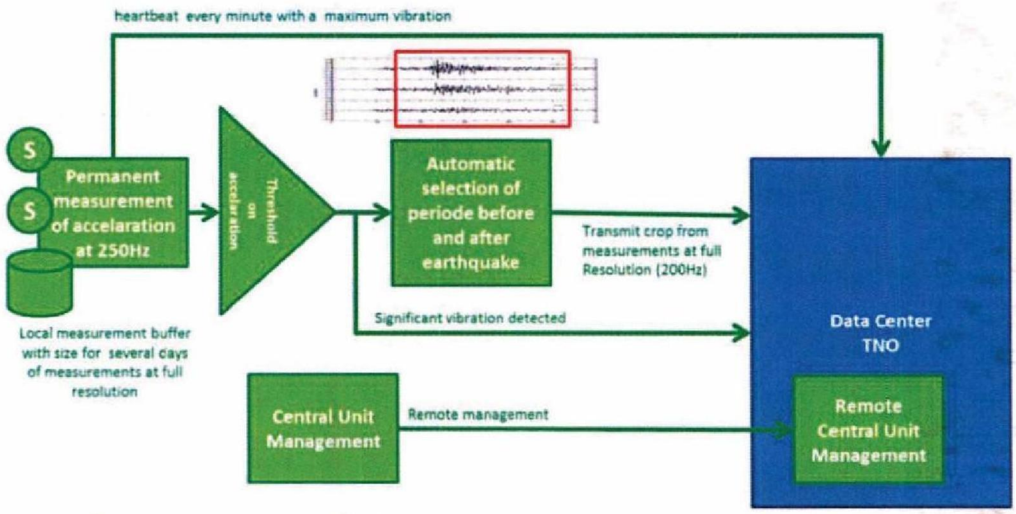


Figure 5.9 *The sensors send their data event based when the vibration level exceeds a certain threshold and send a regular (every minute) heartbeat signal with a maximum vibration.*

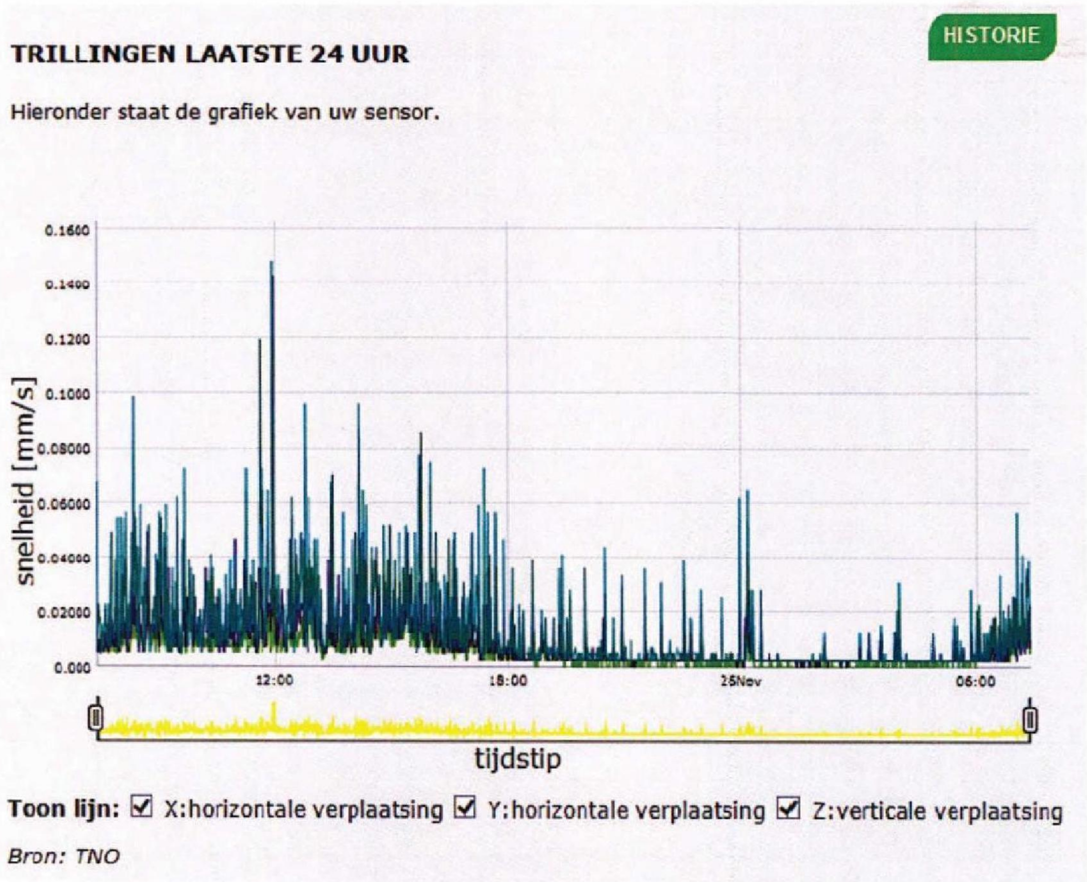


Figure 5.10 *Example of a graph with results of heartbeat measurement*

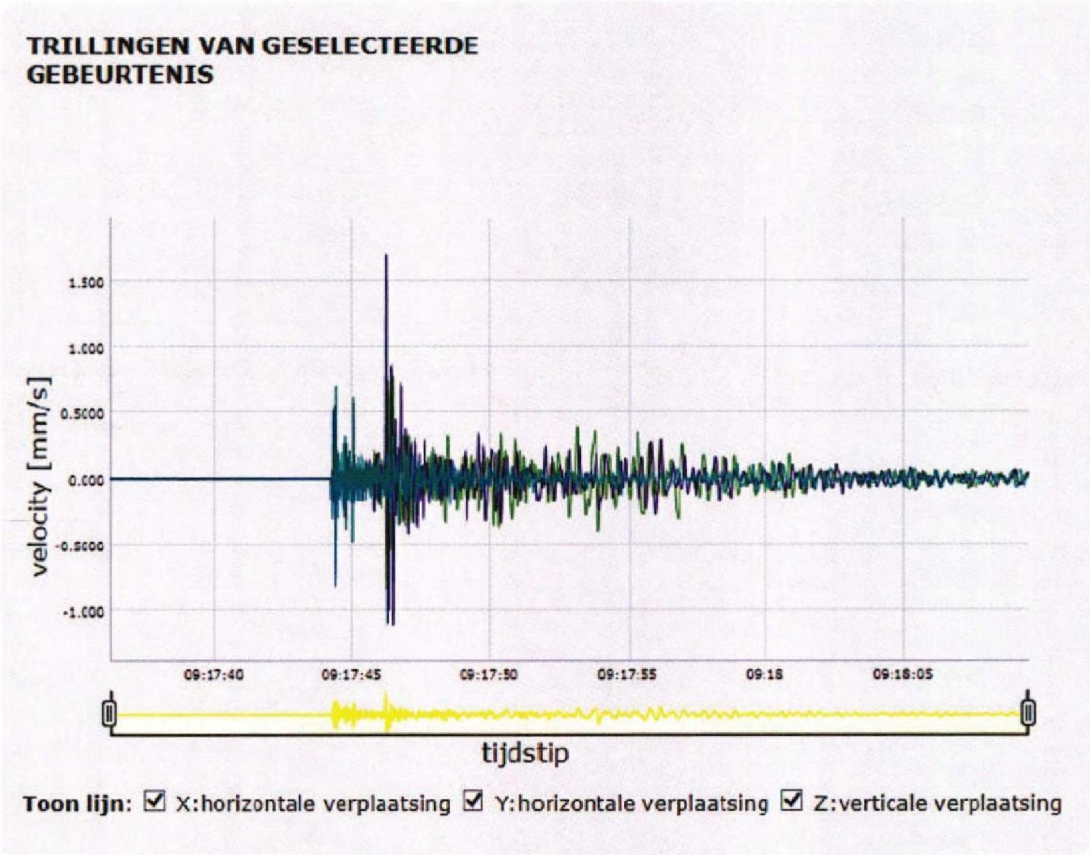


Figure 5.11 Example of a graph with results of an event

To investigate the transfer of the ground movement into the building through the foundation, geophones from the flexible network will be placed in the direct vicinity of a number of houses with a TNO Sensor. This will allow direct comparison between the ground movement near the house with the movement at the foundation level.

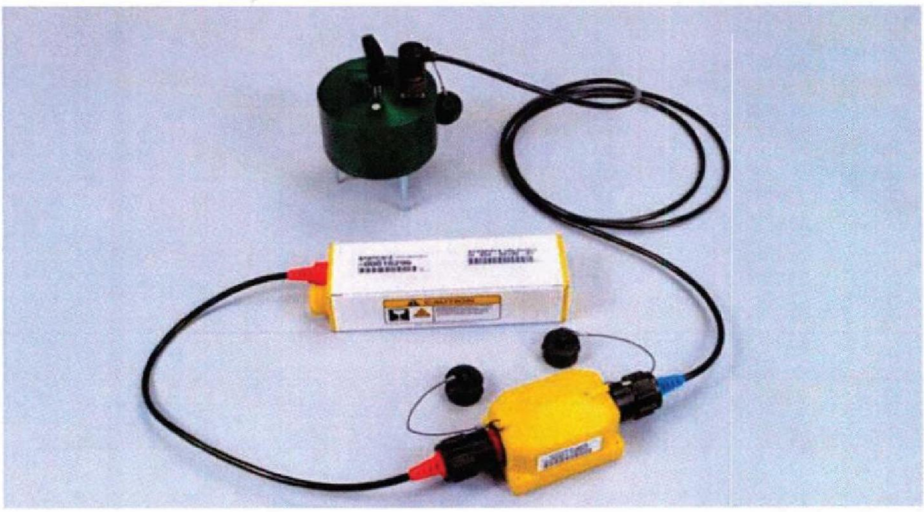


Figure 5.12 Node of the Flexible Network consisting of a battery pack (white), memory unit (yellow) and geophone (green).

5.2.3 Building Inspections

To improve the understanding of how sensitive buildings in the Groningen field area are for damage caused by earthquake vibrations, regular building damage surveys are carried out as part of the TNO monitoring network.

As part of the sensor installation, an initial inspection of damage on the outside of the building (e.g. cracks in exterior walls) is carried out. During this initial inspection, any characteristic properties of the building are logged that may be relevant for damage analysis at a later stage.

After each significant earthquake a repeat inspection is carried out for those houses where a maximum peak velocity exceeding 1 mm/s was observed, to establish potential additional damage caused by the earthquake. The nature and degree of that damage is then classified in a damage category that is, in turn, linked to the vibration. By plotting the measurements of all the buildings in the monitoring network against the vibration velocity, relationships can be established between the two.

5.2.4 Data Transmission and Communication

The total monitoring network consists of the building sensors and the TNO Vibration Data Centre, which collects and handles the measured data. Data is securely transferred from the building to the Vibration Data Centre using the password-protected household internet connection.

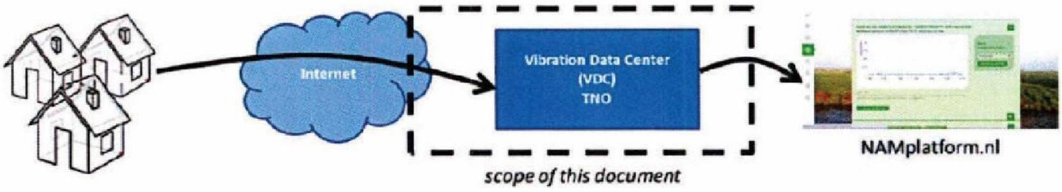


Figure 5.13 Measurements are securely transferred by making use of the household internet connection

At the TNO Vibration Data Centre the data is analysed and then sent to NAM, where it is published at the website www.nam.nl. There are limitations to the level of detail at which the vibration data can be shared publicly, to protect the privacy of the participating homeowners. Homeowners can see the response of the sensor in their own house at a password protected web-page.

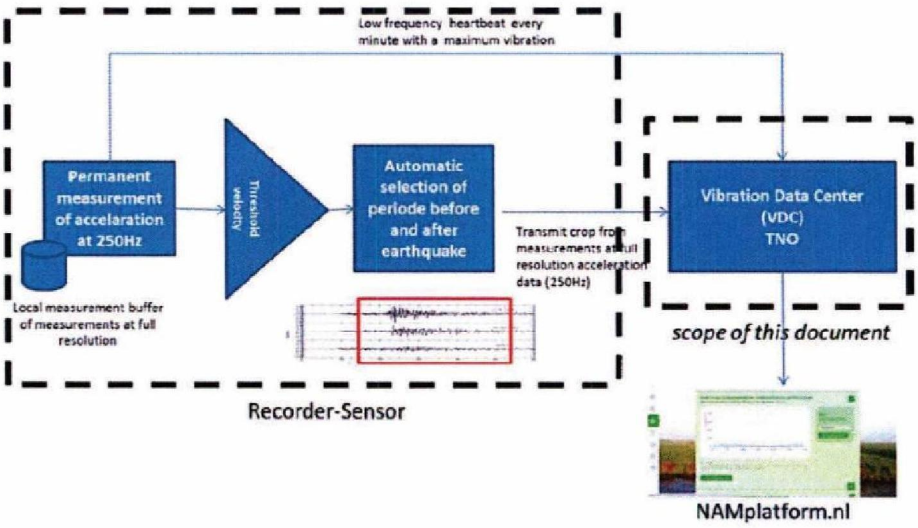


Figure 5.14 Data transfer from vibration monitoring system to Vibration Data Center (VDC)

5.2.5 First Insights from the Damage Inspections

Since installation of the TNO sensors, five earthquakes with a magnitude larger than 2.5 have been recorded. After the earthquakes houses where the TNO sensor was triggered were visited for a damage survey.

Location	Date	Magnitude
Garmerwolde	30-09-2014	2.8
Zandeweer	05-11-2014	2.9
Woudbloem	30-12-2014	2.8
Wirdum	06-01-2015	2.7
Hellum	30-09-2016	3.1

Table 4.1 Five earthquakes with magnitude larger than 2.5on the Richter Scale, since the TNO Network was installed.

Over these five earthquakes a total of 167 damage surveys have been carried out, including 145 first repetitive surveys, 21 second first repetitive surveys and 1 third first repetitive survey (Ref. 19).

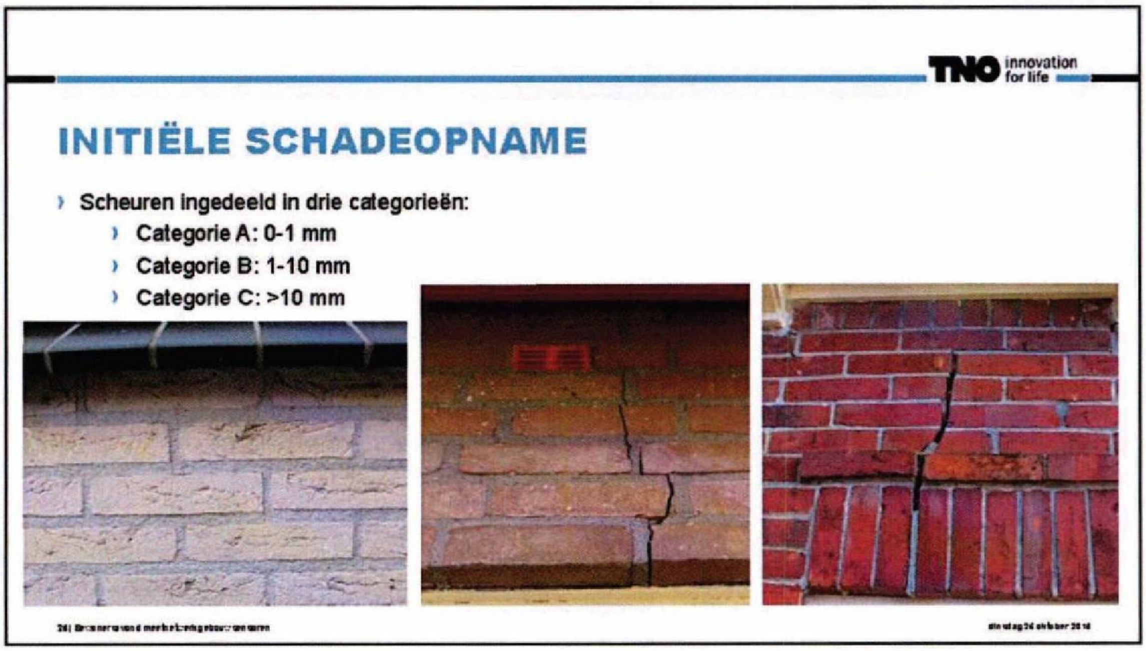


Figure 5.15 Classification of cracks used in the damage surveys by TNO (Ref. 19).

The number of cracks with an increase in crack width and/or crack length is about 1% of the total amount of initial reported cracks. A major part of the newly reported cracks was already present, but not reported at the initial damage survey. These were very small and overlooked or unreported. At 21 houses, the cracks were repaired between damage surveys. About 2% of the repaired cracks were cracked again after the earthquake.

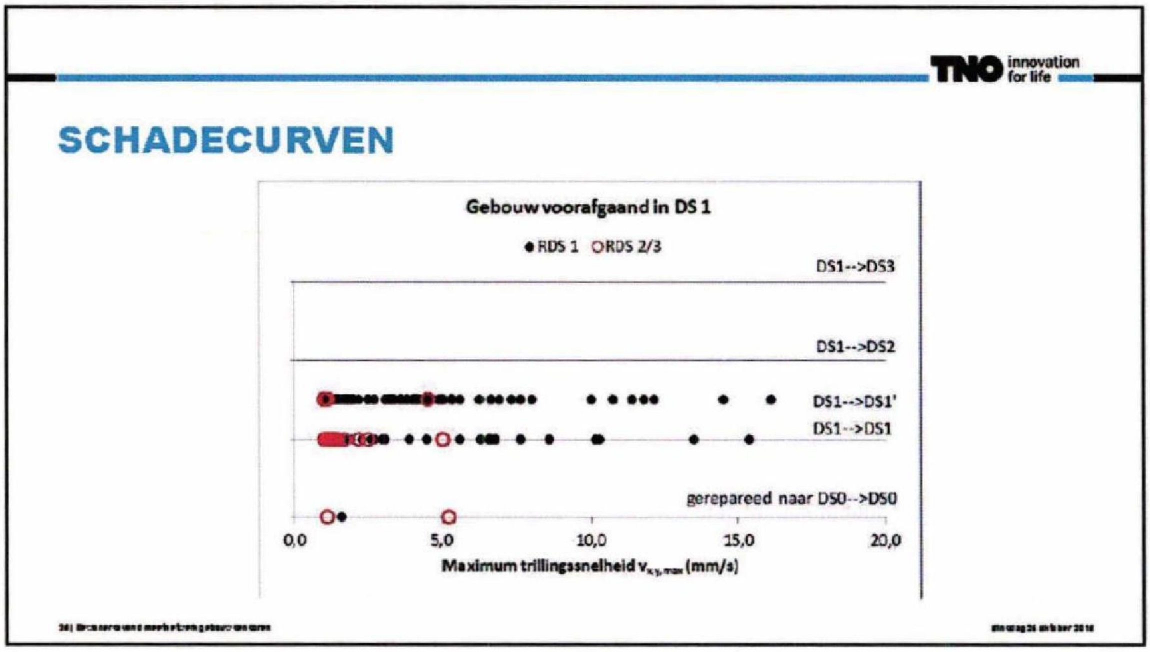


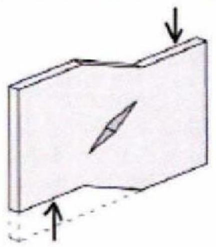
Figure 5.16 Result of TNO damage surveys. No building has moved from DS1 into DS2.

For most of the houses that were categorised by TNO in damage state DS0, having no reported cracks, home owner reported one or more new cracks. Consequently, these houses are categorised to a higher damage state (DS1). Several of the new reported cracks might already have been present at the time of the initial damage survey, therefore it could not be verified if these buildings were initially already in DS1 (due to earthquakes or other causes like settlement or heavy traffic) or not. For all houses categorized in damage state DS1 and DS2, the earthquakes didn't result in an increase of damage state. The TNO sensor network already provided valuable data on building damage over the period since mid-2014 and will continue.

5.3 Observations from the field

A large collection of damage photos in and around the Groningen field has been collated following damage claims. Although in an ideal situation the damage should be evaluated in the field immediately after an earthquake, there is still scope to review the photos to identify the level of damage and the most probable underlying cause or causes. The prototype of a diagnostic decision support tool for structure damage in masonry, developed by De Vent (Ref. 21), provides a framework for such an activity. The tool introduces 60 damage patterns, identified by their key characteristics and each linked to its possible causes (see Fig. 5.17 below for example). Through this exercise it is expected to be possible to identify buildings with damage whose most probable cause is purely from earthquakes in the field.

A. Damage pattern

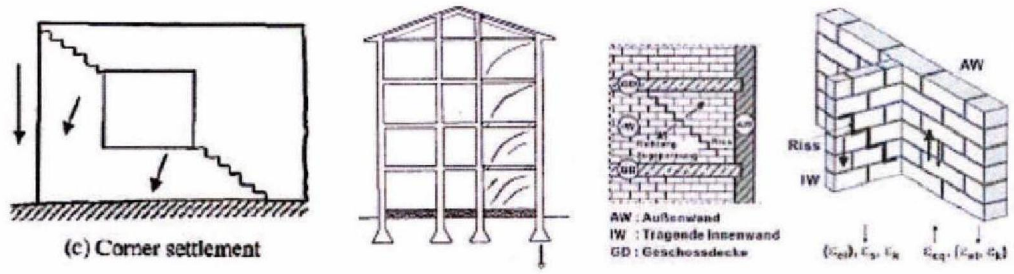


symptoms:

- ■ S: crack
- ■ S: crack direction is diagonal
- ■ S: crack has constant size or is tapered towards both ends
- ■ S: deformation
- ■ S: deformation in-plane
- ■ S: deviation from horizontal: bed joints are not horizontal anymore

context conditions included in pattern:

- ■ G: damage appears in column or wall



Examples. [Hendry and Khalaf 2001] Fig. 7.3 c, [Mastrodicasa 1993] Fig. 304, [Schubert 2009] case 2.2.3.1.

B. Hypotheses

- ☐ 1.B **Vertical settlement: one-end-settlement / one-end-heave**
- ☐ 2.1.15 **Overloading due to change in load, vibrational, natural or induced earthquake**
- ☐ 2.1.16 **Overloading due to change in load, vibrational, machinery or traffic**
- ☐ 3.1.1 **Hindered dimensional changes, temperature/moisture induced, difference in behaviour between two types of units in masonry**

Figure 5.17 Illustration of a damage pattern, examples from practice and hypotheses of most probable cause from the decision support tool for structural damage in masonry

5.4 Levels of shaking experienced by buildings in the field

Using the latest developments in ground-motion prediction for the Groningen field, it will be possible to estimate a distribution of the levels of ground shaking experienced by each of the buildings in field, with specific focus on those with damage claims and those that are classified as highly likely to be earthquake-damaged (as discussed in the previous point). These levels of ground shaking can be described in terms of various intensity measures (PGA, PGV, spectral acceleration, duration of ground shaking, number of repetitions of strong ground shaking etc.). Conditional ground shaking maps, which are maps of ground shaking conditioned on the observed levels of ground shaking (as obtained from the strong motion network), will be produced. These maps account for the fact that close to recordings the levels of ground shaking will be similar to the recorded value (due to spatial correlation). These maps can be used to produce empirical fragility functions by relating the predicted levels of ground shaking with the observed damage.

6 Building Response Method: Damage Assessment based on Experiments on full scale buildings and calibrated Simulation Models

Throughout 2015 and 2016, two sets of shake-table tests of full-scale unreinforced masonry buildings houses were conducted in Eucentre in Pavia, as part of Study and Data Acquisition Plan of 2014 (Ref. 2). These experiments focused primarily on near-collapse of these buildings, but also generated a wealth of information regarding the damage to unreinforced masonry buildings.

The current plan aims to conduct a detailed follow-up analysis of the damage-related information obtained in these tests. In addition, several more building typologies will be tested on the shake-table in Eucentre and at LNEC in Portugal. These tests are scheduled for 2017 and 2018. Finally, we also plan to consider the feasibility of shaking real, existing buildings in the field (in-situ testing) – and learn more about the potential benefits of such tests over the shake table tests in the laboratory. A preliminary plan for the in-situ testing of existing buildings is described below.

6.1 Experimental Testing

Extracting the desired information requires post-processing and further evaluation of the experimental damage data from the shake-table tests by EUCENTRE and Mosayk. This includes:

a. Identification of global damage states (e.g. no damage, minor structural damage and moderate non-structural damage, significant structural damage and extensive non-structural damage, near collapse and collapse);
b. Thresholds at which these damage states were observed in the tests, in terms of level of ground shaking (PGA, PGV, spectral acceleration) and engineering demand parameters (e.g. global drift, peak inter-storey drift ratio (IDR), residual inter-storey drift ratio (RIDR) or peak floor acceleration (PFA)).

The figure below (Fig. 6.1) shows an example of the identification of four damage states from the first shake table test, along with the associated global drift (in terms of displacement at second floor divided by the height to that floor).

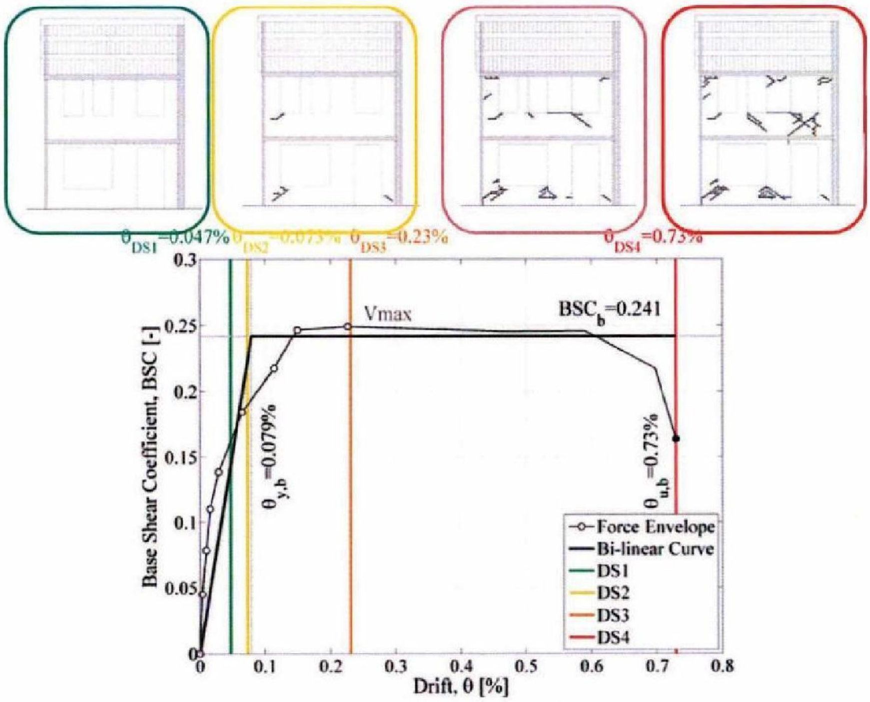


Figure 6.1 *Definition of the observed damage states on the envelope backbone curve from the experimental testing campaign on the terraced house*

Figure 6.2 *Photo of engineers inspecting the building after exposure to an earthquake during the shake-table experiment in Volkskrant 14 september 2015 article by Jurre Van den Berg*

More effort is needed to extract various intensity measures and engineering demand parameters from both of the experimental tests (i.e. the terraced house and the detached house) for different levels of observed damage. This activity will also be carried out for the upcoming laboratory tests, including those on reinforced concrete wall-slab subassemblies, non-structural elements, as well as the in-situ dynamic tests (see next section). The latter will potentially provide an opportunity for studying the potential for damage in real buildings with foundations and non-structural elements (e.g. partition walls, parapets, chimneys), founded on the soils within the field, and that could already have existing damage due to deterioration with time, settlement, previous ground shaking etc.

6.2 In-situ Dynamic Testing

Unreinforced masonry buildings can suffer from many shortcomings. They may have been modified over time by homeowners, they may have been subject to degradation and subsidence, and they may also include additional elements that could collapse, such as chimneys and parapets. Usually, the latter are not included in these experimental tests.

In-situ shake table testing of structural systems could potentially be undertaken to gain a better understanding of the capacity of these buildings to withstand earthquake action. Detailed feasibility studies will inform the decision to commence with an in-situ testing program. An in-situ shake-table test program would potentially offer the following benefits:

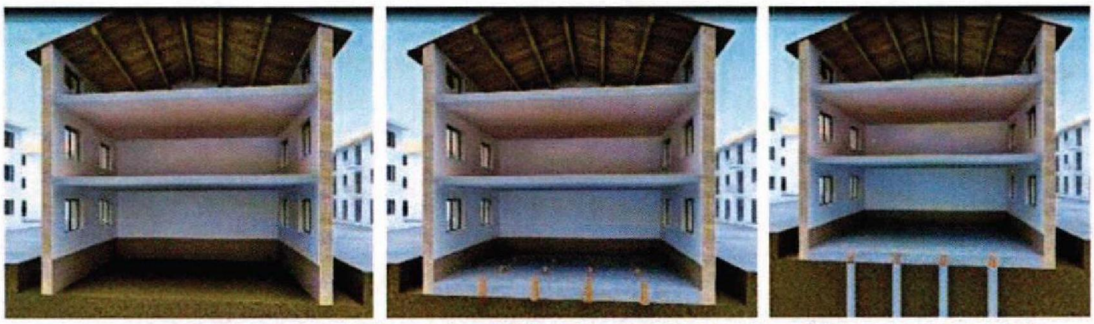
- The tests will be performed on real existing buildings in real conditions, except for soil-structure interaction. The results will thus provide indications on the effects and impact of (i) non-structural elements; (ii) the actual state of maintenance; and (iii) the actual material properties.
- As anticipated, the interaction between soil and foundation is not included, since a sliding layer will be introduced (see below). However, and though not included in the presently foreseen plan, the foundation and soil will be instrumented, allowing to infer data on their response and interaction.
- The possibility of re-testing of the existing buildings after the implementation of local or global strengthening measures. This will allow for an immediate evaluation of the effectiveness of different techniques. This applies either at a life safety performance level or at a damage control performance level.

Studio Calvi from Pavia, Italy, will conduct a feasibility study for this testing approach. Based on their results, a detailed plan will be made for a pilot test, the results of which will inform the decision when and how to launch the dynamic in-situ testing program.

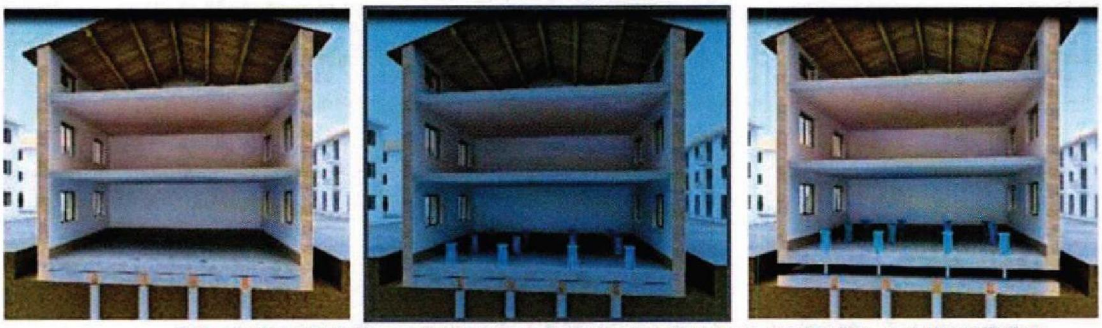
It has to be underlined though, that the loading control will be poorer in dynamic in-situ testing than in laboratory testing. For example, the actual properties of materials and elements are not necessarily known. These dynamic in-situ tests, therefore, will not replace the lab shake table tests, but rather complement them. However, before the shake test in-situ material test of for instance masonry properties will neec to be carried out.

The test requires construction of a new foundation system under the existing building, lifting the structure, insertion of some isolation devices, and application of dynamic excitations to the building (see Figure 6.3 below). This in turn requires the design and construction of an ad hoc mobile laboratory, equipped with all the instruments required for the tests, i.e.:

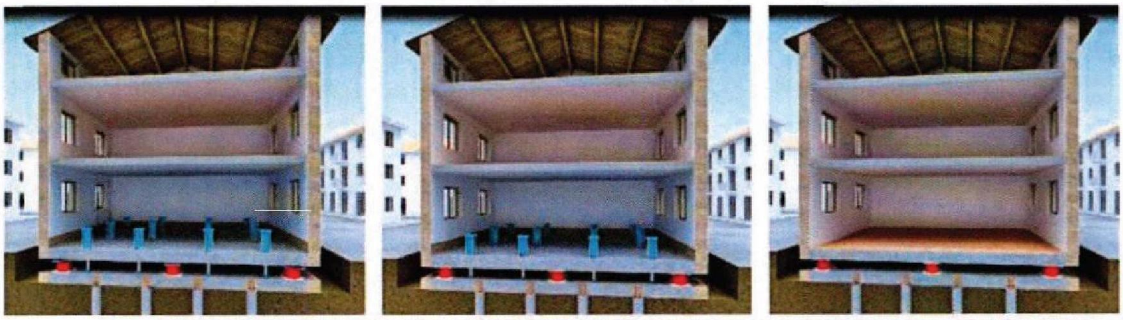
a. Power generator, UPS, Hydraulic pumping system, Accumulator racks, Refrigerators, Actuators with servo-valves, Electronics and controllers, Hydraulic piping, Electrical distribution
b. Cameras, Accelerometers, Data acquisition



From left to right: Phase 1 "Demolition of ground floor"; Phase 2 "Construction of new foundations: RC slab and piles"



From left to right: Phase 3 "Construction of a new RC upper slab"; Phase 4 "Installation of jacks"; Phase 5 "Uplifting"



From left to right: Phase 6 "Installation of isolation devices"; Phase 7 "Lowering and finishing works"

Figure 6.3 *General approach: required activities and phases: sequence of activities required to uplift the building and place the isolation system*

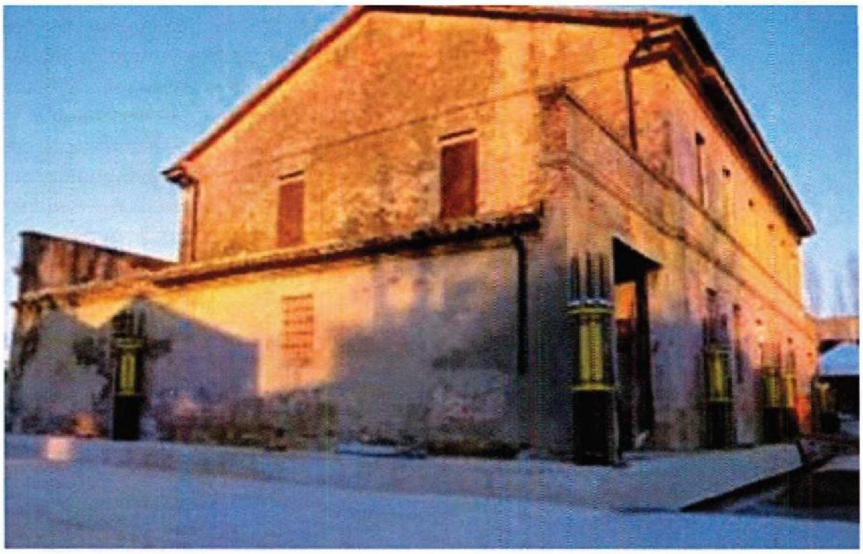


Figure 6.4 Example of an Italian masonry building jacked-up for introduction of isolators

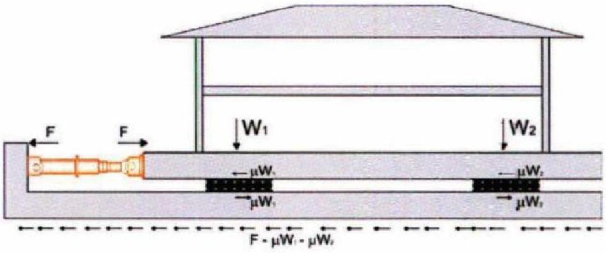


Figure 6.5 Scheme for in-situ shaking of an actual building

This innovative set of tests may constitute a very valuable complement to the laboratory tests, thus allowing for a more complete calibration of the structural models and ensuing fragility functions, with a specific focus on damage assessment. The program commences with a feasibility study phase after which the potential benefits of the test over the already planned research program will be reviewed. If found that such a test would provide additional benefits, a pilot test will be carried out to confirm the test objectives can be reached. Concerns are: unknown material properties, unnoticed damage of the building during excavation, unclear interpretation of the test results.

6.3 Deriving Fragility Functions

One potential difficulty with the validity of the experimental test results is that the buildings are subjected to incremental levels of ground shaking. This may be fundamentally different from the repeated cycles of ground shaking experienced by the buildings in the field. This creates a potential for progressive damage. This renders it impossible to derive the levels of ground shaking and engineering demand parameters at which different levels of damage are expected to occur exclusively from these results. This implies that there continues to be value in continuing the analytical modelling of unreinforced masonry (URM) and reinforced concrete (RC) structures.

The cross-validation exercises that have been carried out so far between the numerical modelling and experimental tests of URM buildings will be revisited, with a focus placed on the estimation of damage initiation and the various damage states experienced by the specimens. A similar cross-validation effort will be undertaken for the upcoming tests on RC structures. Once the modelling tools that are currently being used to develop numerical models are validated in this way, more effort will be placed on running non-linear dynamic analyses at lower levels of intensity to estimate the engineering demand parameter thresholds (so-called limit states) that lead to various damage states. The results of these analyses will then be used to develop fragility functions for different damage states (rather than just collapse states, as has been undertaken to date), as illustrated in Figure 6.6. These fragility functions can be used in the probabilistic hazard and risk methodology to estimate the annual probability of exceedance (or occurrence) of different damage levels as discussed in Chapter 3.

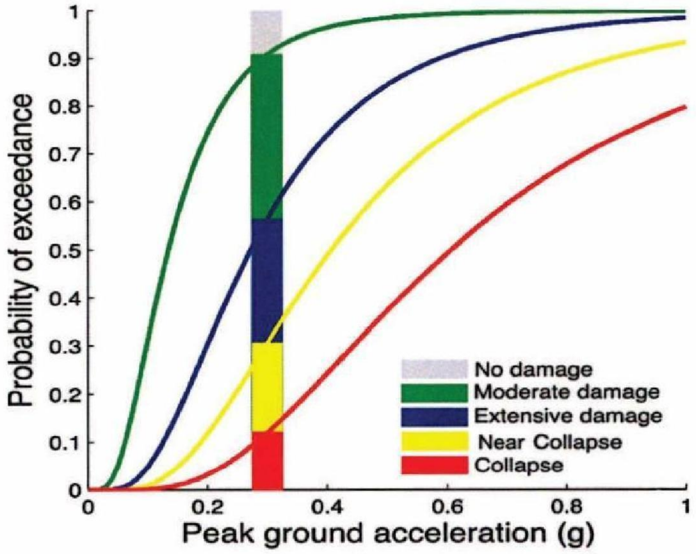


Figure 6.6 Example fragility functions for different damage states

7 Damage Development Method: Sensitivity of Groningen masonry buildings to damage - experimental and computational research

Introduction

This chapter describes studies to determine the sensitivity of building structures in the Groningen region to damage potentially caused by earthquakes. It addresses both the initiation and prevention of damage. The focus of the research is on masonry dwellings (and possibly small commercial buildings), potentially the largest category of vulnerable structures in the Groningen field area.

Knowledge of the first occurrence of damage is currently limited. Our insights are based mainly on empirical and observational methods. The proposed approach aims to extend this current body of knowledge by furthering our understanding of the physics of the initiation of cracks and their subsequent growth. We intend to do this based on mathematical modeling, supported by (additional) laboratory experiments. We thus aim to gain a more thorough understanding of:

1. The initiation of damage and the propagation of damage (especially cracks in masonry), due to several possible causes, including: dynamic vibrations (caused by earthquakes or heavy vehicles or trains); imposed deformations by settlements; and prevented deformation due to thermal shrinkage/expansion.
2. The effect of the combination of these individual causes;
3. The influence of repeated loading on possible damage accumulation.

This research will build on earlier research carried out in the Netherlands and abroad. TU Delft will coordinate the program.

7.1 Study basis and literature survey

The proposed study will take the underlying physics as its point of departure, which is then confronted with (limited) empirical and observational data from the field. To that end, computational models will be developed (nonlinear finite element methods, including fracture mechanics with crack initiation, crack propagation and snap-through of cracks), which will then be tested against the results of laboratory tests. The outcome of this exercise will yield continuous graphs of crack width (or other crack appearance characteristics) versus earthquake intensity (preferably expressed in terms of vibration velocity, see Van Staalduinen & Smits 1993). These graphs will then be transformed to physics-based fragility or resistivity functions. In such an approach, a discretized quantitative damage classification system, as mentioned in section 2, will be used.

In 1997, preliminary modelling studies were performed into the influence of initial stresses in combination with the effects of ground/foundation vibration on building damage (Waarts 1997, Van Staalduinen and Geurts 1998). These were linear elastic calculations of highly simplified models of masonry structures. These studies have so far been used as the basis to link vibration amplitude to the probability of damage. Based on the latest insights, this modelling can be improved and extended. Compared to previously adopted assumptions, the current project will include fracture mechanics concepts[7] (new nonlinear masonry softening models for initiation, propagation and snap-through of cracks), improved 2D plane strain/ plane stress representations, handling of stress concentration factors and mesh dependence, the interaction between soil and building structure, the used material parameters, etc.

[7] Masonry is a quasi-brittle *elastic-softening* material. Once the principal tensile stress or the tensile stresses orthogonal to the joints exceed a certain tensile strength, micro-cracking initiates and the material starts to soften, while the bulk material at either side of the crack unloads elastically. Softening models are able to simulate this continuous process of tracing where cracks initiate, propagate, snap and localize, while other zones unload, eventually resulting in fractured or ruptured facades. Examples of propagation and sudden snap-through are e.g. given in Rots et al. 1997, chapter 6. Please also note here the difference between static and dynamic loads, or more general the effect of loading rate. In static cases, the masonry wall has unlimited time to let this loading/unloading balancing process evolve. In dynamic cases, the inertia ("materiaal traagheid") implies that there is less time to transfer this "info" through the wall, and cracking may be extended and more diffused. Little is known about this. The current research proposal includes these issues.

A first scan of the international literature for repeated loading indicates that there have been studies into the effects of repetitive compressive loading on masonry bridges, but that little research can be found for the specific case in which mainly tensile stresses in brickwork are relevant. With respect to earthquakes, most attention still goes to Ultimate Limit State (ULS) checks. For instance, in the Italian Building Code, a Damage Limit State (DLS) has been defined with reduced drift limits, but an explicit link to crack width, crack patterns and the appearance of cracks, so important to the Groningen situation, is missing. The first occurrence of damage is seldom explicitly considered and little information is available on the effects of repeated loads in combination with small crack widths, and on the cause of damage accumulation. For tunnelling-induced settlement damage such explicit link has recently been established (Giardina et al 2012, 2015). That research for settlement cracking provides important inspiration for the damage forecasting method proposed in the current chapter.

7.2 Outline of the research

Based on the above, a study program is proposed based on the results of a modelling study in combination with a series of laboratory experiments – and the comparison of the results from these two lines of research. The research commences with an extensive *literature survey and the quantification of damage criteria*.

The second part of the research is a *modelling study* based on simplified models of building parts (especially walls, later transverse wall to longitudinal wall combinations or box-type structures) will offer important insights into the relationship between imposed vibrations (in combination with existing stresses in the component) and the onset and growth of cracks. This study will focus on visually detectable in-plane cracks for in-plane situations, and will pay limited attention to both out-of-plane checks and combinations of in-plane and out-of-plane cracking[8]. The main advantage of this study design is that it allows sensitivity analyses and predictions to be prepared for a wide variety of practical situations, assuming a subset has been successfully calibrated to experiments. These sensitivity studies are of critical importance, given the variety and uncertainty in building designs, materials, geometries and loading situations.

The third part of the research involves *experimental research* to verify a selection of the numerical models. This provides validation and calibration. The experiments on detailed crack detection will serve as benchmarks for a selected representative set of loading combinations, including repeated loading. This experimental design is inspired by studies into settlement studies for the Amsterdam Metro line (North-South line), where a (scaled) experiment was done on a masonry façade, with rubber springs and a deformable beam underneath the wall for semi-coupled soil-to-wall interaction (Giardina et al. 2012). This was then extrapolated through modelling to variations in geometry, openings, initial stress variations and pre-damage, with explicit crack-info as a prime output. Subsequently, numerical and experimental analyses can be scaled up from 2D to 3D. There are also parallels with the behaviour of masonry under sustained loading, with creep and its effect on crack formation (e.g. Van Zijl et al 2001).

The fourth part of the research is a *synthesis*. It focuses on the analysis of the predictions and experiments to relate the loading levels to damage limit states such that a relationship can be formulated with crack width and / or strain, which can be used to quantify the damage. In particular, attention needs to be paid to the influence of variations in the material and geometry parameters, and to the influence of variations in the initial loading situation of the actual building stock. Ultimately, relations will be established between the vibration levels and the occurrence of damage.

[8] A first glimpse at Groningen damage cases indicates that most of the cracking emerges in-plane, i.e. cracks have the same width all over the thickness of the wall and they grow in the plane of the wall, not in the thickness of the wall. This is typical of settlement, subsidence and restrained shrinkage induced cracking. It is postulated that it also holds for damage due to light earthquake vibrations. The soil wave generated by the earthquake may have wave lengths in the order of the building length. This implies that the bedding underneath walls is temporarily "lost", and hence a sagging or hogging situation occurs similar to settlement or subsidence, resulting in in-plane cracking. So, in-plane action is important anyhow. Regarding out-of-plane shaking of a wall, at first sight it is not expected that light earthquake vibrations will be strong enough to damage a wall out-of-plane. However, little is known about this when the wall is already pre-damaged and/or consisting of very poor masonry. Therefore, it is important to investigate the (possibly high) margins of damage in case of out-of-plane shaking, especially for walls that are already pre-damaged in-plane. The relations between vibration velocity levels and damage should thus be established for in-plane but also for combinations of in-plane and out-of-plane modes. In addition, it is postulated that most of the in-plane tensile cracking relevant to light earthquake vibrations in combination with differential settlement is vertical (in spandrels) or diagonal (from window corners). The focus is on those. All in 2D wall settings in the first half of 2017, later to be extended to 3D buildings.

This study provides physical support to new factors to be used in the SBR directive (2010) (Ref. 14) for basic cases and for the effects of culmination, degradation, triggering or aggravation by repetition.

7.3 Description of the main parts of the research

7.3.1 Step 1. Establish Study Approach

Literature review, collection, selection of practical damage cases Groningen. Abstracting and reducing these to representative cases for the experimental / numerical research.

Objectives of this phase of the study:

1. **Literature review** into relevant experimental, numerical and theoretical work in this field, with emphasis on acceptance criteria in damage states and specifically the translation to explicit crack characteristics.
2. **Collection and analysis of relevant practical damage cases for Groningen situation.** This includes cases with damage that can clearly be attributed to earthquakes, cases where damage is attributed to multiple causes including earthquakes and cases where damage is primarily attributed to causes other than earthquakes.
3. **Anamnesis and diagnosis of these cases.** With engineering judgement and structural understanding and, if necessary, linear FEM models. Input data from NAM and CVW.
4. **Abstracting and reducing these to a manageable representative set of cases for investigation.**

It is anticipated that these cases will initially reflect typical so-called sagging cases with downward bending and tensile stresses at the bottom of a wall, as well as hogging cases with upward bending and tensile stresses at the top of the wall.

7.3.2 Step 2. Calculation models and model analysis

Objectives of this phase of the study:

1. **Development of a set of computational models of building components**. This includes foundation and soil-structure interaction that allows linear elastic and nonlinear analyses to be carried out. The step from linear to non-linear modelling will be made in this phase of the study. Compared to the previous work phase the following will be added: fracture mechanics softening models for crack initiation, crack propagation and crack snap-through (this was not included in previous calculations, Waarts 1997). Significant improvements can be achieved relative to previous studies by making use of better masonry models developed during the studies carried out as part of Study and Data Acquisition Plan of 2014 (Van Elk, Uilenreef, Doornbos et al., NAM 2014-2016). In addition to the newly developed anisotropic continuum models (e.g. Rots et al. 2016), we will also make use of the previously developed discrete interface models for detailed crack progression on brick-joint interfaces (e.g. Rots et al. 1994). Such models offer support for the detailed calculations required here, but cannot be used for complete buildings, and were consequently absent from Study and Data Acquisition Plan of 2014. Furthermore, improvements with respect to the study by Waarts (1997) will be made regarding the plane-stress / plane-strain combination of wall and soil base, and regarding the parameters.
2. **Studying the effect of loading rate and extend computational or constitutive models with strain rate or loading rate dependence**, either in generic form or via discrete switches between e.g. long-term Young's moduli and strength properties versus short-term Young's moduli and strength properties. It is anticipated that slow processes like settlements give time to the mortar joints to crack slowly, so that strain localization into a single crack occurs while elastic unloading takes place in the material at either side of the crack. For short duration vibrations there is less time for this elastic-softening loading/unloading localization process, the masonry may behave stiffer, stronger and may spread the cracks due to inertia. This may affect both crack propagation and crack distribution (localized versus more distributed smeared out patterns).
3. **Analyses into the onset of cracking and the cracking development in masonry,** under a number of quasi-static loading situations (self-weight, imposed deformations from settlements, imposed deformations from restrained shrinkage, etc.). Sensitivity analyses for different geometries, different material parameters and loading patterns.

4. **Development of a set of mathematical models of building components** including foundation and soil-structure interaction for linear elastic dynamic determination of the response caused by ground vibrations, valid for the frequency of shallow induced earthquakes (about 0-15 Hz), but also passing heavy vehicles and trains.
5. **Performing analyses for the determination of the response under dynamic earthquake loading** (time and frequency domain analysis). To infer at the bottom of the wall: the velocity and displacement of the nodes of the FEM mesh, development of amplitudes, displacement time histories.
6. **Preparation of a set of reduced non-linear elastic calculation models of only the relevant parts of the building** (without soil), on which these velocities or displacements are imposed. For cases of limited crack damage one could (and would like to) eliminate the soil-structure interaction, if possible. This would allow improved and faster sensitivity analysis and experiments. In effect, this focusses on finding an acceptable and reasonable static equivalent and of an acceptable and reasonable decoupled building-soil equivalent. On the basis of the set of reduced non-linear models, execute a number of full non-linear dynamic time-history analyses:
    a. Predict the initiation, propagation, widening and possible snap-through of cracks due to the stresses and strains imposed by the dynamic loads
    b. Sensitivity analysis for different geometries and material parameters
    c. Sensitivity analysis for different levels of the dynamic load
    d. Sensitivity analysis for the various cycles of dynamic load
7. **Testing the validity of the reduced models**, by comparing the results of the reduced models to a small number of calculations with the complete modelling.
8. **Analysis of extended modelling,** including strengthening measures (e.g. reinforced plaster patches added to the masonry, or bed joint reinforcement) that distribute and mitigate the cracking.

Depictions of typical potential modelling results are given below, for sagging and hogging, respectively, along with a targeted graph of crack width versus the load actor.

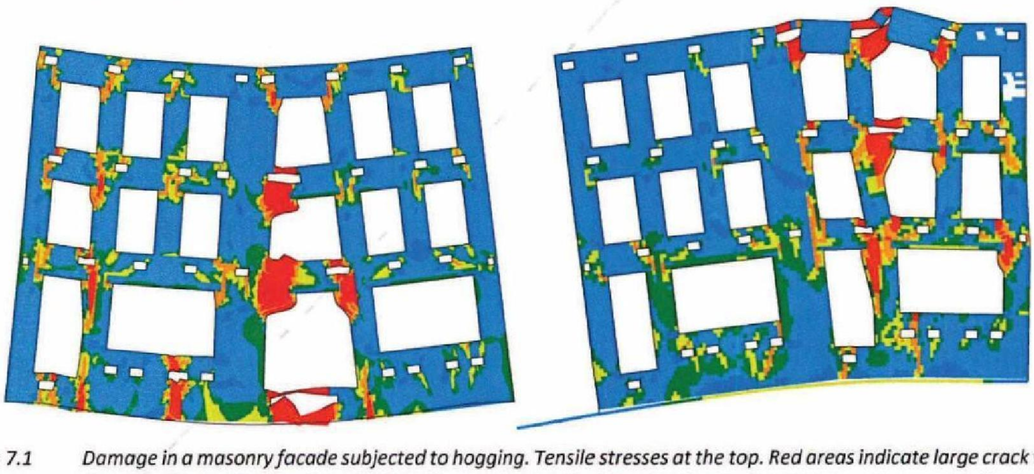


Figure 7.1 *Damage in a masonry facade subjected to hogging. Tensile stresses at the top. Red areas indicate large crack width. Fig. 5.8c Thesis Giardina (Giorgia Giardina, Max A.N. Hendriks, Jan G. Rots, Sensitivity study on tunnelling induced damage to a masonry façade, Engineering Structures 2015, 89, 111–129)*

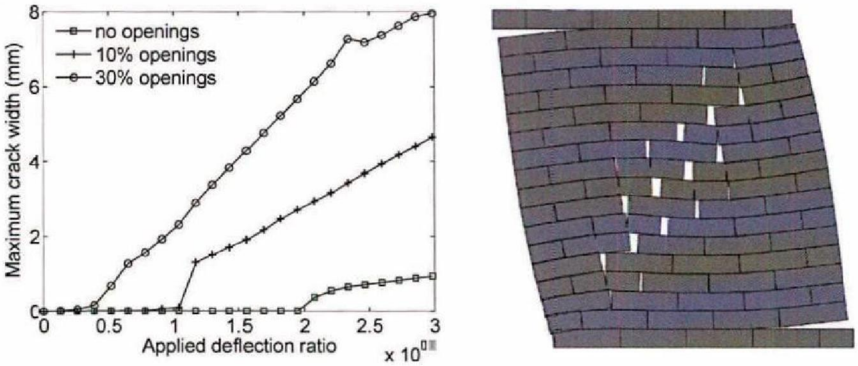


Figure 7.2 *Detailed simulation of building damage; crack width and damage pattern are recorded.*

7.3.3 Step 3 Experiments and experimental analyses

Objective of this phase of the study:

1. **Design of a set of laboratory experiments**, with non-proportional loading consisting of initial stress in the wall plus a load that reflects the effect of the earthquake (and / or settlement and restrained shrinkage and/or passing heavy vehicle/train) to a reasonable extent. Dimensions, design, material usage are yet to be determined (brick and mortar). Based on possible replicated reuse of material combinations from the Study and Data Acquisition Plan of 2014 (Ref. 2), plus weaker materials, because the damage often occurs in old masonry.
2. **Preparation of test protocols and measurement protocols.** Deployment of new photogrammetric measurement techniques (digital image correlation and possibly other non-contact optical measurement techniques), which reveal displacement and deformation contours with precision in the order of 0.1 mm. This allows hairline cracks and larger cracks to be detected and the results can be directly compared with strain contour plots from FEM analysis. Registration of crack mouth opening and sliding displacements, tracking of crack opening paths. This is important for the forensic engineering in damage cases.
3. **Conducting a series of lab tests** in a situation notched (with an initial crack present) and un-notched (without an initial crack present), with several increasing loading levels in order to establish a relationship to the strength of the vibration.
4. **Extended lab tests** The experiments focus on 2D cases, later to be extended to T-, U- or box-like structures with 3D loading situations. Some experiments will include preventive or mitigating measures, including plaster layers or plaster bands with textile reinforcement, or ECC, in order to achieve improved crack distribution.
5. The test series are carried out under a single (first loading) and under repeated loading (several cycles at the same or at an increasing level), to establish crack growth and degradation effects. Some tests are foreseen to study the effect of loading rate on crack propagation and crack spreading, reflecting the difference between long-term processes like settlements and short-term loadings like vibrations, as mentioned and motivated before under the modelling activities.
6. Companion material tests (compression, bending, and shear triplet) will be performed, measuring actual masonry properties.

A preliminary feasibility study last fall resulted in the following concrete proposals for testing in the first half of 2017, to be detailed further and prioritized with NAM:

- In-plane beam tests, medium-scale, notched, symmetric and non-symmetric loading, static and repeated loading – as base cases for the phenomena.
- In-plane wall tests, vertical pre-load and horizontal load, static and repeated loading – representing full-scale real wall cases.
- Out-of-plane wall shake tests, with in-plane pre-damage, dynamic – representing full-scale real wall vibration cases.

A sketch of the envisaged testing programme is given in figure 7.3.

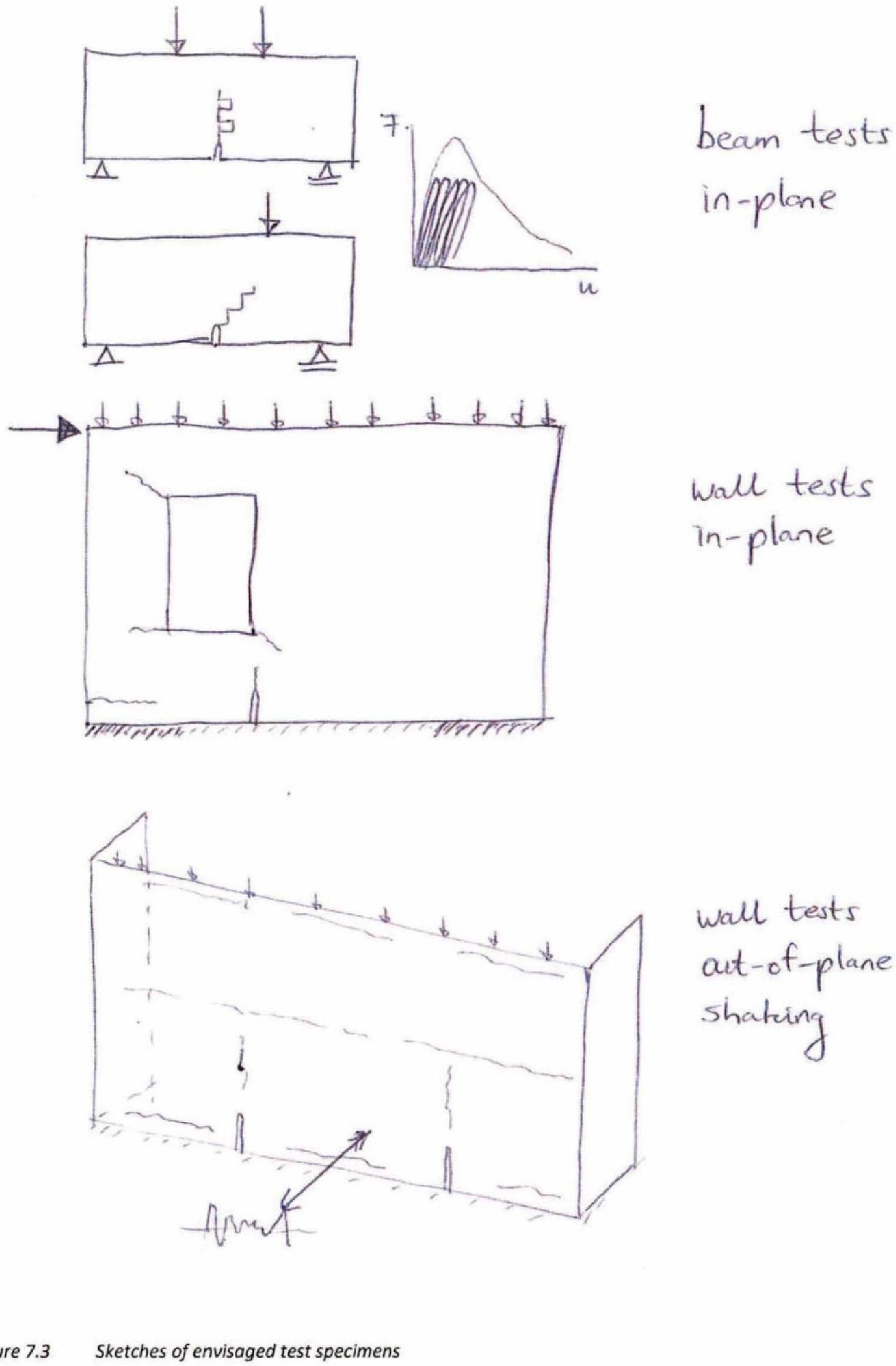


Figure 7.3 Sketches of envisaged test specimens

- **Feasibility.** A preliminary feasibility study for the shake facility was carried out in October 2016, indicating that the Stevin facilities and hydraulics infrastructure fit to that purpose. Groningen typical frequencies, loading rates and load levels required for shaking the large-scale walls can be achieved, both for harmonic and random vibrations. Moderate investments are required in high-speed servo control apparatus, especially large industrial valves, lab space is required and additional manpower to build the table, the frame on the table and the provisions to generate overburden at the top of the wall. An indication of such shake test arrangement is given in the sketch below (from Australian research).

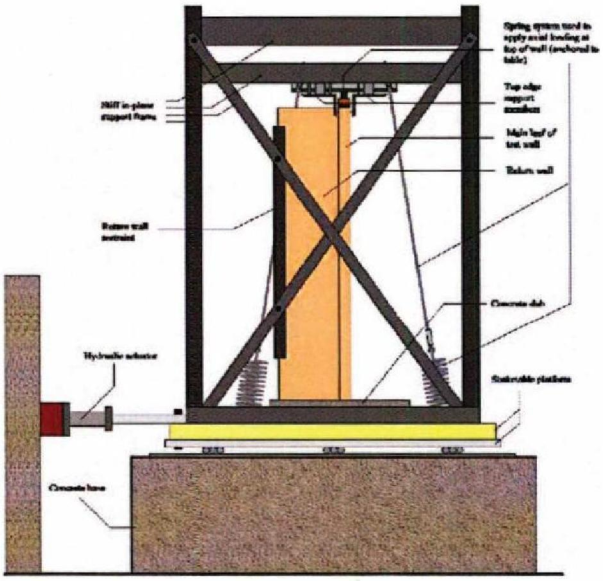


Figure 7.4 Shake-table test arrangement.

7.3.4 Step 4. Analysis, sensitivity studies and synthesis, translation into practice standards

Objective of this phase of the study:

1. **Analysis of the results of the experiments**
2. **Confrontation of experimental results with results from corresponding predictions.**
3. **Title.** Analysis of the influence of various parameters, initial tensile stresses, geometry, load levels and load cycles with a view to determine the combined effect on damage (accumulation) and the effect of repeated loading (degradation).
4. **Extrapolating sensitivity studies of material, geometry and loading conditions.** Establish bandwidths for crack width and crack density or crack spacings (comparable to the typical uncertainty ranges in weather forecasts). This is essential given the high degree of diversification and the focus on the bottom "tail" of the SBR curves.
5. **Translation of results of sensitivity analyses to meaningful lower limits**, taking into account the influence of dispersion.
6. **Comparison of the results with classification systems for damage (Damage States).** The focus is primarily on a damage classification system previously used in tunnelling-induced settlement damage (distinguishing into negligible, very slight, slight, moderate, severe, very severe damage; quantified in terms of crack width for non-linear calculations and equivalent limiting elastic tensile strains for elastic approaches). Produce continuous registrations of the development of crack width as a function of loading scenarios and discretize those via classification systems.
7. **Title.** Determination of the relationship between damage initiation and dynamic load levels and translation to vibration strengths.
8. **Translation of findings from the sensitivity analyses to proposals for measures to prevent damage or to shift damage to higher dynamic vibration levels.** Supporting of preventive and mitigating measures (crack delay and improved crack distribution or crack spreading).

9. **Deliverables:** interim reports and final reports, with physically-based knowledge of crack damage, including test protocols, test results, modelling design, modelling results, analyses, interpretations, projections towards discriminatory guidelines.

7.4 Development of Fragility Curves

The deeper understanding of the processes causing the initiation of damage (cracks) and the development of damage depending on existing stresses in (parts of) the buildings can be combined with insights in what causes pre-existing stresses in a building. Based on this combination the currently existing fragility curves may be refined. These insights can be corroborated and validated with observed damage patterns from experiments and field observations.

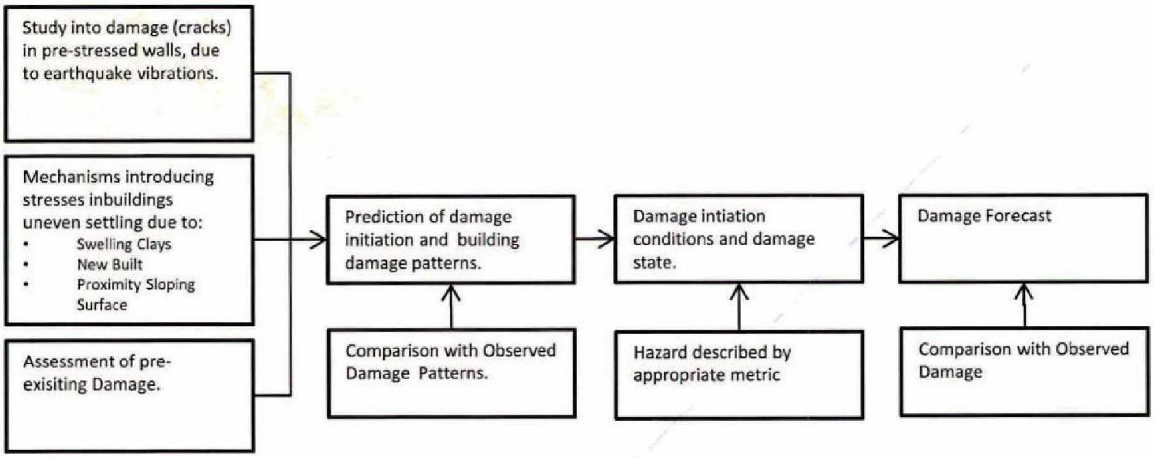


Figure 7.5 Potential work flow diagram for the development of fragility curves.

Feasibility of this methodology for the development of refined fragility curves for buildings in the proximity of sloping surfaces and other potential causes of pre-existing stresses in the building will be carried out.

These insights will be valuable evaluation of building damage and development of repair methods, which avoid damage reoccurring with subsequent earthquakes.

8 Synthesis of the Work streams to develop Fragility Curves

8.1 Introduction

This section evaluates the strengths and weaknesses of each of the three study work streams to develop Fragility Curves for all Damage States. It turns out that each work stream is most optimal for a specific range of the damage spectrum, which runs from light damage (Damage State 1), to building collapse (Damage State 5). Therefore, a combination of the three methods yields the most powerful insights into building damage over the full spectrum of damage states.

8.2 Summary of Advantages and limitations of the work streams

8.2.1 Historical trend method

8.2.1.1 Strengths

This work stream is based on data covering the full Groningen building stock. TNO derive an empirical relationship between the ground velocity and building damage in 2009. The method was successful in predicting (technically, postdicting) the damage for the 2012 earthquake near Huizinge.

This method may be refined by employing three important sets of data:

i) The large volume of additional damage claims and damage assessment data
ii) Recorded levels of ground shaking as obtained through the TNO sensor network. This network covers 300 buildings in the Groningen areas and measures ground/foundation movement
iii) Post-earthquake inspections.

8.2.1.2 Weaknesses

The main limitation of the Historical Trend work stream is that the empirically observed range of transitions due to earthquakes is limited to DS1. This was primarily in URM buildings. A method based on historical building damage data will therefore only be able to forecast building damage transition into DS1 for URM buildings. The building damage resulting from earthquakes larger than those experienced to date cannot be assessed as this will most likely also include transition into DS2 and higher and potentially damage to non-URM buildings. An alternative method based on an analysis of the latest available data cannot circumvent this methodological limitation. This method alone will therefore not satisfy article 7 of the *Instemmingsbesluit*.

A second limitation is that especially for DS1, it is difficult to distinguish earthquake related damage from that due to other causes, further impacting the quality of the available building damage data.

A third limitation is insufficient recording and reporting of the damage. This is especially so for cases where the damage was earthquake-related or the cause of the damage could not be determined and a contribution to the damage from earthquakes could not be excluded. This problem is due to the fact that the damage claims and repair teams of NAM and CWV main focus was initially on efficient handling and settling the large volume of damage claims and efficient repair of damage.

The method will provide a *probabilistic* view on building damage for a population of buildings (that is, it offers insights in the expected damage for a group of similar dwellings). It will not be feasible to extend this method to the assessment of *individual* building damage cases. At best the zone where building damage is to be expected or not to be expected can be established.

Good quality damage assessments are essential for the success of a forecasting method based on the historical damage claims and assessed damage data.

8.2.2 Building Response Method

8.2.2.1 Strengths

To calibrate the numerical models for the development of fragility curves for higher damage states DS4 and DS5 to assess risk, experiments were performed on building elements and full-scale buildings. The laboratory experiments performed on building elements and full-scale buildings also provide data and insights in the initiation and development of building damage.

Assessment of the results of these experiments to establish the limit state thresholds for lower damage states than DS4 and DS5 is in progress. The results will be used to calibrate numerical models that will be used to generate fragility curves for damage states DS2 and DS3 for unreinforced masonry building typologies. These results will also include *observed* damage patterns and will not be contaminated by pre-existing stresses and unknown pre-existing damage. New experimental damage data on reinforced concrete buildings will also become available in 2017 and will also be used to identify damage limit states, calibrate numerical models and produce fragility functions for reinforced concrete building typologies.

8.2.2.2 Weaknesses

it will be very difficult to establish damage state DS1 as hair-line cracks are extremely difficult to identify in building elements and in houses on a shake-table. No plaster was applied to specimen houses on laboratory shake-table. This means that for all practical purposes, the impact of pre-existing stresses and unknown pre-existing damage on future damage can only be investigated analytically, without the benefit of calibration data.

This drawback can potentially be alleviated by the in-situ experiments, which can be tailored to building damage assessment (also DS1). However, feasibility of these experiments needs to be confirmed as a first step, followed by an evaluation of the benefit over laboratory shake-table experiments. These experiments can be executed in 2018 at the earliest.

8.2.3 Damage Development Method: Studies into initiation and growth of cracks in masonry walls.

8.2.3.1 Strengths

The strength of the Damage Development Method to analyse and forecasting future damage is that it, at least in theory, has the ability to take into account all the complexities resulting from pre-existing damage and pre-existing stresses in elements of the building, due to other reasons than earthquakes (like uneven settlement). Insight into the contribution made by each these pre-existing factors is especially important for learning more about the nature of the process leading up to building damage.

8.2.3.2 Weaknesses

An important weakness of the Damage Development Method to forecasting future damage is that it is quite a challenge to translate the results of the experiments and simulations and other analytical exercises to the actual context of the Groningen area. Conducting these experiments and studies will take considerable time. Unfortunately, most results will not be available until after November 1, 2017.

8.2.4 Discussion

Table 8.1 shows an overview of the contribution each work stream makes to the development of fragility curves for each of the five damage states. No single work stream will be able to address the full range of damage states (DS1 through DS5).

Forecasting of Damage State	**Historical Trend Method (§5)** Using Historical Damage Data from Groningen	**Building Response Method (§6)** Based on experiments and tests of building elements and houses	**Damage Development Method (§7)** Based on understanding of crack initiation and development due to vibrations
DS1 **Negligible to slight damage.** **No structural damage,** **Slight non-structural damage.** • Hair-line cracks in very few walls • Fall of small pieces of plaster only • Fall of loose stones from upper part of buildings in very few cases	Extensive historical record for DS1 available. • Inspections of TNO-sensor buildings • Damage claims and damage settlement database Impact of earthquakes on damage could be overestimated in low damage categories.	Hair-line cracks very difficult to identify in building elements and houses on shake-table. No plaster was applied to specimen houses on laboratory shake-table. In-situ shake-table could demonstrate initiation of DS1.	Calculations and experiments provide insight into mechanism of initiation of cracks and growth of cracks. Impact of pre-existing stresses in the buildings is incorporated.
DS2 **Moderate damage** **Slight structural damage, moderate non-structural damage** • Cracks in many walls • Fall of fairly large pieces of plaster • Partial collapse of chimneys	Historical record does not contain any or few instances of DS2	Damage DS2 determined during inspections performed during tests.	
DS3 **Substantial to heavy damage** **Moderate structural damage, heavy non-structural damage** • Large extensive cracks in most walls • Roof tiles detached • Chimney fracture at the roof line • Failure of individual non-structural elements (partitions, gable walls)	Historical record does not contain any instances of DS3	Damage DS3 determined during inspections performed during tests.	
DS4 **Very heavy structural damage very heavy non-structural damage** • Serious failure of walls • Partial structural failure of roofs and floors	Historical record does not contain any instances of DS4	Risk Assessment includes life-safety consequences of DS4	
DS5 **Destruction; very heavy structural damage** • Total of near collapse	Historical record does not contain any instances of DS5	Risk Assessment includes life-safety consequences of DS5	

Table 8.1 Overview of focus of each work stream and damage state.

9 Schedule

9.1 Project Milestones

Based on the milestone dates of the *instemmingsbesluit*, a schedule for the activities in the "Study and Data Acquisition Plan – post-Winningsplan 2016" was prepared in November 2016 and submitted before the deadline of December 1, 2016. The extension of this plan for research into building damage was at that time in progress and the activities not yet included in that the schedule.

This section shows the schedule for the activities for building damage, using the same format as used in the schedule report of 1st December 2016.

9.2 Hazard

The activities for the development hazard for the forecast of future building damage are primarily an extension of the activities included in the "Study and Data Acquisition Plan – post-Winningsplan 2016".

Study Activity	Report available and published at Onderzoeks-rapporten site	Results incorporated in update of hazard and risk assessment	Description of the Activity in S&DAP. Section and Page number
Additional geophone sensors near TNO sensors	1st July 2018	1st November 2018	Section 8, page 69
Wierde Groot Maarslag	1st September 2018	1st November 2018	Section 8, page 69
Next generation ground motion prediction methodology (V4), including hazard metrics for building damage.	1st April 2017	1st June 2017 (hazard) and 1st November 2017 (risk)	Section 9; pages 92 to 98
Effects of shallow swelling clays	Scope of activity adapted for development building damage. Schedule to be submitted 1st February 2017		Section 9; pages 100
Sand map Groningen for liquefaction	1st February 2017	1st November 2017	Section 9; pages 103 and 104
General framework for evaluating liquefaction triggering, adaptation to Groningen specific soil situation.	1st June 2017	1st November 2017	Section 9; pages 104 and 105
Implementation of the Liquefaction Damage Index - Ishihara (LPI_{ISH}) in a probabilistic framework	1st September 2017	1st November 2017	Section 9; pages 104 and 105

Table 9.1 Milestone dates for further studies in support of the development of hazard metrics for building damage.

9.3 Implementation Methodology

The implementation of the methodology for the future building damage forecast requires extension of the current software code. This is needed to allow for the computer-intensive Monte Carlo simulations to reach convergence for the building damage results require extensive testing.

Study Activity	Report available and published at Onderzoeks-rapporten site	Results incorporated in update of hazard and risk assessment	Description of the Activity in S&DAP. Section and Page number
Extending the software code for the Monte Carlo simulation of building damage.	October 2017	1st November 2017	Damage study report section 3; Page 18 - 24

Table 9.2 Milestone dates for implementation of the methodology for the prognosis of building damage (see chapter 3 of this report).

9.4 Work stream 1 (Historical Trend Method)

Work stream 1 will make use of damage claims and observed damage data. The limited historical experience domain (mainly DS1) and the data quality will limit the usefulness of the results for forecasting future building damage.

Study Activity	Report available and published at Onderzoeks-rapporten site	Results incorporated in update of hazard and risk assessment	Description of the Activity in S&DAP. Section and Page number
Advanced Analytics evaluation and vizualisation of damage claims and damage inspections	October 2017	1st November 2017	Damage study report section 5.1; Page 36 - 39
Report by TNO on monitoring building vibrations - analysis earthquakes 2015 and 2015	January 2017	1st November 2017	Damage study report section 5.2; Page 40 - 45
Application of the forecasting method for building damage developed by TNO (kalibratiestudie).	October 2017	1st November 2017	Damage study report section 5.1 Page 34 - 35

Table 9.3 Milestone dates for further studies in support of work stream 1; Damage Assessment based on historical damage claims and damage data (see chapter 5 of this report).

These studies are based on analysis of damage claim and observed data. Depending on the results, these studies will be updated and repeated as more building damage data becomes available.

The research partners of the work stream are TNO (kalibratiestudie and building sensors) and CVW (damage claims data).

9.5 Work stream 2 (Building Response Method)

Work stream 2 is an extension of the studies and experiments already done and in progress for the development of fragility curves for partial and full collapse. Main research partners are EUCENTRE, LNEC, Studio Calvi and Mosayk.

Study Activity	Report available and published at Onderzoeks-rapporten site	Results incorporated in update of hazard and risk assessment	Description of the Activity in S&DAP. Section and Page number
Assessment of damage from previous experiments on terraced house and detached house from early 20th century.	1st September 2017	1st November 2017	Damage study report section 6.1; Page 49
Pseudo-static testing of cast-in-place one-storey RC structure	1st July 2017	1st November 2017	Section 11 Page 109, 110, 111, 112, 113, 118
Shake-table testing of one-storey URM terraced house	1st October 2017	1st November 2017	Section 11 Page 110, 111, 112, 113, 118
Pseudo-static testing of precast two-storey RC structure	1st October 2017	1st November 2017 (early results) 1st November 2018	Section 11 Page 111, 113, 118
Shake-table testing of precast two-storey RC structure	1st December 2017	1st November 2018	Section 11 Page 111, 113, 118
Shake-table testing of two-storey URM detached house	Q1 2018	1st November 2018	Section 11 Page 111, 113, 118
Feasibility investigation in-situ shake-table testing.	1st December 2017		Damage study report section 6.2; Page 50 – 52
Tentative date first in-situ shake-table testing.	Late 2018	1st November 2018 (early results)	Damage study report section 6.2; Page 50 – 52
Follow-up in-situ shake-table testing.	2019 - 2020	1st November 2019	Damage study report section 6.2; Page 50 - 52

Table 9.4 Milestone dates for further studies in support of work stream 2; Damage Assessment based on Experiments on full scale buildings and calibration of analytical models (see chapter 6 of this report).

The research partners of the work stream are EUCENTRE (revisit off results previous tests for damage data and new experimental work and shake-table tests) and Studio Calvi for the in-situ shake-table tests.

9.6 Work stream 3 (Damage Development Method)

Work stream 3 attempts to from a better understanding of the initiation of cracks and damage and development of damage (crack growth). Most of the experiments and modelling studies will be carried out by TU Delft in the team of Prof. Jan Rots.

Study Activity	Report available and published at Onderzoeks-rapporten site	Results incorporated in update of hazard and risk assessment	Description of the Activity in S&DAP. Section and Page number
Brief report on review of relevant literature and on explicit definition of damage.	1st March 2017	1st November 2017	Damage study report section 7.3; Pages 57 to 59
Proposal for explicit and quantified damage classification system in terms of crack width and other crack characteristics.	1st March 2017	1st November 2017	Damage study report section 7.3; Pages 57 to 59
Progress report Computational Modelling – Validation of computational models with respect to the lab tests to be performed. Sensitivity studies and explicit crack width and crack pattern predictions, linked to quantified damage states.	1st August 2017	1st November 2017	Damage study report section 7.3; Pages 57 to 59
Progress report on companion material tests, notched beam tests in-plane and out-of-plane wall tests.	1st August 2017	1st November 2017	Damage study report section 7.3; Pages 57 to 59
Final report Computational Modelling – Validation of computational models with respect to the lab tests to be performed. Sensitivity studies and explicit crack width and crack pattern predictions, linked to quantified damage states.	1st August 2018	1st November 2018	Damage study report section 7.3; Pages 57 to 59
Final report on companion material tests, notched beam tests in-plane and out-of-plane wall tests.	1st August 2018	1st November 2018	Damage study report section 7.3; Pages 57 to 59

Table 9.5 Milestone dates for further studies in support of work stream 3; Damage Assessment based on Experiments on and modelling damage sensitivity (see chapter 7 of this report).

The main research partners of the work stream is TU Delft.

9.7 Status for Prognoses at 1st November 2017

The program for research of building damage is an extension of the "Study and Data Acquisition Plan", which predominantly focused on hazard and individual safety risk. The activities in this extension program will span a period of multiple years. The in-situ shake table testing stands out as a new and innovative activity; these experiments have never before been attempted. Investigations into the feasibility of this approach and preparation for these experiments will require considerable effort.

Activities in work stream 1 (Historical Trend Method) and those based on extended analysis of previous experiments in work stream 2 (Building Response Method) are expected to offer a major contribution to the development of fragility curves for the future building damage forecast, due on November 1, 2017.

The work stream 2 experiments and the activities in work stream 3 (Damage Development Method) will be moving forward, but will not result in final deliverables on November 1, 2017. Depending on the progress made in the coming nine months, this work may still inform the final forecast that will be submitted before November 1, 2017.

Extending the Monte Carlo method with additional hazard assessments for building damage (incl. liquefaction) and additional assessment of building damage for lower damage states (DS1 to DS3) involves a considerable effort. Not only the extension of the tools to include the additional complex scope is important, but also management of run times is important. The flexibility with which sensitivities and alternative can be explored depends to a large extent on the runtimes achieved.

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11 Appendix A – Building Damage in Advices to the Minister

In the advice to the Minister, building damage is an important component. Improved understanding of how damage is caused by earthquakes, the prediction and forecasting of damage are primarily addressed in the advice of the Scientific Advisory Committee and Mijnraad. Below excerpts from the advice of these organisations:

11.1 Scientific Advisory Committee

2. It makes sense to prioritize on a clearly-defined track towards assessment of risk for residents, while it is also in line with the norms of the Commissie Meijdam. However, major public concern is related to the risk to assets, i.e. the damage to houses. Therefore we would expect that the risk assessment also addresses a more complete quantification of risk to assets, or at least gives a road map how this will be done in the future.

11.2 Mijnraad

Schade

De Mijnraad adviseert de NAM binnen twee jaar een rekensystematiek te laten ontwikkelen voor het kwantificeren van het risico op schade, vergelijkbaar met de huidige rekensystematiek voor het risico op overlijden. Dit betekent het meenemen van DS1[12] en DS2 in de risicoanalyses al dan niet via een statistische koppeling aan het optreden van DS3 en hoger.
Daarnaast dient het onderzoek zich te verbreden naar methodes om, al dan niet kwantitatief, het risico op schade en maatschappelijke onrust systematisch in besluitvorming te kunnen nemen.

12 Appendix B – List of Abbreviations

This list of abbreviations covers not only the abbreviations used in this document, but aims to include all abbreviations used in this dossier.

ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonably Practicable
ARUP	Engineering Company named after founder: Ove Arup
Bcm	N.Bcm refers to a volume of a billion normal cubic meters. Normal means the volume is measured at a standard temperature (0 degree C) and pressure (1 bar)
BOA	Begeleidingscommissie Onderzoek Aardbevingen
CBS	Centraal Bureau Statistiek
CEA	China Earthquake Administration
CMI	Compaction Monitoring Instrument
CPT	Cone Penetration Test
CRR	Cyclic Resistance Ration (Liquefaction)
CSR	Cyclic Stress Ratio (Liquefaction)
CT	Coiled Tubing
CVW	Centrum Veilig Wonen
DAS	Distributed Acoustic Sensing
DLS	Damage Limit State
DS	Damage State
DSS	Distributed Strain Sensing
DTS	Distributed Temperature Sensing
EBN	Energy Beheer Nederland
EMS	European Macroseismic Scale
EU	European Union
EZ	Ministerie van Economische Zaken
GR	Gamma-ray
GR	Group Risk
FDSN	Federation of Digital Seismograph Networks
Frl	Friesland
GBB	Groninger Bodembeweging
GMPE	Ground Motion Prediction Equations
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GR	Group Risk

GTS	Gas Transport Services B.V.
GWC	Gas water contact
HRA	Hazard and Risk Assessment
HRBE	High Risk Building Element
IDR	Inter-storey Drift Ratio
ILPR	Inside Local Personal Risk
I&M	Ministerie van Infrastructuur en Milieu
IM	Intensity Measure
InSAR	Interferometric Synthetic Aperture Radar
KNGMG	Koninklijk Nederlands Geologisch Mijnbouwkundig Genootschap
KNMI	Koninklijk Nederlands Meteorologisch Institute
KU Leuven	Katholieke Universiteit Leuven (Catholic University Leuven)
LIDAR	Laser Imaging Detection And Ranging
LOFAR	Low Frequency Array
LPI	Liquefaction Potential Index
LPI_{ISH}	Liquefaction Potential Index - Ishihara
LPR	Local Personal Risk
LNEC	Laboratorio Nacional de Engenharia Civil (Lisbon)
M	Earthquake Magnitude
M_L	Local Earthquake Magnitude
MDoF	Multiple Degree of Freedom System
MVR	Maatschappelijk Veiligheidsrisico
MASW	Multichannel Analysis of Surface Waves
MIT	Massachusetts Institute of Technology
MJP	Meerjaren Programma van de NCG
MSF	Magnitude Scaling Factor (Liquefaction)
NAM	Nederlandse Aardolie Maatschappij B.V.
NC	Near Collapse
NCG	Nationaal Coordinator Groningen
NGO	Non-governmental Organisation
NIED	National Research Institute for Earth Science and Disaster Resilience in Japan
NORSAR	Norwegian Seismic Array (Norwegian independent, not-for-profit, research foundation within the field of geo-science)
NTNU	Norges teknisk-naturvitenskapelige universitet (Norwegian University of Science and Technology in Trondheim)

OGP	Onafhankelijk Geologen Platform
OIA	Objectgebonden Individueel Aardbevingsrisico (Object related individual earthquake risk)
OIR	Object-bound individual risk (same as OIA)
OVV	Onderzoeksraad voor Veiligheid (Safety Board)
PFA	Peak Floor Acceleration
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
PNL	Pulsed Neutron log
PSHA	Probabilistic Seismic Hazard Assessment
PSHRA	Probabilistic Seismic Hazard and Risk Assessment
QRM	Quantitative Reservoir Management
RFT	Repeat Formation Tester
RGR	Reference Group Risk
RIDR	Residual Inter-storey Drift Ratio
RIVM	Rijksinstitute voor Volksgezondheid en Milieu
RTCM	Rate-Type Compaction Model
RTCiM	Rate-Type Compaction isotach Model
RVS	Rapid Visual Screening
RUG	Rijksuniversiteit Groningen
SAC	Scientific Advisory Committee (Winningsplan 2016)
SDoF	Single Degree of Freedom System
SED	Schweizerischer Erdbebendienst (Swiss Seismological Survey)
SINTEF	Stiftelsen for industriell og teknisk forskning (Foundation for Scientific and Industrial Research)
SodM	Staatstoezicht op de Mijnen (also SSM State Supervision of Mines)
SPTG	Static Pressure and Temperature Measurement
SSHAC	Senior Seismic Hazard Analysis Committee
TBO	Technische Begeleidingscommissie Ondergrond (Winningsplan 2013)
Tcbb	Technische commissie bodembeweging
TK	Tweede Kamer (Dutch equivalent of House of Commons)
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, Netherlands Organisation for Applied Scientific Research
TNO-AGE	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek – Advies Groep Economische Zaken
TU Delft	Technische Universiteit Delft
ULS	Ultimate Limit State
UU	Universiteit Utrecht

URM	Un-reinforced Masonry
USGS	United States Geological Survey
USNRC	United States Nuclear Regulatory Commission
V_{TOP}	

13 Appendix C – Complete Bibliography Technical and Scientific Reports and Papers

13.1 Technical and Scientific Reports "Onderzoekrapporten"

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6. Technical Addendum to the Winningsplan Groningen 2013; Subsidence, Induced Earthquakes and Seismic Hazard Analysis in the Groningen Field, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), November 2013.
7. Supplementary Information to the Technical Addendum of the Winningsplan 2013, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), December 2013.
8. Voortgangsrapportage Diepe Geofoons, Nederlandse Aardolie Maatschappij BV, September 2014.
9. Study and Data Acquisition Plan Induced Seismicity in Groningen for the update of the Winningsplan 2016, Nederlandse Aardolie Maatschappij BV, Jan van Elk & Dirk Doornhof, December 2014, submitted in March 2015.
10. Bierman, S, R. Paleja and M. Jones, Statistical methodology to test for evidence of seasonal variation in rates of earthquakes in the Groningen field, April 2015.
11. Risk Methodology; Back to the region, February 2015, Nederlandse Aardolie Maatschappij BV, (forwarded to the national committee on earth quake related risks in April 2015) (EP 201504200668).
12. Meet- en Regel Protocol - mei 2015, Nederlandse Aardolie Maatschappij BV, 1st May 2015.
13. Hazard and Risk Assessment for induced Seismicity Groningen, Part I Hazard Assessment, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st May 2015.
14. Hazard and Risk Assessment for induced Seismicity Groningen, Part II Risk Assessment, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st May 2015.
15. Voortgangsrapportage Diepe Geofoons, Nederlandse Aardolie Maatschappij BV, June 2015.
16. Meet- en Regel Protocol – juni 2015, Nederlandse Aardolie Maatschappij BV, June 2015.
17. In-situ compaction measurements using gamma ray markers, Pepijn Kole, June 2015
18. URM Modelling and Analysis Cross Validation – Arup, EUCENTRE, TU Delft, Reference 229746_032.0_REP127_Rev.0.03 April 2015.
19. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part I, Deltares, Pauline Kruiver and Ger de Lange.
20. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part II, Deltares, Pauline Kruiver and Ger de Lange.
21. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part III, Deltares, Pauline Kruiver and Ger de Lange.
22. Development of Version 1 GMPEs for Response Spectral Accelerations and for Strong-Motion Durations, Julian J Bommer, Peter J Stafford, Benjamin Edwards, Michail Ntinalexis, Bernard Dost and Dirk Kraaijpoel, March 2015.
23. De ondergrond van Groningen: een Geologische Geschiedenis, Erik Meijles, April 2015.
24. A re-estimate of the earthquake hypo-centre locations in the Groningen Gas Field, Matt Pickering, March 2015.

25. Mosayk, Report on software verification against experimental benchmark data, Deliverable D1, October 2014.
26. An activity rate model of induced seismicity within the Groningen Field, (Part 1), Stephen Bourne and Steve Oates, February 2015.
27. An activity rate model of induced seismicity within the Groningen Field, (Part 2), Stephen Bourne and Steve Oates, June 2015.
28. Regularised direct inversion to compaction in the Groningen reservoir using measurements from optical levelling campaigns, S.M. Bierman, F. Kraaijeveld and S.J. Bourne, March 2015.
29. Impact of various modelling options on the onset of fault slip and fault slip response using 2-dimensional Finite-Element modelling, Peter van den Bogert, July 2015
30. Computing the Distribution of Pareto Sums using Laplace Transformation and Stehfest Inversion Break, C. K. Harris and S. J. Bourne, May 2015.
31. Induced seismicity in the Groningen field - statistical assessment of tremors along faults in a compacting reservoir, Rick Wentinck, July 2015.
32. EUCentre Shaketable Test of Terraced House Modelling Predictions and Analysis Cross Validation, staff from ARUP, EUCentre (Pavia) and TU Delft, November 2015 [this document also includes; (1) Instruments full-scale test-house Eucentre Laboratory, (2) Protocol for Shaking Table Test on Full Scale Building (Eucentre) V_1, and (3) Selection of Acceleration Time-Series for Shake Table Testing of Groningen Masonry Building at the EUCENTRE, Pavia, all three by staff from EUCentre (Pavia)],
33. Development of Version 2 GMPEs for Response Spectral Accelerations and Significant Durations for Induced Earthquakes in the Groningen field, Julian Bommer et. Al, October 2015
34. Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field – 3-D Geomechanical Model, GMI, September 2015.
35. Experimental campaign on cavity walls systems representative of the Groningen building stock, Eucentre, October 2015.
36. Procedures of in-situ test, Eucentre, November 2015.
37. Report on structural modelling of non-URM buildings - v2 Risk Model Update - Deliverable D2 update, Mosayk, October 2015.
38. Report on soil-structure interaction (SSI) impedance functions for SDOF systems - Deliverable D3, Mosayk, October 2015.
39. Numerical and experimental evaluation of the seismic response of precast wall, connections, Eucentre, October 2015.
40. Neotectonic Stresses in the Permian Slochteren Formation of the Groningen Field, Rob van Eijs, November 2015.
41. Development of v2 fragility and consequence functions for the Groningen Field, Crowley H., Pinho R., Polidoro B., Stafford P., October 2015.
42. Impact of Production Shut-in on Inter-Event time in Groningen, A statistical perspective, Rakesh Paleja, Stijn Bierman, Matthew Jones, March 2016
43. Statistical methodology for investigating seasonal variation in rates of earthquake occurrence in the Groningen field, S. Bierman, R. Paleja, M. Jones.
44. Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), Hazard and Risk Assessment for induced Seismicity Groningen – Interim Update, 7th November 2015.
45. Groningen Pressure Maintenance (GPM) Study, Progress Report February 2016, Richard Hofmann and team, February 2016.
46. Groningen 2.0 Screening Study Alternatives to the base case approach of NAM to maintain pressure in the Groningen reservoir by nitrogen injection, with a focus on surface measures, Summary Report prepared by the Steering Committee, Chairman Prof. Dr W.C. Turkenburg Final Report February 2015.

47. Terp composition in respect to earthquake risk in Groningen, Dr. ir. E.W. Meijles, Dr. G. Aalbersberg and Prof. Dr. H.A. Groenendijk, March 2016.
48. Unbiased Cyclic Resistance Ratio Relationships for Evaluating Liquefaction Potential in Groningen, Russell Green, Adrian Rodriguez-Marek, Peter Stafford, Julian Bommer, April 2016.
49. Risk Assessment of Falling Hazards in Earthquakes in the Groningen region, Tony Taig and Florence Pickup (TTAC Ltd.), March 2016.
50. Risk Assessment of Falling Hazards in Earthquakes in the Groningen region (Appendices), Tony Taig and Florence Pickup (TTAC Ltd.), March 2016.
51. Winningsplan Groningen 2016, Nederlandse Aardolie Maatschappij BV, 1st April 2016.
52. Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field, PART I – Summary and Production, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
53. Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field, PART II - Subsidence, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
54. Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field, PART III - Hazard Assessment, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
55. Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field, PART IV - Risk Assessment, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
56. Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field, PART V - Damage and Appendices, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
57. Technisch addendum bij Winningsplan Groningen 2016 - Productie, bodemdaling, geïnduceerde bevingen en seismische dreiging en risicobeoordeling van het winningsveld in Groningen, DEEL I – Samenvatting en Productie, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
58. Technisch addendum bij Winningsplan Groningen 2016 - Productie, bodemdaling, geïnduceerde bevingen en seismische dreiging en risicobeoordeling van het winningsveld in Groningen, DEEL II - Bodemdaling, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
59. Technisch addendum bij Winningsplan Groningen 2016 - Productie, bodemdaling, geïnduceerde bevingen en seismische dreiging en risicobeoordeling van het winningsveld in Groningen, DEEL III - Dreigingsanalyse, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
60. Technisch addendum bij Winningsplan Groningen 2016 - Productie, bodemdaling, geïnduceerde bevingen en seismische dreiging en risicobeoordeling van het winningsveld in Groningen, DEEL IV – Risico Analyse, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
61. Technisch addendum bij Winningsplan Groningen 2016 - Productie, bodemdaling, geïnduceerde bevingen en seismische dreiging en risicobeoordeling van het winningsveld in Groningen, DEEL V - Schade en Bijlagen, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
62. Supplement to the Technical Addendum for Winningsplan Groningen 2016, Subsidence Development of Seismicity Maatschappelijk Veiligheidsrisico Epistemic Uncertainties, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st May 2016.
63. Study and Data Acquisition Plan Induced Seismicity in Groningen Update Post-Winningsplan 2016 -Part 1, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.
64. Study and Data Acquisition Plan Induced Seismicity in Groningen Update Post-Winningsplan 2016 -Part 2, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.

65. Oplegnotitie Winningsplan Groningen-gasveld 2016, Nederlancse Aardolie Maatschappij BV, 1st April 2016.
66. Meet- en Regelprotocol 2016 Nederlandse Aardolie Maatschappij BV, 1st April 2016.
67. Groningen Field Review 2015 Subsurface Dynamic Modelling Report, Burkitov, Ulan, Van Oeveren, Henk, Valvatne, Per, May 2016.
68. Groningen Earthquakes - Structural Upgrading LS-DYNA Validation Booklet, Arup Project, June 2016.
69. Groningen Earthquakes - Structural Upgrading, Laboratory Component Testing with Annex: Modelling Blind Predictions, Post-Test Predictions and Analysis Cross Validation, February 2016.
70. Tests for the Characterisation of replicated Masonry and Wall Ties, TU Delft, April 2016.
71. In-Plane Tests on Replicated Masonry Walls, TU Delft, April 2016.
72. Sensitivity study on the influence of the ground motion input components on the seismic response of Groningen URM buildings, EUCentre, April 2016.
73. Induced seismicity in the Groningen field - second statistical assessment of tremors along faults in a compacting reservoir, Rick M. Wentinck, May 2016.
74. A Database of Damaging Earthquakes of Moment Magnitude from 4.0 to 5.5, Cecilia Ines, Helen Crowley, Michail Ntinalexis and Julian Bommer, July 2016.
75. Summary and discussion of software benchmarking for Groningen PSHRA code, Stephen Bourne and Steve Oates, April 2016.
76. Report on Mmax Expert Workshop, Mmax panel chairman Kevin Coppersmith, June 2016
77. Material Characterisation – Version 1.3, Eucentre, P&P, TU-Delft, TU-Eindhoven, October 2015.
78. Local and Moment Magnitudes in the Groningen Field, Bernard Dost, Ben Edwards and Julian J Bommer, March 2016.
79. Independent Review of Groningen Subsurface Modelling Update for Winningsplan 2016, SGS Horizon, July 2016.
80. Human induced Earthquakes, Gillian Foulger, Miles Wilson, Jon Gluyas and Richard Davies, Durham University and Newcastle University, July 2016.
81. Geophysical Measurements of shear wave velocity at KNMI accelerograph stations in the Groningen field area, Deltares, Marco de Kleine, Rik Noorlandt, Ger de Lange, Marios Karaoulis and Pauline Kruiver, July 2016.
82. Measuring changes in earthquake occurance rates in Groningen – Update October 2016, Shell Statistics Group, Rakesh Paleja and Stijn Bierman, October 2016.
83. Meet en Regel Rapportage , NAM, November 2016.
84. TNO rapport, Monitoring Network Building Vibrations - Analysis Earthquakes in 2014 and 2015, ir. H. Borsje, ir. J.P. Pruiksma and ir. S.A.J. de Richemont TNO 2016 R11323/A, December 2016
85. Study and Data Acquisition Plan Induced Seismicity in Groningen Update Post-Winningsplan 2016 - Progress and Schedule, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st December 2016.
86. Subsidence inversion on Groningen using leveling data only, Nederlandse Aardolie Maatschappij BV (Onno van der Wal, Rob van Eijs), December 2016.
87. Petrographic study of well Zeerijp-3A (ZRP-3A) Final Report, Panterra Consultants, November 2016.
88. Petrographic Aspects of the Rotliegend of the Groningen field Inventory and quick-look analysis of petrographic data from the Groningen field, Nederlandse Aardolie Maatschappij BV (Clemens Visser), November 2016
89.

13.2 Technical and Scientific Papers

This appendix contains a list of peer-reviewed and conference papers describing studies executed as part of the research program led by NAM. Conference papers are not been subjected to an external assurance review process by the journal. These are included in a separate paper.

Title	Journal	Peer-review status
A Monte Carlo method for probabilistic hazard assessment of induced seismicity due to conventional natural gas production.	Bulletin of the Seismological Society of America	Peer-reviewed
A risk-mitigation approach to the management of induced seismicity	Journal of Seismology	Peer-reviewed
A seismological model for earthquakes induced by fluid extraction from a subsurface reservoir.	Journal of Geophysical Research: Solid Earth	Peer-reviewed
Out-of-plane shaking table tests on URM single leaf and cavity walls	Engineering Structures	Peer-reviewed
Number of equivalent stress cycles for liquefaction evaluations in active tectonic and stable continental regimes	Journal of Geotechnical and Geo-environmental Engineering	in press
Developing an application-specific ground-motion model for induced seismicity.	Bulletin of the Seismological Society of America	Peer-reviewed
A new stress reduction coefficient relationship for liquefaction triggering analyses	Journal of Geotechnical and Geo-environmental Engineering	in press
Framework for a ground-motion model for induced seismic hazard and risk analysis in the Groningen Gas Field, The Netherlands	Earthquake Spectra	in press
A regional site-response model for the Groningen Gas Field	Bulletin of the Seismological Society of America	Peer-review in progress
An integrated shear-wave velocity model for the Groningen gas field, The Netherlands.	Bulletin of Earthquake Engineering	Peer-review in progress
Framework for developing fragility and consequence models for Inside Local Personal Seismic Risk	Earthquake Spectra	Peer-review in progress
Shaking table test on a full-scale URM cavity wall building	Bulletin of Earthquake Engineering	Peer-review in progress
Salt intrusions providing a new geothermal exploration target for higher energy recovery at shallower depths, Energy (2016)	Journal Energy	Peer-reviewed
The Maximum Possible and the Maximum Expected Earthquake Magnitude for Production-Induced Earthquakes at the Gas Field in Groningen, The Netherlands	Bulletin of the Seismological Society of America (Short Note)	Peer-reviewed

Table 13.1 List of paper published in peer-reviewed journals.

Title	Journal	Conference paper
Liquefaction mapping for induced seismicity in the Groningen gas field.	6th International Conference on Earthquake Geotechnical Engineering	Conference Paper
Geomechanical analysis to evaluate production-induced fault reactivation at Groningen Gas Field	SPE Annual Technical Conference and Exhibition 2015	Conference Paper
Ray modelling for induced seismicity in piecewise linear (Vo-k) models	Meeting on active and passive seismics in laterally inhomogeneous media', Jun 8-12, 2015, Prague, Czech Republic	Poster
In-well distributed strain sensing	Society of Petroleum Engineers	Conference Paper
First advance in determining the regional site-response for induced earthquakes in Groningen, The Netherlands.	Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics	Conference Paper
Location results from a borehole micro-seismic monitoring experiment in the Groningen gas reservoir, Netherlands	6th EAGE workshop on Passive Seismic, Muscat (Oman), 31 Jan Feb, 2016	Poster
Experimental characterization of calcium-silicate brick masonry for seismic assessment	16th International Brick and Block Masonry Conference.	Conference Paper
Out-of-plane shaking table tests on URM cavity walls	16th International Brick and Block Masonry Conference.	Conference Paper
A proposal for the interpretation of the In-situ shear strength index test for brick masonry	26th Italian National Conference on Earthquake Engineering	Conference Paper
Full scale shaking table test on a URM cavity wall terraced house building.	16th World Conference on Earthquake Engineering, 16WCEE 2017	Conference Paper
Shaking table test on a full-scale unreinforced clay masonry building with flexible diaphragms	13th Canadian Masonry Symposium	Conference Paper
Applications of 3D Elastic Wavefield Simulation to Induced Seismicity (2016)	Society of Exploration Geophysicists (SEG) Annual Meeting (October 2016, Dallas).	Conference Paper and Presentation on Conference
Geomechanical Modeling to Evaluate Production-Induced Seismicity at Groningen Field (2016)	SPE Paper 183554 presented at ADIPEC (November 2016, Abu Dhabi)	Conference Paper and Presentation on Conference
A Geomechanical and Seismological Integration Model for Induced Seismicity at Groningen (2016)	SPE / SEG Induced Seismicity Workshop (March 2016, Fort Worth).	Conference Presentations and Abstracts
Wavefield Simulation for Ground Motion Prediction in the Context of Induced Seismicity (2016)	American Geophysical Union (AGU) Fall Meeting (December 2016, San Francisco).	Conference Presentations and Abstracts

Table 13.2 List of paper presented at conferences and in journals without peer-review.

Title	Journal	Conference paper
Integration of Geomechanical and Seismological Models for Production-Induced Seismicity at Groningen Gas Field (2016)	American Geophysical Union (AGU) Fall Meeting (December 2016, San Francisco)	Conference Presentations and Abstracts
The Use of Elastic Wave Field Simulations to Aid in the Development of Ground Motion Prediction Equations, an Induced Seismicity Case Study at Groningen Gas Field (2016)	American Geophysical Union (AGU) Fall Meeting (December 2016, San Francisco).	Conference Presentations and Abstracts
Comparison of elastic wavefield simulations, ray tracing and surface array data at the Groningen gas field: Implications for induced seismic event location and characterization (2017)	Seismological Society of America's Annual Meeting in April, 2017	Conference Presentations and Abstracts
First advances in determining the regional site response for induced earthquakes in Groningen, The Netherlands.	Sixth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Greater Noida, India.	Conference Presentations and Abstracts
Liquefaction Mapping for Induced Seismicity in the Groningen Gas Field,	6th International Conference on Earthquake Geotechnical Engineering, Christchurch, New Zealand	Conference Presentations and Abstracts
Liquefaction Mapping for Induced Seismicity based on geological and geotechnical features.	3rd International Conference on Performance-based Design in Earthquake Geotechnical Engineering (PBD-III), Vancouver	Conference Presentations and Abstracts

Table 13.2 Continued: List of paper presented at conferences and in journals without peer-review.

14 Appendix D – Experts

Apart from scientist, engineers and researchers in NAM and the laboratories of Shell (Rijswijk) and Exxonmobil (Houston), NAM has also sought the advice of internationally recognised experts. Some of the experts collaborating in the research program on induced seismicity in Groningen, led by NAM, are listed below.

External Expert	Affiliation	Main Expertise Area
Damian Grant	ARUP	Building Fragility
Guido Magenes	Eucentre Pavia	Building Fragility
Rui Pinho	University Pavia	Building Fragility
Helen Crowley	Independent Consultant, Pavia	Building Fragility, Injury Model and Risk
Michelle Palmieri	ARUP	Building Fragility
Rinke Kluwer	ARUP	Building Fragility
Sinan Akkar	Bogazici, University Istanbul	Ground Motion Prediction
Ben Edwards	University Liverpool	Ground Motion Prediction
Michail Ntinalexis	Independent Consultant, London	Ground Motion Prediction
Barbara Polidoro	Independent Consultant, London	Building Fragility
Peter Stafford	Imperial College London	Ground Motion Prediction
Julian Bommer	Independent Consultant, London	Ground Motion Prediction and Site Response
Emily So	Cambridge Architectural Research Ltd	Injury model
Robin Spence	Cambridge Architectural Research Ltd	Injury model
Russell Green	Virginia Tech, USA	Liquefaction Model
Tony Taig	TTAC Limited	Injury Model and Risk
Loes Buijze	University Utrecht	Rock Physics / Core Experiments
Chris Spiers	University Utrecht	Rock Physics / Core Experiments
Bart Verberne	University Utrecht	Rock Physics / Core Experiments
Andre Niemeyer	University Utrecht	Rock Physics / Core Experiments
Matt Pickering	Student; Leeds University	Seismic Event Location
Marco de Kleine	Deltares	Site Response and Shallow Geological Model
Pauline Kruiver	Deltares	Site Response and Shallow Geological Model
Ger de Lange	Deltares	Site Response and Shallow Geological Model
Adrian Rodriguez -Marek	Virginia Tech, USA	Site Response Assessment
Mandy Korff	Deltares	Site Response, liquefaction and Shallow Geological Model
Piet Meijers	Deltares	Site Response, liquefaction and Shallow Geological Model

Jan Rots	TU Delft	Building Fragility

Table D.1 The most important expert collaborators.

The experts and academics on this list have worked for a considerable time on studies of this program.

To independently review the studies and assure their results the following experts and academics have been asked to familiarize themselves with the studies and provide their feedback in assurance workshops or reports:

External Expert	Affiliation	Main Expertise Area
Adriaan Janszen	Exxonmobil	Shallow Geological Model
Eric Meijles	University Groningen	Shallow Geological Model
Joep Storms	TU Delft	Shallow Geological Model
Tijn Berends	Student; University Groningen	Site Response and Shallow Geological Model

Table D.2 The assurance team for "Shallow Geological Model".

The assurance team for "Ground Motion Prediction" is shown in table C.3.

External Expert	Affiliation	Main Expertise Area
Gail Atkinson	Western University, Ontario, Canada	Ground Motion Prediction
Hilmar Bungum	NORSAR, Norway	Ground Motion Prediction and panel for the maximum magnitude of earthquakes
Fabrice Cotton	GFZ Potsdam, Germany	Ground Motion Prediction
John Douglas	University of Strathclyde, UK	Ground Motion Prediction
Jonathan Stewart	UCLA, California, USA	Ground Motion Prediction
Ivan Wong	AECOM, Oakland, USA	Ground Motion Prediction Member and panel for the maximum magnitude of earthquakes
Bob Youngs	AMEC, Oakland, USA	Ground Motion Prediction Member and panel for the maximum magnitude of earthquakes

Table D.3 The assurance team for "Ground Motion Prediction". Ivan Wong and Bob Youngs sit also in the panel for the maximum magnitude of earthquakes.

The assurance team for "Building Fragility" is shown in table C.4.

External Expert	Affiliation	Main Expertise Area
Jack Baker	Stanford University, US	Fragility Functions and Risk Analysis
Paolo Franchin	University of Rome "La Sapienza"	Fragility Functions and Risk Analysis
Michael Griffith	University of Adelaide, Australia	Modelling and Testing of Masonry Structures
Curt Haselton	California State University, US	Numerical Modelling of Structures
Jason Ingham	University of Auckland	Seismic Response of Masonry Structures
Nico Luco	United States Geological Survey	Risk Analysis Building Fragility
Dimitrios Vamvatsikos	NTUA, Greece	Fragility Functions and Risk Analysis

Table D.4 The assurance team for "Building Fragility".

The assurance teams have been informed by the extensive technical documentation and in workshops. The recommendations of the assurance teams have been incorporated in the details technical reports (section further work) and in this document. Because of their highly mathematical nature, the seismological models supporting the hazard and risk assessment have been reviewed by Prof. Ian Main (of Edinburgh University). Prof. Main has prepared review letters, which have been shared. For the latest of these review letters see appendix J.

The studies on building fragility have additionally been review by Ron O. Hamburger of the consultancy Gumpertz & Heger. Also this report is attached to this report (as appendix I).

In a workshop conducted following the guidelines for a SSHAC level 3 process, a panel of experts has been asked to evaluate the distribution of Mmax values for the Groningen area, based on the current knowledge and uncertainty.

This panel consisted of:

External Expert	Affiliation	Role
Kevin Coppersmith	Geomatrix Consultants Inc.	Chaiman SHACC Committee
Ivan Wong	AECOM, Oakland, USA	Ground Motion Prediction and Member SHACC Committee
Bob Youngs	AMEC, Oakland, USA	Ground Motion Prediction Member and SHACC Committee
Jon Ake	US Nuclear Regulatory Commission	Member SHACC Committee
Hilmar Bungun	Norsar Norway	Member SHACC Committee
Torsten Dahm	GFZ Potsdam	Member SHACC Committee
Art McGarr	US Geological Survey	Member SHACC Committee
Ian Main	University Edinburgh	Seismogenic Model / Statistics and Member SHACC Committee

Table D.5 The panel for the determination of Mmax distribution.

Additionally the following independent external experts presented to the expert panel:

External Expert	Affiliation	Role
Serge Shapiro	Freie Universiteit Berlin	Independent Advisor
Emily Brodsky	University of California, Santa Cruz	Independent Advisor
Jenny Suckale	Stanford University, Department of Geophysics	Independent Advisor
Gilian Foulger	Durham University, Department of Geophysics	Independent Advisor
Gert Zöller	University of Potsdam Institute of Mathematics and Focus Area for Dynamics of Complex Systems	Independent Advisor

Table D.6 The experts presenting to the panel for the determination of Mmax distribution.

Another workshop was held to discuss the state-of-the-art regarding incorporation of finite fault rupture simulations into the development of ground-motion prediction equations; external expert participants are listed in Table D.7.

External Expert	Affiliation	Role
Norm Abrahamson	University of California at Berkeley	Fault simulations in California GMPEs
Christine Goulet	Southern California Earthquake Center (SCEC)	Validation and benchmarking of fault rupture-based simulation codes
Luis Angel Dalguer	SwissNuclear	Capabilities of finite rupture simulations
Bob Youngs	AMEC Foster Wheeler	Fault simulations in NGA-East GMPEs

Table D.7 External experts participating in workshop on finite fault simulations in GMPE development

15 Appendix E – Universities and Knowledge Institutes

The main partners in the research program into induced seismicity in Groningen are listed below:

Partner	Expertise
Deltares	Shallow geology of Groningen, soil properties and measurements of site response/liquefaction.
University Utrecht (UU)	Measurements of rock compaction and rupture on core samples, understanding of physical processes determining compaction.
University Groningen (RUG)	Shallow geology of Groningen, archaeology.
ARUP	Modelling of building response to earthquakes, management of the program to measure strength of building materials.
Technical University Delft (TUD)	Measure strength of building materials and building elements.
Eucentre, Pavia, Italy	Measure strength of building materials, building elements and shake-table testing of full scale houses.
Mosayk	Modelling of building response to earthquakes.
Studio Calvi	All civil Engineering aspects of earthquake resistance to earthquakes including mitigation and strengthening measures like base isolation.
LNEC	Shake-table testing of full scale houses to collapse.
Magnitude (A Baker Hughes & CGG Company)	Seismic Monitoring (determination of location results deep geophones)
TNO	Potential for earthquakes resulting from injection. Building sensor project.
Avalon	Supplier of geophone equipment permanent seismic observations wells.
Baker-Hughes	Supplier of geophone equipment temporary observation wells.
Antea	Management of the extension of the geophone network.
Rossingh Drilling	Drilling of the shallow wells for the extension of the geophone network.
China Earthquake Administration	Experiments for friction on moving fault surfaces and upscaling of small scale experiments. Research led by University of Utrecht.
National Research Institute for Earth Science and Disaster Resilience, NIED (Japan)	Large Scale Earthquake Simulator facility at NIED, Tsukuba, Japan. Experimental facility for large experiments into friction during rupture.

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☐ DHL SPRINTLINE ☐ DHL JETLINE
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Shipment Waybill Number 031

Shippers account No.: 19057824 2

Date 31-01-2017

1 From (Shipper)

Company: NAM

Address: Schepersmaat 2

Post Code: 9405 TA City: Assen

Country: NL Phone: +31592-363545

Contact Person: [redacted]

Reference: 4512897989.

2 To (Receiver)

Company: Ministerie van Economische Zaken.

Address: Bezuidenhoutseweg 73

Post Code: 2594 AC City: Den Haag

Country: NL Phone: 0703798991

Contact Person: De minister

Delivery instructions: Aan de Minister.

3 Description of Goods:

Number of Packages: 1

Value

Weight

Dimensions Length x Width x Height

Description of contents: Documents.

Shipment insurance (see reverse). We agree that DHL's terms on the reverse apply to this shipment and limit DHL's liability. The (amended) Warsaw Convention or the Montreal Convention may also apply.

Sender's authorisation and signature [redacted]

Cash
Max 2.500 Euro EUR

4 Received by:

Name [redacted]

Remarks 31-01-2017 15:20

[redacted]

Grey section for DHL use only

Collected by DHL driver

Pick-up time:

Arrival .... Depature ....

Delivered by DHL driver [redacted]

[redacted]

Arrival .... Depature ....

1st ex. DHL 2nd ex. for receiver 3rd ex. for sender MD0803429

DHL Same Day Netherlands is an activity of DHL Express (Netherlands) B.V., registered at the Traderegister Almere no. 30076845

1-2-2017

ended weight

g / 1 lb	5 = 10 kg / 20 lb
g / 2 lb	6 = 15 kg / 30 lb
g / 4 lb	7 = 20 kg / 40 lb
g / 10 lb	8 = 25 kg / 50 lb

1

DHL Express