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How to assess 25,000 buildings

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ABSTRACT

Onshore gas extraction can result in induced seismic hazard in regions that have historically never been considered seismic zones. It is estimated that up to 150,000 addresses are within an area of influence of one large gas field. The building stock, which typically comprises unreinforced masonry buildings (URM), is therefore potentially vulnerable to earthquake loading. With up to 25,000 within the central zone, these buildings all require seismic assessment to ensure that there is no unacceptable life-safety risk to the occupants.

Undertaking the seismic assessment of up to 25,000 individual addresses within five years is unprecedented. Traditional building-specific seismic assessment of these addresses is not practical given the time and labour constraints. Conversely, assessment by region is not able to deliver building-specific assessment outcomes. Consequently, an innovative system has been developed that enables efficient and reliable structural assessment. The system relies on a substantial library of pre-assessed non-linear capacity curves that have been established based on a detailed seismic analysis of a sample population of URM buildings.

The methods used are versions of the non-linear pushover (NLPO) and non-linear kinematic (NLKA) analyses advocated in New Zealand guidance documents. These methods are used because they are proven and they provide a balance between solution accuracy and method complexity. The capacity library enables engineers to make rapid seismic assessments of similar typologies and configurations of residential URM buildings. Similarly, varying levels of assessment scrutiny can be applied to building typologies depending on their relative vulnerabilities.

1 INTRODUCTION

When gas extraction-induced earthquakes are emanating from beneath residential areas, there is clearly a need to assess the vulnerability of structures within an area of influence. If the residential and heritage buildings are predominantly of unreinforced masonry and there is considerable uncertainty in the Magnitude of future earthquakes, there are many challenges for the assessment process.

In one region it is estimated that approximately 150,000 occupied buildings have been affected by induced earthquakes to date. The governing body has been tasked with restoring safety within five years to the inhabitants of up to 25,000 house addresses located above the central zone of the gas field.

Therefore, there is now an urgent need to assess the seismic risk of buildings in the region, to strengthen the vulnerable buildings and minimise the risk exposure to the population. Undertaking seismic assessment and identifying necessary structural upgrades of up to 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 code outlines how existing buildings are to be evaluated for compliance with minimum safety levels and if found non-compliant, that retrofit measures need to be implemented. New annexes have also been introduced to qualify the use of non-linear pushover (NLPO) and non-linear kinematic analysis (NLKA) procedures for seismic assessment.

Optimised approaches delivering faster but consistent seismic assessments without jeopardizing the intent of the safety intent are necessary.

2 BACKGROUND

There are many challenges to undertaking seismic assessments of up to 25,000 addresses. The volume of assessments presents an obvious challenge; however, other challenges exist also. Ensuring consistency and appropriateness of outcomes between assessments is critical. As the assessments will take place over several years, there is also a need to include an ability to deal with new knowledge and information as it is received, 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 typically limited.

Considering these challenges, traditional assessment techniques are not well suited to this undertaking. A further complication is 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 tends to change over time. This presents a significant challenge for non-linear time-history analyses, where the output is explicitly linked to the hazard input.

To overcome these challenges, a rethink of how to undertake seismic assessment of a large-scale portfolio of buildings was required. This paper presents a system that allows for rapid seismic assessment utilising a typology-based approach. The system provides efficient, reliable and consistent assessment outcomes.

The optimised seismic assessment system has been developed by many technical consultants, with inputs and feedback from some of the top minds in earthquake engineering. The system relies on a series of modules to facilitate the seismic assessment process. These modules are facilitated by way of a web-based application that guides an assessor through a process.

The in-plane module relies on a library of pre-assessed non-linear capacity curves to enable engineers to make rapid seismic assessments of similar typologies and configurations of residential unreinforced masonry (URM) buildings. These non-linear capacity curves have been established from unique seismic assessments of a sample population of URM houses.

Instead of having to undertake a unique seismic assessment of every individual building, which can take a significant amount of time, it is possible to complete a seismic assessment in a matter of days using this typology-based system. The typology-based system is presented in Figure 1 compared to a traditional seismic assessment method.

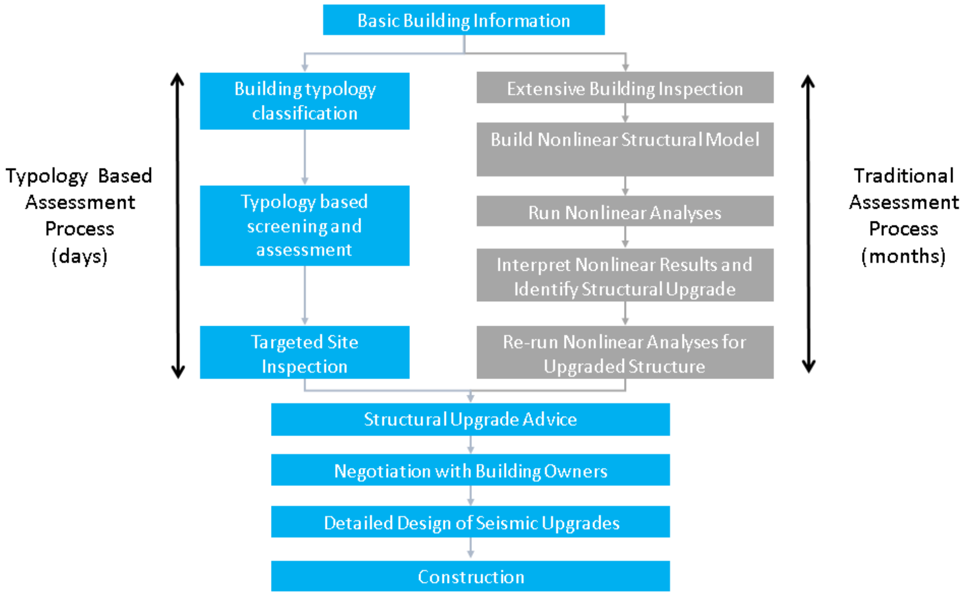


Figure 1. Comparison of typology-based and traditional assessment processes.

Building typologies have been established using simple identifiable features that are linked to the seismic performance of the building. Records for many of these features, e.g. floor type, have already been established and collected in a database. This approach makes it possible to undertake rapid seismic assessments utilising only fundamental building features. Further detail on this typology-based system 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. This assessment method also means that capacity is separated from demand, which addresses the issue of a changing seismic hazard.

2.1 NLPO

The assessment system requires a simplified analysis method 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; Moon et al., 2006; Anthoine et al., 1995; Magenes and Calvi, 1995).

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).

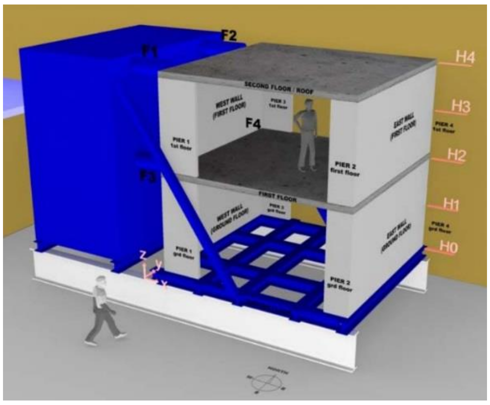
2.2 NLKA

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, which 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

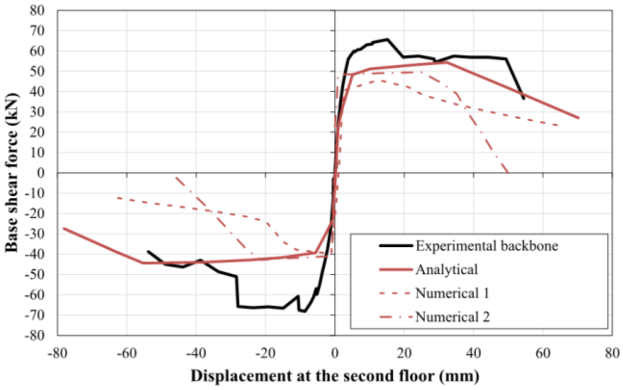
Auckland and University of Adelaide (NZSEE, 2017; Derakhshan et al., 2013). The NLKA method provides a balance between solution accuracy and method complexity; as such, it is a key part of both New Zealand (NZSEE, 2017) and Italian (NTC, 2008) seismic assessment guidelines.

2.3 Validation

The NLPO and NLKA analysis methods presented above are based on well-established principles and international literature (NZSEE, 2017, ASCE/SEI 41-13:2004) which have been calibrated to various existing experimental data. These procedures can generally be used with limited modification for undertaking seismic assessment of buildings. At the same time, a significant number of experimental tests have been carried out on unreinforced masonry construction (Messali & Rots, 2017). The experimental data from these testing programmes provides an opportunity for an experimental analytical validation of the governing code. One such validation exercise was undertaken at TU Delft, as shown in Figure 2. The NLPO and NLKA methods have demonstrated their feasibility and ability to predict the various experimental test results.



(a) Experimental test setup.



(b) Comparison of experimental backbone curve and blind prediction from SLaMA analysis.

Figure 2. Full-scale URM building test performed at TU Delft (Messali and Pair, 2017).

3 OPTIMISED SEISMIC ASSESSMENT SYSTEM

The optimised seismic assessment system is a means of undertaking accelerated building assessments of many relatively similar buildings. It facilitates a process for an assessor to enable consistent and compliant outcomes. The process is shown in Figure 3; each step is facilitated by a software 'module' and is described individually in the following sections.

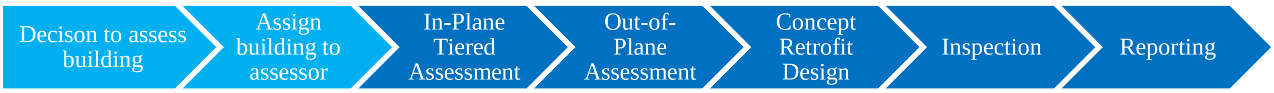


Figure 3: Building assessment process. Optimised seismic assessment process in dark blue.

3.1 In-Plane Tiered Assessment

The tiered assessment module is the technical core that delivers compliant in-plane seismic assessments for individual house addresses to the local seismic demand.

3.1.1 Tier Definitions

The tiered approach is shown diagrammatically in Figure 4. 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.

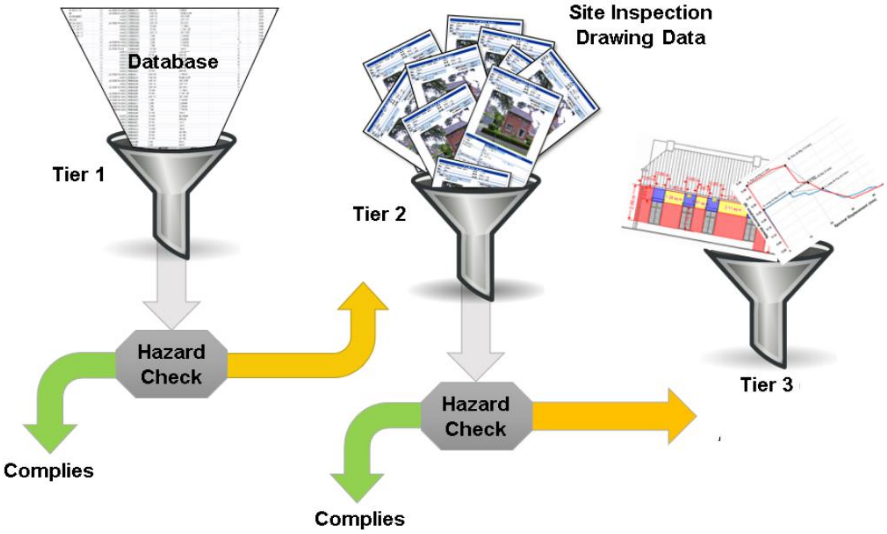


Figure 4. Schematic of tiered assessment process.

3.1.1.1 Tier 1: Typology Assessment

Tier 1 assessments can relatively quickly identify many 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. Tier 1 is based on basic typology assessments. Typology definitions have been developed from NLPO 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 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 Tier 1 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.

3.1.1.2 Tier 2: Typology Assessment

A Tier 2 assessment subjects houses, which have been indicated as potentially non-compliant by the Tier 1 assessment, to increased scrutiny to examine whether structural upgrading is required. The Tier 2 assessment process is like Tier 1 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. Any assumptions that are made to progress the assessment need to be subsequently confirmed on site upon completion.

3.1.1.3 Tier 3: Unique Seismic Assessment

Tier 3 seismic assessments are building-specific and used to assess buildings that are particularly complex, vulnerable and/or outside the capability of the current typology approach. Individual building assessments can be undertaken outside of the optimised assessment system by way of NLPO or a series of simplified Non-Linear Time-History (NLTH) analyses; however, the optimised assessment system includes an in-built analysis programme that facilitates rapid NLPO analysis of URM buildings by way of the SLaMA method. This in-built unique seismic assessment module enables semi-automated pier and spandrel definition, load takedown, capacity calculations and MDOF to SDOF transformations. An example equivalent frame definition from the unique seismic assessment module is shown in Figure 5.

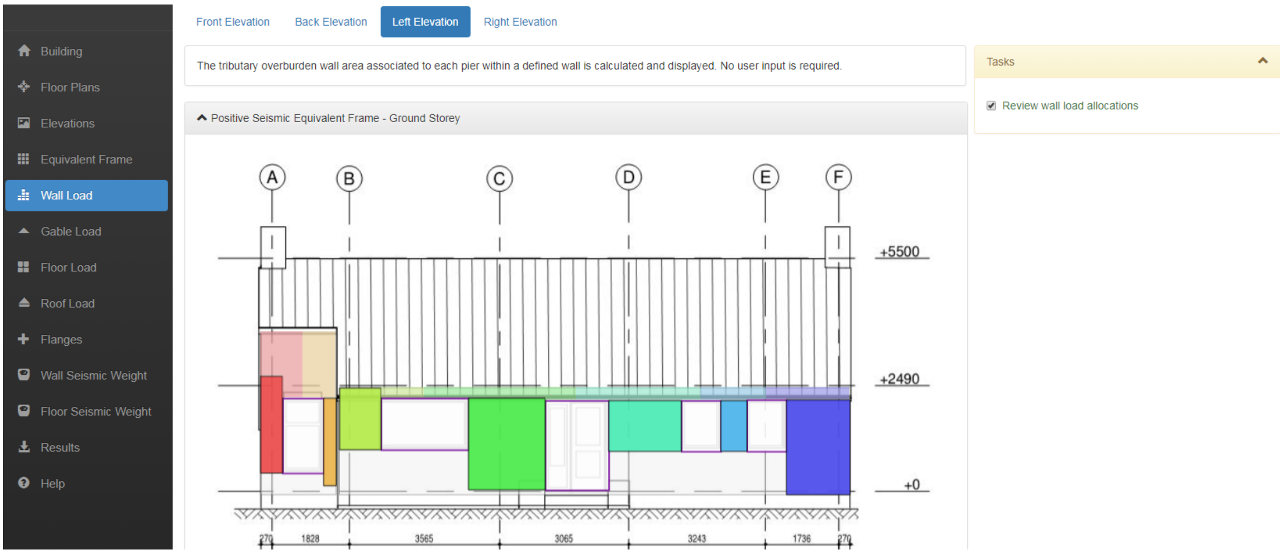
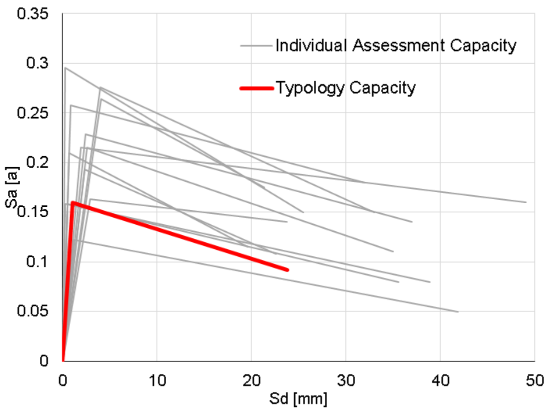


Figure 5: Unique seismic assessment module.

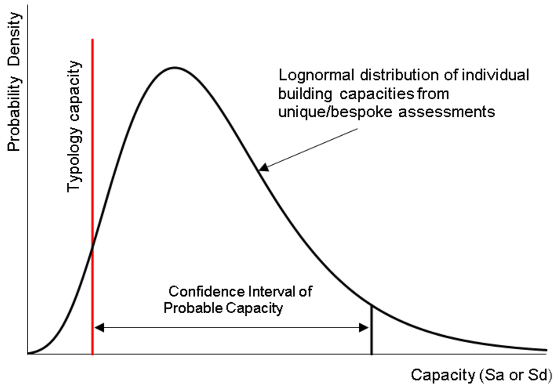
The in-plane assessment module is a learning system that becomes more intelligent with subsequent unique assessments. This occurs by the results of each building-specific assessment being fed back into the typology catalogue and, in doing so, the reliability and applicability of the system is improved.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

3.1.2 Typology Generation

It is helpful to visualize how the assessment data is used to develop the typology capacity curves. Shown in Figure 6 (a) are the in-plane pushover curves for one typology. The 'typology capacity curve' (shown in red) is established by a risk-based approach based on a statistical treatment of unique capacity curves that comply with the governing standards. The typology capacity is defined by the capacity estimate to achieve an acceptable confidence of the probable capacity, assuming a lognormal distribution of the individual building assessments, as shown in Figure 6 (b). A typology capacity curve must contain a minimum number of unique assessments and have an appropriate coefficient of variation to ensure compliance with the standards.



(a) Individual push-over capacity curves and typology capacity curve.



(b) Typology capacity curve from individual assessments distributed lognormally.

Figure 6. Establishment of typology capacity curves.

By using a tiered assessment approach, many 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 following a Tier 1 assessment, it may still be shown to comply by using a Tier 2 or 3 assessment. Tier 3 is less conservative than Tier 2, which is less conservative than Tier 1; as an assessor progresses through the Tiers, conservatisms are removed. If the Tier 3 assessment shows a building does not comply, conceptual retrofit advice can be generated to address the vulnerability.

3.2 Accelerated Out-of-Plane Assessment

Out-of-plane assessment is undertaken using NLKA and is accelerated by considering only the most vulnerable features of a building. The building features typically vulnerable to out-of-plane loading are presented in Figure 7. In most cases, there will be duplicate features in a building that need not be considered.

(a) Chimney. *(b) Gable.* *(c) Walls.*

Figure 7: Typical building features vulnerable to OOP loading.

In-plane and out-of-plane seismic assessment are decoupled in the optimised seismic assessment system; however, information is shared between the two engines to improve efficiency and simplify the process. This allows out-of-plane features to be semi-automatically defined from the geometrical building data already supplied. Data required for the assessment, such as overburden and slenderness, can also be prepopulated from the in-plane assessment module. However, it is the responsibility of the assessor to confirm the appropriateness of any automated data prior to proceeding; the optimised seismic assessment system facilitates an assessment process only, the assessor is ultimately responsible to assessment decisions.

Auto-generate Features | + Add Feature

		Masonry				Top Connection		
Feature	Edit	Leaf	Overburden	Demand $a_g S$ (g)	Capacity (g)	Demand (kN)	Capacity (kN)	Compliance
Generated Longitudinal Interior Wall on Ground Floor		Solid	770 N/m	0.205	0.29	4.4	12	Complies
Generated Longitudinal Exterior Wall on First Floor		Inner & Outer	770 N/m	0.205	0.23	7.8	-	Does not comply
T1 Transverse Interior Wall on Ground Floor		Solid	770 N/m	0.205	0.29	4.4	0	Does not comply
E1 Transverse Exterior Wall on Ground Floor		Inner	770 N/m	0.205	0.25	4.3	0	Does not comply
		Outer	0 N/m	0.205	0.21	3.6	0	
G1 Longitudinal Gable on First Floor		Inner & Outer	770 N	0.205	0.22	3.7	-	Reassessment required

Continue

Figure 8: Out-of-plane assessment in the optimised seismic assessment system.

An example of the types of features that might be considered in a building is presented in Figure 8. In the figure you can see the capacity determined from the NLKA and the demand from the local hazard for each feature and variation of a feature. The capacity and demand are determined for both the wall and the connections to the building.

3.3 Conceptual Retrofit

Where a building, or component of a building, is determined to be non-compliant the assessment process proceeds to conceptual retrofit. The conceptual retrofit module uses inputs from a catalogue of pre-engineered strengthening solutions for typical building details.

There are typically two categories of conceptual strengthening for each of in-plane and out-of-plane, which are listed below. There are multiple solutions available for each, which can be selected by the assessor depending on many factors such as house construction, cost, technical efficacy, homeowner preference, etc.

- Out-of-plane
    - Strengthening the wall.
    - Strengthening the wall to floor connections.
- In-plane
    - Strengthening to address a discrete wall vulnerability that effects overall building safety.
    - Global strengthening to address an overall building capacity deficiency.

The appropriate strengthening solutions are selected by the assessor and assigned to the deficient building element within the concept retrofit module, as shown Figure 9. The in-plane and out-of-plane modules are re-run to reassess overall compliance of the building with the retrofit solutions. This system allows an assessor to trial many different interventions rapidly to arrive at an optimised concept.

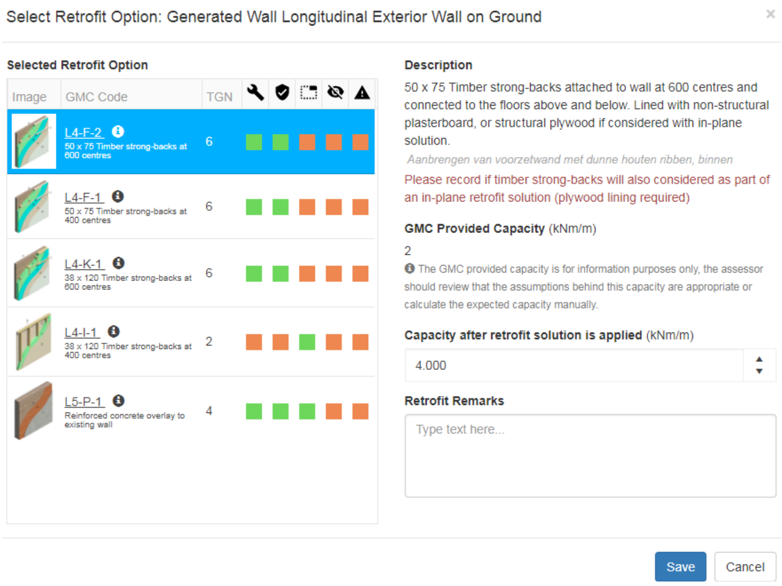


Figure 9: Conceptual retrofit in the optimised seismic assessment system.

3.4 Inspection

Near the end of the process an inspection of the building is undertaken. The purpose of this inspection is to confirm the assumptions made during the optimised seismic assessment. Site inspections are undertaken at the end of the assessment process because it is desirable to only visit an address once due to limitations on time and resources, as well as the social impact multiples visits might have on an occupant.

There are two possible outcomes of the site inspection.

- Assumptions confirmed: Proceed to reporting.
- Assumptions differ: Update assumptions in assessment and proceed to reporting.

A further benefit of the optimised seismic assessment system is that the assessment is completed prior to the inspection; therefore, an inspection can be targeted to only the features that are relevant to the building compliance. For a low vulnerability building that has demonstrated compliance at Tier 1, there may only be fundamental building characteristics, such as floor or wall construction, to be confirmed during inspection.

3.5 Reporting

Two reports must be prepared at the end of the assessment process. A technical report must be prepared for the territorial authority. This report will be a record of the assessment process undertaken, show compliance and, if required, inform the detailed design of the retrofit. Another report must be prepared for the homeowner to describe in plain terms the assessment outcomes, implications and options for engagement during subsequent detailed design.

Preparing these reports manually for up to 25,000 building addresses would be a laborious task; furthermore, it would be difficult to ensure consistency and quality across all buildings. Therefore, the optimised seismic assessment system facilitates automated report generation. The system uses the inputs supplied by the assessor during the assessment process to populate fields in various report templates and produce reports appropriate for the building assessed and the recipient.

3.6 User Interface

The optimised assessment system is facilitated by way of a web-based application, an example of the user interface is presented in Figure 10. The user interface is designed to intuitively guide an assessor through the assessment process and provides helpful and informative links, popups and tooltips.

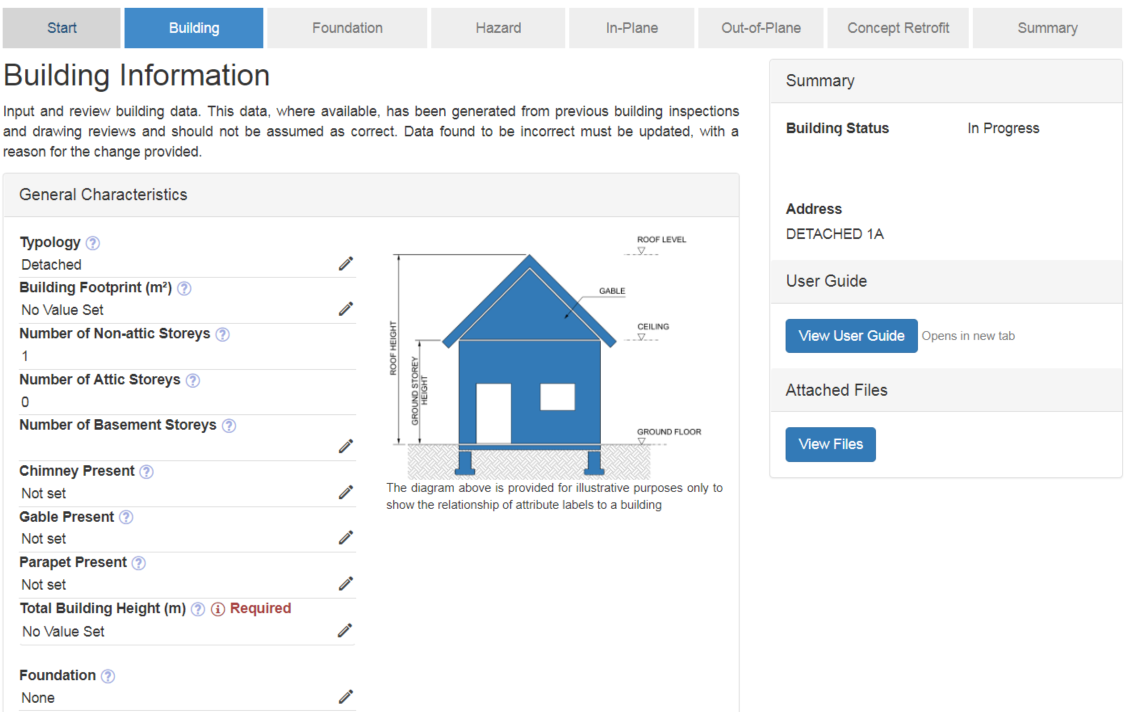


Figure 10: Optimised assessment system user interface.

3.7 System Development

The optimised seismic assessment system has been developed to a point where it is capable of facilitating the following via a web-based application.

- Tier 1 typology assessments semi-automatically.
- Tier 2 typology assessments with the addition of parameters supplied by a suitably qualified assessor.
- Tier 3 unique seismic assessments utilising an efficient in-built detailed seismic assessment module to undertake NLPO.
- Out-of-plane assessment.
- Conceptual retrofit using data from a catalogue of retrofit solutions.
- Automated reporting for various recipients.

4 CONCLUSIONS

Many buildings above a natural gas reservoir require seismic assessment and, if required, retrofit to mitigate the risk from induced earthquakes. This is a huge undertaking that 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 all stakeholders. Consequently, the innovative optimised seismic assessment system was developed to enable quick, consistent and reliable structural assessment. The process is facilitated by way of an intuitive web-based application.

The in-plane module relies on a significant library of pre-assessed non-linear capacity curves 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 based on detailed seismic analysis of a sample population of URM houses using non-linear pushover (NLPO) procedures. The out-of-plane module facilities efficient non-linear kinematic analysis (NLKA) of the most vulnerable building features. The conceptual retrofit module makes use of a catalogue of typical retrofit solutions to enable any non-compliant buildings, or parts of building, to be addressed and instantly reassessed to confirm compliance. The reporting module facilitates automated reporting for various stakeholders.

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 as part of the analytical validation exercise.

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