# DEALING WITH BUILDINGS LIKELY TO BE UNSAFE IN EARTHQUAKE - TECHNICAL CONSIDERATIONS

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## SUMMARY

This is a companion paper to that by Cashin et al [Ref 1] and provides information on technical issues addressed in shaping legislation covering New Zealand buildings likely to be unsafe in earthquake.

The New Zealand earthquake engineering community is conscious of the poor performance of some buildings in major earthquakes overseas, particularly those with critical structural weaknesses. New Zealand buildings are likely to show similar performance, especially those designed and constructed prior to 1976, when more stringent ductility and capacity design provisions were introduced.

Legislation exists in New Zealand to improve the structural performance of unreinforced masonry (URM) buildings (built prior to 1935), but what should be done about buildings built after 1935? In the last five years, a Study Group of the New Zealand Society for Earthquake Engineering (NZSEE) has examined the issue on behalf of the New Zealand Building Industry Authority (BIA) who are responsible for New Zealand's Building Act which governs safety of buildings.

Changes to the Sections of the Act dealing with earthquake-prone buildings are proposed with the intention of extending legislation to cover all buildings except houses and small apartment blocks. But how, why and to what extent should these buildings be subject to legislative requirements? Answering these questions required analysis of some key technical aspects.

This paper outlines the approaches taken and results of investigations into the following technical aspects:

- Development of guidelines for improving structural performance of existing buildings.
- Identification of buildings likely to be affected.
- Assessment of the proportion of buildings affected.
- Assessment of benefit/cost of mitigation for various building types and locations.
- Development of a Rapid Evaluation Method (REM) based on age, type, critical structural weaknesses and comparative performance against current Code requirements.
- Testing of the REM on a range of Wellington buildings.

Though not part of proposed changes to the Act the work included:

- Development of a simple building grading system for seismic risk - suitable as a basis for seeding a market forces approach to the reduction of risk over time.

**The investigations showed that:**

- Benefit/cost analyses provide insights into the issue of acceptable risk.
- Simple evaluation methods were developed.
- Worthwhile benefit/cost ratios were indicated for regions of high seismicity in New Zealand.
- The grading scheme has the potential to contribute strongly to earthquake risk reduction over time.
- The issues encountered, approaches taken and conclusions should be of interest to all countries who have concerns about the earthquake risk of their current building stock.

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## GUIDELINES FOR IMPROVING STRUCTURAL PERFORMANCE

In June 1996 a draft set of guidelines [Ref 2] was issued. The aim of this document was to provide a means of meeting the requirements of a revised New Zealand Building Act, extended to cover all buildings except houses and small apartment blocks.. It was intended that the guidelines would ultimately become a means of compliance within the New Zealand Building Code framework.

The draft document includes provisions for assessing the capability of existing buildings to reach an adequate level of seismic performance and also provides guidance on improving the seismic performance to a minimum level. A rapid method of assessment of buildings is provided but this has since undergone some development as described below. Specific guidance is given on loadings and methods of assessment and performance enhancement for reinforced concrete and structural steel buildings.

A strength of the Draft Guidelines is that a definitive link is provided to NZS 4203 [Ref 3], the New Zealand Loadings Standard for new buildings. A comparison with new buildings is therefore self evident and the risk implications of the adopted standard are clear.

Subsequent work, as described below, showed that further development and updating of these guidelines is required. Other common materials and building systems need to be included and the focus of the assessment provisions needs to be directed towards overall building performance rather than the performance of individual members.

## BUILDINGS AFFECTED

### History of Building Development

*Before 1935* - a) Commercial buildings were generally constructed of unreinforced masonry; b) there was little or no consideration of earthquake effects.

*From 1935 Until 1965* – a) Buildings became increasingly larger (higher); b) lateral strength was provided based on a load distributed uniformly up the height, c) the same loading applied in all parts of the country; d) there were no specific provisions requiring ductile response.

*From 1965 until 1976* – a) Buildings were designed for variable lateral load according to seismic zone; b) design lateral load did not vary with building type and ductility; c) there was no mandatory detailing to enable ductile response; d) there were general requirements only covering desirable structural configuration.

*Since 1976 – a)* Buildings have been designed for variable lateral load according to seismic zone; b) design lateral load varies according to building type and ductility; c) appropriate detailing is required to achieve assumed ductility; d) guidance is given as to acceptable structural configurations; e) capacity design principles have been formalised.

There have been only minor refinements of the fundamental concepts since 1976 which is regarded as the onset of “modern” standards for earthquake design in New Zealand.

### Critical Structural Weaknesses

Reconnaissance visits mounted by the NZSEE to the scenes of major earthquakes over the past two decades have resulted in a consistent message regarding the vulnerability of structures designed prior to modern standards (i.e. 1976). Buildings with critical structural weaknesses are invariably found to have performed the worst, with sudden and brittle member failures leading to overall collapse at relatively low levels of ground shaking. Injuries and fatalities have resulted.

*Critical structural weaknesses include* – a) Poor building configuration, and in particular stiffness and strength irregularities that can generate an unsustainably high concentration of seismic forces; b) inadequate separation from other buildings. Refer Table 2.

## BENEFIT COST ANALYSIS

This section describes the methodology and some results of analyses of benefit/cost (B/C) ratios which could be expected from the strengthening of pre-1976 buildings to improve their performance in earthquake [Ref 4, 5].

Analyses were restricted to:

a) all buildings of four storeys or more in Wellington;
b) those buildings in a) with critical structural weaknesses (termed High Risk Buildings (HRB));
c) buildings similar to b) in other parts of New Zealand.

A wide range of factors was included, notably building condition and seismicity. Calculations were done using both "annualised" probability and "conditional" probability (for which a M7.5 earthquake was assumed to occur at 1, 2, 3…… up to 50 years after mitigation).

For the annual probability approach, worthwhile B/C ratios resulted for Wellington, especially for buildings with critical structural weaknesses. Conditional probability considerations greatly increased B/C ratios, values depending on the time to the major earthquake.

Comparative benefit cost ratios for other centres in New Zealand were examined by analysing HRB's in Auckland, Hamilton, Christchurch and Dunedin.

Variables considered in the analysis were Casualty Costs; Building Replacement Costs; Total Building Area; Replacement of Building Stock; Occupancy; Damage Ratios; Casualty Rates (Injury vs. Damage ratio); Fatality Rates (Fatalities vs. Damage Ratios); Seismicity (Annual or Conditional Probability); Retrofit Costs; Discount Rate; Assessment Period (taken as 50 years); Retrofit Period (taken as 10 years); Business Interruption (BI) Cost Factor (taken as a multiple of physical damage costs) and a Societal Disruption Cost Factor (also a multiple). Sources of base data included references 6, 7 and 8.

Results of analyses based on annual probability are shown in Table 1.

**Table 1: Benefit Cost Ratios and Savings for Various Cases**

| KEY INPUT DATA | | | B/C RATIO AND TOTAL NET PRESENT VALUE (NPV) OF SAVINGS | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | High | | Mid-Range | | Low | |
| Analysis | Building Area Affected ($10^6$ m$^2$) | Replacement Value ($M) | B/C | NPV Savings ($M) | B/C | NPV Savings ($M) | B/C | NPV Savings ($M) |
| General Wellington Case | 1.000 | 2,000 | 3.6 | 13,971 | 0.7 | 238.0 | 0.1 | 0.7 |
| Wellington HRB | 0.190 | 380 | 15.7 | 3,094 | 4.2 | 204.5 | 0.8 | 4.0 |
| Auckland HRB | 0.438 | 877 | 2.7 | 1,234 | 0.7 | 79.6 | 0.1 | 1.5 |
| Hamilton HRB | n/c | n/c | 7.5 | n/c | 1.9 | n/c | 0.3 | n/c |
| Christchurch HRB | 0.120 | 239 | 9.3 | 1,156 | 2.3 | 71.9 | 0.4 | 1.3 |
| Dunedin HRB | n/c | n/c | 3.8 | n/c | 1.0 | n/c | 0.2 | n/c |

**Notes:**

1. n/c = not computed
2. "High" (Low) values represent a combination of high (low ) values for each variable.
3. Mid-range values are considered to be a realistic point between the two extremes
4. Values of NPV Savings include for Business Interruption, Social Disruption, Injuries and Fatalities, whereas Replacement Value refers to the buildings only.

### Key Conclusions

B/C ratios were very significantly higher for high risk buildings, which were found to represent 10-15% of all Wellington buildings of 4 or more storeys.

Overall results indicated the need to focus on the benefits of addressing High Risk Buildings (i.e. those with critical structural weaknesses).

Results graphically illustrate the significant fall-off of earthquake risk outside the central seismic band of New Zealand.

To maximise the B/C ratio and to minimise the evaluation effort it is necessary to quickly and effectively identify the HRBs from the total building stock.

## EVALUATION METHODS

In support of the proposed legislative changes the NZSEE has recommended a 2-stage evaluation process. The initial evaluation would be a coarse screening involving as few resources as reasonably possible. The second evaluation would be more detailed and apply only to those buildings identified in the first evaluation as likely to be not safe in earthquake.

For each building, a Structural Performance Score (SPS) would be determined. SPS is essentially the assessed structural performance of the building compared with current code requirements, expressed as a percentage.

**Figure 1 outlines the process of the initial evaluation.**

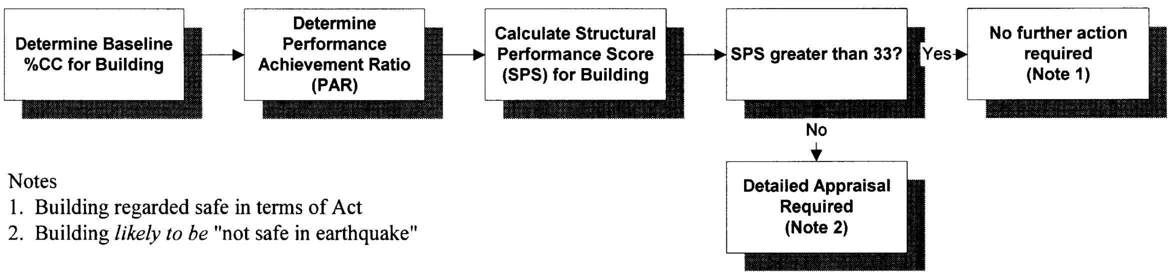


**Figure 1: Initial Evaluation Process**

There are several steps involved in determining SPS as outlined in the following sections.

A score of less than 33 means that the building would be deemed to be not safe in earthquake in terms of the proposed changes to the Building Act (ie less than 33% of code). [Ref 1]

***Key steps in the assessment are:***

1. Determination of Baseline Percent Current Code $(\%CC)_b$

   This is a general measure of the performance (with respect to current code) of a “standard” building in the location in question. This assumes the building is well designed, of regular form, has no critical structural weaknesses and complies with the relevant code provisions at the time it was built.

   It is a “yardstick” against which to measure the effect of critical structural weaknesses which may exist in a particular building of the same general type in that location.

2. Determination of Performance Achievement Ratio (PAR)

   This may be regarded as the ratio of the performance of the particular building, as inspected, in relation to a “standard” building. Thus “standard” buildings would have a PAR of 1.0 and any particular building may be above or below PAR!

   Table 2 provides a simple and quick means of assessing the PAR of a particular building by considering various critical structural weaknesses.

3. Determination of SPS Value

   As shown in Table 2, the Structural Performance Score (SPS) is the result of multiplying the (%CC)b by the PAR value.

4. Not Safe in Earthquake?

   For the purposes of this Initial Evaluation, a building yielding a value of SPS of 33 or less would be considered <u>*likely to be*</u> not safe in earthquake, and therefore to require a more detailed evaluation.

***Choice of Trigger Level***

The proposed legislation sets one-third of “current code” as the trigger level below which action to improve structural performance would need to be taken. This begs two questions:

a. Is this level high enough?

b. To what level should buildings which fall below this trigger level be “strengthened”?

The 33% level is considered high enough to capture the worst of the buildings – those with critical structural weaknesses. However the authors consider that these buildings should be improved so as to meet at least 67% of the performance requirements for new buildings.

### *Effectiveness of Rapid Evaluation Method*

The REM is still under development, but test evaluations suggest that it will successfully identify those buildings requiring attention (ie. those with critical structural weaknesses) with a minimum of effort and an acceptable level of confidence in the result.

Owners may challenge the findings, but it is felt that there would be general acceptance that a higher than normal risk exists, even if the law does not require them to act.

Development of more detailed evaluation procedures is proceeding in full knowledge of the impossibility of prescribing specific solutions for every circumstance. It is planned to use the June 1996 Draft Guidelines as a basis to develop structural performance *objectives* and then to publish general *guidelines* and *examples* of solutions to particular situations. This will enable engineers to extend the principles to new applications. The *objectives* would include clear and unambiguous requirements suitable for adoption by the Building Industry Authority as a means of meeting the recommended amendments to the Building Act, as discussed by Cashin et al [Ref 1].

**Table 2: Assessment of Performance Achievement Ratio (PAR)**

Building Name: Imaginary Towers
Date: January 2000
By: DCH

| **Critical Structural Weakness** | | **Building Score** | **Effect on Structural Performance** | | | |
|---|---|---|---|---|---|---|
| *Plan Irregularity* | | | | | | |
| Presence | | | General | Limited | None | |
| Effect on Structural Performance | | | >30% | < 30% | None | |
| Ratio | A | 0.7 | 0.4 max | 0.7 | 1 | |
| *Vertical Irregularity* | | | | | | |
| *Presence* | | | General | Limited | None | |
| Effect on Structural Performance | | | >30% | < 30% | None | |
| Ratio | B | 1.0 | 0.4 max | 0.7 | 1 | |
| **Short Columns** | | | | | | |
| Presence | | | General | Limited | None | |
| Effect on Structural Performance | | | >30% | < 30% | None | |
| Ratio | C | 1.0 | 0.4 max | 0.7 | 1 | |
| *Pounding Potential* | | | | | | |
| Separation | | | 0<Sep<.005H | .005<Sep<.01H | .01<Sep<.02H | Sep>.02 |
| Ratio | | | | | | |
| Alignment of Floors: <20% St. Ht. | D | n/a | 0.5 | 0.7 | 1 | 1 |
| | | Or | | | | |
| Alignment of Floors: >20% St. Ht. | D | 1.0 | 0.3 | 0.5 | 0.8 | 1 |
| *Site Hazard Effects* | | | | | | |
| Presence | | | General | Limited | None | |
| Effect on Structural Performance | | | >30% | < 30% | None | |
| Ratio | E | 1.0 | 0.5 max | 0.7 | 1 | |
| Other Factors | | | This factor is included to enable allowance for features of the building such as general condition, and overall strength to be taken into account. Maximum value = 1.5 if no CSW's. Maximum value = 1.0 if one or more CSW's generally present | | | |
| Ratio | F | 1.0 | | | | |

Calculation of SPS:

| | |
|---|---|
| Performance Achievement Ratio (PAR) (equals **AxBxCxDxExF**) | 0.70 |

| | |
|---|---|
| Assessed Baseline %CC (%CC)b | 60% |

| | |
|---|---|
| Structural Performance Score (SPS) (equals PAR x Baseline %CC) | 42 |

| |
|---|
| ≥ 33 = OK |
| < 33 = not OK |

## GRADING SCHEME PROPOSAL

The NZSEE, recognising the need to reduce earthquake risk, is pushing to introduce into the property market a system for grading buildings according to their assessed structural performance. This is a separate initiative to the legislative changes. The aim is to raise awareness in the industry and allow market forces to work. Owners of buildings of unacceptably high risk would find themselves under commercial pressure to improve them.

Table 3 indicates the Grading Scheme proposed. This is linked to the SPS value. Determining the Earthquake Risk Grade of a building is a simple matter of determining into which grade band the calculated SPS of the building falls.

This Grade would be included on the building title and thus known to owners, prospective owners and to tenants. Some proponents recommend that a plaque be displayed on the building [Ref 9].

Note that Table 3 includes an indication of the relative risk for buildings designed in different eras. This is expressed as a multiple of the risk inherent in new buildings. The relative risk represented by the progressively decreasing SPS shows the importance of dealing with those with an SPS of 33 or less which have 20 or more times the risk of a building which meets current building code requirements.

**Table 3: Proposed Grading Scheme for NZ Buildings**

| | | | Indicative range of $(\%CC)_b$ according to code (Will vary with location, assessed ductility, features) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Percent Current Code $[(\%CC)_b$ (or SPS)] | Letter Grade | Relative Risk | Current Code or better | 1965-76 No CSW's | 1935-65 No CSW's | Strengthened URM's (2/3 Chapter 8) | URM's Not Strengthened | Buildings with CSW's |
| >100 | A+ | <1 | ■ | | | | | |
| 80 - 100 | A | 1 to 2 times | ■ | | | | | |
| 60- 80 | B+ | 2 to 5 times | | ■ | ■ | | | |
| 40 - 60 | B | 5 to 10 times | | ■ | ■ | ■ | | |
| 30 - 40 | C | 10 to 20 times | | ■ | ■ | ■ | | |
| 20 - 30 | D+ | 20 to 40 times | | ■ | ■ | ■ | ■ | ■ |
| 10-20 | D | 40 to 80 times | | | | ■ | ■ | ■ |
| <10 | E | >80 times | | | | | ■ | ■ |

**Notes:**
1. $(\%CC)_b$ is the ratio of the lateral strength when compared with a building designed and constructed to current code.
2. SPS is the Structural Performance Score for a particular building $(=(\%CC)_b \times PAR)$
3. Letter Grade is an indicator of likely performance in earthquake
4. Relative Risk is the ratio of probabilities that the ultimate strength will be exceeded in any given period of time
5. CSW stands for Critical Structural Weaknesses.

## CONCLUSIONS

The technical back-up for legislation to improve the structural performance of existing buildings presents considerable challenges. The work reported has provided invaluable insights into the issues involved in dealing with earthquake risk in existing buildings in New Zealand.

In particular, the research showed that:

- A wide variation of risk was evident
- A significant number of buildings was affected – sufficient to warrant action
- Worthwhile benefit cost ratios resulted in high seismicity regions even using annual probabilities
- Benefit cost ratios for "conditional" probability are compellingly high for major events assumed to take place within the next decade.
- Buildings with critical structural weaknesses should be specially targeted as they provide the highest benefit to cost ratios.
- The simple evaluation process developed is capable of identifying buildings of high risk.
- A simple grading scheme developed has the potential to generate action through market forces.

Overall, the complexity in dealing with earthquake risk in existing buildings was evident, both technically and socially. Feedback from others who have dealt with these challenges is welcome.

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