Improvements to state school building design including the implementation of low-damage design criteria

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ABSTRACT

The Ministry of Education (the Ministry) owns one of the largest property portfolios in New Zealand, with more than 15,000 buildings spread across nearly 2,100 state schools. Following the 2010 Canterbury earthquake sequence, the Ministry embarked on a significant capital works programme that is expected to continue to 2030 as part of the Ministry's wider School Property Strategy. As a long-term property holder, the Ministry takes a proactive approach to asset management, requiring new school buildings meet specific requirements that consider life-cycle costs, with a focus on repairability and usability after significant seismic events.

This paper presents the key design requirements that enhance the resilience and adaptability of the state school property portfolio, with specific focus on the Ministry's seismic performance criteria. State school design requirements are set out in the Ministry's Structural and Geotechnical

Requirements document. This document was first introduced in 2015 and represents the early codification of Low Damage Design, with successful implementation by designers of a number of school buildings. The latest version (version 3.0) released in October 2020 clarifies and builds on previous versions.

1 INTRODUCTION

1.1 Background

The Ministry of Education (the Ministry) owns one of the largest property portfolios in New Zealand, with more than 15,000 buildings spread across nearly 2,100 state schools. As a long-term property holder, the Ministry retains school property and the responsibility for the maintenance and repair of its buildings. Accordingly, the Ministry has a unique approach to asset management that includes consideration of resilience and life-cycle costs in the design of new school buildings.

The Ministry's structural and geotechnical design requirements, including unique seismic performance criteria, are set out in the Ministry's *Structural and Geotechnical Requirements* (Ministry of Education, 2020a) which form part of the wider *Designing Schools in New Zealand* suite of design documents. The requirements cover both new school building designs and the assessment and strengthening of existing buildings. At a high level, the requirements provide a basis for engineers and other designers to deliver cost-effective school buildings that meet the Ministry's expectations for safety, usability and life-cycle costs (including capital and operating costs, future maintenance obligations and anticipated repairs). These are specific Ministry requirements for state school buildings that extend minimum New Zealand Building Code (Building Code) requirements.

1.2 The Ministry's resilience journey

From the early 2000s the Ministry's approach to building resilience was to adopt a blanket Importance Level 3 (IL3) design requirement for all new school buildings. This had been the practice for many years prior, dating back to the Ministry of Works and technical guidelines from the early 1980s (MWD, 1985). The IL3 designation targeted life-safety performance in extreme events but did not necessarily preclude significant damage at lower levels of shaking that may render the building unusable. This approach resulted in more expensive buildings, but without assurance of good performance at all levels of shaking.

Following the Canterbury earthquakes, the Ministry put considerable effort into understanding the likely seismic performance of its school buildings, including establishing the Engineering Strategy Group (ESG). The ESG led research and full-scale testing on timber-framed buildings which are the predominant construction form across the Ministry's portfolio. The results of this work undertaken by BRANZ showed that timber-framed buildings are inherently seismically resilient and are considered a low life-safety seismic risk (Beattie et al, 2014). This was further supported in the Greater Christchurch Area where approximately 90% of all state schools were able to be re-opened within three weeks of the 22 February 2011 Canterbury earthquake, with only six schools needing to temporarily co-locate with other schools until remedial works could be completed (Ministry of Education, 2015).

A significant national capital works programme aimed at both the redevelopment of existing, and construction of new schools commenced shortly after the Canterbury earthquakes and is expected to continue to 2030 (Ministry of Education, 2020b). Early observation highlighted the trend towards foundation systems that were over-specified, sometimes incorporating ground improvement, adding often significant and at times unnecessary costs. This was considered to be at least partially a result of the loadings associated with the blanket IL3 policy, combined with inherent conservatism in design that followed from the Canterbury earthquakes.

Changes in teaching pedagogy has seen the shift away from standalone, single-storey, timber-framed school buildings to larger, open plan buildings of concrete and steel construction. The result is an increase in building complexity and risk profile, with greater post-earthquake remediation implications.

These factors combined with observations and lessons learnt from the wider industry following the Canterbury earthquakes created an opportunity to rethink how the Ministry should specify school building performance and whether a more cost-effective targeted approach could be achieved.

This paper briefly outlines the 'macro' and 'micro' provisions in the *Structural and Geotechnical Requirements* to provide resilient school buildings and then focuses on the seismic performance requirements and their relationship with the New Zealand Building Code.

2 MINISTRY RESILIENCE REQUIREMENTS IN OVERVIEW

The *Structural and Geotechnical Requirements* sets out a range of requirements that enhance the resilience and adaptability of the property portfolio. At an overarching or 'macro' level, these include:

- Specific state school performance requirements that extend minimum building code performance requirements. In addition to the protection of occupants, larger school buildings are required to remain usable after a reasonably foreseeable natural disaster, with repairs being able to be carried out within reasonable timeframes. This requirement is not only for the primary structure but extends to non-structural elements (such as the cladding, ceilings, partition walls, and building services).
- Comprehensive site-wide geotechnical investigation, analysis, and reporting prior to any bulk and location planning or design commencing, including the requirement for use of the New Zealand Geotechnical Database (NZGD) for all projects. This enables long-term, site-wide planning that maximises the geotechnical opportunities and reduces potential future damage to buildings due to hazards such as flooding and ground movement.
- Specific requirements for how hazard information is gathered and reported, and how project documentation is presented and recorded .
- Risk-based foundation considerations to encourage the use of Settlement-Tolerant Building principles to enable construction in situations of settlement-prone ground with economic shallow foundation systems, where appropriate.
- Encouraging specific engineering analysis and design that does not rely upon some of the more conservative approaches that are embodied in non-specific design codes (e.g., NZS 3604) and Verification Methods.

More specific detailed ('micro') requirements include:

- Specific drift limitations for the primary structural system to ensure repairability after a significant event (SLS2 loading) and to support continued use.
- Ductile detailing of all significant load-bearing elements (column and wall elements) in multi-storey buildings for improved resilience against larger earthquakes.
- Provision of additional superimposed load to allow for reasonable changes to the building over its lifetime (e.g., changes to floor linings, addition of acoustic ceiling tiles).
- Guidance on the use of heavy and brittle cladding, particularly for buildings located in high seismic zones or on settlement-prone ground.
- The protection of partition walls by limiting seismic drift of the primary structure to less than the drift which causes onset of damage, or by providing seismic protection to the partitions (such as sliding head restraints combined with appropriate detailing at partition junctions).

- Requirements for glazing systems to be designed with sufficient clearance to accommodate the full lateral displacement implied by the design level wind or earthquake, with allowance for inelastic drift calculated in accordance with NZS1170.5 (Standards New Zealand, 2004).
- Performance requirements for non-structural elements at different levels of shaking in order to satisfy overall performance expectations.

3 RECAP ON NEW ZEALAND BUILDING CODE PERFORMANCE REQUIREMENTS

Minimum building performance requirements are outlined in clause B1 of the Building Code (New Zealand Building Code, 2018). The overarching structural requirements are:

> **B1.3.2** *Buildings, building elements and sitework shall have a low probability of causing loss of amenity through undue deformation… throughout their lives….; and*
>
> **B1.3.1** *Buildings, building elements and sitework shall have a low probability of rupturing, becoming unstable, losing equilibrium, or collapsing… throughout their lives.*

The Structural Design Actions Standard (NZS1170.5) provide a means for the design of structures to meet these requirements. For regular buildings of Importance Level 2 (IL2) and IL3 such as school and office buildings the earthquake limit state design performance requirements in NZS1170.5 are:

- to avoid damage to the structure and the non-structural components that would prevent the structure from being used as originally intended without repair after a serviceability limit state 1 (SLS1) earthquake (an earthquake corresponding to a 25-year return period for both IL2 and IL3 buildings);

and

- to maintain overall structural integrity and gravity load support under ultimate limit state (ULS) loading (an earthquake corresponding to a 500 or 1000-year return period for an IL2 and IL3 building respectively). There are also additional requirements for parts and non-structural systems required for building evacuation.

An intermediate level of performance is only required for Importance Level 4 (IL4) structures with critical post-earthquake designation (e.g., fire and police stations and buildings designated as emergency centres). The Building Code requires these buildings to be maintained in an operational state, or be returned to a fully operational state within an acceptable short timeframe after an SLS2 earthquake.

While the higher ULS return period for IL3 structures provides greater strength against structural collapse and life safety at high levels of earthquake shaking, there are no intermediate performance requirements between SLS1 and ULS. Hence an IL2 or IL3 building that satisfies the Building Code may be heavily damaged, and potentially require demolition, at a level lower than the ULS level of earthquake shaking, even though it remains safe for occupants.

The Building Code represents the minimum acceptable legal requirements, and the adoption of performance requirements that meet and exceed the Building Code is permitted, and is increasingly becoming more common.

4 STATE SCHOOL PERFORMANCE REQUIREMENTS

A school is a central part of its community and has an important role to play in the aftermath of an event, even though schools are not designated as critical post-earthquake buildings. This general recognition for the need to provide resilience is beyond the minimum performance requirements in the Building Code, which more broadly target life-safety, and is addressed in the Ministry's *Structural and Geotechnical Requirements*.

Resilience is a broad term and can be defined as the ability of a community to survive, adapt and grow, no matter what the circumstances. The principal engineering objective for school buildings is to be operational as quickly as possible after a significant event, even if repairs are required, and to do so in a manner that makes the best use of available resources. The *Structural and Geotechnical Requirements* set clear high-level performance objectives that requires designers to consider the levels of damage that may occur in different levels of shaking, and for the different building forms and uses.

4.1 Seismic performance requirements

The Ministry's seismic requirements for state school buildings are outlined for three levels of earthquake shaking, broadly characterised as follows:

- Minor earthquake shaking that can be expected to occur several times during the life of the building;
- Significant earthquake shaking that can be expected to occur on more than one occasion during the life of the building; and
- Major earthquake shaking that can be expected to occur at least once during the life of the building.

These levels of earthquake shaking correspond to the serviceability and ultimate limit states (SLS1, SLS2 and ULS).

4.1.1 Minor earthquake shaking

For *minor* earthquake shaking (corresponding to a 25-year return period, or SLS1 design levels), the performance requirements in B1.3.2 in relation to amenity apply, with the following clarifications and additional Ministry requirements:

1. The building structure must have <u>no significant reduction in capacity</u>;
2. The non-structural elements of the building must remain <u>intact and attached to the structure</u>;
3. Mechanical, electrical and hydraulic services must remain <u>fully operational</u>;
4. The building must retain <u>functional</u> connections to the overall site services reticulation system;
5. A building should only suffer *readily repairable* damage that does not affect the continued use of the building. Such repairs should be able to be completed either immediately; or in conjunction with normal building maintenance activities (i.e., the building damage is sufficiently low enough that the continued use of the building is not affected while repairs are pending).

4.1.2 Significant earthquake shaking

For *significant* earthquake shaking (corresponding to 100 and 250-year return periods for IL2 and IL3 respectively, or SLS2 design levels), the Ministry has requirements that go beyond the current requirements in the Building Code.

The following performance criteria shall be met following a significant earthquake:

1. Any reduction in capacity of the structure should not compromise its ability to undergo a subsequent ULS event with acceptable performance;
2. The non-structural elements of the building must, in the main, remain intact and attached to the structure, with no impact on safety or access and egress;
3. Mechanical, electrical and hydraulic services that are essential to the continued use of the building either must remain functional, or are designed in such a way to be reinstated or otherwise re-provisioned in an acceptable manner;
4. The building must either retain functional connections to the overall siteservices reticulation system, or be reconnectable or otherwise supplied with such services in a timeframe to be agreed with the Ministry;

5. The building may suffer *tolerable damage*, which is defined as when the building may continue to be used for its intended purpose, but with some reduced amenity, including:
   - Reduced mechanical and electrical function, provided that all building warrant-of-fitness elements remain operational.
   - Loss of function of other non-structural elements that does not impact on safety or access.

   While some reduced amenity is allowable, there should be a suitable margin of resistance to the impact of deformation under a subsequent ULS event;
6. Repairs should be able to be implemented over a standard holiday break, although off-site work, planning and consents may be undertaken outside that period.

4.1.3 Major earthquake shaking

For *major* earthquake shaking (corresponding to a 500 or 1,000-year return periods for IL2 and IL3 respectively, or ULS design levels), the performance requirements in B1.3.1 in relation to life safety apply, with the following additional Ministry requirements.

1. The connections to the overall site services reticulation system should be repairable in a practical manner; and
2. It is desirable that, following a ULS event, a building that is otherwise lightly damaged does not require demolition due to irreparable damage to the foundations. The foundation system in a building should not be the weak link in the hierarchy of damage and there must be an identifiable repair or recovery strategy, provided that the associated cost is acceptable to the Ministry.

4.1.4 Performance criteria for specific building elements

It is recognised that it is possible for designers to interpret and apply some Ministry building performance criteria differently in relation to specific building elements. While it is impractical to cover every situation, more detailed guidance on the behaviour of individual structural and non-structural elements is provided in Appendix A of the *Structural and Geotechnical Requirements.*

This is provided in two parts. The first part, governing the performance of structural elements, is intended to provide designers with guidance as to acceptable outcomes at SLS1, SLS2 and ULS shaking levels, for buildings that are otherwise designed to the Verification Methods of the building code. This may require some adjustment of design acceptance criteria but otherwise assumes a conventional design approach, with allowance for ground quality, and whether buildings incorporate re-levelling capability. The second part governs non-structural elements and may impose additional limits on deflection and possibly the selection of equipment which will be required to be operable after a given level of shaking.

Designers are otherwise able to use first principles and/or use specific design of non-structural elements, such as partitions, in order to demonstrate compliance with the requirements directly.

4.2 Implementation of seismic performance requirements

To ensure general consistency of the application of the Ministry's performance requirements, guidance is provided for the use of seismic design loads and return periods, repairability limits, usability and the post-earthquake inspectability.

4.2.1 Seismic design loads and return periods

Seismic design loads for SLS1 and ULS shall be as stated in NZS1170.5. Seismic design loads for SLS2 shall be generally as defined in AS/NZS1170 for IL4 buildings, as modified by the *Structural and Geotechnical Requirements* to cover school building uses.

The importance level and associated return period requirements with examples of how they relate to state school buildings are shown in Table 1.

The selection of the SLS2 return periods of 100 and 250 years for an IL2 and IL3 buildings, respectively, reflects the relative NZS1170.5 SLS2 to ULS loading to that which is used for IL4 buildings (SLS2/ULS ratio ~ 0.5).

Table 1: Importance levels and return periods for seismic design of school buildings.

Description	Importance Level	School Building Use	Return Periods		
			SLS1	SLS2	ULS
Low risk associated with human life, or economic, social or environmental consequences	IL1	Small ancillary buildings that are not usually occupied (e.g., isolated garages) and < 30 m^2.	n/a	n/a	100 years
Medium risk associated with human life, or economic, social or environmental consequences	IL2	Larger ancillary buildings (e.g., Boiler Houses and standalone administration offices)	25 years	n/a	500 years
		Buildings of lightweight construction, with less than 250 occupants in a block	25 years	100 years[1, 2]	500 years
		All buildings of heavy construction, with less than 250 occupants in block	25 years	100 years[1]	500 years
High risk associated with human life, or economic, social or environmental consequences	IL3	Buildings of lightweight construction, with 250 or more occupants	25 years	250 years[1, 2]	1000 years
		All buildings of heavy construction, with 250 or more occupants	25 years	250 years[1]	1000 years
		Assembly halls, gymnasiums, performance arts buildings, etc. where occupants may congregate	25 years	250 years[1]	1000 years

Table 1 Notes:

1. For buildings on potentially liquefiable soil this SLS2 return period should be regarded as 'indicative', given that in some cases the trigger point for soil liquefaction within a significant portion of the soil column (and which is expected to result in non-trivial building deformation) may occur at a return period other than 100/250 years.
2. For secondary structural and non-structural elements only with the objective of ensuring that buildings will be usable following such an event, even if requiring subsequent repair.

4.2.2 Repairability limits for primary structural elements

Designers of school buildings should ensure primary structural elements are designed to limit SLS2 displacements to the lesser of the repairability limits provided in Table 2 and the limits determined by deformation compatibility of non-structural elements that are reliant on the primary structure for support.

Table 2: Guidance on repairability drift limits for primary structural elements

Material/System	Element	SLS2 Repairability limit
Concrete or structural steel	Ductile moment frame (μ≥3)	0.8% (1 in 125)
	Non-ductile moment frame (μ≤1.25)	0.42% (1 in 240)
	Ductile shear wall	0.4% (1 in 250)
	Non-ductile shear wall	0.2% (1 in 500)
Structural steel	Ductile moment frame	0.8% (1 in 125)
	Ductile braced frame	0.8% (1 in 125)
	Limited ductile or non-ductile braced frame	0.2% (1 in 500)
Structural timber	Frame systems	0.8% (1 in 125)
	Braced frame systems	0.2% (1 in 500)
Wall systems	Timber or metal-stud framed wall systems	0.5% (1 in 200)
	Concrete block wall	0.3% (1 in 333)

4.2.3 Usability following subsequent earthquakes

The Ministry's performance criteria essentially require a building to have sufficient capacity to undergo a SLS2 event and a ULS event, consecutively. While this may at first seem onerous, it is important to consider the difference between the design ductility demand and the actual ductility capacity of a system. For most situations, no additional capacity will be required, but there may be a need to evaluate member ductility, particularly in cases where settlement is significant.

Consider first a building that is not expected to undergo any significant differential settlement in a SLS2 earthquake. In this case, a building should undergo little or no inelastic displacement as a consequence of the shaking, if it is to satisfy SLS2 criteria. Hence there will be no significant residual drift and therefore no reduction in the ULS deformation capacity of the building. No additional work would be required in these cases. Moreover, the displacement capacity is inherently built into a modern building by virtue of compliance with the special seismic design clauses of the material standards, which include deemed-to-comply provisions in order to ensure survival of a significantly greater event than the design earthquake.

In the case of a building on more settlement-prone ground (e.g., from seismically-induced soil liquefaction), there may be significant displacement of the ground and this must be assessed. The assessment should consider the residual displacement imposed onto the primary lateral load resisting system of the building and/or its foundations, independent of the deformation caused by the lateral loading, but with similar effect. If the residual deformation significantly reduces the available capacity of one or more elements, then it may in turn significantly impact the overall building capacity.

Depending on the number and distribution of lateral load resisting elements (i.e., the level of redundancy) this may require mitigation and/or may trigger the requirement to relevel to restore capacity.

There are a number of different approaches that could reduce the potential impact of differential movement and/or mitigate its impact including:

1. By detailing for reserve ductility capacity in excess of what is required for the same structural system on ground where significant settlements are not expected.
2. By using systems that have a suitable degree of redundancy such as using well distributed multi-bay moment resisting frames, which are slightly over designed. This will minimise the impact of differential settlement in a single location as to the extent that the reduction in capacity from the loss of one or two bays only of a frame may not represent a significant reduction in overall capacity.
3. By specifically evaluating the potential member ductility demand that is imposed by the settlement and ensuring that the additional member demand has no significant impact on the system demand.

The above requirements should be followed through in the detailing of secondary structural and non-structural systems that may impact on life safety.

4.2.4 Requirements for repairability and inspectability

Repairability is the ease and ability to identify damage and repair a structure and is a key requirement for state school buildings, particularly for those designed to accommodate potential foundation movement.

For a building to be considered repairable, a practical and specific means of implementation must be available and should consider both structural and non-structural elements such as the potential impact on building services.

Designers also need to consider how foundation and superstructure elements of the building can be readily inspected after triggering events to ascertain what damage has been incurred and repairs that are necessary. Such considerations need to be coordinated with the architect and other relevant designers and outlined in the Design Features Report (DFR).

5 APPLICATION IN PRACTICE

5.1 Use of the Guidelines

The *Structural and Geotechnical Requirements* has been widely adopted by most designers of state school buildings since the initial publication in 2015. The uptake and use is also attributed to the establishment of the Ministry's Design Review Panel (DRP) and the embedment of the Design Review as part of the Ministry's wider quality assurance process. The DRP was established in 2014 to provide independent quality assurance on the design aspects of major school redevelopments and new school projects. The DRP provides a multi-disciplinary and common approach to the evaluation of state building designs, and helps ensure a consistent approach to design is achieved across New Zealand schools (Ministry of Education, 2020c).

Design reviews occur at several stages throughout the design process and are mandatory for all projects greater than $3 million in capital value, and for complex projects irrespective of capital value. Many design issues and lessons emerge from these reviews which are used to target industry training and future revisions of Ministry guidance documents. Most of these issues are common to New Zealand buildings generally, and apply to both new building designs as well as the assessment and seismic strengthening of existing buildings.

The implementation of the *Structural and Geotechnical Requirements* has seen a general shift in the design of new school buildings towards lightweight, steel structures (stiffened portal frame and/or braced frame lateral systems) on shallow concrete foundations.

Several case studies are proposed to be completed to provide quantitative cost comparisons to minimal building code requirements. This will inform other current discussion around the implications, costs and benefits of low-damage seismic design.

5.2 Relationship with other low-damage design guidance

There is a current joint project underway, supported by MBIE and led by Engineering NZ, with the input of SESOC (as lead Technical Society), NZSEE and NZGS, to prepare a New Zealand guidance document for Low-Damage Seismic Design (LDSD). The LDSD guidance will continue to be monitored by the Ministry and is likely to be referenced directly in future revisions of the *Structural and Geotechnical Requirements*.

While the *Structural and Geotechnical Requirements* is focused on state school buildings, the principles and provisions can be applied to buildings in other ownership contexts and situations, noting that it is not comprehensive in the scope and scale of buildings and systems that are addressed.

6 CONCLUSIONS

State school design requirements that exceed minimum Building Code requirements are set out in in the *Ministry's Structural and Geotechnical Requirements* document. This document was first introduced in 2015 and represents the early codification of Low-Damage Design, with successful implementation by designers of a number of school buildings. Several case studies are proposed to be completed to provide quantitative cost comparisons to minimal building code requirements. This will inform other current discussion around the implications, costs and benefits of low-damage seismic design. While the *Structural and Geotechnical Requirements* is focused on state school buildings, the principles and provisions can be adapted and applied to buildings in other ownership contexts and situations.

7 ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution to the *Structural and Geotechnical Requirements* by previous Engineering Strategy Group and Design Review Panel members.

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