ANALYSIS METHODS FOR ASSESSING 23,000 NON-SEISMICALLY DESIGNED BUILDINGS AGAINST AN INDUCED SEISMIC HAZARD

Han KRIJGSMAN¹, Joe WHITE², Rudi ROIJAKKERS³

ABSTRACT

Since the early 1990’s induced seismic events have been occurring in the province of Groningen, located in the northern Netherlands. This has been attributed to ongoing conventional gas extraction from the Groningen gas field, which extends below the region. To date the largest event has been 3.6Mw, with the maximum possible event believed to be approximately 5.0Mw. To date the focus point of every event has been directly above the gas field, at a depth of around 2-3km. Ground level accelerations can therefore be of disproportionately significant magnitudes – the most recent hazard model suggests a PGA of approximately 0.40g (2,475 yr Near Collapse limit state, 0.24g 475y) in the worst affected area. However, the associated displacement demands are relatively small (40-90mm) and event durations are short (< 10 seconds). Groningen has not historically been a seismically active area, as such the regions building stock has not been designed to withstand seismic demands. Many buildings have been constructed using unreinforced masonry (URM) walls as the primary load bearing elements. In 2016, the Dutch Government implemented a strategy to assess, and where necessary strengthen, 23,000 buildings at the centre of the affected area within the following 5 years. Dutch engineers, with help from international seismic experts, have been working in earnest on this task. A key issue has and will continue to be selecting the best method of analysis to provide appropriately accurate results for the specific hazard and specific building types – all within a fast-paced assessment programme. Consideration of the various analysis methods for this purpose is the focus of this paper. A range of options have been explored to date, from detailed non-linear time history analysis (NLTHA) to simplistic modal response analysis (MRSA). However, non-linear push-over (NLPO) analysis has emerged as the most pragmatic option.

Keywords: Induced seismicity; Groningen; URM; push-over;

1. INTRODUCTION

The Netherlands has not historically been a seismically active region. The only exception to this is the southern tip of the country where the Roer Valley Rift System is active (Camelbeeck et al., 1994), most recently causing the 5.4Mw Roermond Earthquake in 1992. Standard design and construction practices in The Netherlands do not consider seismicity. For example – Eurocode EN-1998 (also known as ‘EC8’) has not been adopted within the Dutch Building Act, nor is a National Annex or a Dutch translation of EC8 available.

Since the early 1990’s, induced seismic events have been occurring in the province of Groningen, located in the northern Netherlands. This has been attributed to ongoing conventional gas extraction from the Groningen gas field, one of the largest natural gas fields in the world, which extends below the province. To date, the focus point of every event has been directly above the gas field, at a depth of 2-3km. Thus, whilst the events are low magnitude, resulting effects on the ground surface can be larger than would typically be associated with tectonic events of similar magnitude.

The frequency and magnitude of events has been growing steadily over the past 25 years – refer to Figure 1. The risk of building damage and/or loss of life has been sufficient to cause the Dutch

¹Senior Adviseur, Ir. RO, BORG, The Netherlands, h.krijgsman@borggroningen.nl
²Senior Adviseur, PE CPEng MIPENZ CEng MIstructE, BORG, The Netherlands, j.white@borggroningen.nl
³Senior Adviseur, Ir. RO, BORG, The Netherlands, r.roijakkers@borggroningen.nl
government to implement a wide ranging building assessment and strengthening programme. Starting in 2016, the programme aims to assess, and where necessary strengthen, approximately 23,000 buildings located at the centre of the affected area within 5 years. The Dutch engineering community, in collaboration with international experts, have been working in earnest on this task.

![Figure 1. Number of earthquakes per year in the Groningen region with magnitude > 2.0](image)

A key issue for the engineering community to consider has and will continue to be selecting the best method of structural analysis. The following list highlights the main points informing the consideration of analysis methods.

- Understanding of the hazard has evolved rapidly – resulting in several revisions to the code of practice within a short period of time. It is likely this will continue in the near future. As a result, buildings may need to be re-analysed in the future, preferably quickly. A summary of the codified hazard evolution is provided in Section 2.
- The induced events observed to date have defined a hazard model that suggests significant acceleration demands are possible. However, the associated displacement demands are relatively low, and event durations are relatively short (when compared to natural events) – further exploration of these items is provided in Section 3.
- The Groningen region building stock mostly comprises low-rise unreinforced masonry (URM) structures, often with timber diaphragms. Foundations, either shallow or piled, have not been designed/installed with uplift or lateral demands in mind. Further detail on typical construction of the building stock is provided in Section 4.
- Prior to recent events, the Dutch engineering community did not have significant seismic design or analysis knowledge. Collectively a steep learning curve is being pursued with impressive results. However, it must be recognised that there is a finite amount of engineers available with the necessary skill set for detailed and complex analyses.
- In order to meet the government target of 23,000 buildings in 5 years a fast rate of progress is necessary. Detailed analyses with long build and run times are unlikely to result in the necessary rate of progress.

2. AN EVOLVING CODIFIED HAZARD

In July 2012 the Royal Netherlands Meteorological Institute (KNMI) published a report (Dost et al. 2012) summarising an investigation of the induced seismicity in the Groningen region. KNMI concluded the seismicity rate to be a stationary process with a maximum expected magnitude 3.9Mw. Following the 3.6Mw Huizinge event in August 2012, one month after this publication, it was
recognised that the area could be prone to events with larger magnitudes than previously thought. More importantly, the increased rate of seismicity implied a breakdown of the stationary assumption in the seismic hazard assessment (Dost et al. 2013).

The first document defining the hazard for buildings in the province was referred to as ‘The Interim Advice’ (NEN 2014), which was published in May 2014. Only 10 pages long, it mainly comprised a hazard map with PGA values, an acceleration spectrum shape (specific to the Groningen region) and definition of a few factors to be used in conjunction with EC8.

In February 2015 the ‘Interim Advice’ was replaced by a preliminary Code of Practice (Nederlandse Praktijkrichtlijn or NPR, with the number 9998 (NEN 2015)). The hazard map from the ‘Interim Advice’ was effectively maintained, while the spectrum shape was changed. Much additional information was provided though, such as a Dutch translation of the most relevant clauses from EC8, and confirmation of factors that must be published in an EC8 National Annex.

In December 2015 a final version of the NPR9998 was published (NEN 2015). This document redefined the hazard, with significant changes to PGA values. The spectral shape became dependent on the PGA at a reference level of 30m minus surface level. Displacement demands in the central area increased from maximum 30-40mm to maximum 130-150 mm, while the PGA value in the same location reduced from 0,42g (475y surface level) to 0,36g (475y 30m- level).

In June 2017, another version of the NPR9998 was published (preliminary, for comments only (NEN 2017)), again with a very different hazard – PGA values have reduced and the spectral shape has changed again. However, displacement demands have significantly reduced to similar levels given in the February 2015 version. The underlying hazard model assumes a maximum possible event of 5,0Mw (NAM 2016). Figure 2 shows PGA values across the region, with a 475 year return period, again at surface level:

![PGA values across the region](image)

**Figure 2. Groningen PGA values with a return period of 475 years per June 2017 NPR9998**

The NPR9998 is still a code of practice and not a National Annex. This means that the code is still not part of the Dutch Building Act (situation December 2017), and as the building industry is not obliged to meet its requirements. It is not clear if or when this will change.
3. HAZARD CHARACTERISTICS AND DEFINITION

The codified hazard in the Groningen area has been based upon ground motions that have occurred during induced earthquakes to date. As with a tectonic scenario, achieving an appropriate level of accuracy in the definition of the hazard is key. Underestimation could lead to insufficient levels of safety, whereas overestimation could lead to significant costs and unnecessary impacts on society. Following the Huizinge earthquake, a research programme was set up that is still ongoing. The aim has been to extrapolate data from the low magnitude (< 3.6Mw) events to date, to the predicted maximum magnitude event (5.0Mw).

In June 2017 a report describing ‘Version 4’ of the Groningen ‘Ground Motion Model’ (GMM) was published (Bommer et al. 2017). This GMM predicts amplitudes and durations of ground motions. An important feature of the GMM is the explicit inclusion of field-specific non-linear site amplification functions. The top layers of soil across the Groningen region are typically soft, which can cause local amplification or de-amplification of ground motions.

The non-linearity of the soft soils is dependent on the magnitude of ground acceleration. Figure 3 shows results from non-linear soil column analyses, comparing the input PGA and the surface PGA. Each individual point represents a single analysis result using the ‘Best Estimate’ soil profile. Generally de-amplification has been observed for input PGAs higher than about 0.15g.

![Non-linear response curve for PGA](Vasileiadis et al. 2015)

Amplification also depends upon the spectral content of accelerations. Generally de-amplification occurs in the short period band (spectral ratio < 1.0) whilst amplification is evident in the long period band (spectral ratio > 1.0) – refer to Figure 4. This causes the definition of a response spectra at surface level to be non-linear.
In the June 2017 version of the NPR, Version 4 of the GMM model has been implemented. Rock layer ground motions have been used to generate dynamic inputs for a large number of soil column analyses, covering the entire region. Over 6,000 probabilistic soil column analyses have been captured in one database. Using a web based application (NEN 2017), engineers are able to access the database by defining a given location in the Groningen region. The database provides a site specific response spectrum at surface level for that location.

The hazard, as defined, leads to a maximum PGA (for a 2,475 year return period) of 0.40g. The spectral shape varies per return period due to the non-linear soil characteristics described previously. See Figure 5 for an example spectrum:

When the response spectrum is expressed in terms of displacements another distinctive outcome can be seen, refer to Figure 6.
Displacement demands are low relative to a typical tectonic hazard; approximately 40-90mm for the worst affected areas.

Duration is a key factor in the performance of structures constructed from unreinforced masonry (URM), where degradation of both strength and stiffness under dynamic loading often occurs (Bommer et al. 2004). As such, the hazard definition must take this issue into account. Since the Groningen hazard is predicted and extrapolated from small events, a predictive equation is required for the chosen definition of the ground-motion duration.

The duration of Groningen induced events observed to date have been shorter than typical tectonic events. Furthermore, there has been an inverse relationship between duration and the magnitude of ground acceleration – i.e. large magnitude ground accelerations have had a short duration. This relationship is shown in Figure 7, which plots the horizontal PGA of ground motion records considered within Version 4 of the GMM, against their significant duration. There is a clear pattern – higher levels of acceleration (> 50 cm/s²) are associated with short durations (< 1.0 seconds), whereas all longer durations (> 6.0 seconds) are associated with low amplitudes (< 5 cm/s²).
Figure 7 also shows that records with high PGA / short duration, are typically obtained at epicentral distances of less than 4 km, whereas the long-duration, low-amplitude records are generally from stations at epicentral distances of at least 8 km. Durations in the Groningen region have always presented features that are not typically encountered in other areas. The observations from Figure 7 are consistent with the current hypothesis that waves are subjected to multiple refractions and reflections. This is thought to relate to the effect from the particular velocity structure of the Groningen gas field. The net effect of these phenomena is that durations in the Groningen region appear to increase rapidly with distance within the first several kilometres from the source.

To summarize what sets Groningen apart from tectonic hazards is the high acceleration demand, low displacement demand and short duration. Together with the building stock, that is not designed for seismic demands, this forms the basic challenge to find the most effective assessment approach.

4. GRONINGEN BUILDING STOCK

Although the province of Groningen is mainly agricultural and not densely populated relative to the rest of the Netherlands, worldwide it is one of the most populated regions above a natural gas field. The total number of buildings possible at risk in the region is more than 250,000, of which 150,000 are regularly occupied by people. Over 80% of buildings are residential, with the majority being terraced or semi-detached, which are relatively repetitive (NAM 2015). Refer to Figure 8.

![Building stock Groningen](image)

Figure 8. Composition of the building stock in the Groningen region

It is estimated that over 90% of the ‘at risk’ buildings are constructed with unreinforced masonry (URM) walls (NAM 2015), in combination with either reinforced concrete or timber floors. The URM can either be clay or calcium silicate bricks, or in more modern structures calcium silicate block. Refer to Figure 9.
Houses typically have pitched roofs constructed of timber framing covered with clay roof tiles. Walls are typically double leaf, each being 100mm thick, with a 50-100mm cavity between. Large window openings at ground level on both front and back façades are common, almost fully omitting a lateral system in the longitudinal direction. Refer to Figures 10 and 11.

Due to the prevalence of soft soils, foundations are often piled – either with timber or lightly reinforced concrete piles, or even in combination with a small concrete extension on top of the timber pile. Shallow strip foundations constructed from either masonry or concrete are also encountered. With either shallow or piled foundations, the common theme is that uplift was not a consideration in their original design, nor designed for considerable lateral forces.
5. NLTHA (MICRO MODELLING)

In the early stages of understanding the hazard – before the government led assessment programme began – engineers investigating the problem began modelling structures using non-linear time history analysis (NLTHA) in order to determine the capacity in the most accurate way, in search for maximum capacity to meet the high demands. Specifically, these models have followed a ‘micro modelling’ approach where each component is formed by a fine mesh of finite elements. Constitutive material properties are assigned to these finite elements. Interfaces between components and/or finite elements should also be defined. Both explicit and implicit solvers have been utilised. A 30m deep soil block has typically also been modelled below buildings, extending hundreds of metres in each orthogonal plan direction. This is the most detailed, most complex, and (typically) most accurate method available.

A micro NLTHA approach offers several key benefits:

- The time dependence of the analysis allows the short duration and transient nature of the ground motions to be taken into account – therefore a realistic representation of strength/stiffness degradation and hysteretic damping is possible.
- NLTHA evaluates structures on the basis of strains and rotations, which are effectively displacement, so the specific nature of the Groningen hazard (i.e. low displacement demand) can be captured.
- Inclusion of a soil block allows soft soil amplification/de-amplification to be modelled as well as all components of soil structure interaction.
- The fine mesh of finite elements provides a detailed set of results with localised damage illustrated.
- Explicit modelling in particular allows collapse of the structure to be evaluated directly.

However, these benefits come at a price:

- Significant time is required to build and run these models. For example, the run time for a single family house would typically be > 8 hours for one ground motion record (where at least 7 records are needed by code provision).
- Large amounts of data are produced, and results are so detailed it is difficult (perhaps impossible) to verify by simple analysis such as hand calculations.

Furthermore, it has to be questioned whether such detailed modelling is appropriate for structures that are often poorly constructed. As engineers initially searched for the ‘most accurate capacity’ it was believed that literally all structural elements must be modelled. In some cases this has led to models with a ‘brick-by-brick’ level of detail, or where even the nails in a timber floor are included in a model (Willford, 2015).

Time considerations were initially not really relevant as accuracy was the only goal. However, in the more recent context of rapidly assessing 23,000 buildings, model build and run times certainly have become relevant. Also, engineers need to be able to quickly gain confidence in a given model by using more approximate methods – which is not really possible with a micro NLTHA approach.

The ability to run sensitivity analyses is also important to consider. Detailed models can be disproportionately sensitive to certain material properties or modelling parameters so it is essential this is assessed. Long model run times inevitably inhibit the ability to do so. Inclusion of a soil block in the model can be meaningless unless a range of soil properties are considered. The NPR9998 demands the use of upper- and lower bound soil properties, all with a set of at least 7 signals.

For these reasons, micro NLTHA has generally been found to be impractical for the fast paced Groningen assessment programme.
6. MRSA

In reaction to the issues described with micro NLTHA, engineers have turned toward modal response spectrum analysis (MRSA). In terms of computer based analysis, MRSA is at the opposite end of the complexity scale to micro NLTHA. MRSA is typically the most widely employed method of analysis amongst seismic engineers due to its versatility and relative simplicity.

With regard to the Groningen situation, it offers the following benefits:

- Widely available and ‘simple’ software can be used that is already prevalent in the Netherlands, such as SCIA Engineer.
- Construction of the analysis model is very similar to that which Dutch engineers are already familiar with from static analysis – node, line and shell elements with elastic material properties and evaluation of those elements based on forces or stresses.
- Model build and run times are short – particularly if masses are lumped to diaphragms.
- As a linear method, MRSA can be executed by engineers with relatively limited understanding or experience with seismic theory – albeit with reasonable oversight.
- The method can be applied to virtually any structural geometry or arrangement.
- Torsion and other irregular modes of vibration often form part of a buildings response due to irregular layouts. MRSA is a dynamic method, so this behaviour is accounted for – this would not be the case with an equivalent static method that is typically completed by hand.

The immediate benefit of employing MRSA has been an increase in progress compared to utilising micro NLTHA. However, the results from analyses are more onerous, and there are concerns regarding the accuracy of results:

- MRSA cannot capture the compression-only properties of URM and soil. Therefore, the predominant rocking response of walls and foundations is suppressed in MRSA. A ‘behaviour factor (q)’ can be used to account for rocking, but there is limited guidance for this in either the NPR 9998 or EC8/EC6. Also, the use of a q factor for this purpose becomes problematic when there is a mixture of walls expected to rock and walls expected to yield or rupture in shear, which is common in Groningen. This issue can fundamentally undermine the accuracy of MRSA.
- MRSA is a force based method, and thus structures are primarily evaluated on forces and/or stresses. As discussed – acceleration or force demands are relatively high, therefore MRSA is conservative compared to methods that consider displacements, which are relatively low.
- In many cases Groningen buildings do not have dominant modes of vibration – rather, mass participation is spread sparsely across hundreds of modes. Lumping of mass at diaphragms can reduce this effect, but regardless the large amount of ‘secondary’ modes without any identifiable ‘primary modes’ can undermine the validity of CQC (or SRSS) modal addition.
- Many buildings in Groningen are 1-2 storey, with periods in the ‘upward slope’ range between T=0 and the constant acceleration branch (‘plateau’) of the spectrum. It is likely periods will lengthen during the course of an event due to stiffness degradation and soil flexibility. Thus loads will likely increase. This effect cannot be modelled in MRSA.
- Earthquakes in the Groningen area are expected to have a short duration. The response spectrum used to define seismic loading in MRSA does not include consideration of duration of the seismic loading. Consequently MRSA is unable to capture the benefits of short duration events which can be significant for the seismic performance of degrading systems i.e. unreinforced masonry buildings.

In summary – for the specific hazard and construction types in Groningen, MRSA provides an answer for a given building in a reasonable period of time, but that answer can have limited accuracy and is often conservative.
7. MACRO NLPO AND NLTHA

In the previous two sections, methods at opposing ends of the complexity and time scale have been discussed. Over the past year the Groningen engineering community and in particular BORG, have been exploring the use of non-linear push-over (NLPO) analysis as a compromise. Specifically, a ‘macro modelling’ approach is being pursued, where building components are represented by single finite elements. This approach offers several benefits:

- Model build and run times are more practical – the run time for a single family house is < 5 minutes. This allows many sensitivity analyses to be run. So whilst macro modelling can compromise a small percentage of accuracy in a single analysis, the impact of major variations in material properties can be evaluated across several analyses, thus leading to an increased level of accuracy overall.
- Demand and capacity are separated in NLPO. So if/as the Groningen hazard continues to evolve, models can be revisited and re-assessed far quicker than with other methods.
- Structures are evaluated on the basis of displacements rather than forces, thus the specific nature of the induced hazard (i.e. low displacement demand) can be accounted for.
- Gap elements placed between component sized finite elements capture the compression-only capacity of URM and soil, thus rocking behaviour can be evaluated.
- Scaling of the response spectrum using codified equations can account for soil structure interaction effects via the calculated target displacement.
- Results can be approximately verified by simpler methods such as hand calculations.

There are however some limitations to NLPO that must be considered:

- NLPO was not intended to be applied to buildings without dominant modes, such as those with flexible diaphragms. In such situations appropriate load patterns should be applied that are synonymous with dominant mode behaviour.
- Irregular structures must also be modelled with MRSA to determine torsional behaviour and associated increases in displacement demand – effectively displacement demands should be calibrated with an MRSA.
- The duration of events is not taken into account – therefore strength and stiffness degradation are likely over-estimated as peak demands are in reality only transient.
- Similarly, hysteretic damping can only be estimated and applied to the response spectrum. Potentially, the net effect of damping could quickly be over-estimated, when degradation effects are limited or rocking behaviour is dominant. Refer to Figure 12:

![Figure 12. ADRS-plot with push-over curves: type A building with single piers, mainly rocking failure behaviour; type B building with flange effects, diagonal tension dominant failure](image-url)
Where these issues are deemed to be significant and either leading to conservatism or inaccuracy, most software that can run an NLPO analysis can also run NLTHA with only small modifications to the model. The model run times for macro NLTHA models is significantly lower than for micro NLTHA, with a single family home taking approximately 10 - 20 mins.

8. CONCLUSIONS

The ongoing induced seismicity situation in Groningen represents a unique challenge. The hazard imposes different demands upon building compared to tectonic earthquakes – for which most seismic analysis tools were conceived. The scale and urgency of the assessment programme is perhaps uniquely fast-paced, and must be tackled by an engineering community that is ‘learning on the job’.

NLTHA following a micro modelling approach provides the greatest level of accuracy, but the time frames required and inability to verify results by hand calculations makes it impractical. MRSA is much simpler and quicker, but the results are too conservative and can have questionable accuracy. Macro NLPO offers the best compromise of all issues at hand, and can quickly be converted to a macro NLTHA when necessary.

9. REFERENCES