16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
THESSALONIKI 18 - 21 JUNE 2018

PRACTICAL SEISMIC ASSESSMENT METHODOLOGIES NPR 9998:2018 – ANNEX G AND H

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ABSTRACT

Gas extraction activity has resulted in induced earthquakes in the Groningen region. There is now an urgent need to assess the seismic risks to buildings in the region, which have not been designed to resist earthquake loading and are particularly vulnerable given their age, materials and construction method.

NPR 9998:2015 was prepared to provide timely guidance to stakeholders for seismic assessment and strengthening of existing buildings, in particular the large number of unreinforced masonry residential buildings in the region. However, the 2015 NPR had some departures and inconsistencies when compared to international seismic assessment standards. One such inconsistency is the emphasis that the NPR put on non-linear time history analyses (NLTHA). Unfortunately, NLTHA of unreinforced masonry structures is a complex exercise which requires a large degree of input parameter calibration and validation. Consequently, the number of building assessments able to be undertaken was far short of targets and the requirement to strengthen buildings, and extent of any strengthening works required, was inconsistent.

The 2018 revision of NPR 9998, in particular Annex G and H, was developed to simplify the seismic assessment procedure while maintaining the level of reliability and technical rigour. This paper describes the background to, and the development of, these Annexes.

Annex G provides the procedure to use non-linear static pushover analysis (NLPO) to assess in-plane behaviour of buildings, based on the modified capacity-spectrum approach. Annex H describes a non-linear method for assessing the out-of-plane (OOP) vulnerability of unreinforced masonry walls (URM) termed a non-linear kinematic analysis (NLKA).

Keywords: Groningen; Induced Seismicity; Unreinforced Masonry; Non-linear Kinematic Analysis; Non-linear Pushover Analysis

1. INTRODUCTION

1.1 Background to Seismicity in Groningen

The Groningen onshore gas field was discovered in 1959 and production began soon after. The gas field, which is located in the north of the Netherlands, is the largest in Europe. The recoverable volume of gas was approximately 2,800 billion cubic metres, 60% of which has since been extracted. The original reservoir pressure was 350 bar; as the gas has been extracted the pressure has reduced, causing the underlying rock formations consolidate. Typically, this process is gradual; however, rarely it happens quickly releasing a pulse of energy that is observed at the surface as an earthquake (Deltares, 2011). Over the past three decades, as reservoir extraction has continued, these induced earthquakes have increased in frequency and magnitude. Figure 1 (a) presents the location of historic earthquakes in the Groningen region.

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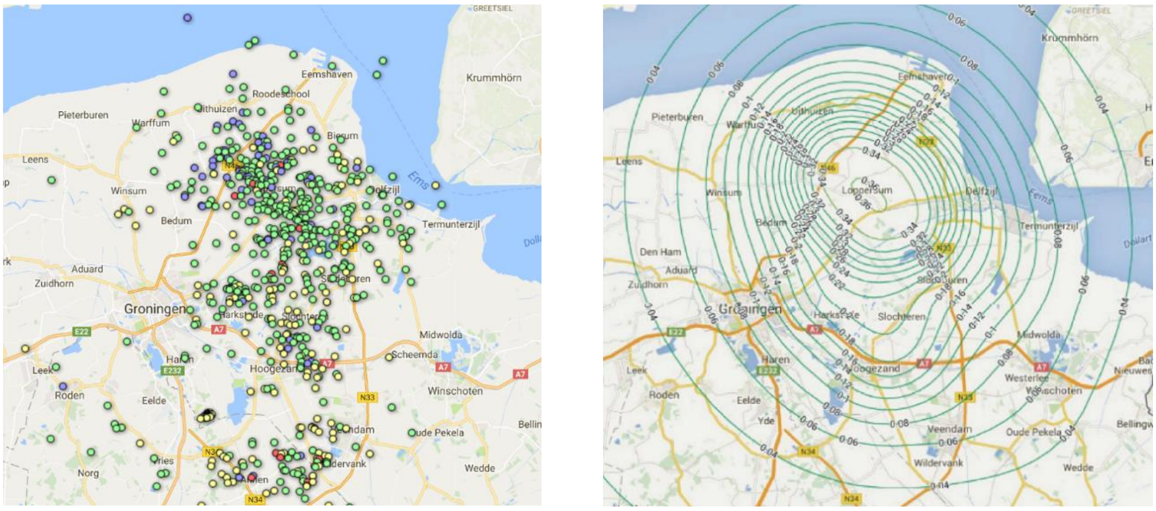


(a) Historic earthquakes (KNMI, 2017).

(b) Seismic hazard map (NEN, 2015).

Figure 1. Seismicity in the Groningen region.

The induced earthquakes are felt strongly at the surface due to both their relatively shallow depth and the soft soil overlying the reservoir. Furthermore, because the north of the Netherlands is not susceptible to tectonic earthquakes, seismic design provisions have not historically been required for structures and as a result, the building stock in the Groningen region is typically of unreinforced masonry (URM) construction and therefore particularly vulnerable to earthquake loading.

Therefore, there is now an urgent need to assess the seismic risks of buildings in the Groningen region in order to strengthen the vulnerable buildings and minimise the risk exposure to the population.

1.2 Development and Application of NPR 9998:2015

To be able to assess the vulnerability of buildings in the region to induced earthquakes, a Standard describing the hazard and method of compliance is required. However, because the region was not a known seismic region there were no seismic design provisions within the building Standards of the time. Seismically active regions of Europe typically use a National Annex to Eurocode 8 (CEN, 2004) to provide seismic design provisions. Eurocode 8 (CEN, 2004) is a modern and internationally recognised seismic Standard. The Netherlands has no National Annex to Eurocode 8 (CEN, 2004) as it was believed that tailoring Eurocode 8 to the Dutch situation, where a distinction may need to be made between tectonic and induced earthquakes, would require a thorough study that would delay the production of the Standard (NEN, 2015).

Instead, the 'Dutch Practical Guideline' (NPR 9998:2015) was prepared and published to provide timely guidance to stakeholders involved in the construction of new buildings and the assessment of existing structures – in particular the large number of unreinforced masonry residential buildings in the region (NEN, 2015). However, the 2015 version of the NPR had some departures and inconsistencies when compared to international seismic assessment standards. One such inconsistency is the emphasis that the NPR put on non-linear time history analyses (NLTHA).

Unfortunately, NLTHA of unreinforced masonry structures is a complex exercise, which requires a large degree of input parameter calibration and validation. These analyses are time-intensive, computationally demanding, the results are inseparable from the demand and, although they may appear to be more sophisticated and precise, they are not necessarily more reliable or accurate than more simple analysis methods. For example, there are many factors that an analyst must consider when undertaking a NLTHA that are not prescribed by the NPR. Considering only the soil substructure, let alone the soil-structure interface and structural model itself; how does one select an appropriate suite of earthquake records?

Are tectonic records excluded? What scaling is applied to the records? Is spectral matching appropriate? How are boundaries treated? And so on.

Considering only one factor, damping, the decisions that an analyst makes about its extent and how it is modelled can have a profound effect on the analysis output that can completely change the assessment, and subsequent retrofit, decisions. As shown in Figure 2 and 3, blind prediction competitions held by research facilities have shown that even when all the input parameters are known, the best researchers in the world cannot predict actual structural response to an earthquake (Restrepo et al., 2010; Terzic et al., 2015). The probability of predicting response when the inputs are unknown will be low.

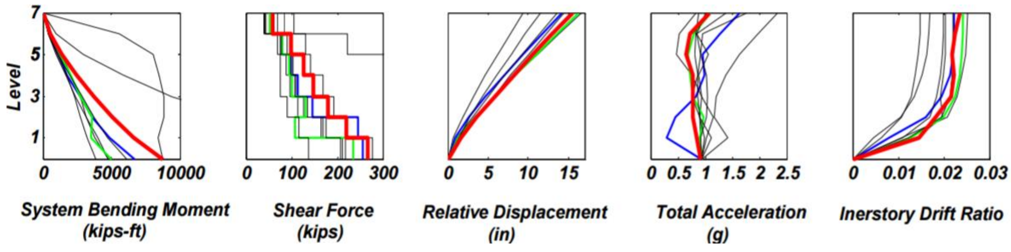


Figure 2. Plot from UCSD wall test (Restrepo et al., 2010).

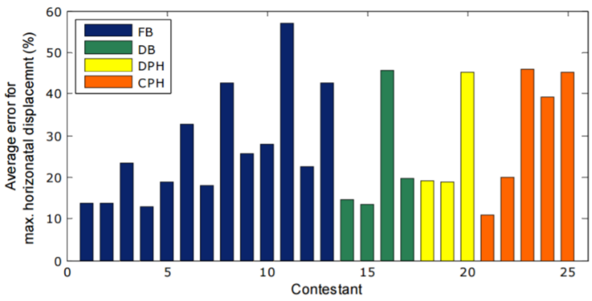


Figure 3. Plot from UCSD column test (Terzic et al., 2015).

A further issue was that there was limited data pertaining to the induced earthquakes that had occurred to date and the fundamental faulting mechanism was not well understood. The definition of the NPR 9998:2015 design spectra (Figure 4) had repercussions not only due to the comparatively high spectral accelerations prescribed, but also in that the spectral shape was missing the constant velocity branch, which resulted in the design spectra being inappropriate for use in displacement space.

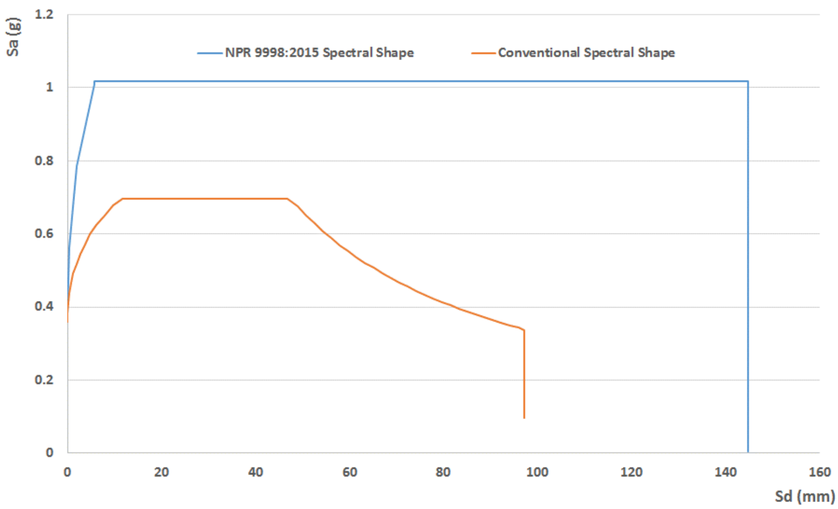


Figure 4. Comparison of NPR 9998:2015 and conventional spectral shapes.

Consequently, the number of building assessments able to be undertaken was far short of targets and the requirement to strengthen buildings, and extent of any strengthening works required, was inconsistent. The NPR committee and the local engineering community recognise a need to shift focus from attempting to predict building response during an earthquake using NLTHA, to undertaking building vulnerability assessments using tools that are sufficiently accurate to enable consistent outcomes to be achieved

2. REVISION TO NPR 9998:2015

NPR 9998:2015 was updated in 2017-18 to address some of the identified short-comings with a large number of studies completed by various universities, research groups and engineering consultants. This includes an improved understanding of the seismic hazard, structural behaviour of the unreinforced masonry typically used in Groningen and improved analysis procedures.

The 2018 revision of NPR9998, in particular Annex G and H, was developed to simplify the seismic assessment procedure while maintaining the level of reliability and technical rigour. The methods prescribed in the Annexes are less complicated and can be more pragmatic than NLTHA, which enables more rapid vulnerability assessment, whist maintaining an appropriate level of reliability.

The assessment of URM buildings can be split into two main components; in-plane and out-of-plane, as shown in Figure 5. It is important that both components are considered; however, for the purposes of a vulnerability assessment, these components can effectively be decoupled and analysed separately.

Annex G provides the procedure to use non-linear static pushover analysis (NLPO) to assess in-plane behaviour of buildings, based on the modified capacity-spectrum approach. Annex H describes a non-linear method for assessing the out-of-plane (OOP) vulnerability of unreinforced masonry walls (URM) termed a non-linear kinematic analysis (NLKA).

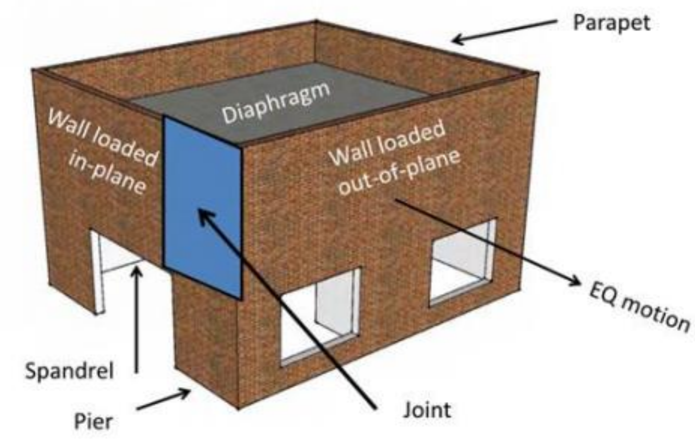


Figure 5. Building schematic displaying in-plane and out-of-plane loading.

URM buildings are typically more vulnerable to out-of-plane loading than in-plane loading, as evidenced by calculation, experimental tests and observations following historical earthquakes. Figure 6 presents a typical out-of-plane failure that occurred during the 2011 Christchurch earthquake and resulted in multiple fatalities. For this reason, out-of-plane vulnerability assessment is generally undertaken first.

Figure 6. Example of out-of-plane wall failure from Christchurch earthquake (Fairfax, 2011).

In addition to having the largest influence on reducing building vulnerability, in-plane building capacity cannot manifest if OOP failure occurs. This process demonstrates the general hierarchy of strength that exists within a URM building, which can be useful in guiding the assessment process. With reference to Figure 7, which presents the capacity ‘chain’ for a typical URM building, the overall capacity of the building will be limited by the capacity of the weakest link in the chain, and the ability of each component to fully develop its capacity will typically be dependent on the performance of the components to the left of it on the chain. This also suggests that the assessment of component capacities should proceed from left to right.

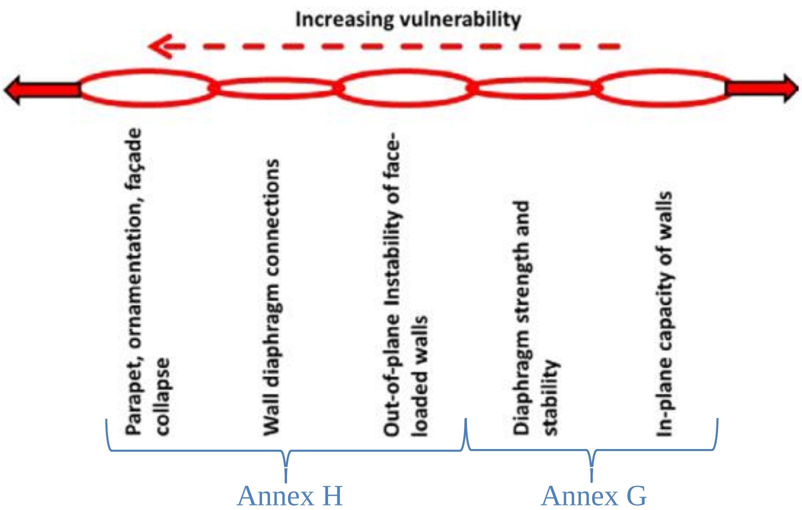


Figure 7. Hierarchy of URM building component vulnerability, demonstrated by way of the capacity ‘chain’ schematic (NZSEE, 2016).

3.1 Annex G: Non-Linear Pushover Analysis

Annex G provides guidance on the application of non-linear static pushover (NLPO) analysis for the seismic assessment of existing building. NLPO is a commonly used analysis procedure used to inform the seismic assessment of existing buildings. There has been extensive research and validation of NLPO as an analysis method to determine the likely non-linear response of buildings to earthquake loading. The theoretical basis for the NLPO approach described in Annex G is the equivalent linearisation approach for capacity spectrum assessment (ATC 40, 1996, NZSEE, 2016) and the substitute structure approach using direct displacement-based design (DDBD) (Priestley et al., 2007). The method described in Annex G has been specifically adapted to the building typologies typical of the Groningen region, with particular emphasis on unreinforced masonry buildings.

Using NLPO, an increasing lateral force is applied to a model of the building, which accounts for the non-linear mechanisms that may form, in every analysis time-step. The lateral force is usually applied in a load vector that approximates the relative acceleration associated with the first mode of vibration of the structure, which is dominant in the building types the method is intended to be applied to. With reference to Figure 8, as the building exceeds its elastic limit and begins to respond non-linearly, the internal actions will redistribute as plastic hinges form. The number of plastic hinges that form increases with increasing lateral force until a global mechanism develops, giving the expected capacity of the building in the form of a non-linear pushover curve.

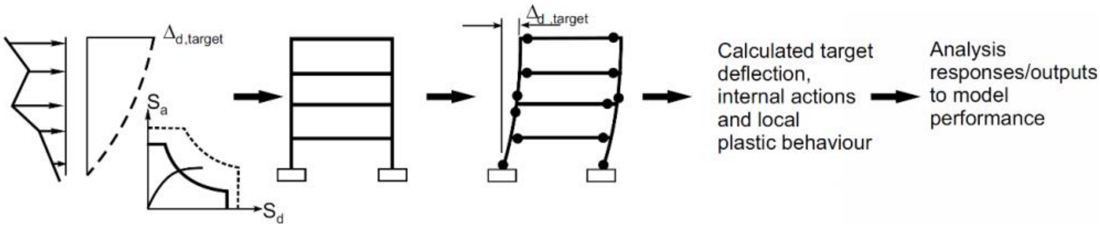


Figure 8. Non-linear static pushover assessment (NZSEE, 2016).

The procedure simplifies a complex multi-degree-of-freedom (MDOF) system into an equivalent single-degree-of-freedom (SDOF) model, such that a SDOF equivalent non-linear pushover capacity curve can be compared to seismic demand in the form of acceleration-displacement response spectra (ADRS) in order to estimate the likely response. The seismic demand curve is modified to account for energy dissipation, ductility and damping. This process is demonstrated schematically in Figure 9.

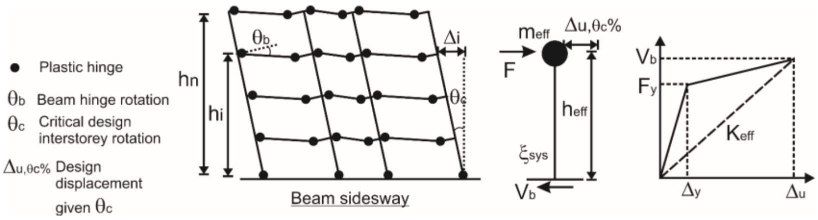


Figure 9. Conversion of MDOF system to an equivalent SDOF system (NZSEE, 2016).

Annex G has adopted some of the more recent thinking from international literature (NZSEE, 2016 and ASCE-41-18) and local research for seismic assessment of unreinforced masonry buildings:

- The component strength and drift capacities for various pier and spandrel mechanisms are based on the latest international literature from New Zealand, Australia and North America.
- A new equation for Near Collapse drift capacity of rocking piers based on the latest research by TU Delft (Messali & Rots, 2017) was introduced.
- Introduction of a global drift acceptance criteria. For example, a two storey unreinforced masonry building with a ductile response (rocking piers) has 0.8% global drift limit at the effective height. This is calibrated from multiple non-linear pushover and time history analyses and shaking table tests.
- A new damping-ductility equation, calibrated for masonry-type hysteresis and Groningen-specific ground motions, is introduced. This was calibrated to NLTHA of simple SDOF models.
- Simplified approach for soil structure interaction was introduced, including the incorporation of the soil foundation compliance effect, which increases displacement capacity, by way of a spectral reduction damping factor. The FEMA 440 (2005) approach to calculate soil radiation damping was also incorporated. An upper bound of soil damping contribution of 15% was introduced.

- Introduction of pseudo non-linear pushover analysis using sequential elastic analysis. Whilst this is a common simplified non-linear analysis method, this has only recently been included in the NZSEE (2016) guidelines.
- A simplified hand-calculation based non-linear pushover method termed Simple Lateral Mechanism Analysis (SlaMA) for unreinforced masonry building is introduced. This is based on the SlaMA approach outlined in NZSEE (2016).
- Lastly, a focus on the global building Near Collapse response instead of individual local elements response. Assessors are permitted to consider whether the failure of an individual local element would result in collapse or partial collapse of a building. In addition to the global drift limit, guidance was given for the definition of Near Collapse limit state for a number of scenarios, refer to Figure 10.

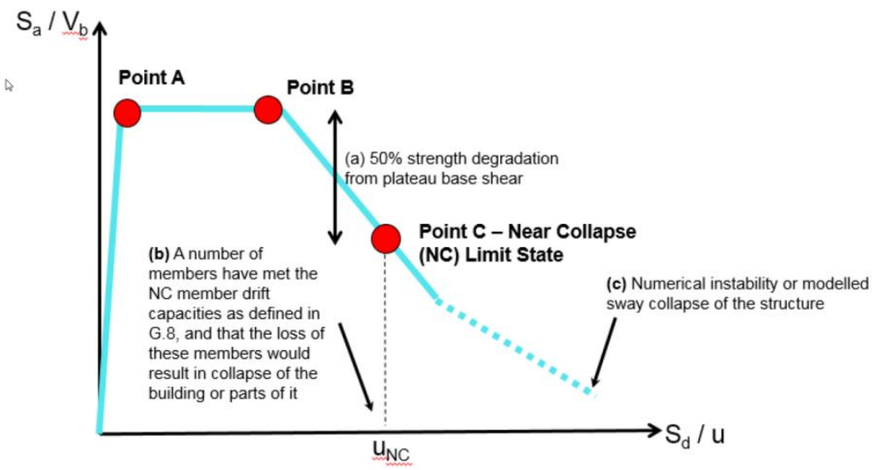


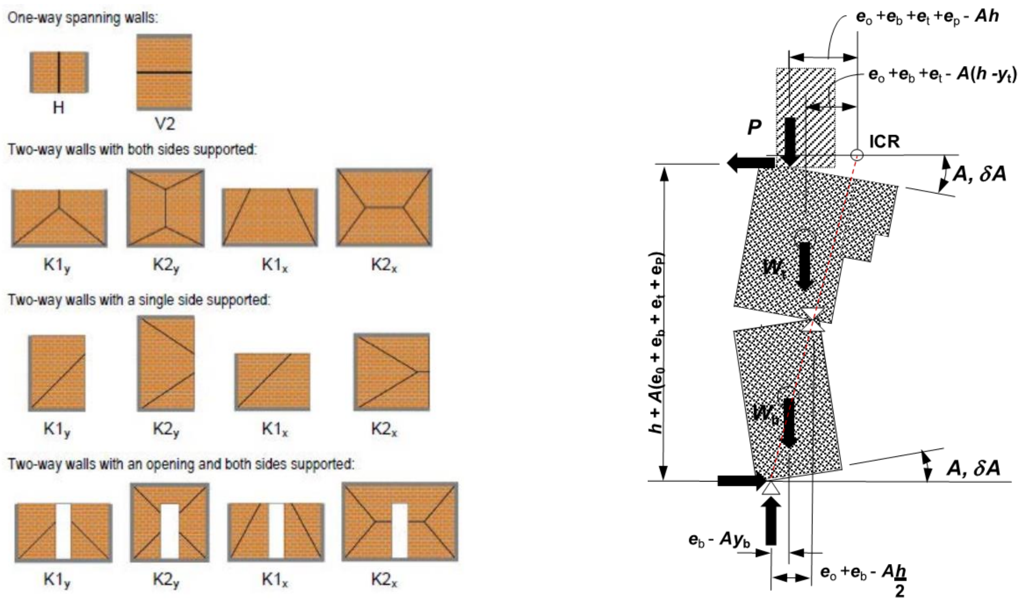
Figure 10. Global Near-Collapse (NC) limit state acceptance criteria (NZSEE, 2016).

3.1 Annex H: Non-Linear Kinematic Analysis

Annex H provides guidance on the application of the non-linear kinematic analysis (NLKA) method to the seismic assessment of unreinforced masonry (URM) walls subjected to out-of-plane (OOP) earthquake actions. The NLKA is a means to estimate the OOP structural capacity of URM walls based on the geometry, loading and boundary conditions. The method is based on virtual work principles and takes into account the non-linear behaviour of walls when responding OOP. The method is intended to provide an appropriate balance between method complexity and solution accuracy.

The theoretical basis for the NLKA approach was proposed in the 1980s (Priestley, 1985). Over the following decade the methodology was further developed (Blaikie & Spur, 1993; Blaikie, 1999, 2001 & 2002), which culminated in its inclusion in the guidance document 'Assessment and improvement of the structural performance of buildings in earthquakes' (NZSEE, 2006). Following the Canterbury earthquake sequence, where widespread damage was sustained by URM buildings (Dizhur et al., 2011), an experimental campaign was established to improve assessment methodologies for URM buildings. The advancements of this research (Derakhshan et al., 2014) were incorporated into the update to the NZSEE guidance document (NZSEE, 2016), which formed the basis of Annex H.

The NLKA method is based on the principle of virtual work; therefore, the probable failure mechanism of the wall must be known to determine a solution. The probable failure mechanism – or crack pattern – is related to the support conditions and geometry, as shown in Figure 11 (a). Generally, the simplifying assumption is made that masonry walls span one-way vertically. This assumption reduces the number of possible solutions that are possible, which are then able to be used to determine solutions for most typical building typologies. A schematic of a vertical spanning wall is presented in Figure 11 (b); the figure defines parameters and also presents the mechanisms relating to both face-loading and interstorey displacement.



(a) Idealised cracking patterns for masonry walls. (b) One-way spanning wall out-of-plane mechanism.

Figure 11. Idealised out-of-plane wall behaviour (NZSEE, 2016).

The first step of the NLKA is to determine, based on geometrical relationships, the wall displacement at which overall instability occurs. As you approach the instability displacement, decreasing amounts of energy are required to cause a given increase in displacement; consequently, the wall response becomes dependent on the characteristics of the earthquake. Because of this, a fraction of the instability displacement is defined as the ultimate displacement, this is 60% and 30% in the cases of one-way spanning walls and cantilevers respectively. The dynamic properties of the wall are determined based on relationships derived using virtual work methods. A design spectra, which has been appropriately modified for dynamic amplification and system damping, can then be used to determine the displacement demand of the equivalent SDOF system. This can then be compared to the ultimate displacement capacity to assess compliance. A step-by-step process is described in Annex H to guide an assessor through the assessment procedure; furthermore, a chart-based simplified assessment procedure is described also for rapid wall vulnerability assessments.

Formulations for more complex wall geometries, such as two-way spanning walls or heavily penetrated walls, can be determined; however, these types of solutions have not been sufficiency verified by experiment and as such are not included in Annex H presently. Multi-leaf walls are able to be considered using the NLKA method. If the leaves are sufficiently connected, then the wall can be assessed as one integral unit. Generally, the ties provided in cavity walls do not have sufficient shear strength or stiffness for the two leaves to be considered integrally; therefore, the capacity of each wall is assessed independently, whilst acknowledging that they will deform concurrently. Generally, an exterior leaf will have less capacity than an inner leaf because it has a lower axial load. In this case, and if sufficient cavity ties have been provided, the load from that exterior leaf can be transferred to the interior leaf. This will decrease the capacity of the interior leaf, but increase the overall capacity of the cavity wall. A step-by-step procedure to adapt the generalised NLKA method to cavity walls in presented in Annex H.

The OOP capacity of URM walls is related also to the restraint conditions at each end. Annex H provides guidance on what types of boundary conditions can be used in a NLKA, and how they relate practically to typical construction practices.

4. VALIDATION

The procedures outlined in Annex G and H are also contained in recognised international guidelines and Standards; therefore, they have been previously validated by those committees and verified through application by the engineering community. However, to address concerns that the procedures may not translate to the construction practices prevalent in the Groningen region a validation study was undertaken. The goal of the study was to undertake analytical-experimental validation of the NLPO and NLKA procedures, as outlined in Annex G and H, against selected large-scale experimental tests. Data from the following tests was used:

- TU Delft – 2016: Clay Masonry Terraced House (Ravenshorst et al., 2016)
- TU Delft – 2017: Calcium-Silica Masonry Terraced House (Messali and Pair, 2017)
- EU Centre – 2016: Out-of-plane Components Tests (Graziotti et al., 2016a)
- EU Centre – 2015: Terraced House (Graziotti et al., 2015)
- EU Centre – 2016: Detached House (Graziotti et al., 2016b)

It was observed that the NLPO assessment, performed in accordance with Annex G, predicted the performance point (in terms of non-linear global displacement) of the test specimens with appropriate accuracy; discrepancies were generally conservative. The outputs from the large-scale shake table experiments were not ideally suited to validating the NLKA method, since full non-linear mechanisms were not generally observed. This is to be expected, since testing a large-scale specimen to collapse puts at risk the safety of the experimenters and equipment. However, validation against the available dynamic out-of-plane component tests showed that the NLKA method is appropriate for assessing wall vulnerability.

Some recommendations were made as a result of the validation study to improve the consistency of the NLPO and NLKA methods, as described in Annex G and H respectively, when applied specifically to building typologies typical of the Groningen region. These recommendations were incorporated into the final versions of the Annexes.

5. CONCLUSIONS

A large number of buildings in the Groningen region require seismic assessment and, if required, retrofit to mitigate the risk from induced earthquakes. This is a huge undertaking and is significant to the regional and national economy. As a consequence of inadequate knowledge of the induced earthquakes, a relatively untested seismic standard and a focus on NLTHA for all buildings, the number of building assessments that have been completed has fallen short of targets, which is unacceptable to the gas field operator, government and public.

The introduction of simpler and more pragmatic seismic assessment procedures in NPR 9998:2018 is a step change in the overall seismic assessment programme. The introduction of the NLPO procedure in Annex G for in-plane assessment has reduced the timeframe to complete an individual building assessment from months to days. From our experience comparing NLPO and NLTHA results, and also validating Annex G against experimental test data, NLPO in accordance to Annex G has been demonstrated to be able to reliably assess the Near Collapse behaviour of unreinforced masonry buildings. The introduction of the NLKA procedure in Annex H for out-of-plane behaviour assessment has also reduced the timeframe to identify the key vulnerabilities in these buildings. Typically, out-of-plane deficiencies are more common than in-plane; therefore, a simple and easy-to-use procedure for assessment is critical.

The uptake of the NLPO and NLKA procedures outlined in Annex G and H by the local consultants, and the consistent (and correct) use of the procedures, are critical to the overall success to the seismic risk mitigation programme.

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