Practical examples of using qualitative assessment methods to assess the earthquake risk of historic structures in the Christchurch area

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ABSTRACT: The New Zealand Society for Earthquake Engineering recommends a qualitative procedure for assessing the earthquake risk of buildings. This procedure has become a requirement by both local authorities and building owners with the results holding more weight than was perhaps originally intended.

While the procedure is valid for the majority of building types, many historic buildings will fall into the lowest classification despite any qualities they may have. To remain in use the building will usually require a detailed quantitative assessment, which is often not feasible.

This paper considers that as historic buildings are often non-engineered, qualitative assessments are more appropriate than quantitative assessments. Three practical examples are presented.

The assessments use the principals of the NZSEE qualitative procedure and extend them to provide a comprehensive qualitative assessment. They aim to produce a more appropriate risk classification based on identifying past performance, historic and current use, structural qualities of weaknesses, damage causes, probable collapse mechanisms and highest risk elements. The assessments also enable the identification of a pragmatic approach for improving the building's performance.

The buildings assessed are all managed by the Department of Conservation and include: Fort Jervois on Ripapa Island (1880), The Sign of the Packhorse Hut (1916) and Godley Head Battery (1940s).

1 INTRODUCTION

Assessing the structural performance and earthquake-prone nature of the New Zealand building stock has been gaining importance over the years, with the update to the Building Act in 2004, the Canterbury earthquake sequence in 2010-11 and new legislation becoming law soon, this is set to continue.

The majority of guidance available relates to modern engineered buildings using modern materials. When this guidance is applied to historic or traditional non-engineered buildings without due consideration, the results can put the buildings at risk of heavy-handed alterations which are not structurally compatible or at worst detrimental to the existing structure.

An increased awareness of suitable approaches to the assessment of historic buildings is needed to reduce the risk facing New Zealand's historic buildings as the demand for assessments increases.

This paper presents practical examples of using appropriate qualitative assessment methods to assess the earthquake-proneness of three historic buildings. It is hoped that other assessors may find useful insights in the examples that can be applied to the assessment of other buildings and help protect New Zealand's built heritage.

2 REVIEW OF ASSESSMENT METHODS

The current accepted guidance which is set out in the document "Assessment and Improvement of the

Structural Performance of Buildings in Earthquakes" published by the New Zealand Society for Earthquake Engineering (NZSEE 2006), offers good general guidance along with procedures for two levels of assessment; the Initial Evaluation Procedure (IEP), a course qualitative screening process, which can be undertaken with few resources, and the Detailed Assessment which involves full quantitative analysis of the building. If the IEP results in an earthquake-prone building then the full Detailed Assessment is recommended to confirm the results.

The IEP gives a baseline score for the building based on a comparison to modern design codes and then allows some adjustment of this score based on engineering judgement. When considering historic buildings, they will immediately score in the earthquake-prone range due to the code comparison and therefore rely on engineering judgement or a quantitative assessment to score in the non earthquake-prone range.

A comparison of design codes such as this is inherently difficult for historic buildings as they were typically designed to a different philosophy. Many traditional-type buildings are not engineered to a design code but instead designed to rules of thumb by experienced craftsmen. This leads to redundancies, multiple load paths and low stresses, all of which can be beneficial to the building's performance and provide reserve capacity. It is not possible to consider any of these qualities in a simple comparison of design codes.

Similarly, when attempting a quantitative analysis of historic buildings these redundancies can quickly make any modern analysis complex and time consuming. To validate any such analysis material testing would usually be required adding further to the cost. Simply put, reverse engineering a non-engineered building is difficult. In many cases, such as small or low risk buildings, this level of analysis is not appropriate, economic or feasible.

Without code comparisons or quantitative analysis it remains that a comprehensive qualitative assessment based on engineering judgement is the most appropriate and valuable assessment tool for many historic or non-engineered buildings. It is this type of assessment that is presented here.

3 THE BUILDINGS

Figure 1. Fort Jervois

Figure 2. Sign of the Packhorse

Figure 3. Godley Head

The buildings included are all managed by the Department of Conservation who engaged URS to undertake seismic assessments of the buildings for submission to the Canterbury Earthquake Recovery Authority (CERA).

The buildings are all historic, unusual and low-occupancy with limited risk. They are exactly the kind of buildings that could suffer from poor understanding and lack of good engineering judgement, and good examples to take advantage of a comprehensive qualitative assessment.

The buildings are as follows:

- **Fort Jervois**, 1886, Figure 1: An island fort in Lyttleton Harbour built due to the 'Russian Scares' of the 1870 & 80s. The structure is a single storey bunker with four 'disappearing gun' emplacements built from a mixture of unreinforced concrete, stone and brick masonry.
- **The Sign of the Packhorse Hut**, 1916, Figure 3: A small back country rest house designed by architect Samuel Hurst Seager CBE, built from stone rubble masonry and situated between

Christchurch and Akaroa on Banks Peninsula.

- **Godley Head Coastal Defence Battery**, 1940s, Figure 2: A complex of reinforced concrete buildings built in the 1940s as part of the World War II coastal defence, which included a number of accommodation buildings, gun emplacements and bunkers.

4 ASSESSMENT METHOD OVERVIEW

The qualitative assessment method adopted for these buildings uses a holistic approach based on first principals. It considers the building's history, use, condition, performance and all other appropriate attributes to provide a reasonable estimate of the expected performance and likely failure mechanisms in future seismic events. The outline of the approach is as follows:

- Information Gathering
  - Desktop research
  - Building inspection
- Qualitative Assessment
  - Structural behaviour and load paths
  - Materials and condition
  - Damage assessment and failure modes
  - Risk assessment
- Recommendations
  - Building improvements

5 INFORMATION GATHERING

For any assessment gathering information is the first and one of the most important steps. This was found to be especially true when assessing these historic buildings. The information gathering was undertaken in two stages, firstly a desktop review of all available documents and secondly a building inspection. The more information that was gathered the more straightforward the assessment was found to be and so it is recommended to others that the value of this stage is not underestimated. In practice the next stage of qualitative assessment actually began in the back of the assessor's mind while gathering the information.

For modern buildings more reliance can be placed on the design drawings, which can be confirmed with a quick walk round the building. This, however, is rarely the case for buildings of any significant age as drawings, if any do exist, are unlikely to accurately portray the current state of the building. A review of a wide range of documents and detailed site inspections gave many useful insights into the buildings' past and present condition.

5.1 Desktop research

While a review of documents such as original drawings, specifications, alterations, assessments and seismograph records have obvious benefits, of equal importance was a review of the building's history. This can tell the assessor what the original purpose of the building was, what conditions the building has already experienced, previous uses and what alterations might have been made. It may also give indications of how the building has been maintained and its present condition.

For the above example buildings, an overview of their history was found with simple Internet searches, useful information was found on the DOC, NZHPT and IPENZ websites.

Fort Jervois was built by a prominent engineer Sir William Jervois and described as the strongest fort in the British Empire. This indicates it was built to a high standard and is not typical for the period. This was confirmed when reviewing the specification that contained many detailed drawings. The fort also contained four very powerful disappearing guns that had been fired (though not in anger). The recoil from such guns would have resulted in significant forces on the building, see Figure 4.

An historic photo of the Godley Head underground bunkers, see Figure 5, on the other hand proved useful at it indicated the construction methods used. Excavations were cut and cover for No.1 and No.2 bunkers and tunnelling for No.3. This was useful information not found on record drawings which provided an idea of the ground conditions.

With very little record information on the Packhorse Hut, the Internet search gave basic the details of Architect, date, construction materials, original purpose and layout. See Figure 6.

The review of information was undertaken prior to carrying out the inspections in order to determine which areas of the building were likely to be the most critical and need closer attention and which areas were missing information. This made the inspections more efficient. In the case of these examples they had all experienced considerable shaking during the Canterbury earthquakes and all were expected to exhibit damage. This review also enabled an estimate of where damage would be expected became useful to determine how the buildings actually behaved in response to the events.

Figure 4. Disappearing gun at Fort Jervois

Figure 5. Construction of the bunkers at Godley Head

Figure 6. Historic photo of Packhorse Hut

5.2 **Building Inspection**

The inspections aimed to get as much useful information about the building as possible in the time available. They were generally non-intrusive visual inspections and included:

- Taking and referencing photographs, at each elevation, room and key details.
- Comparing the building to existing drawings, recording alterations and confirming key dimensions.
- Recording the construction materials, their condition and the construction quality.
- Recording damage, its likely causes and potential repairs.

In the case of the Packhorse Hut, no drawings were available so the building was measured and sketched up on site. Since it was built from random rubble masonry that is well known to have a poor seismic response, the walls were inspected closely, looking at rebates and wall heads to determine the construction method, quality, typical stone sizes and wall thicknesses. A hammer was used to get an idea of the stone hardness and integrity as well as the strength of the mortar. Connections between the masonry and timber roof were investigated. A penknife was used to test the timber for rot or dampness. These are all relatively straightforward steps that help to build a picture of the building's structure and condition. Any cracks found in the masonry were assessed immediately on site to determine possible causes and effects in order to enable further as required.

For Fort Jervois it was clear that the drawings available were not accurate or to scale and so new drawings based on site observations were prepared. It was also necessary to determine if differences were subsequent alterations or not, as far too often damage to historic building is associated with poor alterations which change load paths or use incompatible materials. There was nothing to suggest that this was the case here, as usual clues in the materials, construction or detailing were not found.

In constructing Fort Jervois numerous different materials were used, with walls being constructed of dressed ashlar stone (both basalt and scoria), random rubble, brick or concrete, and the roof of railway sections joists with either concrete or brick jack arches between. The extent of all materials and their quality was noted where possible, however due to the fort's age it was suspected that wrought iron and lime mortars could have been used. Experienced material practitioners can usually tell by sight and so samples were taken off site for confirmation. The University of Auckland tested mortars, and a sample of the metal was taken to an experienced metal worker (both at no cost to the project). Identifying the construction materials was important in order to understand the damage and select appropriate repairs.

Fort Jervois had a significant amount of damage, it was clear that some was due to deterioration however it was not necessarily easy to determine the extent of earthquake damage. It was therefore considered important to record and categorise all the observed damage. This can be a time consuming task for a complex building such as this. A damage classification system was used to immediately classify the significance of the damage. This was recorded on site along with the likely causes, effects and possible repairs methods. It was found that doing this on site was efficient as it was far easier to determine these factors. The classification system used was that recommended by Historic Scotland (Historic Scotland 2000) and has three categories: Urgent, Necessary and Desirable. This level of coarse assessment tool was entirely appropriate for the initial inspections and proved an incredibly useful tool.

6 BUILDING ASSESSMENT

Having gathered all available information the qualitative assessment was undertaken with an aim to understand how the structure behaves, its likely failure modes and finally the risks associated with it.

6.1 Structural behaviour and load paths

The first step was to determine the load paths for transfer of both gravity and seismic loads. The most intuitive and straightforward way to do this was by sketching the layout and typical sections or elevations of the buildings. Going through this process of drawing was found to be a useful tool in understanding the structure, its qualities and weaknesses, with the added advantage that the sketches then made communication of the issues straightforward.

In determining the load paths the most highly loaded or stressed elements of the building were then identified and the requirements for connections between them assessed qualitatively.

In the case of a simple building, such as the Packhorse Hut, intuitive areas such as the chimney and gable walls were identified, but other areas such as the masonry above windows and the pier adjacent to the front entrance archway were also identified as potential weaknesses, see Figure 7.

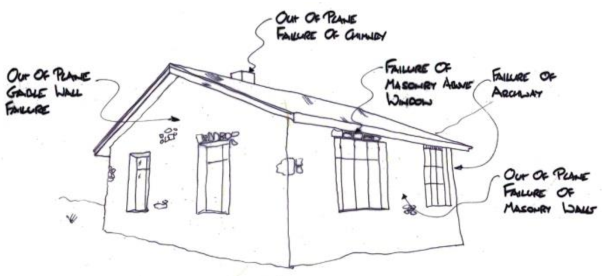

Figure 7. Packhorse Hut

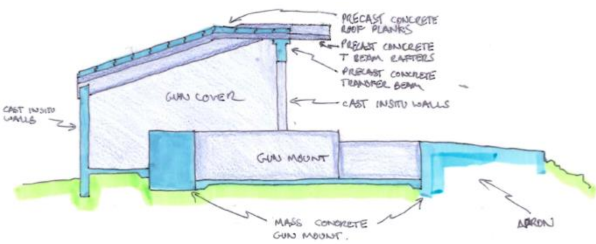

Figure 8. Section through Godley Head Gun Emplacement

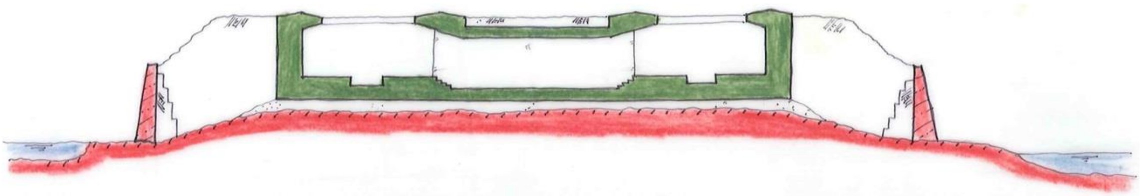

Figure 9. Section through Fort Jervois

At Godley Head the load path analysis of the bunker type buildings indicated they were incredibly robust. However, the overhead concrete gun shelters relied on connections between precast elements to remain stable, see Figure 8. These connections were quite clearly minimal and so were identified as critical structural weaknesses.

It was also important in this stage to keep in mind any alterations to the loads or load paths over the life of the building. For example, Godley Head and Fort Jervois were built to resist loads from both incoming and outgoing ordnance, and are known to have experienced the later. The structures are no longer required to resist these loads and therefore are likely to have inherent reserve capacity.

6.2 Materials and condition

Now aware of the load paths and the demands on the structural elements, the condition was assessed to determine if it would affect the capacity of that element to resist the demand.

For example would a lack of mortar in the rubble masonry walls of the Packhorse Hut affect its ability to withstand out of plane seismic loads? A simple first principal analysis suggests it would as this reduces the section depth, and reference to such resources as the University of Auckland research on masonry (Ingham 2013), the NIKER catalogue (NIKER) and the Attribute Score Method (NZSEE 2006) provided additional insights into the performance of various masonry wall types.

In the case of Fort Jervois would the deterioration of the railway section joist affect their ability to resist gravity or seismic loads? The load path assessments indicated only gravity is critical and some research to find railway section properties and reducing them to an estimated corroded section gave an idea of the current strength. Again looking at the load paths, it was clear that there were numerous redundancies in the structure such that if one joist did fail, the roof would not be likely to collapse.

6.3 Failure modes and damage analysis

Following determination of the load paths and the condition of the structures it was then possible to predict the lower bound failure mechanisms and consequently the likely damage. This predicted damage was then compared to the observed damage in an attempt to correlate the two. At this point it was also possible to identify what was likely or unlikely to have been earthquake damage.

For example, at the Packhorse Hut the failure mechanisms for the masonry walls and chimney were generally out of plane failure, either by toppling or buckling. No damage was observed that indicated these failure modes had initiated and so it can be inferred that "where no distress is evident the structure may have assumed to have withstood the test of time" (Bowman 1988). The damage that was observed at the window heads and the chimney top, however, did not equate to any predicted failure mode. Therefore the possible modes that would cause such damage were investigated and it soon became clear that the stone 'arches' at the window heads would be highly stressed under gravity loads and likely just to have settled as a result. On the other hand, the chimney damage was likely to have been primarily caused by weathering deterioration in its exposed location and then dislodged by the earthquake shaking.

Figu ween precast elements at Godley Head

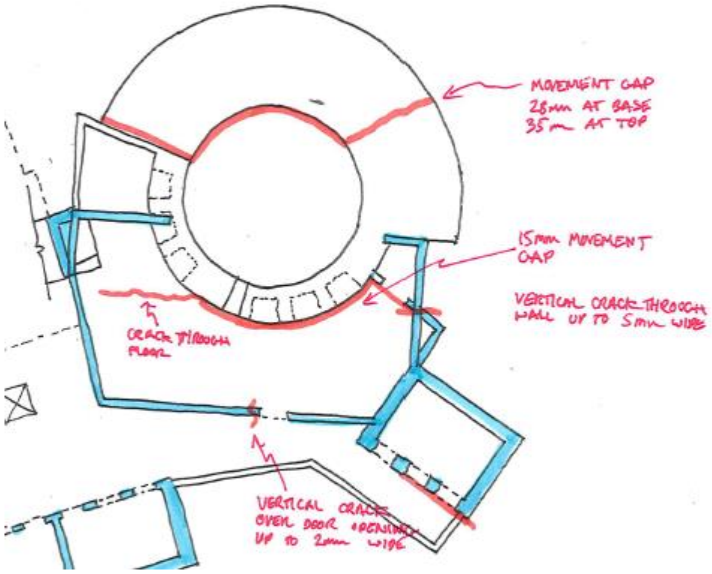

Figure 11. Movement of the ground at Godley Head

At Godley Head the weaknesses at the connections between precast elements identified in the load path analysis correlated with the observed movement of these elements, confirming that this mode was in fact one of the lower bound failures of the structure. See Figure 10.

A lot of damage and movement to the gun emplacements at ground level was also observed. The explanation for this became clear when plotting all the damage on a plan shown in Figure 11. The damage related to movement in one direction towards the cliff edge, which determined the failure mode was slope failure of the non-engineered fill material under the structure as identified in the historic photos.

Several of the most likely failure modes were identified for each building, with simple calculations or rules of thumb used to determine their severity.

6.4 **Risk Assessment**

With the critical seismic failure modes understood the likely risk to life can then be assessed. Factors considered included; if the failure had potential to harm life; the location, the occupancy; whether it would be a ductile or brittle failure; and would it cause progressive collapse.

The highest risk failure mode is then the lower bound for the building, and using simple calculations and engineering judgement it can be determined if this causes the building to be 'earthquake-prone'. It should be noted that due to the qualitative nature of the assessment, it was not thought appropriate to give more accuracy to the results other than whether the structure is earthquake-prone or not.

At Fort Jervois the likely failures included the collapse of internal single skin brick walls, falling spalled concrete of the roof, and collapse of the parapet walls. The risk assessment identified the parapet walls as the greatest potential risk to life. These walls were checked with basic calculations (Griffith 2013) and were found not to be earthquake-prone due to favourable proportions. Since the masonry was of high quality with good mortar strength and there were no signs of existing damage this result was considered appropriate. In addition, the fort is rarely visited which reduces the risk even further. The building was therefore not considered to be earthquake-prone.

In the case of Godley Head gun shelters the evidence of movement of the precast roof elements, the deterioration of the connections and likelihood of further ground movements suggested a high risk of failure of the shelter structures as a whole. These were therefore considered to be earthquake-prone. The bunker type buildings, on the other hand, were incredibly robust and were not likely to cause risk to life even with further small ground movements.

At the Packhorse Hut it was found that there were limited or no connections between the highest risk elements such as the chimney and the gable walls and the roof structure. Although they had performed satisfactorily to date, rubble masonry typically has poor behaviour and so without adequate connections the building was considered earthquake-prone.

7 IMPROVEMENTS

The assessment process identifies elements of all buildings that could be addressed to improve the performance of the building as a whole and reduce risk.

The first level of improvement was to return the structures back to at least as good as the original condition where possible, reversing any deterioration over their lifetime. Since the structures have proved the test of time the act of returning them to their original condition could be expected to give the buildings the same life expectancy again.

The second level of improvement was to provide additional resilience and reduce the likelihood of failure, improving on its original condition. When proposing any interventions careful consideration was given to the consequences to ensure that they were indeed improvements and ensure there were no adverse effects. For these buildings, any improvement to their performance was considered a positive outcome and therefore there was no requirement to quantify them. To avoid adverse effects to the existing structure load paths were kept as close to the original designs as possible, compatible materials were used and alterations to any existing structure were minimised.

The Packhorse Hut repairs to the stone masonry, such as repointing and stitching of cracks with 'helibars' were recommended to return the walls to their original condition. A new timber ceiling diaphragm and connections to the walls were also recommended to ensure all masonry elements were tied together and could distribute lateral loads efficiently. The advantage to this form of alteration was that little original fabric was removed as the ceiling was not original and in poor condition.

The Godley Head recommendations included re-waterproofing the structures to avoid further deterioration, local repairs to damaged concrete, provide new or additional connections between the precast elements and to monitor the ground movements.

For Fort Jervois there were extensive repairs that would be required to return the building to its original state. The classification system was therefore used to give options for three levels of repair: *Urgent* - repair required to maintain structural integrity of the building, *Necessary* - repair recommended prior to reopening to the public, *Desirable* - largely cosmetic repair to reduce future deterioration. Repairs typically involved repointing, stitching of cracks, masonry repairs, and removing or repairing spalled concrete or corroded iron structural elements.

Consideration was given to the improvements in order to protect the heritage and authenticity of the buildings, with special thought given to minimal intervention, reversibility and honesty. Guidance for working with heritage buildings was taken from NZHPT publications (McClean 2010) and is not covered by this paper.

8 CONCLUSIONS

It was found that by going through this comprehensive qualitative assessment process, the buildings, their history and likely performance were all readily understood. The more comprehensively each step was undertaken the easier it was to undertake the next, and by the end sufficient evidence and understanding was obtained to allow the correct engineering judgement to be applied in assessing the buildings likely performance. The added advantage was that appropriate improvement methods were available without additional work.

While these assessments typically took more time than say the Initial Evaluation Procedure, it was considered by all those involved that the outcome was valuable and appropriate for these types of buildings. It is recommended that others assessing similar historic buildings should carry out a similar form of qualitative assessment.

9 ACKNOWLEDGEMENTS

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