HOW TO ASSESS 25,000 ADDRESSES IN FIVE YEARS

Andrew BAIRD\textsuperscript{1}, Craig MUIR\textsuperscript{2}, Peter BEAZLEY\textsuperscript{3}, Rob JURY\textsuperscript{4}, Weng Yuen KAM\textsuperscript{5}

ABSTRACT

Extraction of gas from onshore gas fields has resulted in induced seismic hazard in regions with limited experience with earthquakes. The residential building stock in some of these regions include significant numbers of unreinforced masonry (URM) construction which are particularly vulnerable to earthquakes. It is estimated up to 150,000 addresses are within the reservoir area of one large gas field and more than 25,000 residential addresses within the central zone of the gas field.

The undertaking of 25,000 seismic assessments in five years is unprecedented. Traditional one-by-one seismic assessment of these addresses may not be practical when considering the labour and time constraints. A coarse macro-level assessment meanwhile is not able to deliver building-specific assessment and strengthening requirements. Consequently, an innovative system has been developed which enables fast and reliable structural assessment. The system relies on a substantial library of pre-assessed non-linear capacity curves that have been established on the basis of detailed seismic analysis of a sample population of URM houses. This library enables engineers to make rapid seismic assessment of similar typologies and configurations of residential URM buildings.

In this paper, the underlying concepts of the system are presented. The experimental-analytical validation exercise of the underlying detailed analysis is discussed. Some of the challenges and lessons learnt from the development activity of the system are discussed in the context of its applicability to other type of structures and for other similar seismically-active regions needing large-scale seismic assessments.

Keywords: seismic assessment; unreinforced masonry; induced seismicity

1. INTRODUCTION

The largest gas field in Europe covers approximately 900 km\textsuperscript{2}, a region home to approximately 600,000 inhabitants. It is now accepted that there is a relationship between gas being extracted from gas fields and earthquakes (Haak et al., 1993; Segall et al., 1994). Such earthquakes are linked to the gas being located in a porous layer of sandstone at a shallow depth, as shown in Figure 1 (left). As gas is extracted, the pressure decreases and this sandstone compresses. Usually this is a gradual process leading to surface subsidence, however, the movement of the sandstone layers can also happen quickly, causing minor earthquakes (Deltares, 2011). Although the gas field has been in operation since 1959, it is only recently that the region has begun to be affected by shaking greater than M3.0, as shown in Figure 1 (right). The largest earthquake to date was a magnitude M3.6 occuring on August 2012 (KNMI, 2013). This earthquake shaking caused damage to houses and other buildings nearby. At the end of 2012, sufficient gas remained in the field for another 50 years of production and it is estimated that approximately 150,000 occupied buildings have been affected by induced earthquakes to date (Centraal Bureau voor de Statistiek, 2012; NAM, 2013; Ministry of Economic Affairs, 2013).

\textsuperscript{1}Project Manager, BICL(NL) B.V., Bangkok, Thailand
\textsuperscript{2}Senior Structural Engineer, BICL(NL) B.V., Christchurch, New Zealand
\textsuperscript{3}Associate, BICL(NL) B.V., Groningen, Netherlands
\textsuperscript{4}Senior Technical Director, BICL(NL) B.V., Wellington, New Zealand
\textsuperscript{5}Associate, BICL(NL) B.V., Auckland, New Zealand
As a result of these earthquakes, the gas production in the region has been limited since 2014. The governing body has been tasked with providing safety to those living above the gas field consistent with other regions. The aspiration of the governing body is to restore safety within five years to the inhabitants of 25,000 house addresses located above the central zone of the gas field.

It is a matter of urgency to assess the life safety risk of these dwellings in order to identify necessary strengthening measures to restore the safety of the population in the region. Undertaking seismic assessment and identifying necessary structural upgrades of 25,000 addresses in five years presents an extraordinary challenge. Individual seismic assessments at such scale have not been fully achieved in any high seismicity area to date, let alone a region where earthquakes were unheard of until recently.

As part of the response to this, a new governing code was developed for both assessing existing buildings and design of new buildings. The guideline outlines how existing buildings are to be evaluated for compliance with minimum safety levels and if not sufficient, that retrofit measures need to be implemented. New annexes have also been recently introduced to qualify the use of non-linear pushover (NLPO) and non-linear kinematic analysis (NLKA) procedures for seismic assessment.

Optimized approaches delivering faster but consistent ways for seismic assessment without jeopardizing the intent of the safety are necessary. This is in line with the recommendation provided by the International Review of in April 2017 (Wiemer, 2015). This paper presents the underlying concepts of the system being developed to undertake large scale seismic assessment.

2. RETHINKING SEISMIC ASSESSMENT

The challenges of undertaking seismic assessments of 25,000 addresses are numerous. The sheer volume of assessments in a limited time presents an obvious challenge, however, other challenges also exist which are amplified when undertaking such a large volume of work. Ensuring consistency and appropriateness of outcomes between assessments is critical. As the assessments will take place over a number of years, there is also a need to include an ability to deal with new knowledge and information as it comes to light, without significant re-work. It is important that structural upgrades can be easily determined from assessments without the need for further detailed analysis. Information available on individual houses is also typically limited. Where multiple site inspections would be used to reduce uncertainty and reveal unknowns, the limited time, resources and perceived social impact means that only a single site inspection is possible per address.

Considering the above challenges, traditional assessment techniques do not lend themselves well to this huge undertaking. One-by-one assessments require extensive time and effort, including building inspection, modelling and interpretation, etc., as shown in Figure 2. Adding to this difficulty is the challenge of an ever shifting hazard. Significant research has gone into understanding and quantifying the seismic hazard caused by gas extraction, however, a consequence of this is that the seismic hazard
has changed numerous times in the space of a couple of years (Spetzler and Dost, 2017). This presents a significant challenge for non-linear time-history analyses of which the output is explicitly linked with the hazard input. If the hazard changes, it requires re-running models, and re-determining assessment outcomes.

In order to overcome these challenges, a rethink of how to undertake seismic assessment of a large scale is required. This paper presents a seismic assessment system that allows for rapid seismic assessment and provides a quick and reliable assessment outcome. The assessment system utilises the NLPO and NLKA methods which are discussed in the following sections and in more detail in a companion paper by Muir et al., 2018.

The seismic assessment system has been developed using these methods by a number of technical consultants including BICL (NL), with inputs and feedback from some of the top minds in earthquake engineering. The system relies on a significant library of pre-assessed non-linear capacity curves in order to enable engineers to make rapid seismic assessment of similar typologies and configurations of residential unreinforced masonry (URM) buildings. These non-linear capacity curves have been established on the basis of detailed seismic analysis of a sample population of URM houses.

Instead of having to undertake a detailed seismic assessment of every individual building, each of which can take months, it is possible to complete a seismic assessment in a matter of days using this typology based system, as shown in Figure 2. A typology based assessment system is based on identifying the critical features of a building to group it into a typology. The structural upgrades required can then be found for this building typology based on the seismic hazard at the particular building’s location.

Building typologies have been established using simple identifiable features which are linked with the seismic performance of the building. Many of these features, e.g. floor type, have already been established and collected in a database for many of the buildings. The system has been configured with this in mind, which makes it possible to undertake rapid initial screening assessments to identify buildings that are particularly low/high risk. Further details of the tiered assessment approach is described in subsequent sections.
By undertaking assessment using NLPO and NLKA, it is also possible to decouple analysis of the in-plane and out-of-plane masonry behaviour, and hence decouple the associated structural upgrades of each, as shown in Figure 3. This assessment method also means that capacity is separated from demand. This overcomes the aforementioned issue of a changing seismic hazard.

[Diagram showing in-plane and out-of-plane elements in unreinforced masonry buildings (left), damage to unreinforced masonry buildings in Christchurch following M6.3 22 February 2011 earthquake (right)]

2.1 NLPO (Capacity Spectrum Method)

The assessment system requires a simplified analysis method in order to develop a library of NLPO curves that define the in-plane capacity of each typology. Non-linear pushover (NLPO) is a commonly used nonlinear analysis procedure for seismic assessment of existing structures. There has been extensive research and validation of the NLPO as an analysis method to determine the likely nonlinear response of URM buildings in earthquakes (Knox, 2012; Anthoine et al., 1995; Magenes and Calvi, 1995; Moon et al., 2006).

The modelling approach used to find NLPO curves for the assessment system is based on the Simple Lateral Mechanism Analysis (SLaMA) method. SLaMA is a simple nonlinear analysis technique that provides an estimate of the global probable capacity of the structure as the summation of the probable capacities of the individual mechanisms (NZSEE, 2017). The capacities of the individual mechanisms can be represented in elasto-plastic form with strength and maximum deformation equal to the assessed probable strength and maximum deformation capacity respectively, as shown in Figure 4 (left).

When considering the in-plane strength capacity of URM walls, the individual mechanisms can be determined by identifying the piers and spandrels that make up the wall and calculating the capacity of the different possible failure mechanisms of each individual element. The limiting mechanism capacity determines the mode of behaviour and the basis for the calculation of the deformation capacity.

For URM walls with openings of differing sizes and relatively weaker piers compared to stronger spandrels, Moon et al. (2004) have recommended that the effective height of each rocking pier is represented as the height over which a diagonal compression strut is most likely to develop in the pier at the steepest possible angle that would offer the least lateral resistance, refer to Figure 4 (right). As a result, effective heights for some rocking piers adjacent to unequal size openings will vary depending upon the direction of loading. The pier geometry is important for determining the expected failure mechanism, considering diagonal tensile, toe crushing, in-plane rocking or bed-joint sliding.
Finally, the SLaMA assessment procedure converts the structural system into an equivalent single-degree-of freedom model such that an SDOF equivalent nonlinear pushover capacity curve can be compared with the seismic demand in the form of acceleration-displacement response spectra (ADRS) as shown in Figure 5.

2.2 NLKA Method

The non-linear kinematic analysis (NLKA) is a stability and displacement-based inelastic method for assessing face-loaded unreinforced masonry walls. The inelastic displacement capacity of the wall is determined using virtual work methods and compared against the displacement demand. This is determined using the spectral displacement, including modifications for wall position within the building and the wall properties. These procedures are based on NZSEE guidelines and research carried out at the University of Auckland and University of Adelaide (NZSEE, 2017; Derakhshan et al., 2013).

NLKA is a way to undertake reliable calculations on the out-of-plane (OOP) structural performance of unreinforced masonry walls based on the geometry of the walls. The NLKA method takes into account both the elastic and non-linear behaviour of the failure mechanisms. The NLKA method provides a balance between solution accuracy and method complexity; as such, it is a key part of both New Zealand (2017) and Italian (2008) seismic assessment guidelines. 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 6. The NLKA method is a displacement-based assessment method, which is able to account for the non-linear behaviour of masonry walls as they displace OOP when subjected to inertial face-loads resulting from earthquake acceleration.

![Diagram of cracking patterns](image)

**Figure 6. Idealised cracking patterns for masonry walls (from NZSEE, 2017)**

### 2.3 Assessment Assumptions

The situation of undertaking numerous seismic assessments is unique and requires a departure from what would be considered a typical building assessment approach since information available on individual houses is typically limited. Where multiple site inspections would be used to reduce uncertainty and reveal unknowns, the limited time, resources and perceived social impact means that only a single site inspection is possible per address. Consequently, a thorough and robust set of assumptions and assessment criteria are required in order to expedite the assessment process. If no specific information is available, assumptions need to be made that will subsequently be confirmed on site at completion of the assessment.

### 2.4 Validation

The NLPO and NLKA analysis methods presented above are based on well-established principles and international literature (NZSEE, 2017 and ASCE/SEI 41-13:2004) which have been calibrated to various existing experimental data. These procedures can generally be used with limited modification for the purpose of undertaking seismic assessment of buildings. At the same time, a significant number of experimental tests have been carried out on unreinforced masonry construction (Messali et al, 2017). These tests have been performed principally at three different laboratories (TU Delft, TU Eindhoven and EUCentre, Pavia). The experimental data from these testing programmes provides an opportunity for an experimental analytical validation of the governing code.

A rigorous experimental-analytical validation has been undertaken, including verification against full-scale building tests (either blind or post-diction) carried out at TU Delft and EU Centre (Pavia), as shown in Figure 7 (left). The NLPO and NLKA methods have demonstrated their feasibility and ability to predict the various experimental test results. In general, NLPO assessment gives a good prediction of the performance point (in terms of non-linear global displacement), as exemplified in Figure 7 (right).
Discrepancies are generally on the safe/conservative side. The predicted maximum displacement shown in Figure 7 (right) were extended in an effort to try and predict full structural collapse. Such a collapse of the test frame did not occur during testing, which means that the maximum predicted deformations are also conservative.

Figure 7. Experimental test setup of URM building at TU delft (left), comparison of experimental backbone curve and blind prediction from SLaMA analysis (left) (Messali and Pair, 2017)

3. TIERED ASSESSMENT APPROACH

Adopting a multi-tiered assessment approach allows for dealing with different levels of information which is vital when trying to assess 25,000 buildings. It provides a method for identifying low and high risk buildings and a workflow that prioritises interventions and allocation of resources. The tiered assessment approach leverages off recognised trends in building behaviour, allowing for assessments to be based on critical building parameters only. Buildings can be grouped by these critical building parameters, which are physically observable or measureable, to develop a database of building capacities. This approach also recognises that information on some buildings will always be varied, with some buildings requiring complex assessments and complex analysis, however it is vital that these do not hold-up assessments where the outcome is easily determinable.

A tiered assessment approach allows for a trade-off between efficiency and complexity. If an assessment system were to assess every possible building, a large number of parameters would be required to define all possible typologies. Consequently, a huge number of individual building assessments would be required to adequately define each unique typology. Conversely, if the classification system is too coarse, then the difference between individual building performance is not refined enough to provide useful outcomes, and many buildings will still require individual assessment. Finding a balance between efficiency and complexity is difficult, but vitally important.

3.1 Components of Tiered Assessment Engine

The tiered assessment engine is the technical core that delivers compliant seismic assessments for individual house addresses to the local seismic demand. Key components of the engine are:

1. A building database, with the geographical location, local seismic hazard, and the typology attribution of each single building. This makes use of the seismic hazard data and rapid visual screening data;

2. Seismic analyses on individual addresses to determine the capacities and develop the characterization of the typology or sub-typology based on seismic attributes. These assessments are based on NLPO and NLKA assessments in accordance with the governing code.
3. Allocation of remaining addresses, which are not individually analysed, to the typology characterization using seismic attributes developed in step 2, a process that will be semi-automated using a purposely developed IT platform that links building data, seismic hazard and typology characteristics.

3.2 Tier Definitions

The tiered approach is shown diagrammatically in Figure 8. With each successive assessment tier, more parameters are required to better refine seismic performance. Each tier of the approach represents an assessment of increasing refinement. If a building is deemed to comply at one tier, then no further assessment is required and only a final inspection is required to confirm that the building conforms with the typology that it has been assessed under. If the building does not comply, then it passes to the next tier of the assessment system.

![Figure 8. Schematic of tiered assessment process](image)

3.2.1. Initial Screening

Initial screening assessments can relatively quickly identify a large number of low-risk houses that comply with the governing code. These are generally buildings that are very strong and/or located in regions of low seismicity. In-Plane (IP) and Out-Of-Plane (OOP) assessments are based on basic typology assessments. Typology definitions have been developed from NLPO and NLKA using a sample of buildings. Typologies are based on limited parameters (e.g. floor type, wall type, wall length) which can be derived from available databases.

The basic process of an initial screening assessment is shown in Figure 9. The process relies on an input of basic building information to classify a building into an appropriate typology. The corresponding typology capacity of the building is then found by looking up the typology capacity catalogue. The assessment can then take place by comparing the typology capacity with the local seismic hazard to determine if the building is compliant. The initial screening assessment is a semi-automated process using the already collected basic building information and building catalogue definitions as inputs. The semi-automated process can deliver instant outcomes once the necessary (assured) data is available.
3.2.2 Detailed Screening

Detailed screening assessment subjects houses, which have been indicated as potentially non-compliant by the initial screening, to increased scrutiny to examine whether structural upgrading is required. The detailed screening process is similar to the initial screening, but relies upon a greater level of detail to classify the building typology, and corresponding typology capacity. The building parameters that are required to determine the building typology require either site inspection or review of drawings. This approach allows effort to be spent reducing the assessment conservatism only in the houses where it is justified and might affect the assessment outcome.

3.2.1 Unique Seismic Assessment

Unique seismic assessments are essentially building-specific that are outside of the capability of the current screening capability. Individual building assessment can be performed with either NLPO or a series of simplified Non-Linear Time-History (NLTH) analyses. IP and OOP assessment is integrated in NLTH analysis. This tier is required for buildings that do not fall into a given typology, or where insufficient data exists to adequately define a typology. The outcomes of each unique seismic assessment can be fed back into the tiered system through the development of an increased typology capacity catalogue.

The assessment system is also a learning system that becomes more intelligent with subsequent unique assessments. This occurs by the results of each building-specific assessment being fed back into the screening catalogue and, in doing so, the reliability and applicability of the system is improved. Over time, this process should result in there being fewer unique assessments required.

4. OUTPUTS

The assessment engine is a cloud-based tool that engineers can use to undertake quick and reliable structural assessments. The tool make use of existing building information databases and the typology capacity catalogue that has been developed through numerous NLPO and NLKA seismic assessments.

It is helpful to visualize how the assessment data is used to develop the typology capacity curves. Shown in Figure 10 (left) are the in-plane push-over curves for one typology. The plot shows the push-over curve of all buildings that fit this typology. The ‘typology capacity curve’ (shown in red) represents the push-over capacity of this typology and is defined by the capacity estimate to achieve 95% confidence of the probable capacity, assuming a lognormal distribution of the individual building assessments, as shown in Figure 10 (right). The definition of this typology capacity must consider a minimum number of unique assessments and an appropriate coefficient of variation to define a typology capacity that is consistent with the annual safety target.
Figure 10. Individual push-over capacity curves and typology capacity curve (left), derivation of typology capacity curve from individual assessments distributed lognormally (right)

To understand how effective the building parameter definitions are at assessing the overall building stock, the typology capacity curve can be compared to the seismic demand. The spectral shape of the seismic hazard varies depending on location, so it is necessary to use the capacity spectrum method at each location to determine the expected outcome. This is not a primary output of the system, but a useful method to refine the building parameters used to define typologies so they are most effective at separating compliant from non-compliant buildings. An example of the comparison between capacity and demand is shown in Figure 11. When the capacity is less than the spectral demand, the in-plane capacity of the building is deemed non-compliant.

Figure 11. Capacity spectrum method to determine compliance

By using a tiered assessment, a large number of low-vulnerability buildings can be shown to be compliant with their local demand quickly and cost-effectively. If a building is found to not comply under an initial screening assessment, it may still be shown to comply by using a more detailed screening assessment. If the detailed screening assessment shows a building does not comply, conceptual retrofit advice can be generated to address the vulnerability.

4.1 System Development

At the time of writing this paper, the assessment tool has been developed to a point where it is capable of undertaking initial screening assessments semi-automatically by interrogating existing building information databases, seismic hazard and capacity catalogues. It is also capable of undertaking detailed screening assessments with the addition of parameters supplied by a suitably-qualified assessor. The
current beta-version software has shown that the system is capable of undertaking rapid vulnerability assessments.

Further development is currently underway to increase the number of building assessments in order to increase the typology capacity catalogue and build confidence in the statistical relationships for the typology parameters. The next phase of assessment system is the development of seismic retrofit concept design functionality, including a library of typical as-built and retrofitted details to be implemented as part of the cloud-based tool.

5. CONCLUSIONS

Extraction of gas has resulted in induced seismic hazard in a region with limited experience with earthquakes. It is now a matter of urgency to assess the life safety risk of approximately 25,000 dwellings to restore the safety of the population in the region. Traditional one-by-one seismic assessment of these addresses may not be practical when considering the labour, time and financial constraints. Consequently, an innovative cloud-based tool has been developed which enables a quick and reliable structural assessment.

The seismic assessment system relies on a significant library of pre-assessed non-linear capacity curves in order to enable engineers to make rapid seismic assessment of similar typologies and configurations of residential URM buildings. These non-linear capacity curves have been established on the basis of detailed seismic analysis of a sample population of URM houses using non-linear pushover (NLPO) and non-linear kinematic analysis (NLKA) procedures.

Rigorous experimental-analytical validation of the underlying detailed analysis used to develop a library of capacity curves has been undertaken. A number of full-scale building tests have been carried out at TU Delft and EU Centre (Pavia) as part of the analytical validation exercise.

Although still under development, the assessment system has shown that it is capable of undertaking rapid vulnerability assessments by interrogating existing building information databases, seismic hazard and capacity catalogues. Further development is underway to develop of seismic retrofit concept design.

7. REFERENCES


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