Hazard and Risk Assessment for Induced Seismicity Groningen

Study 2 Risk Assessment

Update 1st May 2015

Contents

Introduction

The people living in Groningen have been confronted with increasing intensity of the effects of induced earthquakes. This has been the source of anxiety and frustration among the community. NAM, the ministry of Economic Affairs, and regulator SodM face the challenge of formulating an adequate response to the induced earthquakes. To that end, the currently existing instruments for assessing and mitigating these effects – as set down in mining regulations, risk policies and, for example, building codes – need to be extended and made fit-for-purpose.

Therefore, a new risk methodology was developed and initially used in the Winningsplan 2013. This new methodology combines NAM's own internal safety standards, including the important role of monitoring, national and international analogues. It will be progressed towards a dedicated risk assessment framework for the Winningsplan 2016. For this latter purpose the risk methodology has been shared with the Groningen Scientific Advisory Committee established by the Ministry of Economic Affairs (Ref. 17). This committee is tasked to develop a national policy on risks associated with induced earthquakes. This policy will be used, per decision on the Winningsplan 2013 (Ref. 19), to assess the Winningsplan 2016. Supporting elements, such as a national annex to the Eurocode 8 Building Code addressing the fragility of buildings.

This Study 2 on Risk Assessment addresses the risk assessment elements of the risk methodology, following the causal chain pictured used in Study 1. The work in Study 2 covers for the first time a fully probabilistic risk assessment, which as yet can only be used qualitatively as it awaits quantitative calibration following studies such as site response measurements at the geophone network locations and a shake table test for a terraced house. The additive attributes for the full risk dimension, including the regional social impacts are to be merged into the 'equation' to evaluate acceptability of gas production[1].

This report includes the first results of an integrated probabilistic risk assessment and qualitatively demonstrates the importance of further studies to better understand aspects such as ground motion prediction and fragility of buildings. Further studies on fragility and ground motion prediction will be the basis for the first quantitative / calibrated results in future updates (see figure 5).

Data presented in this report should be read or interpreted with due caution taking into account the remaining scientific uncertainties and further calibration, refining of models, validation taking place in 2015 and 2016.

History of induced Earthquakes in Groningen

Since 1986, relatively small earthquakes have occurred near producing gas fields in the provinces of Groningen, Drenthe and Noord-Holland. Over time, these events were considered to be a negative, but not an insuperable, consequence of gas production. Since the Huizinge earthquake, however, it is recognized that the earthquakes also pose a potential safety risk.

In the early 90's, a multidisciplinary study was initiated by the Ministry of Economic Affairs and guided by the above-mentioned Scientific Advisory Committee. This study focused on the relationship between gas production and earth tremors. It was concluded that the observed earth tremors were of non-tectonic origin and most likely induced by reservoir depletion (i.e., gas production). An agreement was set up with Royal Dutch Meteorological Institute (KNMI) to install a borehole seismometer network in the Groningen area. The network has been active since 1995 and

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[1] This report is the report as indicated in article 6-1 of the decision from the Minister of Economic Affairs of 30 January 2015

was designed to detect earth tremors, pinpoint their locations and quantify their magnitudes. Additional accelerometers were installed in areas with highest earth tremor frequency.

1986	First induced earthquake observed (Assen M= 2.8)
Early ’90	Multidisciplinary Study (1993) concluded: • “Earthquakes in North-Netherlands are induced by gas production”
1995	Seismic network operational
1995	KNMI estimates a maximum magnitude for Groningen: M_{max}= 3.3
1995	Agreement between NAM, Groningen and Drenthe on damage claim handling
1997	Roswinkel earthquake with M= 3.4
1998	KNMI adjusts estimate of maximum magnitude: M_{max}= 3.8-4.0
2001	Legal regulations damage claim handling set established by Parliament Establishment of Tcbb (Technische commissie bodembeweging):
2003	Technisch Platform Aardbevingen (TPA) established
2004	KNMI adjusts estimate of maximum magnitude: M_{max}= 3.9
2004	First Probabilistic Seismic Hazard Analysis by TNO and KNMI
2006	Westeremden earthquake with M= 3.4
2009	Calibration study by TNO (Damage analysis)
2011	Deltares assesses the Building Damage in Loppersum and confirms M_{max}= 3.9
2012	Huizinge earthquake with M= 3.6

Figure 1 Sequence of main events until the earthquake of 16th August in Huizinge

Two factors triggered a renewed focus and widespread attention for the issue of seismicity induced by gas production in Groningen. First, the earthquake near Huizinge (16 August 2012) with magnitude M_w=3.6 was experienced as more intense and with a longer duration than previous earthquakes in the same area. Significantly more building damage was reported as a result of this earthquake compared to previous earthquakes. Second, a general realization and concern developed in society that seismicity in the Groningen area has increased over the last years.

NAM reacted to these developments by initiating a series of new initiatives to better understand the relationship between gas production and safety. These are described in the NAM “Study and Data Acquisition Plan”, issued in October 2012 in support of a new Winningsplan 2013. This is further described in the next section.

Study and Data Acquisition Plan

The Study and Data Acquisition Plan describes the relationship and goals of all study and research effort by NAM and was shared with SodM and the Ministry of Economic Affairs (Ref. 1) in November 2012 and made public early 2013. Regular updates of the study progress were reported to the advisory committee of the Minister of Economic Affairs (TBO), the regulator (SodM) and her advisors (TNO-AGE and KNMI) and the "Dialoogtafel Groningen". The most recent update was reported to SodM in March 2015 (Ref. 13).

The main objectives of the plan are to:

1. Understand the impact of the earthquake hazard on buildings and the safety of the community
2. Perform a fully integrated Hazard and Risk Assessment for the Groningen region, with all uncertainties fully and consistently recognised and quantified
3. Identify and develop mitigation options:
   - Production measures
   - Pressure maintenance options
   - Optimised Structural Upgrading program:
     - Identify highest risk buildings
     - Establish optimal structural upgrading methodology

Other objectives are to:

4. Address areas of different scientific views, and initiate additional studies or measurements to create consensus,
5. Effectively monitor subsidence and seismicity,
6. Continuously improve our understanding of the physical mechanism leading to induced seismicity and the resulting hazard and reduce the uncertainty in the hazard and risk assessment.

To achieve these objectives, NAM has sought the assistance and advice from external experts for each expertise area from academia and knowledge institutes. The total cost of the study and data acquisition program for the period 2014 – 2016 is estimated to be almost € 100 mln. This program is reviewed every 6 months and adjusted if necessary.

Some of the activities in the Study and Data Acquisition Plan are not expected to directly support the Hazard and Risk Assessment of Winningsplan 2016. They rather serve to increase the understanding of physical processes and therefore lend support and physical background to the hazard and risk assessments. These activities are not expected to reach a level of maturity in the short term where they can be used to lend support to predictions. Examples are, the planned laboratory experiments on the Zeerijp core to investigate rupture and compaction processes in reservoir rock.

Winningsplan 2013

Intermediate results of the studies into induced seismicity carried out in 2013 were shared with the technical advisory committee of the Ministry of Economic Affairs (TBO) at three two-day workshops held in May, July and August 2013, and in several intermediate technical meetings focusing on specific technical issues. The study results were reported to the Minister of Economic Affairs and SodM in November 2013 in the "Technical Addendum to the Winningsplan - Groningen 2013" (Ref. 3, 4 and 5). This report also contained a probabilistic Hazard Assessment complemented by a deterministic Risk Assessment.

- Probabilistic analysis is based on chance incorporated in all uncertainties
- Deterministic analysis is based on specifically defined scenarios

In addition to the Winningsplan 2013, NAM also issued a Borgingsprotocol and a Monitoringplan in December 2013, enabling regular revisits of the risk assessment on the basis of acquired monitoring data.

The aforementioned "Technical Addendum to the Winningsplan - Groningen 2013" (Ref. 4 and 5) gives a full overview of the results of the studies carried out by NAM by the end of 2013.

Winningsplan 2016

The work done during 2013 provided new insights and received generally positive comments from peer reviewers and the TBO, but was by no means conclusive or complete. Many technical questions remained unresolved (Ref. 8 and 9), while uncertainties in the geomechanical parameters and in the estimated seismic hazard were still large. Some of the remaining uncertainty stems from lack of knowledge and data (epistemic uncertainty) and is therefore prone to be further constrained with ongoing data acquisition and analysis. The “Study and Data Acquisition Plan” was therefore continued in 2014 and 2015 and will be continued in the years thereafter.

The “Study and Data Acquisition Plan” is considered to be ambitious and comprehensive:

- It involves many external entities: commercial parties, academics, university laboratories and independent experts (Appendix A)
- The scientific work is subjected to an extensive voluntary and compulsory assurance program, through independent peer-review (Appendix B)
- Bases hazard and risk assessments on evidence and data, not solely on expert opinion or expert community consensus
- The Scientific Advisory Committee (SAC) appointed by the Minister of Economic Affairs provides independent oversight of the studies for the Winningsplan 2016

With the limited data available in 2013 to support or reject the available theories and models, the hazard assessment in 2013 was intended to be conservative. With the ongoing acquisition of new data and the progress of the studies, the hazard assessment will gradually become more reliable. Consequently, the assessed hazard and its associated uncertainty are expected to decrease.

In January 2014, the Minister announced the intention to approve the Winningsplan Groningen 2013 subject to the condition that NAM would submit a new Winningsplan in 2016 based on further and emerging insights and study outcomes (Ref. 12). It was realized that the hazard could potentially increase (and there were more uncertainties for the longer period of time) and that new insights were to be gained from ongoing studies and monitoring. The final decision on the Winningsplan was made on 30 January 2015 (Ref. 19) with a number of conditions. For the purpose of this report, the conditions in article 6 and in article 4 of the final decision from February 2015, are most pertinent. Article 4 demands an assessment of the hazard and risks per relevant region within the Groningen Field by 1st of May 2015. Several other conditions, e.g. the risk methodology, production caps, monitoring requirements and mitigation measures in terms of structural upgrading, are related to this hazard and risk assessment (as input or output) but are not discussed here.

The current report presents the intermediate update for mid-2015 (1 May 2015) of the Hazard and Risk Assessment for Winningsplan 2016. Since these intermediate results are extracted from an on-going work plan designed for delivery in 2016, they should be interpreted with caution given that some elements of the models, which are currently significantly more advanced than those presented in the Winningsplan 2013, are still evolving and maturing further using newly available data from the monitoring programme will only be incorporated in a next version as they are currently not yet complete/mature.

Hazard and Risk Assessment

An important topic in NAM's research program focuses on the assessment of the hazard and risk to which people and buildings in the immediate vicinity of the gas field are exposed. The research on hazard and risk has been split in two studies, as explained in the Introduction section. Study 1 discusses the hazard assessment, this Study 2 discusses the risk assessment. The hazard is defined as: *the annual frequency or probability, associated with different levels of ground motion, at which buildings and other objects are exposed to earthquakes induced by the production of gas*. A commonly used measure of the hazard is the Peak Ground Acceleration (PGA).

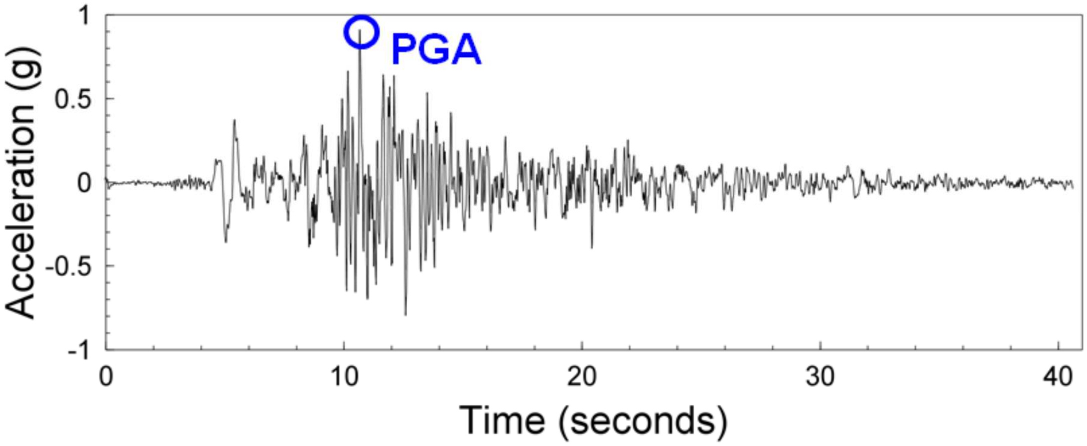

Figure 3 Acceleration record for a typical strong tectonic earthquake, with the PGA indicated.

Other important parameters for characterizing the hazard include:

- the spectral acceleration;
- the duration of earthquake accelerations;
- and the number of cycles.

A possible consequence of the seismic hazard is damage to, and in exceptional cases even collapse of, buildings and other objects. To date no buildings have collapsed due to an earthquake. Potential injuries or casualties for people located close to or inside these buildings can result from falling building elements or from the (partial) collapse of buildings.

The hazard and the risk of building collapse and the subsequent impact on people is assessed by a statistical methodology. The most widely used method is the Probabilistic Hazard and Risk Assessment or PHRA. The statistical Monte-Carlo method is used to perform the calculations for this hazard and risk assessment. This method entails repeated random sampling of the input variables to obtain numerical results for hazard and risk. This method is a common approach in solving physical and mathematical problems. It allows the uncertainties in all parameters to be consistently reflected in the PHRA, giving the full distribution of the hazard and risk and therefore also the hazard and risk at a given exceedance level.

Scope and Expertise Required

The hazard and risk assessment needs to span from the cause (gas production) to the effect (injuries and casualties). The uncertainties in each individual step need to be estimated and consistently incorporated in the total assessment.

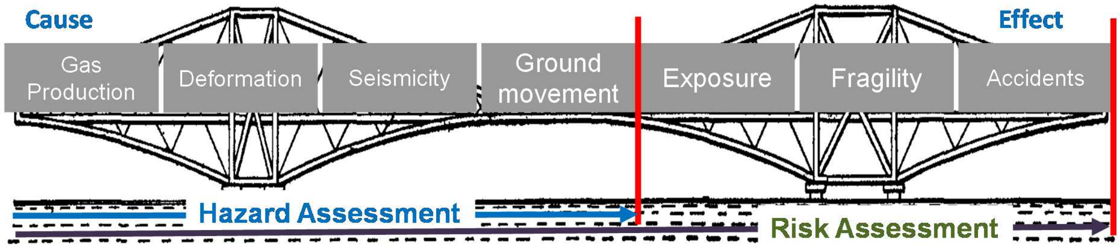

Figure 4 The Hazard and Risk Assessment requires a "bridge" to be built from the cause (gas production) to the effect (building collapse and potential casualties).

The causal chain starts with gas production, reducing the gas pressure in the reservoir and causing deformation of the reservoir rock. Deformation in turn can cause sudden movement in the subsurface, in other words: seismicity. This compartment of the "bridge" is addressing processes in the deep subsurface; the "geo-domain". This requires geological, geophysical and geomechanical expertise. The seismicity generated in the subsurface causes the ground motions or accelerations at surface which are affecting buildings and people. The prediction of ground motion is therefore the crucial link between the processes in the deep subsurface near the gas reservoir and the effects on buildings at the surface.

With sufficient knowledge of buildings, their structural strength, and of the presence of people in these buildings (the exposure), the risks can eventually be assessed. This is described in this Study 2. Especially expertise in the civil engineering domain is vital to be able to carry out this assessment.

Progress Probabilistic Hazard Assessment

Based on the available earthquake catalogue and other data specific for the Groningen field, a probabilistic seismological and hazard model was built in 2013. Where observational data was sparse or did not exist, analogue data and methods from tectonic earthquake regions were used as the best available data in the absence of appropriate data. This model formed the basis of the probabilistic hazard assessment supporting the Winningsplan 2013. In this Winningsplan, hazard maps were presented that showed the PGA for a given period, and with a given probability of exceedance level.

Relatively sparse observational data from the Groningen area was available at that time. Both the number of earthquakes that had occurred and the number of observation sites were limited. From the start of monitoring in 1994 till August 2012, some 188 earthquakes with magnitude larger than M=1.5[2] had been recorded. For the prediction of the occurrence of larger events, NAM did not make an estimate of the hazard based on theoretical considerations, which would need to be supplemented with potentially biased expert judgment and the consensus views within the earthquake community. Instead, NAM prepared a hazard assessment based on the scarce evidence available from the Groningen area, complemented, where appropriate with evidence and methods derived from tectonic earthquakes (mainly in southern Europe). This is a conservative approach: for low exceedance levels, the hazard is more likely to be adjusted downwards than upwards, when updates are based on an expanding set of newly acquired acceleration data.

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[2] NAM is confident an earthquake with magnitude greater than or equal to $M \geq 1.5$ will be detected wherever the earthquake occurred in the field and irrespective of its timing. An earthquake of smaller magnitude might remain undetected, for instance, among the noise from activities at surface.

Hence, the acquisition of more data, the completion of more studies and the better quantification of uncertainties, are very important. This led NAM in 2012 to embark on a large program to acquire more and more relevant data. The main objective of this campaign is to make the hazard assessment more reliable. As assumptions used tended to be conservative, the assessed hazard and its associated uncertainty are likely to decrease. The various activities included in the data acquisition campaign are described below.

In 2013, geophone strings were placed in the two existing deep monitoring wells (Zeerijp-1 and Stedum-1) located in the Loppersum area, where seismicity is highest. With these two geophone strings placed at reservoir depth (some 3000 m), even small earthquakes could locally be monitored and their origin determined better relative to the interpreted fault system at reservoir level. Conclusions from the analyses of data retrieved from these geofoons are:

- The recorded micro-seismic events are in accordance with KNMI observations
- 98.3% of the analysed events originate from the gas reservoir
- Location of the events are in line with the known structural characteristics of the field

Early 2014, 10 additional GPS stations were placed to monitor subsidence better. In 2013 also a campaign started to extend the existing geophone and accelerometer network. In 2014 some 42 shallow (200 m deep) geophone wells were drilled with 4 geophones placed at 50 m intervals in each of these wells. In 2015, drilling continues. Phase I of this project consisting of almost 60 geophone stations is expected to be completed mid-2015. However, drilling will be continued with Phase II adding another 11 stations. At each of these stations also a surface accelerometer will be placed.

In 2014 the first dedicated deep well designed for seismic monitoring was drilled at the Zeerijp location to a depth below the Rotliegend reservoir. A second well will be spudded in May 2015. In this second well an extensive reservoir section will be cored. Three laboratories are awaiting arrival of sections of this core to perform rock experiments on both compaction and rupture processes. Mid 2015, NAM plans to install geophone strings in these dedicated wells. Additionally, a geophone string will be placed in the existing observation well Ten Boer-4, near the Eemskanaal cluster.

Each earthquake will now (depending on the magnitude) be recorded from multiple observation points. Based on studies of the geophone and accelerometer data collected and compaction data measured from experiments in laboratories, the hazard model can now, and will continue to be, improved. For each successive improvement of the hazard model, based on studies and monitoring, conservatism in the model will be reduced as conservative assumptions are replaced by constraints derived from actual field observations. This means we feel confident that the assessed hazard at low exceedance levels of 0.2%/year or less is more likely to decrease than increase overall as a result of further data collection and studies.

Schedule

Early 2014, the progress of the various studies and the status of the hazard and risk assessment were reviewed. This underlined and clarified the interrelations between the various research activities and provided an opportunity to re-direct the research effort towards resolving the largest uncertainties and the most relevant research questions.

For each study domain, progress was envisaged with the hazard and risk model increasingly being refined and the model parameters improved.

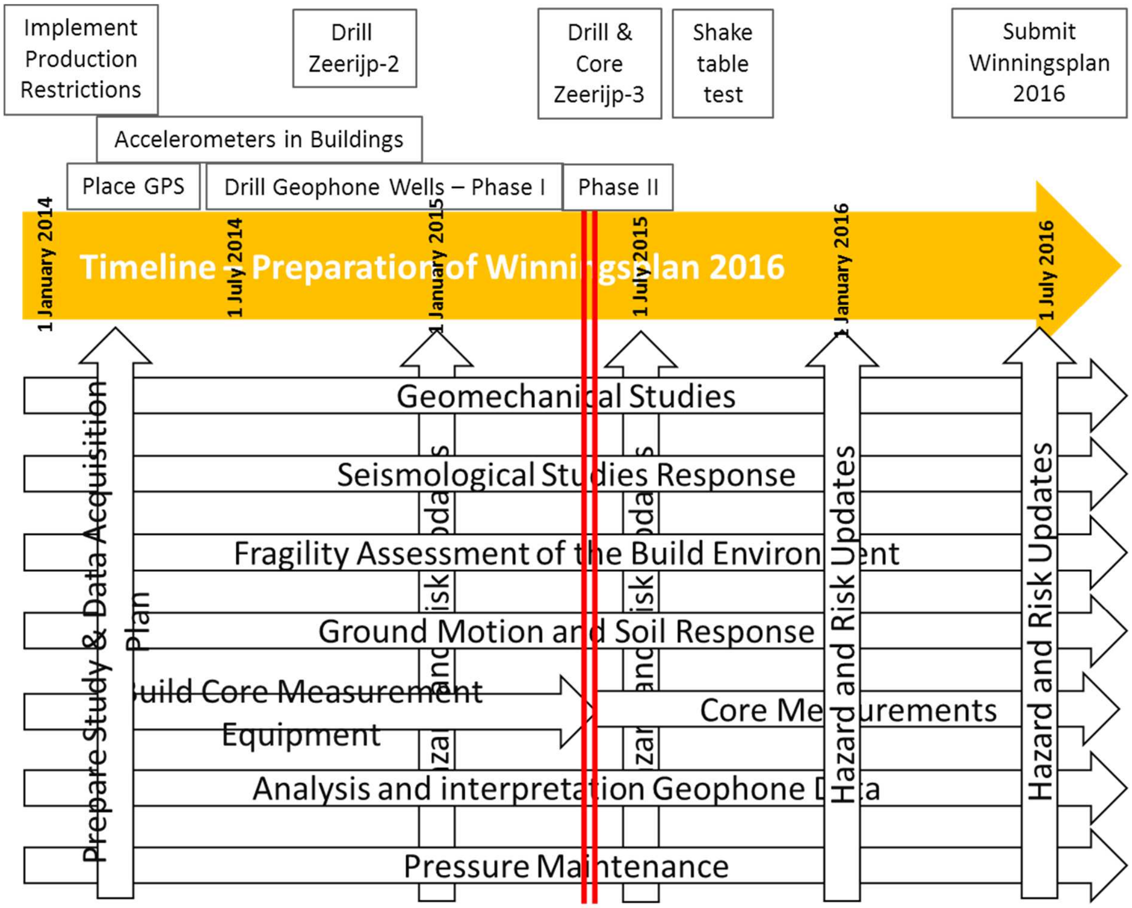


Figure 5 *Schedule for the research program for the Winningsplan 2016 as presented in the "Study and Data Acquisition Plan".*

Successive improvements at the half-yearly status reviews will be used to re-direct and optimise the research efforts. This is further discussed for each domain in the next sections. Note that the initial timeframe for the studies and half-yearly updates was different from the current timeframe as introduced by the February 2015 decision on the Winningsplan 2013 (Ref. 12).

Table 1 shows the current schedule for updates of the hazard and risk assessment in preparation of the Winningsplan 2016.

Target Date	Maturity Version	Status of Hazard and Risk Assessment
1st January 2015	0	Demonstrate capability to extend the probabilistic hazard assessment into the risk domain.
1st May 2015	1	First probabilistic Hazard and Risk Assessment. Important elements of the hazard assessment still in development (in particular site response). First version with probabilistic Risk Assessment for identification of most fragile buildings to optimise the structural upgrading program.
1st January 2016	2	Include site response into the ground motion prediction methodology. Hazard and Risk Assessment with most important input included.
1st July 2016	3	Final Hazard and Risk Assessment for Winningsplan 2016. The results of the full research effort is included in this assessment.

Table 1 Main deliverables for each inventory update of the hazard and risk assessment

Main new Elements Risk Assessment – May 2015

This section discusses the progress made in the risk assessment since Winningsplan 2013 was submitted on 29th November 2013. While Winningsplan 2013 was based solely on a deterministic hazard assessment, Winningsplan 2016 will be based on an integrated and fully probabilistic hazard and risk assessment.

The planned activities are all discussed in detail in the Study and Data Acquisition Plan issued early 2015 and the accompanying studies catalogue (Ref. 11). Progress will be reviewed every half-year and the research program re-directed if required. In case of a large adjustment an update of the Study and Data Acquisition Plan will be issued.

Progress Probabilistic Risk Assessment

The risk assessment for Winningsplan 2013 was performed using a deterministic framework. For a number of specific earthquake cases, each with the maximum magnitude of M=5 (normative scenarios), the risk consequence was evaluated. The earthquake cases were located in the most seismically active area around Loppersum. Numbers of buildings potentially ending up in the near collapse (Damage State 4) or collapse (Damage State 5) state and hence the potential casualties were evaluated by NAM (Ref. 6) and SodM (Ref. 11). Earlier this year a similar assessment was done as part of the Impact Assessment of the NPR (Ref. 33).

The risk assessment requires a complete inventory of all buildings in the area. NAM has requested ARUP to build the initial database of all buildings in the area, by merging existing databases and further extending this with direct observations and screening of local buildings.

To estimate the fragility of the buildings in the area, the buildings have been categorised into 40 typologies (Ref. 27). For these typologies a number of representative buildings were chosen for detailed investigation of their seismic capacity. Some of 67 typologies have been clustered based on shared characteristics. The main category of buildings are unreinforced masonry (URM) buildings. Masonry has properties that are difficult to model. The study into the fragility of these buildings started with a modelling cross-validation report (Ref. 29). This was followed by an extensive experimental program to determine the properties of the materials locally used in the construction of URM buildings (Ref. 30). This program will proceed during the remainder of 2015 with the testing of building elements (e.g. walls and piers) and a full scale shake table test at the Eucentre facilities in Pavia, Italy planned for September 2015.

In the main category of non-URM buildings, the precast reinforced concrete buildings are particularly important. In addition to detailed modelling of these buildings an experimental program to assess the strength of the precast connections is in progress.

To assess the relationship between the different building typologies and soil conditions, accelerometers have been placed at the foundations of buildings in the Groningen area. This includes both public (20 accelerometers) and residential buildings (200 accelerometers). The selection of these buildings was done to cover different building typologies and soil conditions. The geographic spread and distance to stations of the geophone network was also taken into account. The data recorded by the sensors in public buildings is shared via a web-portal (feitenencijfers.namplatform.nl) and with the regulator and other parties to allow for scientific analysis.

Below summarises the main improvements incorporated in the risk model for this assessment (mid 2015) and the next assessment (late 2015) per category.

Building Fragility

Improvements for Version 1 (Mid 2015)

- Modelling of out-of-plane failure for URM walls/façades
- Modelling of shear failure, sliding, unseating and buckling phenomena for non-URM structures
- Modelling of progressive collapse
- New Nonlinear Static Procedure based on URM-calibrated hysteresis models and accelerograms with appropriate magnitude and duration ranges
- Fragility functions in terms of spectral ordinates and magnitude (improved 'efficiency' and 'sufficiency')
- Nonlinear structural models for 20+ real buildings from the Groningen region developed and analysed
- Parametric numerical analyses and sensitivity studies to inform building-to-building variability and correlation
- Nonlinear dynamic analyses to validate pushover analyses
- Cross-validation of URM nonlinear modelling strategies
- Study of sensitivity of fragility functions to nonlinear site amplification and soil-structure-interaction

Improvements for Version 2 (End 2015)

- Improved capture of the influence of duration on the fragility functions through use of a structural response parameter other than peak drift
- Modification of low-acceleration tail of fragility curves to converge to zero rather than very small finite values
- Laboratory and in-situ test data to calibrate numerical models of structures
- Further improve numerical models of index buildings, including also soil-structure interaction
- Further refinement of fragility functions based on empirical evidence, particularly from smaller earthquakes

Consequence Modelling

Improvements for Version 1 (Mid 2015)

- Collapse modes were identified for each building typology from the analytical modelling efforts, and used to assign expected volume loss based on empirical evidence
- Influence of magnitude has been incorporated in the estimation of volume loss / collapsed area
- fatality ratios have been correlated with volume loss using empirical evidence
- the outside fatality risk has been addressed
- the method incorporates an estimation of the uncertainties in the fatality ratios, which will be used in the risk sensitivity studies

Improvements for Version 2 (End 2015)

- Agreed definition of "near a building" is needed to estimate outside local personal risk;
- Focus on the inputs required to estimate *group risk* (for people both inside and outside of buildings), such as the inclusion of the occupancy of the space outside of buildings
- Populate the volume loss vs. fatality ratio plot with more empirical evidence for buildings relevant to those in Groningen field
- Relate empirical evidence of collapsed material (for different collapse mechanisms and for different magnitude earthquakes) to the numerical modelling activities

Structural Upgrading Plan

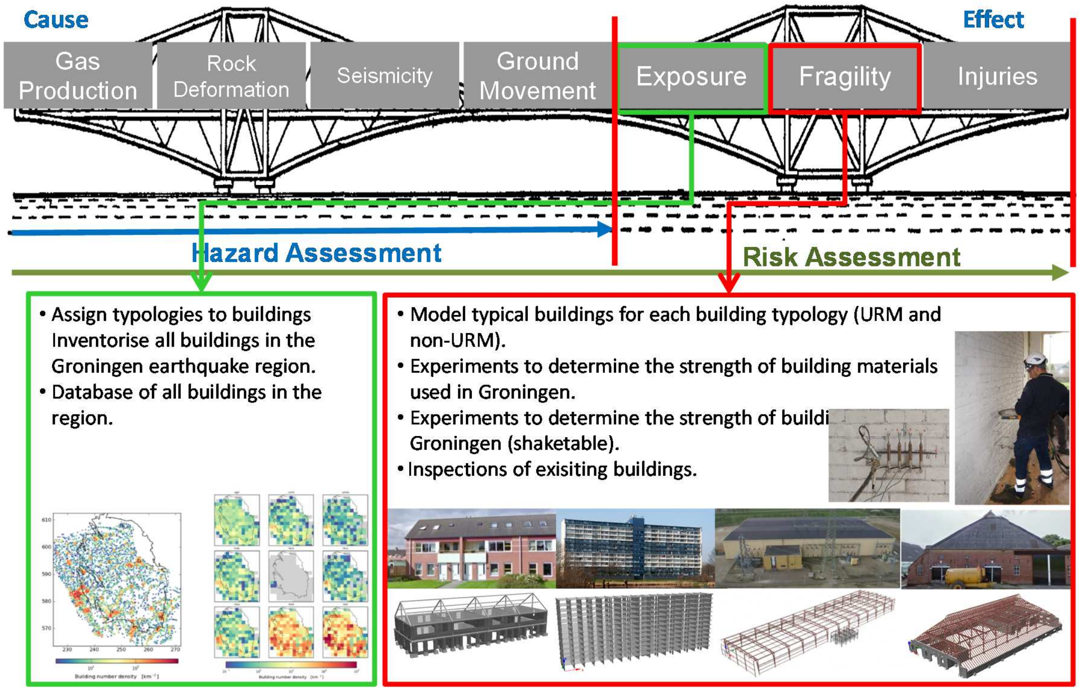
Improvements for Version 1 (Mid 2015)

- First upgrading plan prepared based on preliminary prioritisation
- Incorporates assumed pace, volume of work and high level societal constraints to ensure practical feasibility

Improvements for Version 2 (End 2015)

- Pace, volume and scope improved definition based on first actual upgrade experience (CVW)
- Improved basis for risk-based prioritisation building on the V1 Risk Model
- Societal constraints based on dialogue with community and building corporations

Exposure Database



- Assign typologies to buildings Inventorise all buildings in the Groningen earthquake region.
- Database of all buildings in the region.

- Model typical buildings for each building typology (URM and non-URM).
- Experiments to determine the strength of building materials used in Groningen.
- Experiments to determine the strength of buildi Groningen (shaketable).
- Inspections of exisiting buildings.

Figure 4 The elements 'exposure' and 'fragility' as part of the risk assessment.

The exposure database combines a number of existing public and proprietary datasets related to the buildings and population within a total area, with proper care to privacy regulations. This currently extends 3 km (in all directions) from the boundary of the Groningen gas field. These datasets include the Basisregistratie Adressen en Gebouwen, Dataland address use, and Bridgis population. Merging this data into a single Geographical Information System (GIS) allows for the identification of the coordinates of each individual property within the region. This database provides an initial estimate of the number of occupants within these properties during the day and night. Also, the usage category of each property is available, which makes it possible to make a distinction between residential, commercial, industrial, agricultural, recreational, educational, and religious buildings.

The most important characteristic that influences the seismic response of a building, is the construction material of the walls, frames and floors. This might be constructed from unreinforced masonry, steel, reinforced concrete, or timber. Buildings can be grouped into categories according to their construction material and systems; Groningen structural engineers have currently identified a total of 67 categories for the buildings in the region. A database containing construction material information for each property in the Netherlands is not currently available, and so this information needs to be pieced together from the available data related to the age, usage and location of the buildings. A number of Groningen structural engineers have provided their local knowledge of construction practices over the last century, in order to allow such inferences to be made (Ref. 27).

The exposure database currently includes 258,886 properties and a daytime population of 568,159 people. Current estimates indicate that around 75% of the residential population lives within unreinforced masonry buildings.

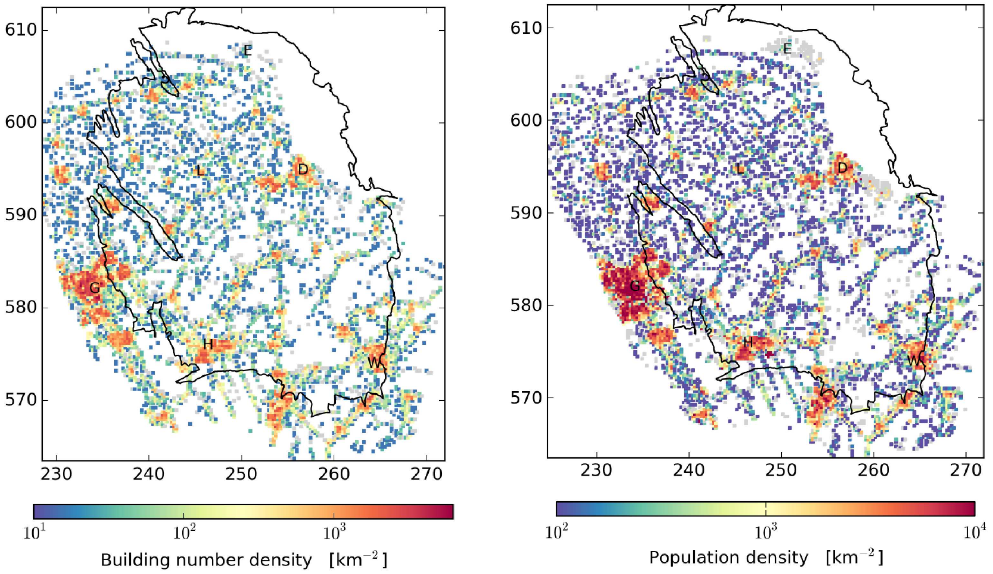


Figure 6 *Building density (left) and population density (right) in the Groningen field exposure database measured on a 250 by 250 m regular grid. The letters 'D', 'E', 'H', 'L', 'W' denote the place names Delfzijl, Eemshaven, Hoogezand, Loppersum and Winschoten respectively, and the black line denotes the outline of the Groningen gas field. The maximum building number density is 12,300 /km^2 found within the city of Groningen (G).*

Fragility of Buildings

Fragility curves provide estimates of the probability of structural failure of buildings. These are provided with a given specific level of spectral acceleration and include the variability between buildings (geometrical and material) and earthquakes (Ref. 32 and 33).

In the Winningsplan 2013, a description of building fragility was used based on 19 typologies and the resistance of the buildings to earthquakes was based on fragility curves taken from literature. This fragility description was for generic buildings, not typical for the Groningen area, and for exposure to tectonic earthquakes. As the duration of tectonic earthquakes is substantially longer than that of the earthquakes observed in the Groningen area, an adjustment was made to these fragility curves to capture the impact of duration on the building response. The fragility curves have also been adjusted for the specific Groningen building practises and materials.

Two main categories of building typologies were investigated in more detail. These are masonry buildings and non-masonry buildings. The latter include reinforced concrete, steel and timber constructions.

Modelling of masonry buildings requires in-depth knowledge of the material properties manufactured and used locally, and the possibility to capture these properties faithfully in numerical models. Therefore the program to assess the fragility of masonry buildings was started with (1) a program to measure masonry properties of buildings and materials in the area and (2) a measurement of the strength of building elements and (3) a shake table test of a terraced house in the Eucentre laboratory in Pavia (Ref. 31). In parallel, a study to validate the methods for analytically assessing the response of Groningen masonry buildings to strong ground shaking has been undertaken (Ref. 30).

A large number of existing non-masonry buildings were numerically modelled. For reinforced concrete, steel and timber buildings validated models were used (Ref. 28 and 29). Laboratory tests are currently undertaken to gain insights in floor/wall/ceiling connections in pre-cast reinforced concrete buildings. The results of these tests will be used to further calibrate the numerical models.

Numerical models, subsequent calibration through in-situ and laboratory testing on materials, connections, structural components and full-scale buildings tests, help to improve fragility curves for the buildings in Groningen.

Injury Model

Once fragility curves are available for each building typology in the region, they can be combined with the hazard model. This gives an estimate of the annual probability of structural failure for each type of building. Examples of structural failure include the outwards collapse of masonry walls, the collapse of roofs onto the floor, and the sliding and unseating of buildings from their foundation. Each of these failure modes lead to very different consequences in the amount of collapsed debris within the building. The amount of collapsed debris has a direct impact on the likelihood of fatalities.

Fatalities are measured as a fatality ratio. This is the number of fatalities divided by the number of occupants in a building during an earthquake. Fatality ratios for buildings with varying degrees of collapsed material have been obtained from past earthquakes around the world. This data is predominantly available for earthquakes with a magnitude greater than 7 on the Richter scale, which exceeds the magnitude range within the Groningen hazard model (Ref. 34). Therefore, a database of the consequences of smaller magnitude earthquakes is being developed. This will be used to validate the current fatality ratio and to develop a risk model for injuries and fatalities outside buildings.

Structural Upgrading Program

A structural upgrading program is ongoing in the Groningen Area, with the objective to improve the safety for occupants of buildings in the area by making buildings more earthquake resistant. As of the end of 1Q 2015, work carried out in this program to date includes more than 7,000 building inspections and 600 structural upgrades (including both temporary strengthening, and permanent measures to reduce building collapse risk and secure potential falling objects). Structural upgrading activity is planned to continue to ramp-up through year-end 2015 and into the coming years.

The program is expected to result in a significant reduction of life safety risk. Therefore a structural upgrading scenario has been incorporated into the Probabilistic Hazard and Risk Assessment (PHRA) model input, so that the risk reduction benefits of the program are reflected in the model results. The scenario has been developed with the aim of representing a structural upgrading program that is challenging in terms of volume of work, the pace of work and the amount of risk reduction, yet achievable given expected social and practical constraints. The scenario included in the PHRA is a simplified, yet representative version of the anticipated actual structural upgrading program. Emerging new runs, including latest subsurface and surface insights, will inform, over time, to what extend such scenario needs to be up scaled, or downscaled or refocused.

The PHRA scenario is based on current assumptions and analysis regarding the pace of execution and risk-based prioritisation, and these are subject to uncertainty and change. Moving forward, as the risk assessment maturity/granularity increases, and learnings are made regarding execution capability, the structural upgrading program will further evolve and be optimised to reduce the risk to building occupants as fast as practically possible.

The structural upgrading scenario in the PHRA can be summarized as follows:

- The scenario assumes that a total of approximately 40,000 buildings will be upgraded over the next 7 years. This is within the range of the impact assessment conducted for the NPR steering committee, which estimated the number of buildings requiring to be upgraded to meet the draft Dutch Building Decree for earthquake resistant design (NEN-NPR 9998). The actual number of buildings to be upgraded is subject to change as the risk assessment matures and the NEN-NPR 9998 is finalised.
- The pace of work for the overall structural upgrading plan is assumed to increase significantly over the next four years due to the anticipated “learning curve” and increasing execution capacity, from 3,000 upgrades in 2015, to >8,000 upgrades per year in 2018/19. This plan was developed in accordance with the NPR steering group advice, and covers all structural upgrading activities, including work to address building collapse risks and falling object risks. The PHRA model input covers the subset of the total plan that addresses building collapse risks (1,000 in 2015 and 3,500 in 2016).
- The scenario includes assumed constraints on the amount of work that can be executed in a village in any year. Such constraints are expected to occur due to the need to carry out structural upgrading work at each location safely and efficiently while minimizing social disruption (e.g. by limiting the number of streets that are simultaneously closed within a village). Specifically, the scenario constrains the number of buildings that can be upgraded in any village to 15% of the total buildings per year in 2015, increasing with learning curve to 25% per year by 2018/19.
- Within the assumed overall pace of work and location constraints, the scenario prioritizes buildings for upgrade based on relative life safety risk factors as follows, with the aim of reducing safety risk to building occupants as fast as practically possible:

- The program starts in the area of highest predicted PGA and then works outwards. Consequently, in the PHRA scenario, work is concentrated in 8 municipalities – Loppersum, Ten Boer, Eemsmond, Slochteren, Delfzijl, Appingedam, Bedum and Winsum. In practice it is expected that for the actual structural upgrading program some proportion of the work will be carried out in the other municipalities in Groningen area (e.g. De Marne) as the risk for individual buildings is considered.
- Within a given location, buildings are prioritized based on basic typology, with Terraced Houses given the highest priority, since their design/construction generally leads to lower earthquake resistance than other building types.

The actual structural upgrading program will be further optimised with the risk assessment results of the current PHRA, working towards the objective of prioritising the program based on the relative risk of individual buildings to allow the safety risk to building occupants to be reduced as fast as practically possible. Figure 8 shows the starting scenario. This is a scenario that will be optimized in practise.

PRELIMINARY STARTING SCENARIO

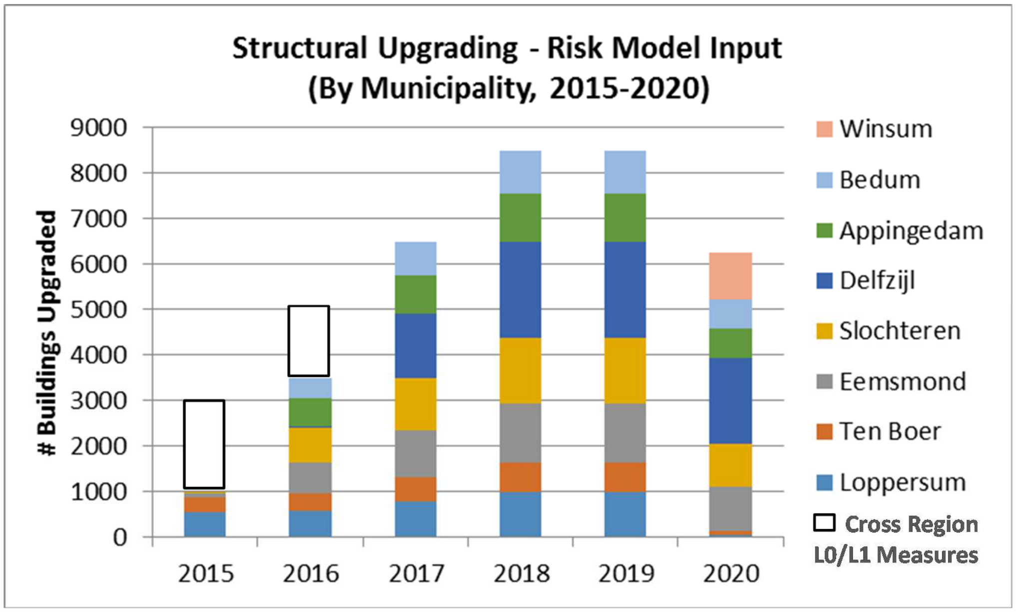


Figure 8. Structural Upgrading scenario included in PHRA model by municipality (stacked bars), and total Structural Upgrading Plan (solid line). The total plan was developed in accordance with the NPR steering group advice, and covers all structural upgrading activities, including work to address building collapse risks and falling object risks.

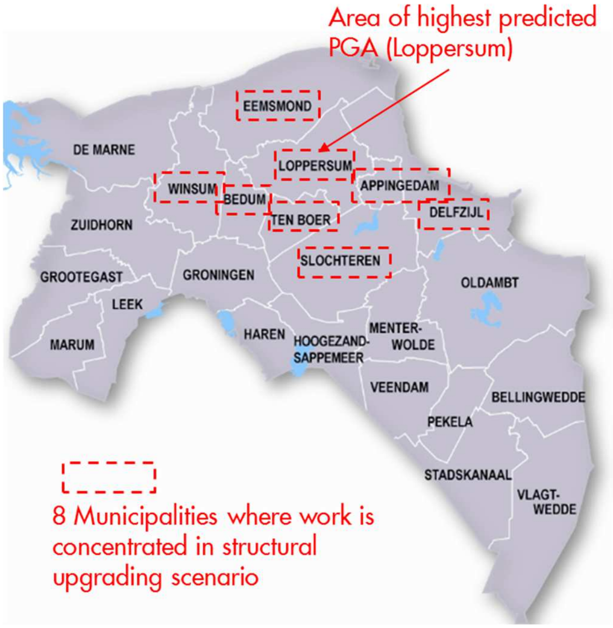


Figure 9. Municipalities where work is concentrated in structural upgrading scenario

Risk Metrics

The results from the probabilistic hazard and risk analysis (PHRA) are summarised via two risk metrics which relate to the annualised probability of fatality for an individual – "Inside Local Personal Risk" and "Mean Inside Local Personal Risk", which are defined as follows:

Inside Local Personal Risk

"Inside Local Personal Risk" (ILPR) is generally defined as the annual probability of fatality for a person, who is continuously present without protection at a specific at-risk location. For Groningen earthquakes, LPR is defined as follows: *"the probability of death of a fictional person who is permanently in or near a building"* (Ref. xx). In this definition of LPR, the fictional person is either inside the building, or outside "near" to the building. In the PHRA in this report, "Inside LPR" focuses on the risk to building occupants inside the building. In practice, it is recognized that occupants of buildings spend some of their time in the outside area near the building, and this will be considered for the year-end 2015 update of the risk assessment. To carry out this risk assessment, it will be necessary to develop a clear definition for the at-risk area outside and near to the building.

Mean Inside Local Personal Risk

"Mean Inside LPR", which is calculated for an individual building, is defined as the annual probability of fatality for a person who is continuously inside a building. "Inside LPR" assumes that the person stays inside the building 100% of the time, and the location of the person is uniformly and randomly distributed inside the building (i.e. if 10% of the building collapses there is a 10% probability that the person will be in the collapsed part of the building). "Mean Inside LPR" is the mean of "Inside LPR" across a number of buildings, weighted by the estimated day/night population of each building. Both "Inside LPR" and "Mean Inside LPR" are taken as an average across the forecast period of the PHRA, and have units of average probability of fatality per year.

Group Risk

"Group Risk" (GR), also known as "Societal Risk", will be assessed for the first time in the year-end 2015 risk assessment. GR is associated with how often to expect events involving different numbers of fatalities, and is defined as the frequency with which events involving N or more fatalities are expected within a given population. This is shown in an f/N curve. To prepare an assessment of GR, both the event and the population need to be defined. The event is in this case "an earthquake", and the population can be defined based on the area of interest (e.g. an individual building, an urban area such as Groningen City, or the entire region affected by earthquakes).

For the assessment of GR it is important to consider the risk to people both inside and outside (near) buildings, and to have a reliable occupancy estimate, particularly for buildings with larger populations. These areas will be addressed such that GR can be assessed for the year-end 2015 Risk Assessment.

Risk Assessment

This report presents the first probabilistic Risk Assessment performed for induced seismicity in Groningen. It is not an update of a previous risk assessment. Unlike the work for the hazard assessment, it cannot be compared directly with previous work. The risk is not yet quantified as key input for calibration will only become available in the second half of 2015. However, with the new risk assessment methodology, it is possible to simulate the risk consequence of the historical earthquakes observed in the Groningen gas field and compare these with the observations to date. This will give a first impression of the reliability of this risk assessment.

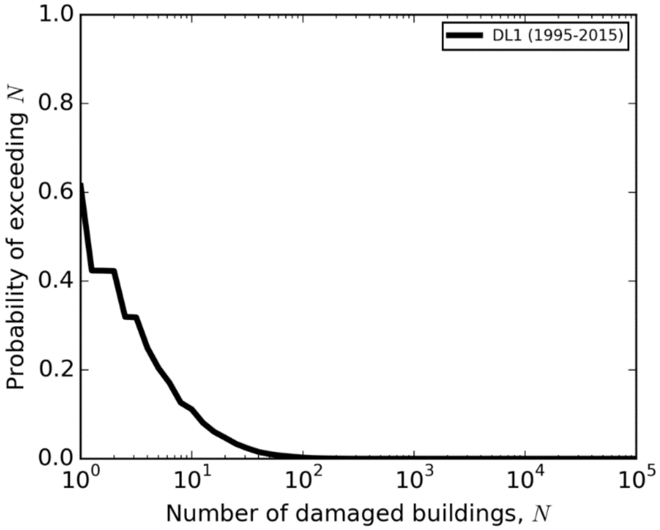


Figure 10 Simulated probability of collapse of buildings in Groningen using historical earthquake data from Groningen 1995-2015 (KNMI Catalogue) and the risk methodology

Figure 10 shows that, based on the current risk methodology, there is an almost 60% chance that we would have observed one (1) collapsed building in the period 1995 to 2015. In reality, no building collapse has been observed during this period. Based on this outcome, the methodology behind the risk assessment seems valid and for the data, if anything, conservative. However, this probability is on the high side of what can be tolerated based on the empirically observed response of the building stock to the historical earthquakes.

To assess the range of possible outcomes of the risk assessment and the sensitivity of this outcome to the uncertainty in the various input parameters, a logic tree approach was used. This tree has 6 factors (compaction model, seismological model, Ground Motion Prediction Equation (GMPE), exposure model, building fragility model, consequence model for injuries) that cover each element of the risk assessment from gas production to injury. For each factor, three levels are recognized: a best-estimate and upper and lower bounds each with their own likelihood.

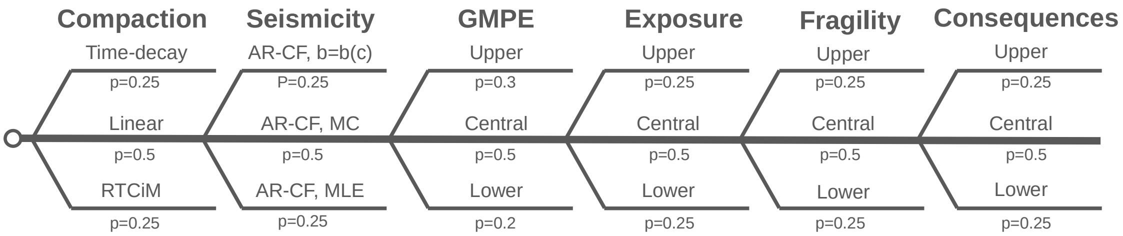


Figure 11 The logic tree used to assess the influence of epistemic uncertainties on the probabilistic seismic risk assessment.

The solid horizontal line through the logic tree represents the “base case”. For each of the main inputs alternative options are shown around this base case. Initially, the risk is evaluated using the base case and a single alternative. This results in 13 assessments. Then combinations of two alternatives are assessed. This results in 73 assessments. Together these assessments give an impression of the range of the risk assessment results based on the remaining uncertainty in the input.

Assessment: Inside Local Personal Risk (ILPR)

Uncertainty

With the risk assessment methodology we can determine the inside Local Personal Risk (ILPR) for each building. Based on the mean day-night occupancy of these buildings an assessment can be made of the number of people in the Groningen area exposed to inside local personal risk. Fig. 12 shows the number of people exceeding an inside local personal risk, when the field is produced at 39.4 Bcm/year without additional mitigation measures implemented. The black line shows the mean inside LPR (the mean outcome of all 73 logic tree cases) and the grey region denotes the range of uncertainty in the outcomes. This reflects the current low level of maturity of some of the contributing elements of the risk assessment.

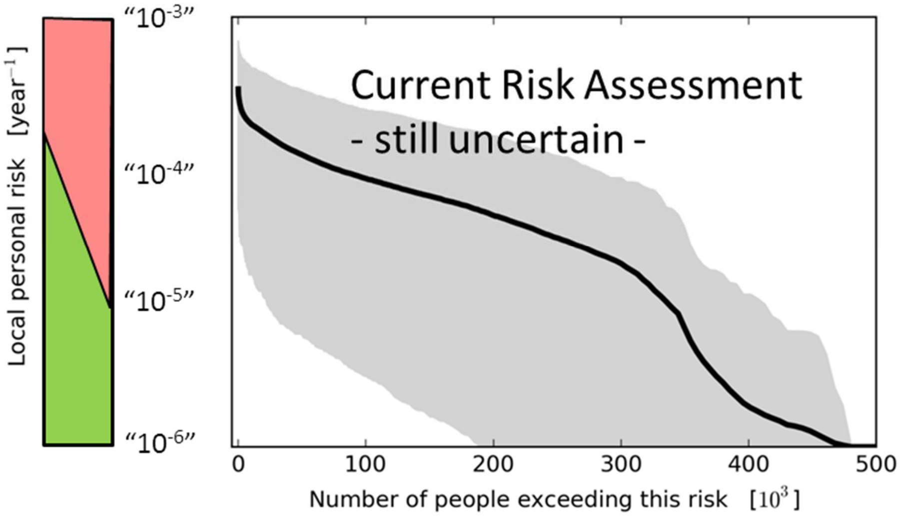


Figure 12 The cumulative distribution of indicative local personal risk and the sensitivity to epistemic uncertainty. This case is based on a production level of 39.4 Bcm and no implementation of the structural upgrading programme. Period: 1-7-2016 / 1-7-2021[3]

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[3] Where in this report inverted quotes have been used it indicates that these numbers are indicative only and can not be considered as conclusive

The main contributors to the large spread in the risk assessment are shown in figure 13 for three risk metrics: mean ILPR, the size of the population with a mean ILPR above 10^{-5}/year and mean ILPR above 10^{-4}/year. The uncertainty in the Ground Motion Prediction, the Building Fragility and Injury models are consistently the main contributors to this spread in risk. The Study and Data Acquisition program is in execution for each of these models to better understand and reduce, based on evidence, the uncertainty.

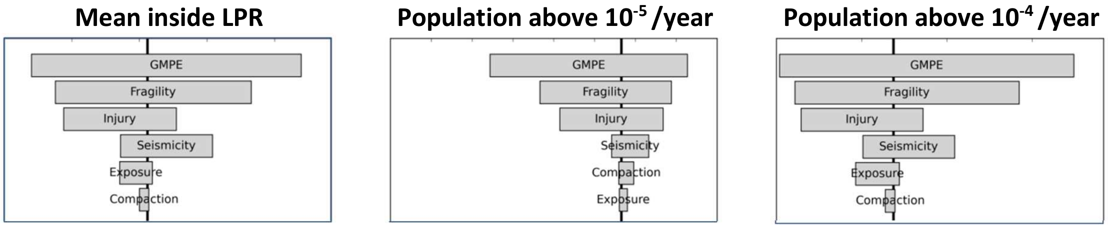

Mean inside LPR
Population above 10^{-5} /year
Population above 10^{-4} /year

Figure 13 *Relative sensitivity of the assessed risk to the epistemic uncertainties identified in the logic tree (Figure 11) according to three different measures: mean inside LPR, population above 10^{-5}/year, and population above 10^{-4}/year.*

The mean ILPR can also be shown spatially in 3 X 3 km areas above the Groningen gas field, which is done in Figure 14. “Mean Inside LPR” is the mean of “Inside LPR” across a number of buildings, weighted by the estimated day/night population of each building. The maps show three different scenarios. The middle map is the base case realisation which corresponds with the solid horizontal line in the logical tree of figure 11. The other two maps show variations in ground motion prediction. This has the largest impact on the mean ILPR (see figure 13). Figure 14 gives an impression of the spatial distribution of the risk and the variation in the mean ILPR. This shows that in this first risk assessment substantial epistemic uncertainty remains. This assessment is based on the 39.4 Bcm/year production scenario without the structural upgrading program.

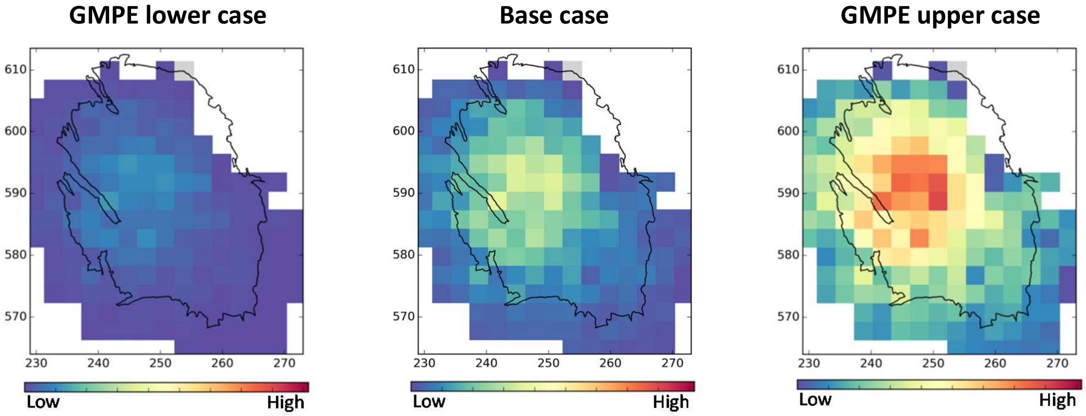

GMPE lower case
Base case
GMPE upper case

Figure 14 *Mean ILPR at per 3x3km area over all building classes, weighted by their average day-night inside population. Period: 1-7-2016 / 1-7-2021*

Impact of measures

The risk impact of two groups of measures will be discussed: 1) production adjustments and 2) structural upgrading of the buildings in Groningen. Figure 15 shows the measures for which the risk impact was evaluated. Two production levels are considered for the risk assessment: 39.4 Bcm/year and 33 Bcm/year, with and without the implementation of a structural upgrading plan. This results in 4 combined risk mitigation scenarios.

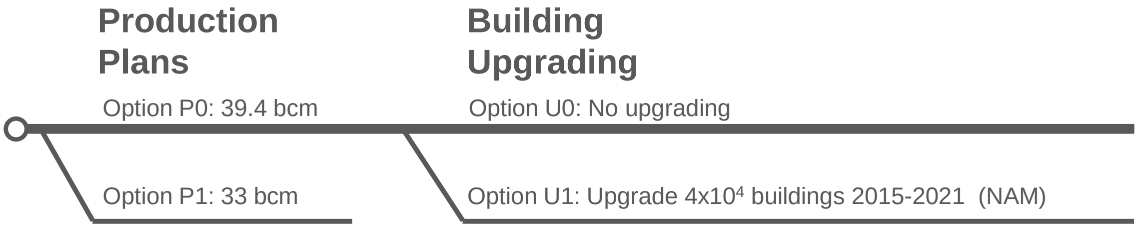


Figure 15 Summary of the mitigation measures considered in this risk assessment.

A risk assessment for a scenario based on 21 Bcm/year was considered. However, as shown in Study 1, figure 22 and 23, the difference in hazard between the 21 Bcm/year and the 33 Bcm/year scenario is very small compared to the uncertainties. As the hazard assessment is the basis for the risk assessment, running a dedicated risk assessment for the 21 Bcm/year scenario would therefore result in a very similar risk assessment, certainly within the large uncertainties the risk assessment currently has. The remainder of this study therefore focusses on the two before mentioned scenarios labelled P0 and P1 (Figure 15).

The outcome of the two risk mitigation scenarios is shown in figures 16 and 17. Each risk mitigation scenario is depicted by a black line. The bold black line depicts the scenario without any mitigation measures taken. The figure shows that implementation of these measures lowers the ILPR. Yet their joint impact is still within the currently existing uncertainty range. This uncertainty range is still large and is expected to reduce with advance of the Study and Data Acquisition Plan. The relative impact of the mitigation measures (compared to the uncertainty range) will increase.

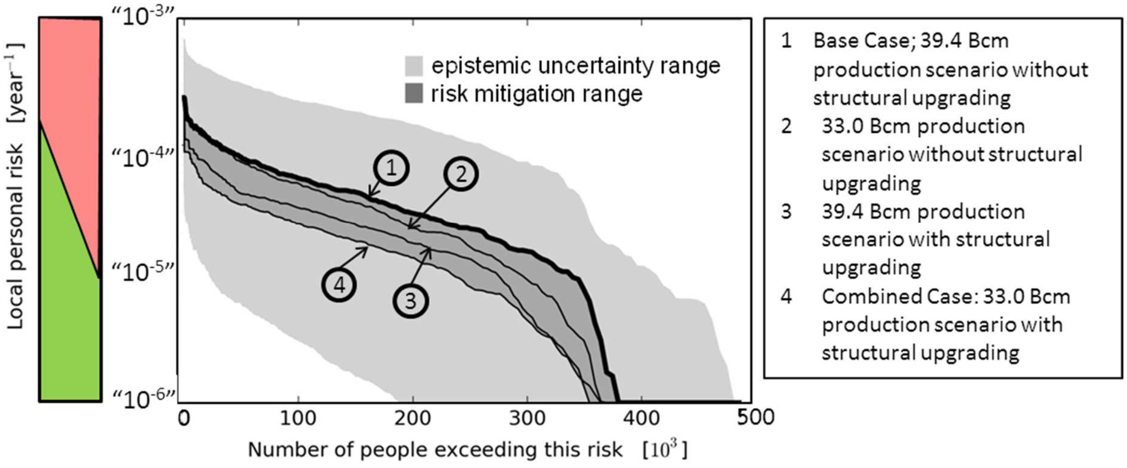


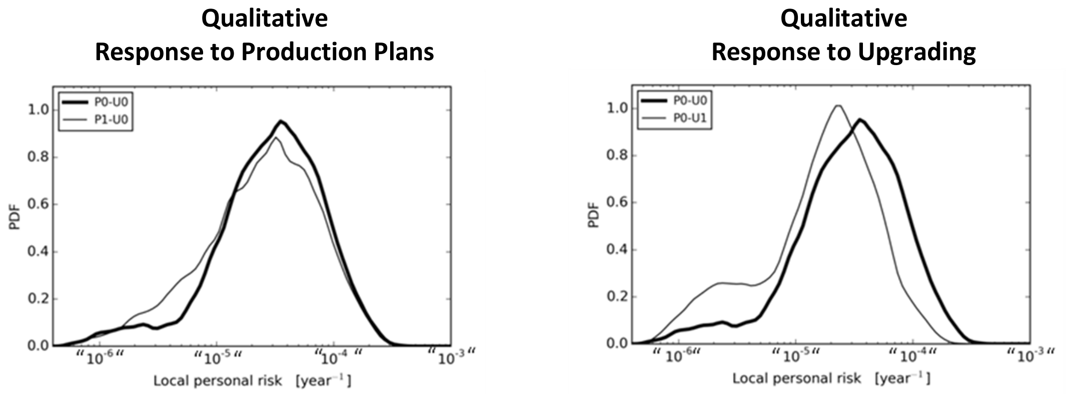
Figure 16 The cumulative distribution of indicative local personal risk under each of the four combinations of the mitigation measures relative to the currently assessed range of epistemic uncertainty as previously shown in Figure 12 (period: 1-7-2015 – 1-7-2021)

Another way of presenting the impact of the risk mitigation scenarios is done in figure 17. In both graphs, the bold line represents the distribution of ILPR without a risk mitigation measure taken (base line scenario). The second line represents the distribution of ILPR with the mitigation measure (production reduction in 17.a and structural upgrading in 17.b).

Figure 17.a shows that the impact of production reduction is that people exposed to ILPR in the intermediate range are moved to lower ILPR levels. This is because the production in the high-seismic area of Loppersum has already been strongly reduced as of February 2014. An additional production reduction to 33 Bcm/year will mainly affect intermediate seismicity areas (outside the Loppersum are) of the field where the ILPR is predominantly in the mid-range. The regions where the higher ILPR occurs is much less affected by an additional production reduction.

Figure 17.b shows that the structural upgrading programme mainly addresses the building typologies and the area where people are exposed to the higher ILPR. This is because these buildings are prioritized in the structural upgrading programme. The ILPR for these buildings is, therefore, moved to the lower range.

The risk assessment for these risk mitigation measures is done for the period: 1-7-2015 – 1-7-2021. During the 5 year period the effectiveness of the Structural upgrading programme increases as more houses have been upgraded. The assessment in Figure 17.b therefore shows an average over the 5 year period.


Qualitative Response to Production Plans

Qualitative Response to Upgrading

Figure 17 The assessed influence of risk mitigation measures on the probability density function (PDF) of local personal risk on a log-scale. (period: 1-7-2015 – 1-7-2021)

Figure 18 shows the impact of each of the four risk mitigation scenarios on the ILPR risk metrics. The scenario based on a production level of 39.4 Bcm/annum without the implementation of a structural upgrading programme is used as a base case (vertical black line). The impact of the measures are shown relative to this reference case. Structural upgrading programme has a greater impact on lowering the mean ILPR than the other considered mitigation measures.

Mean ILPR

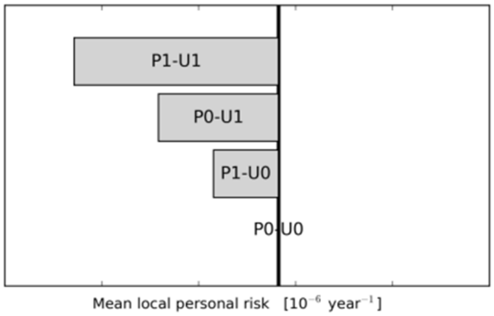
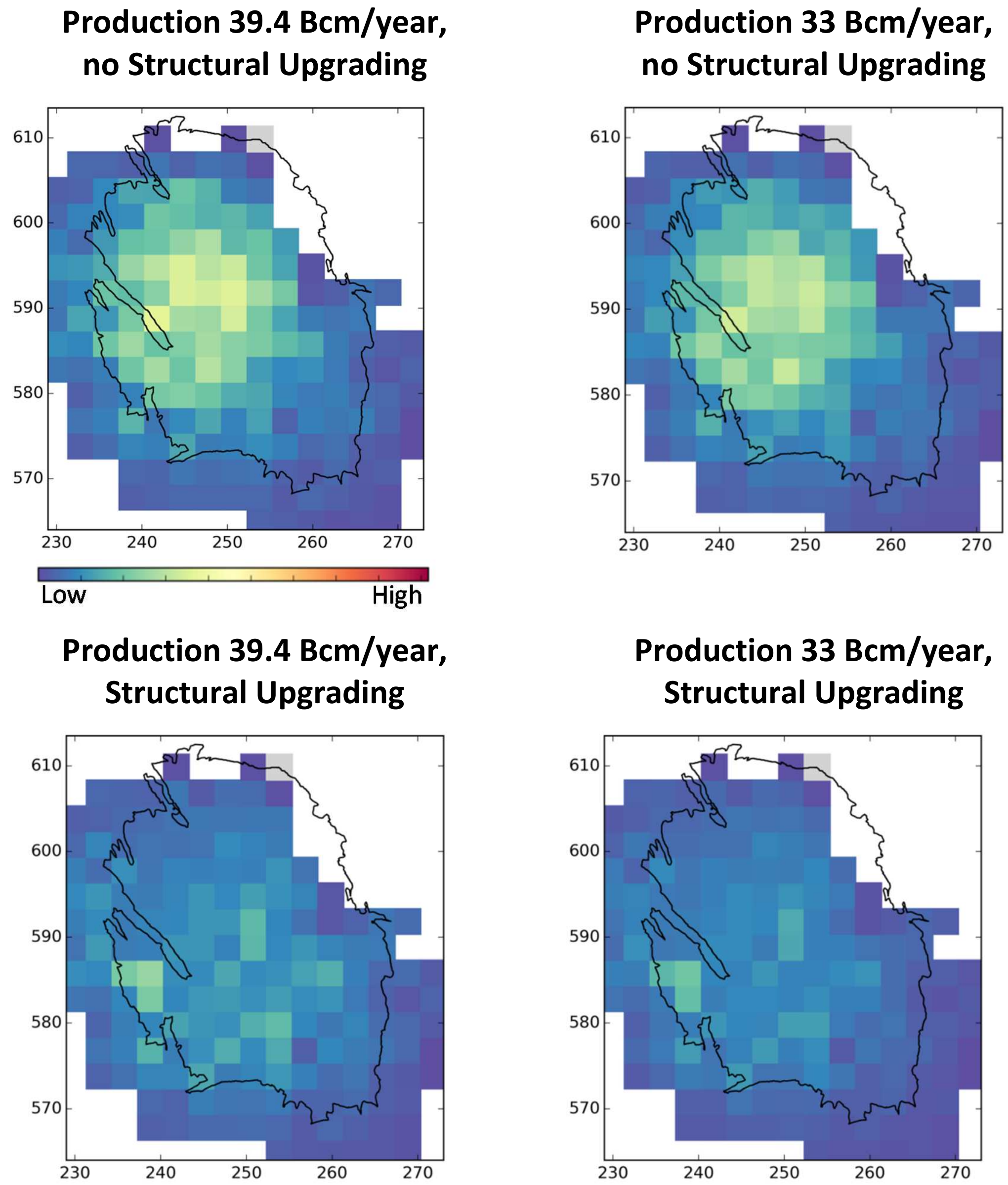


Figure 18 The influence of mitigation measures on the assessed base-case probabilistic seismic risk assessment. See figure 15 for a description of the different mitigation scenarios.

Similar to figure 14, the impact of the risk mitigation scenarios on the mean ILPR can also be shown spatially in 3 X 3 km areas above the Groningen gas field, which is done in Figure 19. Four cases are shown; production scenarios for 39.4 Bcm/year and 33 Bcm/year both with and without implementation of the structural upgrading program.

All four maps in figure 19 are made for the period 1-7-2015 – 1-7-2021. During this period the structural upgrading plan is being implemented. This means, the 5 year evaluation period also contains the initial years, during which relative few buildings have yet been upgraded and the effect of upgrading is therefore relatively weak. Figure 20 shows the risk assessment for the period 1-7-2011 to 1-7-2022, after the full structural upgrading plan implemented. This maps show the substantial effectiveness of the risk mitigation measures to reduce seismic risk in Groningen. The map also indicates there might be further scope for optimisation of the current structural upgrading plan, especially in the south of the field.


Production 39.4 Bcm/year, no Structural Upgrading

Production 33 Bcm/year, no Structural Upgrading

Production 39.4 Bcm/year, Structural Upgrading

Production 33 Bcm/year, Structural Upgrading

Figure 19 *For four scenarios the mean ILPR at each location over all building classes weighted by their average day-night inside population is shown (based on base case GMPE). Period: 1-7-2015 – 1-7-2021.*

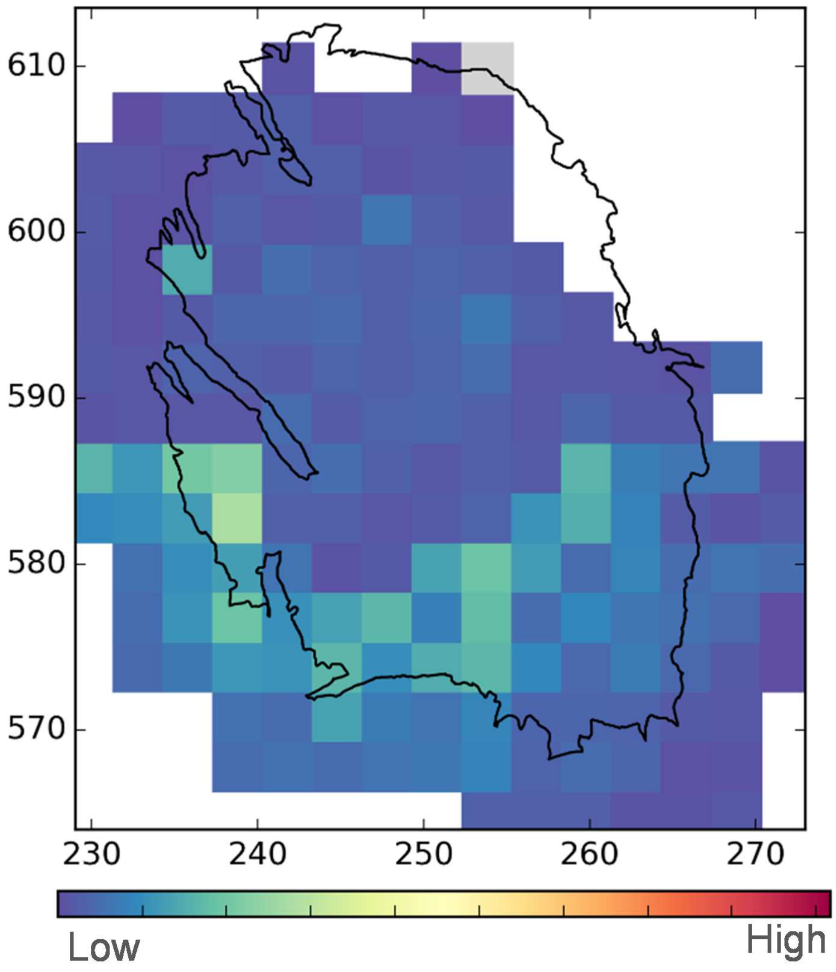


Figure 20 For the production scenarios of 39.4 Bcm/year the mean ILPR after implementation of the structural upgrading at each location over all building classes weighted by their average day-night inside population is shown (based on base case GMPE). Period: 1-7-2021 – 1-7-2022.

Industry and Infrastructure

NAM supports owners of infrastructure and industry in developing risk assessments for their properties. This including the following:

- Advice on the hazard (PGA map, etc.)
- Provide a list of reputable companies that can carry out the risk assessment
- Pay for the Risk Assessment
- Provide any other relevant information obtained from the studies and structural upgrading program

As for Winningsplan 2013, the risk assessment presented in this report covers buildings only. The assessment of the risks of infrastructure was addressed in a study performed by Deltares. There are a subset of reasons that these assessments are not yet part of this study:

- Many industrial and infrastructure objects are very specific and assessment of risk requires intimate knowledge of these objects resides with the owners;
- The knock-on effects after an initial failure of an element of an industrial object are very important (e.g. release of a chemical substance). These knock-on effects are already described in the quantitative risk assessments performed by the industrial owner;
- There is a different legal framework for industrial/infrastructure objects (versus buildings), with different responsibilities for the object owners (Ref. 15).

Conclusion

This report presents the first, albeit preliminary, full probabilistic risk assessment for the Groningen gas field. It describes the fully integrated Risk Assessment from gas production to possible damage and injury.

The uncertainty in the first probabilistic risk assessment is still very large. As a result, no quantification can yet be given of the seismic risk based on this assessment.

The current report presents an interim update for mid-2015 of the risk assessment for Winningsplan 2016. Since these interim results are extracted from an the ongoing Study and Data Acquisition Plan, designed to deliver results in mid-2016, these should be interpreted with appropriate caution. Many elements of the models are still further evolving and maturing using newly available data.

With these caveats in mind, the following conclusions could be drawn:

1. The sensitivity of the assessed risk to epistemic uncertainties in the elements of the assessment was shown using a logic tree. The assessment of the impact of the historical earthquakes was compared with the actual historical observation on building response. This provided an initial indication that the fragility curves do not grossly over-estimate the current absence of building collapse. Further work will need to confirm how conservative these curves are.
2. There is better understanding of the effectiveness of mitigation measures for the Groningen gas field (production and structural upgrading). Risk sensitivity to mitigation measures was assessed for two production scenarios and the structural upgrading programme. Level of maturity of mid-2015 risk assessment means absolute risk values are not reliable due to current large epistemic uncertainty, e.g.:
    a. Lack of non-linear site response in ground motion prediction
    b. Unreinforced masonry (URM) structural models not yet validated with experimental and field data
3. Relative risk values are useful for risk mitigation prioritization. They show the relative impact of production reduction and structural upgrading on the spatial ILPR. Additionally, this methodology provides a tool for further optimization of the structural upgrading program.

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29. Report on structural modelling of non-URM buildings, Mosayk, April 2015
30. URM Modelling and Analysis Cross Validation – Arup, EUCENTRE, TU Delft, Reference 229746_032.0_REP127_Rev.0.03 April 2015.
31. Plan of approach for URM material testing, ARUP, Eucentre and TU Delft, March 2015.
32. Report on v0 Partial Collapse Fragility Functions, Helen Crowley and Damian Grant, October 2014
33. Development of v1 Fragility Functions for Structural Failure, Helen Crowley, Damian Grant and Rein de Vries, April 2015
34. Analysis of deep compaction measurements in the Groningen field, Pepijn Kole, Dirk Doornhof and Antony Mossop, May 2015 (in preparation)
35. SodM, "P500 Engels ref-06-risico-analyse-aardgasbevingen-groningen"
36. TNO, "TNO 2013 R12071, Safety considerations for earthquakes (2013); Steenbergen, R.D.J.M.; Vrouwenvelder, A.C.W.M.; Scholten N.P.M. (ERB)"
37. SodM, Letter on reporting requirements as part of the final decision on the winningsplan, annex "SodM expectations for NAM 1st of May risk report", 31 March 2015, 15046197

Note: For each document the link to the document on the web-site, where the document was issued has been provided. Some of these links might have become obsolete.

For those documents without a current link, a link to a www.namplatform.nl site will be provided in the next update of the report.

Appendix A - Partners

The main partners in the research program into induces 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.
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.
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.
Anthea	Management of the extension of the geophone network.
Rossingh Drilling	Drilling of the shallow wells for the extension of the geophone network.

Appendix B - 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 involved in the research program on induced seismicity in Groningen, led by NAM, are listed below.

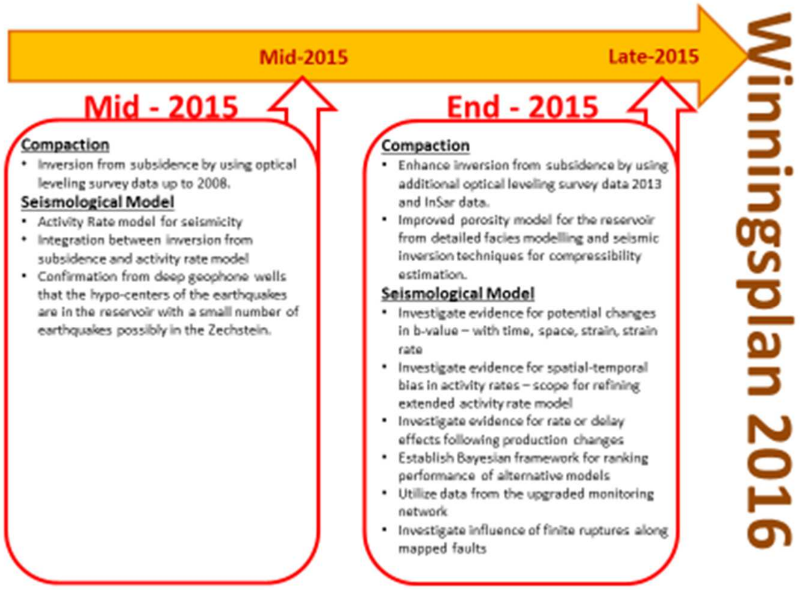
External Expert	Affiliation	Role	Main Expertise Area
Gail Atkinson	Western University, Ontario, Canada	Independent Reviewer	Ground Motion Prediction
Sinan Akkar	Bogazici, University Istanbul	Collaborator	Ground Motion Prediction
Hilmar Bungum	NORSAR, Norway	Independent Reviewer	Ground Motion Prediction
Jack Baker	Stanford University, US	Independent Reviewer	Building Fragility
Julian Bommer	Independent Consultant, London	Collaborator	Ground Motion Prediction and Site Response
Tijn Berends	Student; University Groningen	Independent Reviewer	Site Response and Shallow Geological Model
Loes Buijze	University Utrecht	Collaborator	Rock Physics / Core Experiments
Fabrice Cotton	GFZ Potsdam, Germany	Independent Reviewer	Ground Motion Prediction
Helen Crowley	Independent Consultant, Pavia	Collaborator	Building Fragility and Risk
John Douglas	University of Strathclyde, UK	Independent Reviewer	Ground Motion Prediction
Ben Edwards	University Liverpool	Collaborator	Ground Motion Prediction
Paolo Franchin	University of Rome “La Sapienza”	Independent Reviewer	Building Fragility
Damian Grant	ARUP	Collaborator	Building Fragility
Michael Griffith	University of Adelaide, Australia	Independent Reviewer	Building Fragility
Russel Green	Virginia Tech, USA	Collaborator	Liquefaction Model
Brad Hager	Massachusetts Institute of Technology	Independent Advisor	Geomechanics
Curt Haselton	California State University, US	Independent Reviewer	Building Fragility
Rien Herber	University Groningen	Independent Facilitator	General
Rob van der Hilst	Massachusetts Institute of Technology	Independent Advisor	Geomechanics
Jason Ingham	University of Auckland	Independent Reviewer	Building Fragility
Adriaan Janszen	Exxonmobil	Independent Reviewer	Shallow Geological Model
Mandy Korff	Deltares	Collaborator	Site Response, liquefaction and Shallow Geological Model

Table continued:

External Expert	Affiliation	Role	Main Expertise Area
Marco de Kleine	Deltares	Collaborator	Site Response and Shallow Geological Model
Pauline Kruiver	Deltares	Collaborator	Site Response and Shallow Geological Model
Florian Lehner	University of Vienna	Independent Reviewer	Rock Mechanics
Ger de Lange	Deltares	Collaborator	Site Response and Shallow Geological Model
Nico Luco	United States Geological Survey	Independent Reviewer	Building Fragility
Eric Meijles	University Groningen	Independent Reviewer	Shallow Geological Model
Guido Magenes	EUCentre Pavia	Collaborator	Building Fragility
Ian Main	University Edinburgh	Independent Reviewer	Seismogenic Model / Statistics
Piet Meijers	Deltares	Collaborator	Site Response, liquefaction and Shallow Geological Model
Michail Ntinalexis	Independent	Collaborator	Ground Motion Prediction
Barbara Polidoro	Independent Consultant, London	Collaborator	Ground Motion Prediction
Matt Pickering	Student; Leeds University	Collaborator	Seismic Event Location
Rui Pinho	University Pavia	Collaborator	Building Fragility
Adrian Rodriguez - Marek	Virginia Tech, USA	Collaborator	Site Response Assessment
Emily So	Cambridge Architectural Research Ltd	Collaborator	Injury model
Robin Spence	Cambridge Architectural Research Ltd	Collaborator	Injury model
Chris Spiers	University Utrecht	Collaborator	Rock Physics / Core Experiments
Joep Storms	TU Delft	Independent Reviewer	Shallow Geological Model
Jonathan Stewart	UCLA, California, USA	Independent Reviewer	Ground Motion Prediction
Peter Stafford	Imperial College London	Collaborator	Ground Motion Prediction
Peter Styles	Keele University	Independent Advisor	Geomechanics
Tony Taig	TTAC Limited	Collaborator	Risk
Dimitrios Vamvatsikos	NTUA, Greece	Independent Reviewer	Building Fragility
Brecht Wassing	TNO	Collaborator	Geomechanics

Table continued:

External Expert	Affiliation	Role	Main Expertise Area
Ivan Wong	AECOM, Oakland, USA	Independent Reviewer	Ground Motion Prediction
Stefan Wiemer	ETHZ Zurich	Independent Advisor	Geomechanics
Teng Fong Wong	University Hong Kong	Independent Reviewer	Rock Mechanics
Bob Youngs	AMEC, Oakland, USA	Independent Reviewer	Ground Motion Prediction
Mark Zoback	Stanford University	Independent Reviewer	Seismological Model and Geomechanics



Mid - 2015

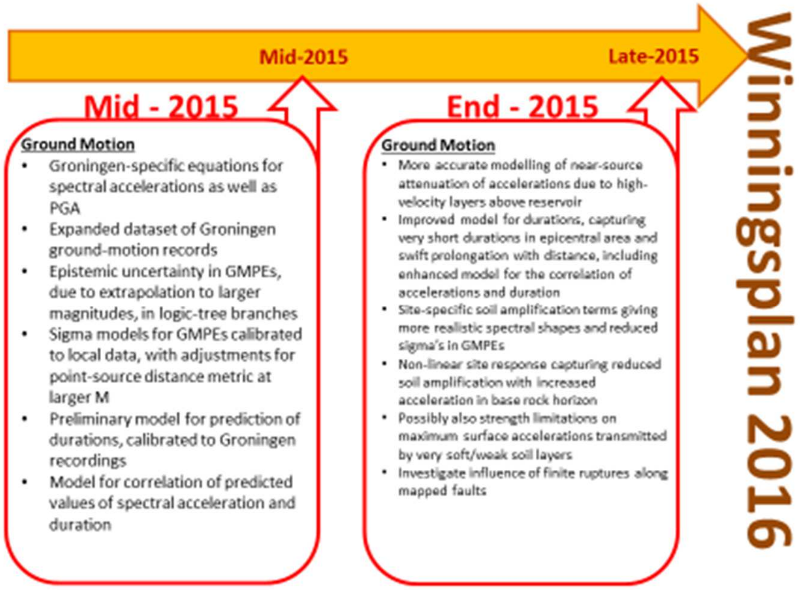
Compaction
- Inversion from subsidence by using optical leveling survey data up to 2008.

Seismological Model
- Activity Rate model for seismicity
- Integration between inversion from subsidence and activity rate model
- Confirmation from deep geophone wells that the hypo-centers of the earthquakes are in the reservoir with a small number of earthquakes possibly in the Zechstein.

End - 2015

Compaction
- Enhance inversion from subsidence by using additional optical leveling survey data 2013 and InSar data.
- Improved porosity model for the reservoir from detailed facies modelling and seismic inversion techniques for compressibility estimation.

Seismological Model
- Investigate evidence for potential changes in b-value – with time, space, strain, strain rate
- Investigate evidence for spatial-temporal bias in activity rates – scope for refining extended activity rate model
- Investigate evidence for rate or delay effects following production changes
- Establish Bayesian framework for ranking performance of alternative models
- Utilize data from the upgraded monitoring network
- Investigate influence of finite ruptures along mapped faults

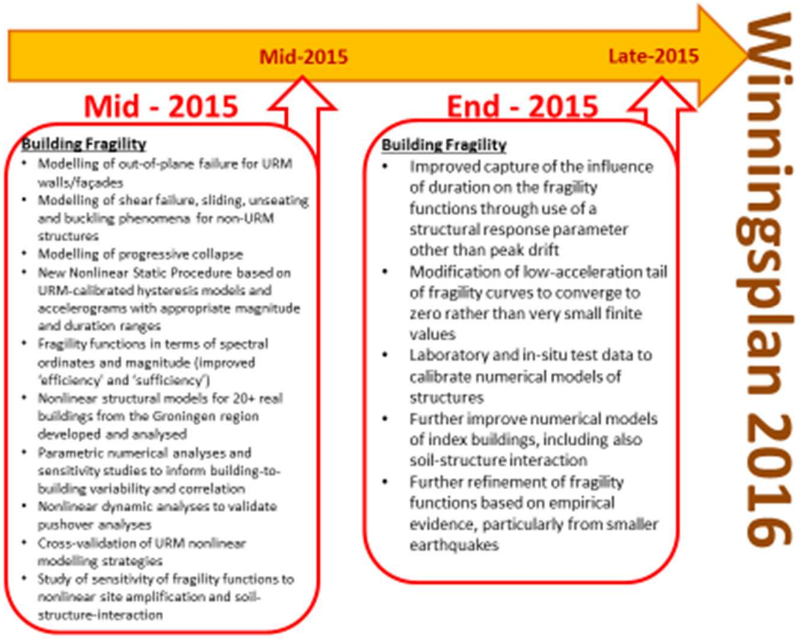


Mid - 2015

Ground Motion
- Groningen-specific equations for spectral accelerations as well as PGA
- Expanded dataset of Groningen ground-motion records
- Epistemic uncertainty in GMPEs, due to extrapolation to larger magnitudes, in logic-tree branches
- Sigma models for GMPEs calibrated to local data, with adjustments for point-source distance metric at larger M
- Preliminary model for prediction of durations, calibrated to Groningen recordings
- Model for correlation of predicted values of spectral acceleration and duration

End - 2015

Ground Motion
- More accurate modelling of near-source attenuation of accelerations due to high-velocity layers above reservoir
- Improved model for durations, capturing very short durations in epicentral area and swift prolongation with distance, including enhanced model for the correlation of accelerations and duration
- Site-specific soil amplification terms giving more realistic spectral shapes and reduced sigma's in GMPEs
- Non-linear site response capturing reduced soil amplification with increased acceleration in base rock horizon
- Possibly also strength limitations on maximum surface accelerations transmitted by very soft/weak soil layers
- Investigate influence of finite ruptures along mapped faults

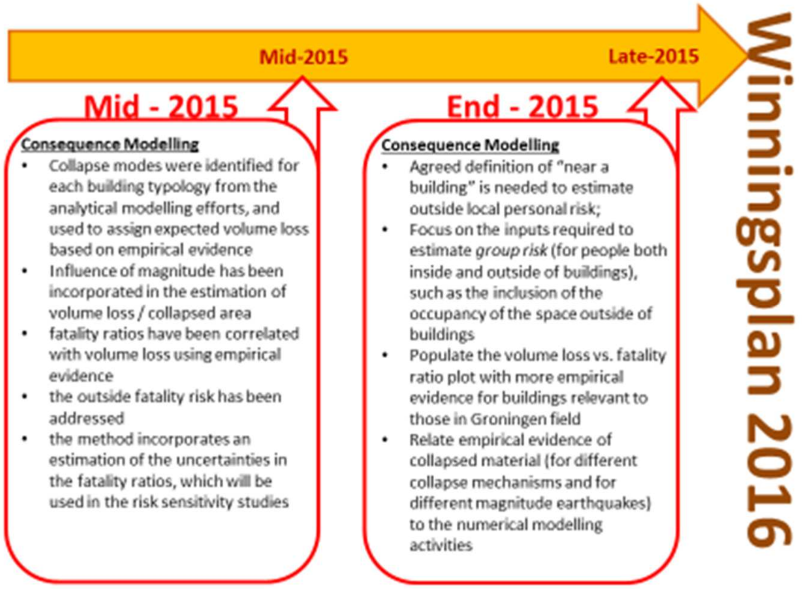


Mid - 2015

Building Fragility
- Modelling of out-of-plane failure for URM walls/façades
- Modelling of shear failure, sliding, unseating and buckling phenomena for non-URM structures
- Modelling of progressive collapse
- New Nonlinear Static Procedure based on URM-calibrated hysteresis models and accelerograms with appropriate magnitude and duration ranges
- Fragility functions in terms of spectral ordinates and magnitude (improved 'efficiency' and 'sufficiency')
- Nonlinear structural models for 20+ real buildings from the Groningen region developed and analysed
- Parametric numerical analyses and sensitivity studies to inform building-to-building variability and correlation
- Nonlinear dynamic analyses to validate pushover analyses
- Cross-validation of URM nonlinear modelling strategies
- Study of sensitivity of fragility functions to nonlinear site amplification and soil-structure-interaction

End - 2015

Building Fragility
- Improved capture of the influence of duration on the fragility functions through use of a structural response parameter other than peak drift
- Modification of low-acceleration tail of fragility curves to converge to zero rather than very small finite values
- Laboratory and in-situ test data to calibrate numerical models of structures
- Further improve numerical models of index buildings, including also soil-structure interaction
- Further refinement of fragility functions based on empirical evidence, particularly from smaller earthquakes

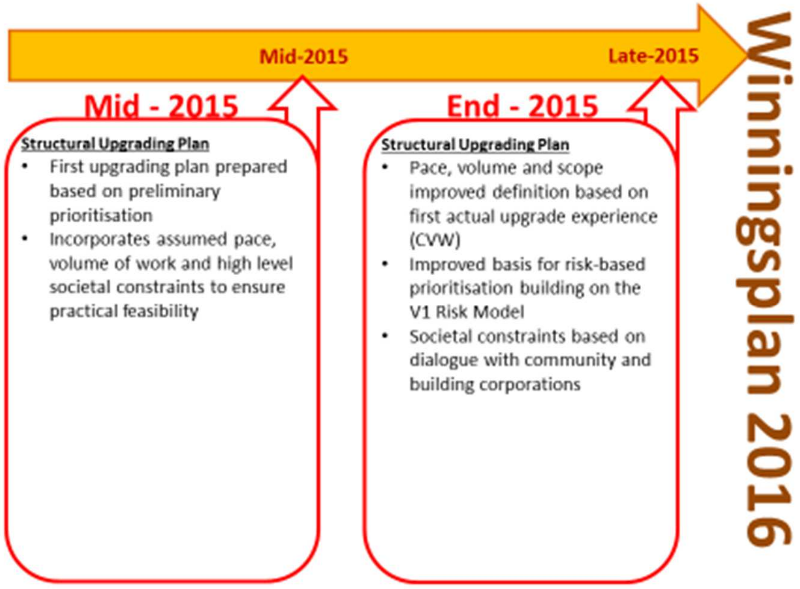


Mid - 2015

Consequence Modelling
- Collapse modes were identified for each building typology from the analytical modelling efforts, and used to assign expected volume loss based on empirical evidence
- Influence of magnitude has been incorporated in the estimation of volume loss / collapsed area
- fatality ratios have been correlated with volume loss using empirical evidence
- the outside fatality risk has been addressed
- the method incorporates an estimation of the uncertainties in the fatality ratios, which will be used in the risk sensitivity studies

End - 2015

Consequence Modelling
- Agreed definition of "near a building" is needed to estimate outside local personal risk;
- Focus on the inputs required to estimate *group risk* (for people both inside and outside of buildings), such as the inclusion of the occupancy of the space outside of buildings
- Populate the volume loss vs. fatality ratio plot with more empirical evidence for buildings relevant to those in Groningen field
- Relate empirical evidence of collapsed material (for different collapse mechanisms and for different magnitude earthquakes) to the numerical modelling activities



Mid - 2015

Structural Upgrading Plan
- First upgrading plan prepared based on preliminary prioritisation
- Incorporates assumed pace, volume of work and high level societal constraints to ensure practical feasibility

End - 2015

Structural Upgrading Plan
- Pace, volume and scope improved definition based on first actual upgrade experience (CVW)
- Improved basis for risk-based prioritisation building on the V1 Risk Model
- Societal constraints based on dialogue with community and building corporations