Annexes G and H of the Dutch Seismic Practice Directive NPR9998

M.J. Fox, C.A. Muir, P.L. Beazley, W.Y. Kam, R.D. Jury & R.D. Sharpe
Beca Ltd, New Zealand

A.C. Baird
Beca (Thailand) Co. Ltd., Thailand

ABSTRACT

The province of Groningen in the north-east of the Netherlands is currently experiencing a period of induced seismicity as the result of sustained gas extraction from an underlying gas field. These anthropogenic earthquakes have triggered the need to assess, and where necessary retrofit, the relatively vulnerable building stock. As the Netherlands is not historically a seismic country, there was a lack of seismic guidelines and hence the practice directive NPR9998 was developed to meet the needs of this rather unique situation. A key part of NPR9998 is the Annexes G and H, which enable engineers to undertake Nonlinear Pushover Analysis and Nonlinear Kinematic Analysis, respectively. Both annexes are tailored towards expedited assessments and are based on section C8 of New Zealand's Technical Guidelines for (seismic) Engineering Assessments.

The paper starts with an overview of the induced seismicity situation in Groningen and the need to assess and strengthen houses. The development of NPR9998 Annexes G and H is then presented, with a specific focus on how it addresses societal needs in the Groningen region. Following this, discussion is provided around differences to the New Zealand Guidelines before looking into the more innovative aspects of the annexes' development, which include comparison against shake table tests and calibration to the results of detailed seismic risk analyses.

1 INTRODUCTION

In response to induced seismicity in the province of Groningen in the Netherlands, the Dutch Standards Committee developed the Dutch (seismic) Practice Directive NPR9998 (NEN 2018). Within NPR9998 are the Annexes G and H, which enable engineers to perform Nonlinear Pushover Analysis and Nonlinear Kinematic Analysis, respectively. Both annexes were developed from the New Zealand Technical Guidelines for (seismic) Engineering Assessments (MBIE 2017) with additional research and development from a Dutch task group. Useful insights can thus be gained from comparing the Dutch and New Zealand approaches.

The induced seismicity case in Groningen is rather unique and so some background on the situation is first provided before moving onto an overview of NPR9998 and the development of Annexes G and H. This is followed by a comparison of some of the key aspects of the Dutch and New Zealand approaches and then finally discussion on the calibration of Annex G to experimental test results.

2 INDUCED SEISMICITY IN GRONINGEN

The Dutch province of Groningen, in the north-east of the Netherlands, has experienced an increased level of seismic activity over the last two decades as the result of sustained gas extraction from the Groningen gas field. The Groningen gas field, shown in Figure 1a, was discovered in 1959 and is one of the largest gas fields in the world, with initial reserves estimated at ~2,900 billion cubic metres (Jager & Visser 2018). The gas produced from the field services all of the Netherlands' domestic needs, as well as being exported to Belgium and Germany.

It is widely accepted that the earthquakes occurring in the region are induced by gas production activities. As the field is depleted, compaction of the reservoir sandstone occurs. This in turn causes additional stress on existing critically stressed faults that transect the reservoir (Bourne *et al.* 2014). The first earthquake recorded in the region was a M2.4 event in 1991; however, it was the M3.6 Huizinge Earthquake in 2012 that triggered a significant public response. Following the 2012 Huizinge Earthquake, the Dutch State Supervision of Mines (SodM) published a report concluding that continued gas extraction would lead to more frequent and larger magnitude earthquakes than previously experienced. This led to considerable concern amongst the local population (van der Voort & Vanclay 2015) and subsequent efforts to address the earthquake issue. On the technical front these efforts include: (i) damage assessment and repair, (ii) development of seismic hazard and risk models, (iii) experimental testing campaigns (e.g. Graziotti *et al.* 2018), (iii) development of methodologies for rapid seismic assessment, and (iv) publication of national seismic guidelines in the form of the Dutch practice directive NPR9998.

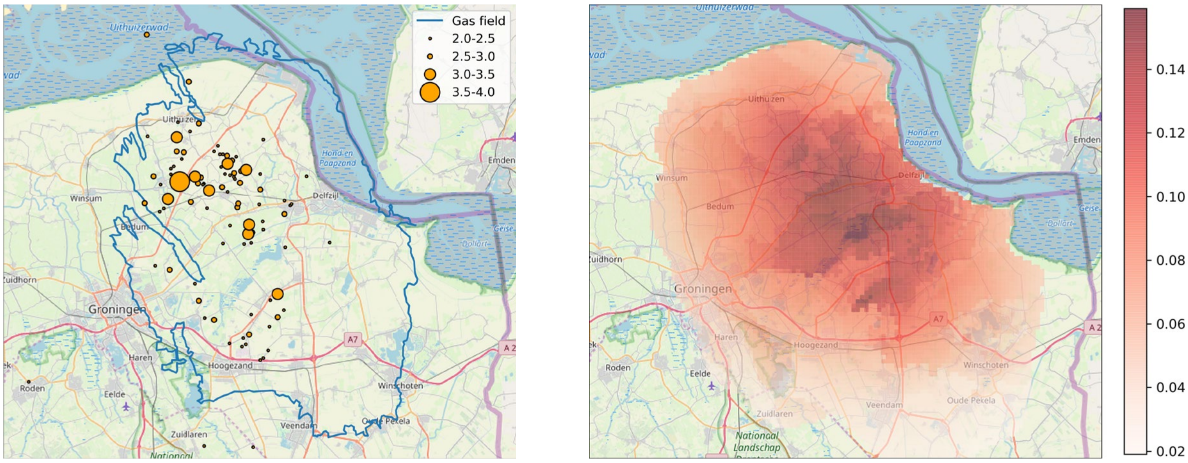
To understand the seismic setting in Groningen, it is helpful to compare the seismic hazard to that of New Zealand. Since 2012, the Royal Netherlands Meteorological Institute (KNMI) has produced six different seismic hazard maps, which reflect changes in scientific understanding of the seismicity as well as the impact that changing gas production scenarios have on the predicted seismicity. Figure 1b shows the hazard map in use as at November 2018, where the maximum peak ground acceleration across the region for a 475 year return period is around 0.16 g. This is comparable to Hamilton in terms of intensity; however, it should be acknowledged that there are potentially differences in terms of other predicted earthquake characteristics, such as duration. In 2019 the decision was made to cease gas production by 2022, which is predicted to significantly reduce the seismic hazard as the production rate decreases.

3 NPR9998 AND ANNEXES G & H

3.1 Overview

NPR9998 is the Dutch practice directive for "Assessment of structural safety of buildings in case of erection, reconstruction, and disapproval – Induced earthquakes – Basis of design, actions and resistances (sic)," which is published by the Dutch Standards Committee. The first version of NPR9998 was published in 2015 and then revised versions were published in 2017 and 2018. The rapid rate of revisions reflects the ongoing improvement in the understand of the seismic response of typical Dutch houses. However, it could also be argued that it is a result of making sure the latest guidance was available to engineers, even if imperfect and incomplete, rather than withholding it until completion.

An alternative to NPR9998 could have been for the Netherlands to adopt the existing Eurocode 8 (CEN 2004, 2005) into its national building laws, and indeed there were some proponents of this approach



(a) (b)

Figure 1:(a) Extent of Groningen gas field and epicentres of earthquakes from the last 30 years with magnitude greater than 2.0 (earthquake data from https://data.knmi.nl/datasets/aardbevingen_catalogus/1 - last accessed 10 December 2019). (b) 475 year return period peak ground acceleration for the v5 hazard model and T1 time period (data from http://seismischekrachten.nen.nl/ last accessed 10 December2019).

(Brouwer *et al.* 2010). However, the decision to develop and implement NPR9998 reflects the need to address a very specific problem, namely the seismic assessment and retrofitting (when required) of a large, vulnerable buildings stock over a short period of time in a single province of the Netherlands. In this sense it offers several advantages over Eurocode 8:

- It is tailored to meet a specific risk objective, which is that the Individual Risk of fatality due to earthquakes should be not greater than 10^{-5} per year. This level of risk is based on the idea that the probability of death for Dutch people due to an accident is about 10^{-4} per year and that the probability of death due to a structural failure should be smaller by a factor of 10 to 100 (Steenbergen *et al.* 2015).
- It specifically and exclusively addresses the induced seismicity problem in Groningen. This means that it considers the specific seismicity of the region, focuses on the specific building typologies that are common in Groningen, and allows for expedited approaches to address the problem of assessing a very large number of buildings in a short amount of time.
- It considers Groningen and Dutch-specific masonry construction practice, which is substantially different from other forms of masonry construction in Europe. Experimental and numerical research into the Dutch masonry material, construction details, elemental and global structural behaviour were undertaken in support of the NPR development and calibration.
- It can be readily updated to suit rapidly changing conditions. For example, changes in seismic hazard or new understanding of the seismic response of typical Dutch building typologies.

3.2 Annexes G & H

In the 2017 version of NPR9998, annexes G and H were added to allow for Nonlinear Pushover Analysis (NLPO) and Nonlinear Kinematic Analysis (NLKA), respectively. In general, Annex G is applicable to all building types, but it has a strong focus on unreinforced masonry (URM) structures, which make up the majority of the Groningen building stock. Annex H on the other hand is applicable to the out-of-plane analysis of URM walls, and is intended to complement in-plane analyses performed using Annex G.

These annexes were added to NPR9998 as means of offering an expedited approach to seismic assessment of residential URM buildings. This came largely in response to the previous (2015) version of NPR9998 having too much focus on sophisticated nonlinear time-history analysis, which meant that some assessments of relatively small buildings were taking up to several months. NPR9998:2015 also included an elastic analysis methodology for out-of-plane assessment, which is more suitable for new design rather than the assessment of existing structures.

In addition to being able to assess buildings more quickly, the combination of NLPO and NLKA via Annexes G and H offered the additional advantage of decoupling capacity from demand. This meant that in an environment where the seismic hazard was regularly being updated it was not necessary to reanalyse a structure if the seismic demand changed, but simply re-evaluate the capacity to demand ratio. This is a significant advantage compared to NLTHA, which for any significant change in hazard would require the analysis to be re-run.

The development of Annexes G and H started with the proposal of two “strawmen” that were developed from the New Zealand Technical Guidelines for (seismic) Engineering Assessments (hereinafter referred to as the New Zealand Guidelines), in particular section C8. The strawman versions of the annexes were then developed to completion by a Dutch task group comprising practitioners, academics and several international members. Regular meetings were generally sufficient to progress the annexes, but a workshop involving a wider group of experts was also held in June 2018 to resolve several of the more challenging issues.

4 COMPARISON TO NEW ZEALAND GUIDELINES

Given the starting point for the development of Annexes G and H, it is useful to compare them to the New Zealand Guidelines, in particular where there are significant differences in approach.

4.1 Probabilistic basis

For both NPR9998 and the New Zealand Guidelines, the focus is on life safety, rather than damage limitation or operational continuity. One significant difference though is the probabilistic basis. NPR9998 has a clearly stated risk target of an Individual Risk no greater than 10^{-5} per annum. Through a rigorous analysis (Straalen *et al.* 2018) it is shown that a reasonable means of achieving this target is by having a conditional probability of collapse of less than 5% when subjected to ground shaking intensity corresponding to a 2475 year return period. This results in NPR9998 typically defining capacities in terms of the 5th percentile for the Near Collapse[1] limit state.

This is in contrast to the New Zealand Guidelines, which define capacities in terms of their probable (i.e. mean) values. Furthermore, assessments evaluate the ultimate limit state (ULS), rather than Near Collapse, for 500 year return period ground shaking intensity. ULS is defined in the commentary to the New Zealand Seismic Design Standard (NZS1170.5 – Supp. 1 2004) as a “limit state at a lower level of structural response (than collapse).”

4.2 URM pier failure mechanisms and drift limits

In the 2017 version of NPR9998 the same four UMR pier failure mechanisms were considered as in the New Zealand Guidelines: rocking, toe crushing, diagonal tension and bed-joint sliding. In the 2018 version the toe crushing mechanism was removed. This was based on the understanding that toe crushing was simply the ultimate failure mechanism for rocking. Removing the toe crushing mechanism removes consideration of

[1] The “Near Collapse” limit state in NPR9998 corresponds to the structure being “about to collapse.” This differs from the “Near Collapse” definition in Eurocode 8: Part 1, which is closer to the “Significant Damage” limit state defined in NPR9998.

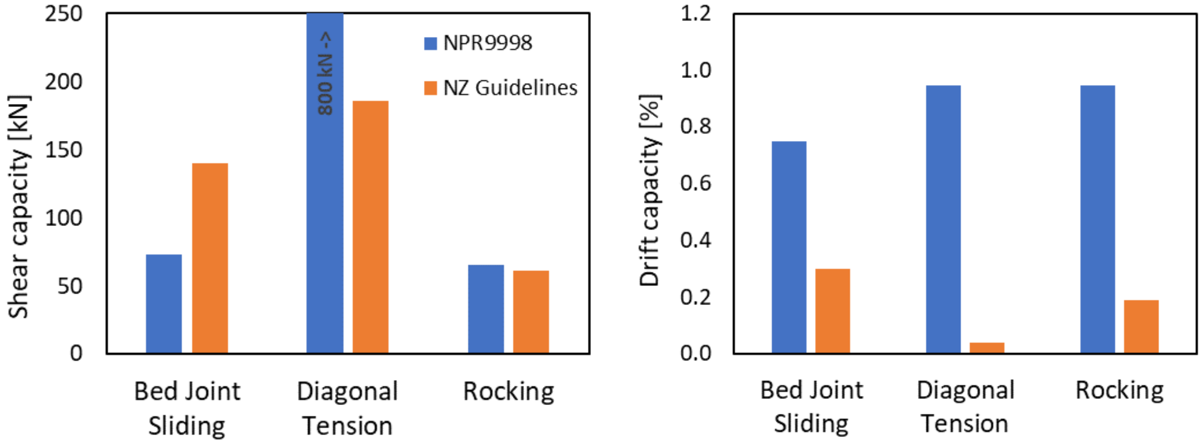


Figure 2: Comparison of shear and drift capacities for a 2.5 m high by 4.0 m long clay brick unreinforced masonry pier in accordance with NPR9998 and the New Zealand Guidelines.

premature toe crushing, i.e. toe crushing behaviour prior to uplift; however, this is unlikely to occur in the low-rise masonry buildings for which Annex G is intended.

The diagonal tension mechanism was also removed as an explicit failure mechanism and instead included as an upper limit on generic shear failure, which also includes bed-joint sliding, to better align with Eurocode 6 (CEN 2005). The drift limit for this upper limit shear failure mechanism was set equal to that of a rocking pier. This was based on research from TU Delft (Messali & Rots 2018), which found that there was not a significant difference between shear and flexural drift capacities for the dataset analysed (Messali 2018). One possible unintended outcome of this is that engineers may be discouraged from implementing retrofit measures that suppress diagonal tension failure in piers.

Drift limits in NPR9998 for the various failure mechanisms are based on the 5th percentile Near Collapse capacity. This naturally results in significant differences to pier drift capacities calculated in accordance with C8 of the New Zealand Guidelines. However, it is nevertheless informative to compare the two. Figure 2 shows the shear and drift capacities of a 2.5 m high by 4.0 m long clay brick masonry pier, calculated in accordance with both NPR9998 and C8. The difference between the shear capacities is minimal for the rocking mechanism but significant for both shear mechanisms. In the case of bed-joint sliding, the New Zealand approach considers cohesion across the full cross-section whereas NPR9998 considers cohesion only across the area in compression, hence the larger capacity following the New Zealand approach. For the diagonal tension mechanism, the differences are quite considerable; however, it should be noted that the wording in NPR9998 is not clear around the nature of this failure mechanism, referring in the latest English draft version to "shear tension." It is the authors' assumption that this can be equated to diagonal tension failure.

The comparison of drift capacities reveals even more insightful differences. In the case of bed-joint sliding, C8 recommends limiting the drift capacity to 0.3%, but notes that the vertical load carrying capacity is expected to be reliable up to drifts of 0.75%. The difference shown in Figure 2 is therefore consistent with the difference in limit states being evaluated by the two different guidelines. The diagonal tension mechanism shows a staggering difference, which is a result of fundamental differences in the assumed behaviour. NPR9998 assumes that the pier still has load carrying capacity after its diagonal tension capacity has been exceeded, whereas the New Zealand approach assumes that exceedance of the shear capacity signals complete failure of the pier. Rocking also exhibits significant differences in drift capacity. Although the drift capacities are calculated for different limit states (as discussed in Section 4.1), it would be expected to see reasonably similar values on account of the fact that NPR9998 is intended to provide 5th percentile

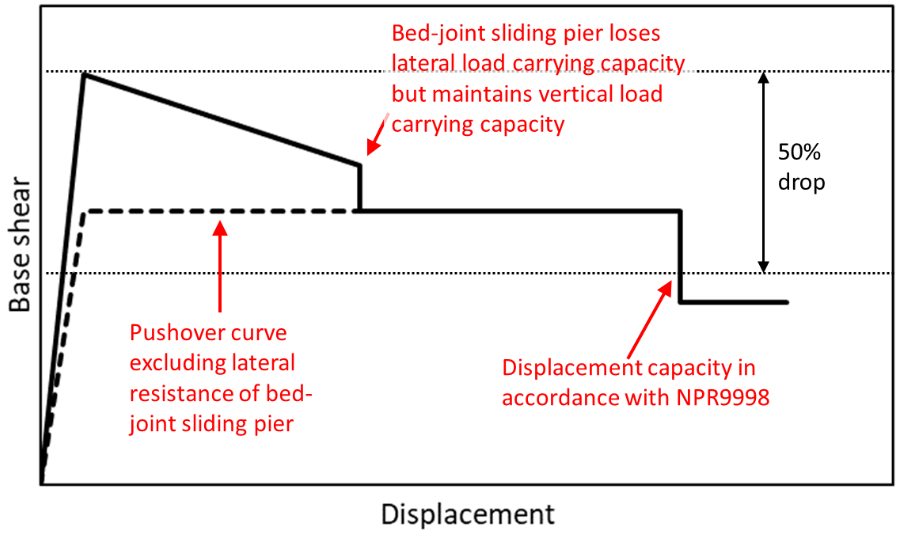


Figure 3: Example pushover curve illustrating (i) the displacement capacity in accordance with NPR9998 and (ii) the effect of excluding the contribution from a bed-joint sliding pier that has lost its lateral load carrying capacity but is able to still support gravity loads.

values, whereas the New Zealand Guidelines are intended to give probable values.

4.3 Global displacement capacity

A key step in pushover or SLaMA analysis is determining the global displacement capacity of the structure (i.e. the end of the pushover curve). The approach to defining this point is quite different between NPR9998 and the New Zealand Guidelines. In NPR9998 Annex G the displacement capacity is defined as the minimum of three criteria:

- The base shear has dropped below 50% of the peak resistance of the structure (see Figure 3).
- A number of members have met the Near Collapse member drift limits, and loss of these members would result in collapse of the building or parts of it.
- Dynamic instability of the structure or explicitly modelled loss of gravity-load carrying capacity of the load bearing structure.

The first criterion differs from the commonly used "20% strength drop," but it is intended to account for the system being evaluated at the Near Collapse limit state (rather than say Significant Damage). These global drift capacities were initially developed based on engineering judgment and established criteria from literature (e.g. ASCE-41, 2013), but eventually were calibrated against sample building assessments and building fragility curves developed from extensive numerical and experimental tests (Crowley *et al.* 2017).

The New Zealand Guidelines, by comparison, are much less explicit in how the displacement capacity should be defined. More reliance is therefore placed on the judgement of the engineer to determine when the structure as a whole has exceeded its global displacement capacity. Take for example the pushover curve in Figure 3, which is intended to represent a URM wall comprising three piers: two that have a rocking mechanism and one that fails in bed-joint sliding. At a pier drift of 0.3% the bed-joint sliding pier is assumed to lose its ability to resist lateral loading; however, the engineer might deem that it can still support gravity loads out to larger displacements, and thus the global displacement capacity is not limited to "failure" of the individual pier.

The more prescriptive definition of global collapse capacity was required for NPR9998 as the local engineers had less experience in seismic engineering. It could be argued that the New Zealand Guidelines rely too heavily on engineering judgment and are therefore susceptible to inconsistencies in assessment outcomes if the practitioners are not consistent in their application of judgment and assumptions. In our view, New Zealand Guidelines could be further improved by providing more explicit criteria for global collapse capacities, though further research may be required to establish such criteria for all building types.

4.4 Design response spectra for out-of-plane assessment of URM walls

Annex H of NPR9998 provides guidance on the use of NLKA for the out-of-plane assessment of URM walls. The major difference to the New Zealand Guidelines is the seismic demand, which for NPR9998 is based on Eurocode 8 and given by Equation 1 below:

$$S_{a;d} = max\left\{a_{g;d}\frac{1}{q_a}\left[\frac{3\left(1+\frac{z}{H}\right)}{1+\left(1-\frac{T_a}{T_1}\right)^2}-0.5\right]; a_{g;d}\frac{1}{q_a}\right\} \tag{1}$$

where:

$a_{g;d}$	is the design ground acceleration in units of g;
q_a	is the behaviour factor of the element;
z	is the height of the element above ground level;
H	is the height of the building;
T_a	is the fundamental period of vibration of the (wall) element;
T_1	is the fundamental period of vibration of building in the relevant direction.

This equation is based on elastic resonance and therefore the seismic demand experienced by a wall responding as a “part” to face loading is strongly dependent on the ratio of the period of the building to the period of the wall itself. This is illustrated in Figure 4, which shows a significant peak in demand around the

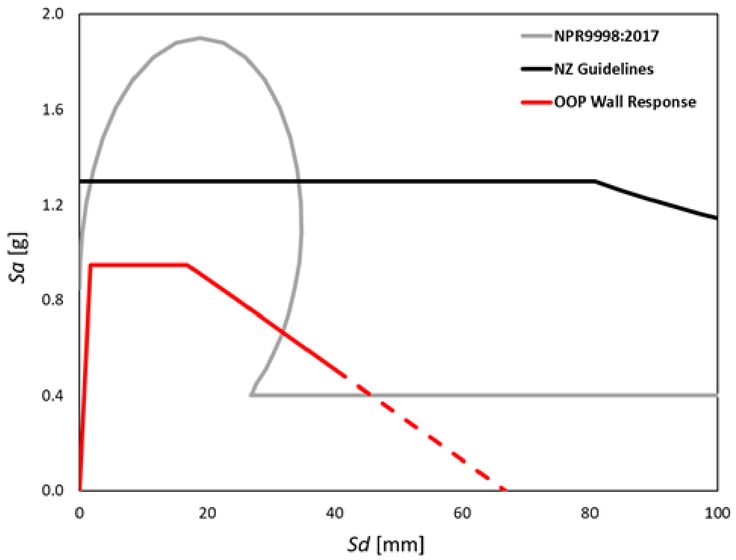


Figure 4: Comparison of response spectra for parts loads when used in consideration with NLKA for the out-of-plane assessment of URM walls.

fundamental period of the supporting structure (in this case 0.2 s). The rationale behind this approach is clear when both the supporting structure and the part itself are responding elastically; however, this is unlikely to be the case during a damaging earthquake. A more effective means of expressing seismic demand could be to use an approach similar to that of the New Zealand Guidelines, which is based on the Parts and Components loading from the New Zealand Seismic Design Standard - NZS1107.5 (2004) (with some modifications to be compatible with displacement-based methods). As shown in Figure 4, this presents a more even seismic demand across a range of periods.

5 CALIBRATION WITH OTHER APPROACHES

As mentioned in Section 2, the stakeholder response to induced seismicity invoked multiple lines of technical work, including experimental testing and a detailed hazard and risk assessment. The opportunity was therefore taken to evaluate NPR9998 against observations from the other lines of work and use the findings as a form of calibration for future changes.

5.1 Comparison to experimental testing

Experimental testing campaigns of full scale Dutch URM houses were performed at a number of research institutes, including the EUCENTRE in Italy, LNEC in Portugal, and TU Delft in the Netherlands. Both quasi-static cyclic tests and dynamic shake table tests were performed and the results of these were compared to pushover curves derived using SLaMA in accordance with NPR9998 Annex G.

Figure 5 shows comparisons with a quasi-static cyclic test performed at TU Delft and a shake table test at the EUCENTRE. It can be observed that the SLaMA results give a reasonably good match to the experimental testing; however, the base shear tends to be underpredicted. This was determined to primarily relate to flange effects in rocking piers, which can be significant for Dutch building typologies. Consequently, more focus was placed on the accurate consideration of flange effects for analyses performed in accordance with NPR9998 Annex G.

Although comparisons to experimental tests can provide useful insights for calibrating assessment methods, it must be kept in mind that the aim of codified assessment methodologies is not to predict the response of individual buildings. The aim is instead to deliver acceptable risk-focused outcomes across a large range of buildings. It is therefore inevitable to find discrepancies between experimental test results and analyses using codified methodologies.

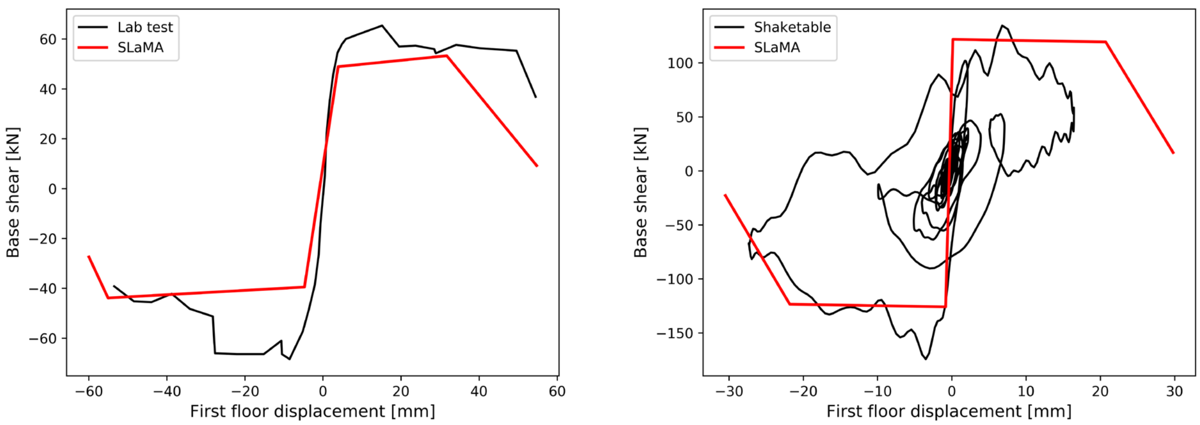


Figure 5: Comparison of pushover curves using SLaMA in accordance with NPR9998 and experimental test results from a quasi-static cyclic test (left) on a calcium silicate block terraced house (Ravenshorst et al. 2016) and shake-table test (right) of a clay brick detached house (Kallioras et al. 2018)

5.2 Comparison to risk analysis

Comparisons of Annex G were also made to the results of regional seismic risk studies, which looked at the seismic risk in a probabilistic sense across the entire building population. Although direct comparisons could not be made on an individual building level, it was found that the number of compliant/non-compliant buildings evaluated using Annex G was comparable to the findings of the risk studies

6 CONCLUSIONS

Comparisons have been made between the Annexes G and H of NPR9998 and the New Zealand Guidelines for (seismic) Engineering Assessments. From these comparisons the following observations can be made:

- NLPO/SLaMA and NLKA offer an expedited approach to seismic assessment, which is a key part of addressing the induced seismicity in Groningen within a practical timeframe.
- There are some substantial differences in pier capacities when calculated using the New Zealand Guidelines and NPR9998. Furthermore, there are differences in how the range of potential failure mechanisms are considered. Future work should investigate the source of these differences.
- The ultimate displacement capacity of a pushover analysis is very clearly defined in NPR9998. On the other hand, defining the ultimate displacement capacity in accordance with the New Zealand Guidelines requires application of engineering judgement.
- Consideration must be given to how seismic demand is defined for parts when used in conjunction with NLKA. It is unlikely that response spectra based on elastic resonance will be suitable for use with nonlinear displacement-based analysis methods.
- Comparison of code-based analysis methods to experimental testing can provide useful insights. However, it must be remembered that the intent of the code is to achieve acceptable risk-focused assessment outcomes, not predict the response of buildings to a single loading regime.

REFERENCES

Bourne, S.J., Oates, S.J., Van Elk, J.J & Doornhof, D. 2014. A seismological model for earthquakes induced by fluid extraction from a subsurface reservoir. *Journal of Geophysical Research: Solid Earth.* 119:8991-9015.

Brouwer, J.W.R., Van Eck, T., Gouthbeek, F.H. & Vrouwenvelder, A.C.W.M. 2010. *The meaning of Eurocode 8 and induced seismicity for earthquake engineering in the Netherlands.* Proceedings of the 5th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, San Diego, California.

CEN. 2004. *Eurocode 8 – Design of structures for earthquake resistance- Part 1: General rules, seismic actions and rules for buildings*. EN 1998-1. European Committee for Standardization, Brussels, Belgium.

CEN. 2005. *Eurocode 6 – Design of masonry structures - Part 1-1: General rules for reinforced and unreinforced masonry structures*. EN 1996-1-1. European Committee for Standardization, Brussels, Belgium.

CEN. 2005. *Eurocode 8 – Design of structures for earthquake resistance- Part 3: Assessment and retrofitting of buildings*. EN 1998-2. European Committee for Standardization, Brussels, Belgium.

Crowley, H., Pinho, R., Polidoro, B., & van Elk, J. 2017. Developing fragility and consequence models for buildings in the Groningen field. *Netherlands Journal of Geosciences*, 96:247-257.

de Jager, J. & Visser, C. 2018. Geology of the Groningen field – an overview. *Netherlands Journal of Geosciences*. 96:3-15.

Graziotti, F., Penna, A. & Magenes, G. 2018. A comprehensive in situ and laboratory testing programme supporting seismic risk analysis of URM buildings subjected to induced earthquakes. *Bulletin of Earthquake Engineering*. 17:4575-4599.

Kallioras, S., Guerrini, G., Tomassetti, U., Marchesi, B., Penna, A., Graziotti, F. & Magenes, G. 2018: Experimental seismic performance of a full-scale unreinforced clay-masonry building with flexible timber diaphragms. *Engineering Structures.* 161:231-249.

MBIE. 2017. *The Seismic Assessment of Existing Buildings: Technical Guidelines for Engineering Assessments*. July 2017. Version 1.

Messali, F. 2018. Personal communication.

Messali, F. & Rots, J.G. 2018. In-plane drift capacity at near collapse of rocking unreinforced calcium silicate and clay masonry piers. *Engineering Structures*. 164:183-194.

NEN. 2018. *NPR9998 - Assessment of structural safety of buildings in case of erection, reconstruction, and disapproval – Induced earthquakes – Basis of design, actions and resistances.*

NZS1170.5. 2004. *Structural Design Actions - Part 5: Earthquake Actions – New Zealand*. Standards New Zealand.

NZS1170.5 Supp 1. 2004. *Structural Design Actions - Part 5: Earthquake Actions – New Zealand Commentary*. Standards New Zealand.

Ravenshorst, G., Esposito, R., Schipper, R., Messali, F., Tsouvalas, A., Lourens, E.M. and Rots, J.G. 2016. *Structural behaviour of a calcium silicate brick masonry assemblage: quasi-static cyclic pushover and dynamic identification test.* Delft University of Technology, Department of Structural Engineering. Version 5, 27 October 2016.

Steenbergen, R.D.J.M., Vrouwenvelder, A.C.W.M. & Scholten, N.P.M. 2015. *Safety considerations for earthquakes.* TNO Report TNO 2013 R12071.

Straalen, I.J.J., Steenbergen, R.D.J.M. & Vrouwenvelder, A.C.W.M. 2018. *Background Report NPR 9998:2018 Part A: Terminology and Safety Philosophy.* TNO Report TNO 2018 R10254.

van der Voort, N. & Vanclay, F. 2015. Social impacts of earthquakes caused by gas extraction in the Province of Groningen, The Netherlands. *Environmental Impact Assessment Review*. 50:1-15.s