Simple Methods to Evaluate Structural Irregularity Effects

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ABSTRACT: Simple analysis methods are available for designing regular structures. For irregular structures, these simple methods are restricted by code regularity limits that lack proper analytical justification. This paper summarises a recent study on structural irregularity effects, involving the quantification of effects of different types, and degrees of, irregularity on structures designed for earthquake using simplified analysis methods. Irregularity types considered include vertical irregularities (e.g. mass, strength-stiffness irregularities), horizontal diaphragm flexibility, and torsional irregularity. Simple design tools describing the change in response due to irregularity are developed. This facilitates designers and plan checkers to rapidly evaluate the likely effect of irregularity on structures. The work was undertaken to provide a rigorous technical basis for new regularity provisions in the New Zealand seismic design Standard, NZS 1170.5.

1 INTRODUCTION

No structure is perfectly regular. Because it is impossible to avoid irregularity in a structure, it is important for designers to be aware of their effects and to consider them appropriately in design. Many simple analysis methods, such as the NZS 1170.5 (SNZ, 2004) *Equivalent Static* (**ES**) method, are calibrated using the seismic response of regular structures. For structures with discontinuities such as a significant difference in storey stiffness, strength or mass, with irregular plans (Figure 1), or with flexible diaphragms, the ES method may underestimate the actual demands and produce unsafe structures. For this reason, many current world-wide codes (e.g. IBC, 2003 and NZS 1170.5), provide limitations on the maximum degree of irregularity for structures designed according to the ES method. For example; NZS 1170.5 defines irregularity (in *Clause 4.5*) as:

(a) Vertical stiffness irregularity (soft storey) – The lateral storey stiffness is less than 70% of adjacent storey stiffness or less than 80% of average stiffness of storey above or below.

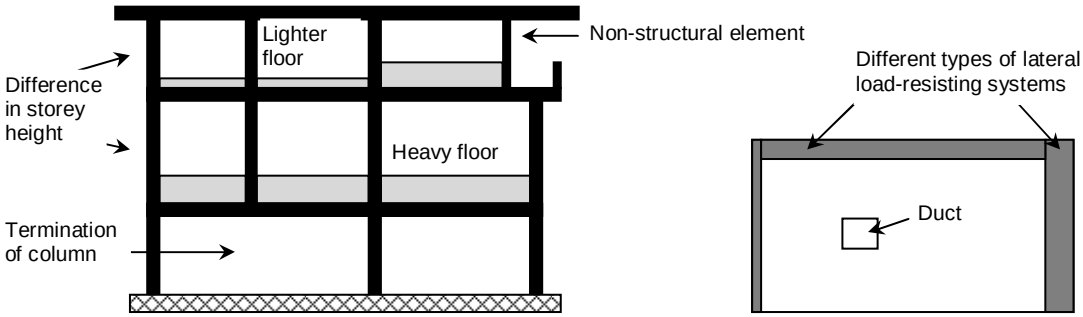
(b) Vertical strength irregularity (weak storey) – The storey shear strength is less than 90% that in the storey above.

Thus, when a structure does not satisfy the above regularity limits, and many similar limits for other types of irregularities, more advanced analysis methods, such as the 3D dynamic analysis, are required to be used. Here, although more detailed analysis procedures may give a more realistic understanding of the behaviour of a structure, they require more design information and effort. More importantly though, the code regularity limits lack proper technical basis, and are based on engineering judgment (SEAOC, 1999). Also, it is also not clear how much the demands are likely to change with different degrees of irregularity. Therefore, there is a need for rigorous justification of the regularity limits.

Many interesting studies have been undertaken on horizontal irregularity effects, such as those summarized by Chopra and Goel (2004) and De Stefano and Pintucchi (2006), but vertical irregularity has received less attention (e.g. Valmundsson and Nau, 1997, Michalis et al., 2006). Although those studies have produced qualitative information on irregularity effects, they do not provide simple

methods for design office use, and the structures analysed are not always code compliant. Also, the conclusions derived from their works, may not be directly applicable to NZ codes.

This paper summarises recent research findings on structural irregularity effects that involve



(a) Vertical irregularity *(b) Plan irregularity*

Figure 1. Examples of structural irregularities

quantifying the effects of different types and degrees of irregularity on structures designed for earthquake using simplified analysis techniques (MacRae and Deam, 2009). The irregularity types considered, the methodology adopted to evaluate their effects, and the corresponding findings are presented in the following sections.

2 VERTICAL IRREGULARITY EFFECTS

2.1 *Methodology*

A simple methodology for evaluating vertical irregularity effects for shear-type of structures was developed (Sadashiva *et al*. 2009). The method has the following steps:

1. Define an *engineering demand parameter* (**EDP**) that characterises structural damage. *The peak interstorey drift ratio over the structures height has been used as the EDP to assess the vertical irregularity effects in this paper*.
2. Choose a set of target (design) interstorey drifts that span the range of values that could be used by the designers (e.g. from 0.5% to 3%). Then, for each target interstorey drift:
   a) Design a regular structure using the ES method to the target interstorey drift ratio.
   b) Introduce an irregularity into the structure, and use the ES method to redesign this structure to the same target interstorey drift ratio.
   c) Conduct *inelastic dynamic time-history analysis* (**IDTHA**) on each regular and irregular structure with each earthquake record, and obtain the peak interstorey drift ratios. The median peak interstorey drift ratio is then obtained for all the records in the suite.
   d) Evaluate the performance for all of the ground motion records as either a) the difference between the median peak interstorey drifts of the two structures or b) the probability that the demand for the irregular building is greater than the demand for the regular building. *Approach a) is used in this paper.*
3. The performance distributions for chosen degrees of irregularity, and target interstorey drift ratio may then be used to characterise the effect of both of these variables and select appropriate limits.

2.2 *Choice of structural configurations and definition of regular structures*

Simple one-dimensional models (often called "stick" models) of 3, 5, 9 and 15 storey shear-type of structures were considered. Such simple models are both adequate for determining the overall structural response, and also facilitate conducting an extensive parametric study (Cruz and Chopra,

1986). All the models were assumed to be in Wellington, and designed using the NZS 1170.5 ES method. The additional actions and deformations due to P- effects were also included in design, in accordance with the NZS 1170.5 provisions. A representative set of structural ductility factors, , of 1, 2, 3, 4, 6, and *design* (target) *interstorey drift ratios* (**DISDR**) ranging between 0.5% and 3%, were adopted for this study.

The regular structures (the *base* structures for this study) were designed with a constant floor mass at every level. For stiffness and strength distributions over the height of the structures, two desirable configurations (Paulay and Priestley, 1992) were chosen. Real frames were assumed to fall between these two extreme design configurations:

(a) *Constant interstorey drift ratio* (**CISDR**) –

The stiffness distribution for this model gradually reduces over the building height, and the absolute storey stiffnesses were iterated on until all the storeys achieved the DISDR simultaneously.

The storey strengths provided were the minimum required to resist the design forces from the ES method.

For this model, all storeys had a constant storey strength-to-stiffness ratio.

(b) *Constant Stiffness* (**CS**) –

A uniform stiffness distribution over the building height was provided for this model.

The storey strength distribution over the height of structure was either:

i. The minimum required to resist the code design forces, resulting in a varying strength distribution. This model is henceforth referred to as **CS-VSTG** for *constant stiffness* and *varying strength;* or

ii. The strength required to resist the design force at the first storey was provided for all storeys. Therefore, this design model had a *constant stiffness* and a *constant strength* distribution (**CS-CSTG**), resulting in a constant strength-to-stiffness ratio at all storeys.

Unrealistic structures were avoided in this study by eliminating structures that had storey strength-to-stiffness ratios outside the range of 0.3% and 3% (Sadashiva, 2010 [a]). These boundary values were based on the likely storey strength-to-stiffness ratios for realistic structures, determined using the empirical relations (Priestley *et al*., 2007) giving yield drift ratios for different types of *lateral-force-resisting* (**LFR**) systems. Also, in the design process, the structures with the horizontal design action coefficient (used for base shear calculation) governed by the lower limit (*Equation 5.2(2)*, NZS 1170.5, 2004), were not considered for analyses (Sadashiva *et al*., 2009).

2.3 *Creating irregular structures*

The irregular structures were created by modifying the chosen irregularity (property) of each regular structure, and redesigning the structure using the same method as used for regular base structure, until the target DISDR was attained at the critical storey. Since both the regular, as well as the irregular structures are designed to the same DISDR, a meaningful comparison between their responses was obtained. In this study, the sensitivity of the location and magnitude of irregularity was investigated by applying irregularities of varying degrees, separately at the first storey/floor level, mid-height storey/level and topmost storey/level.

2.4 *Structural analyses and interpretation of results*

All structures were modelled with a combination of vertical shear beam and a vertical flexural beam.

Here, the vertical flexural beam represents all the continuous columns in the structure. Its inclusion is important to avoid unrealistically high drift concentrations by representing structural behaviour well (e.g. Tagawa, 2005, Sadashiva *et al*., 2009). The shear beams had a bilinear hysteresis loop with a bilinear factor of 1%. The damping effects within the structures were represented by a tangent stiffness proportional Rayleigh damping model that uses the absolute form of the equation of motion, and 5% critical damping was applied to the first mode and the mode corresponding to the number of storeys.

The time-history analysis program, RUAUMOKO (Carr, 2004), was used for all the *inelastic dynamic time-history analysis* (**IDTHA**). A set of 20 earthquake ground motion records developed for Los Angeles, with probabilities of exceedance of 10% in 50 years, were used for the ground motion suite (SEAOC-ATC-CUREE). Response spectra were developed for each of the selected records, and the records were scaled to the NZS 1170.5 elastic design level spectral acceleration values for the period calculated in the city chosen. The structural ductility factor and the structural performance factor were both equal to unity.

For every IDTHA conducted, the peak *interstorey drift ratio* (**ISDR**) at every storey, and within the structure, was obtained. The median peak ISDR was calculated for the earthquake record suite, which was then used to compare the responses of regular and irregular structures. The following steps were used to compute the relationship between the *increase in median peak interstorey drift ratio*, $ISDR_{incr}$, due to irregularity and degree of irregularity:

Step 1. For a combination of structural form, structural ductility factor, design interstorey drift ratio, structure height, and the storey/floor level of irregularity, the median peak ISDR for the *regular* structure, $ISDR_R$, is computed from the IDTHA results for the record suite. In a similar way, the median of peak interstorey drift ratio for the *irregular* structure, $ISDR_I$, is obtained. Thus, the increase in median peak ISDR due to irregularity, $ISDR_{incr}$, is calculated by Equation 1.

$$ISDR_{incr} = \left(\frac{ISDR_I}{ISDR_R} - 1 \right) * 100 \ (\%) \qquad (1)$$

Step 2. Step 1 is repeated for all the combinations of structural form, structural ductility factor, design interstorey drift ratio, structure height, storey/floor level of irregularity, and degree of irregularity.

Step 3. For each degree of irregularity, the maximum value of $ISDR_{incr}$ is found. This is represented by $ISDR_{max_incr}$ in this paper.

2.5 *Type of vertical irregularity*

2.5.1 *Mass Irregularity*

The effects of mass irregularity on shear-type structures were evaluated by applying different mass ratios at a chosen floor level for irregularity. Here, the mass ratio is defined as the ratio of mass at a floor level in the irregular structure, to the mass at the corresponding level of the regular structure. Four mass ratios of 1.5, 2.5, 3.5 and 5, were used in this study.

The drift demands were sensitive to both the magnitude and floor level of the mass irregularity. Increased mass, when present at either the first floor or at the roof, generally produced higher drift demands than when located at the mid-height level (Sadashiva *et al*., 2009).

Figure 2 shows the maximum increase in median peak ISDR, $ISDR_{max_incr}$, obtained for each mass ratio for all the design models. A generally conservative estimate of $ISDR_{max_incr}$, based on the most critical structural form, structure height, structural ductility factor, design interstorey drift ratio and floor level of irregularity, can be obtained, as given by Equation 2 where IRR = Irregular response ratio (which specifies how much the irregular response is greater than the regular response); and MR is the mass ratio.

$$IRR\ (\%) = 15\ (MR - 1) \qquad (2)$$

Equation 2 may be used for design. For example, designers can easily estimate the likely increase in drift demand due to a specified mass ratio. Also, the figure shows that the NZS 1170.5 mass regularity limit of 1.5 corresponds to a maximum increase in median peak ISDR of about 7.5%.

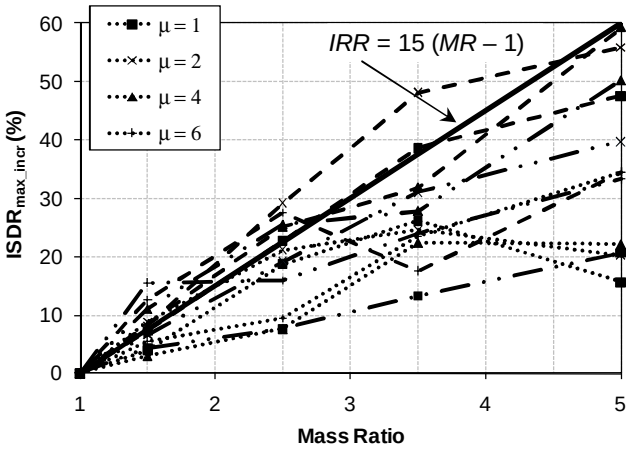


Figure 2. Maximum increase in median peak interstorey drift ratio due to mass irregularity.
CISDR CS-VSTG CS-CSTG

2.5.2 *Strength-Stiffness Irregularity*

As shown in the introduction, NZS 1170.5 specifies separate regularity limits for stiffness and strength irregularity. However, in many practical cases, a change to storey stiffness results in a modification to the strength at the same storey. Therefore, realistic correlations between storey stiffness and strength were determined for some of the common LFR systems. Coupled vertical stiffness-strength irregularity effects due to (a) a change in member property at a storey of uniform storey height structures; and (b) a change to a storey height were investigated (Sadashiva *et al*., 2010 [b], 2010 [c]) as explained below.

2.5.2.1 *Stiffness-strength irregularity due to change in member property*

Realistic correlations between stiffness and strength due to a change in a storey member property were represented by stiffness modification factor, $_k$, and strength modification factor, $_v$. The storey stiffness varied either in proportion to the storey strength (Group 1) or with unequal modifications for storey stiffness and strength (Group 2), to appropriately model the LFR system. A range of modification factors for the two groups were used.

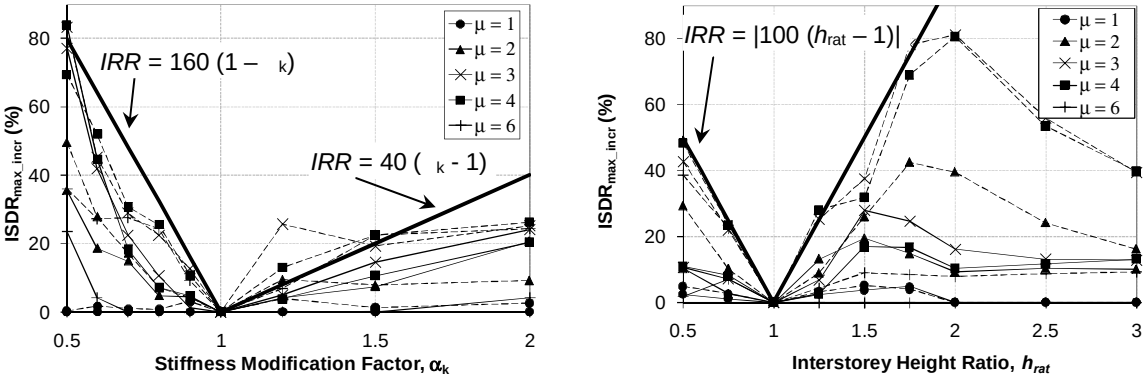
The stiffness modification factor, $_k$, was only applied to one storey at a time in the regular structure. The modified structure was then redesigned, and all storey stiffnesses were scaled uniformly by a scaling factor, , until the critical storey reached the DISDR. Both the regular, as well as the irregular structures, had the same storey strength-to-stiffness ratios. This required the provided storey strengths to be different to the strength demands. Here, the strength at the irregular storey was provided as the product of the $_v$ factor, the factor and the strength at the corresponding storey of regular structure. The strengths provided within the other storeys were the product of the factor and the corresponding regular storey strengths.

Group 1 structures produced higher drift demands than Group 2 structures. The topmost storey was more critical than any other storey for the CISDR building designs with an equal reduction in storey stiffness and strength, but the first storey was more critical for the CS-CSTG designs. With equal increase in storey stiffness-strength, placing the irregularity at the mid-height storey produced higher demands than the regular structures, for both building designs. Figure 3(a) shows the parameter, $ISDR_{max_incr}$, plotted against the stiffness modification factor for both the design models having equal storey stiffness-strength relation.

2.5.2.2 *Stiffness-strength irregularity due to storey height modification*

Coupled stiffness-strength irregularity effects due to a change to a storey height were studied. A parameter, *interstorey height ratio*, $\boldsymbol{h_{rat}}$, was defined as the ratio of the modified interstorey height, $\boldsymbol{h_m}$, to the initial interstorey height, $\boldsymbol{h_o}$. A range of values between $h_{rat} = 0.5$ and $h_{rat} = 3$ were used to calculate the stiffness and strength modification factors according to the realistic stiffness-strength relations obtained for the LFR systems considered. Irregularity was introduced into these structures by applying h_{rat} at a storey, adjusting the stiffness-strength modification factors, and scaling with the factor, like the method as explained in Section 2.5.2.1.

A modified storey height that results in a change to storey stiffness alone was found to produce more adverse irregularity effects than the other stiffness-strength relations. For this group, the effects of a taller storey were more than those due to a short storey in the structure, as shown in Figure 3(b). Here, for structures with either CISDR or CS-CSTG configuration, a taller first storey was found to increase the median peak ISDR for short period structures, and a taller mid-height storey was most adverse for taller structures. A simple equation that can be used to estimate the likely increase in response due to a modified interstorey height was developed, and shown in Figure 3(b). This equation, along with the realistic correlations between storey stiffness and strength, can also be used to obtain the governing code regularity limit.



(a) Stiffness-strength irregularity due to change in member property

(b) Stiffness-strength irregularity due to a modified storey height

Figure 3. Maximum increase in median peak interstorey drift ratio due to coupled stiffness-strength irregularity (from critical realistic stiffness-strength relations). ——— CISDR - - - - - - - - - CS-CSTG

3 PLAN IRREGULARITY EFFECTS

Due to space constraints, the torsional irregularity study has been omitted from this paper. Further information on this topic can be found in MacRae and Deam (2009).

3.1 *Flexible floor diaphragm effects*

Many design codes (e.g. FEMA 356, 2000) classify diaphragms as either flexible or rigid depending on the flexibility ratio, In NZS1170.5, Clause 6.1.4.1 specifies that "[w]here diaphragms are not rigid compared to the vertical elements of the lateral [load]-resisting system, the model should include representation of the diaphragm's flexibility". Here, a "flexible diaphragm" is defined as one "that is sufficiently flexible that the maximum lateral deformation is more than twice the average inter-storey deflection at that level" (i.e. > 2) and a rigid diaphragm as one with < 2. The = 2 boundary value is again based on engineering judgement rather than quantitative analyses.

Simple structural models of single storey structures with lumped distributed diaphragm masses and multi-storey systems having different deformation types, and different LFR element configurations, were analysed to evaluate the diaphragm flexibility effects (Sadashiva *et at*., 2010 [a]). The elastic single storey structures showed the maximum effects of diaphragm flexibility, as outlined below.

The simple single-storey structure comprising of two parallel

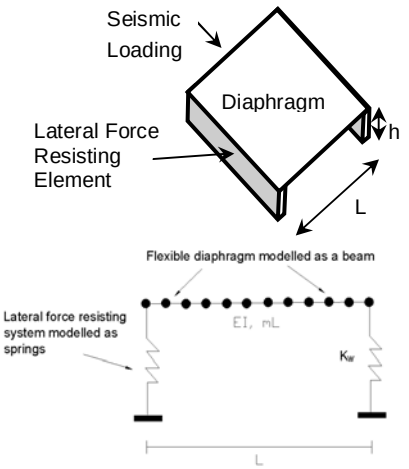


Figure 4. Simple single storey structure with flexible diaphragm resting on walls.

walls and a floor diaphragm shown in Figure 4 was used in this study to provide non-dimensional demand parameters. The analysis method consisted of the following steps:

Step 1. Design a suite of structures by selecting an appropriate range of fundamental periods due to rigid diaphragm assumption, T_{RIGID}, and estimate the wall stiffness, k_W, associated with each period for a diaphragm mass, m, according to Equation 3. The selected T_{RIGID} values for this study were 0.1, 0.5, 1 and 2.0s.

$$k_W = \frac{4\pi^2 m}{T^2_{RIGID}} \tag{3}$$

Step 2. Select an appropriate range for the diaphragm flexibility ratio, γ, and use a static analysis to calculate the diaphragm stiffness, k_F, for each γ, according to Equation 4. The range of flexibility ratios considered in this paper is $1 \leq \quad \leq 4$.

$$k_F = \frac{k_W}{\gamma - 1} \tag{4}$$

Step 3. Assuming a realistic value for the modulus of elasticity, E, calculate the second moment of area, I_x, using Equation 5(a). Here, the mid-span flexural displacement, $_B(L/2)$, in Equation 5(a), is given by Equation 5(b) for a uniformly distributed load, w, applied to a simply-supported beam.

$$wL = k_F \, \delta_B \tag{5a}$$

$$\delta_B(L/2) = \frac{5wL^4}{384EI_x} \tag{5b}$$

Step 4. Conduct dynamic time-history analysis. The RUAUMOKO (Carr, 2004) program was used for carrying out all the analyses described in this paper. Caughey damping model with a constant damping ratio of 5% for all modes, and the set of 20 records used for vertical irregularity, was used for time-history analysis.

Then, for every ground motion record, and for every combination of T_{RIGID} and γ:

(a) Calculate the structure period with flexible diaphragm, T_{FLEX}, the peak displacement, δ_{TOT}, the maximum diaphragm displacement, δ_F, the corresponding wall displacement, δ_W, the maximum wall shear force, V_{FLEX}, and the diaphragm bending moment, M_{FLEX}.

(b) Calculate the dimensionless fundamental period increase, T_{INCR}, wall shear force ratio, V_{RATIO}, peak displacement increase, $\delta_{MAX,RATIO}$, dynamic displacement ratio, δ_{RATIO}, and diaphragm bending moment ratio, M_{RATIO}. Here, the dimensionless parameters are defined as the respective demand obtained from structures with a flexible diaphragm, divided by the demand with a rigid diaphragm.

Step 5. Calculate the median value of each non-dimensional demand indicator calculated in step 4 for each of the 20 records and plot them separately, using γ as the independent variable.

Figure 5 shows the non-dimensional demand parameters calculated based on the median responses, plotted against the flexibility ratio for the selected rigid diaphragm periods. As shown in the figure, the effect of diaphragm flexibility increased with decreasing $T_{RIGID.}$ The figure also shows that the trend in the response variation for wall shear forces and diaphragm bending moments closely match where the forces are lower for taller (longer period) structures. This similarity is expected; because it follows the trends in the acceleration response spectra, and indicates that for tall structures no special consideration for forces is required.

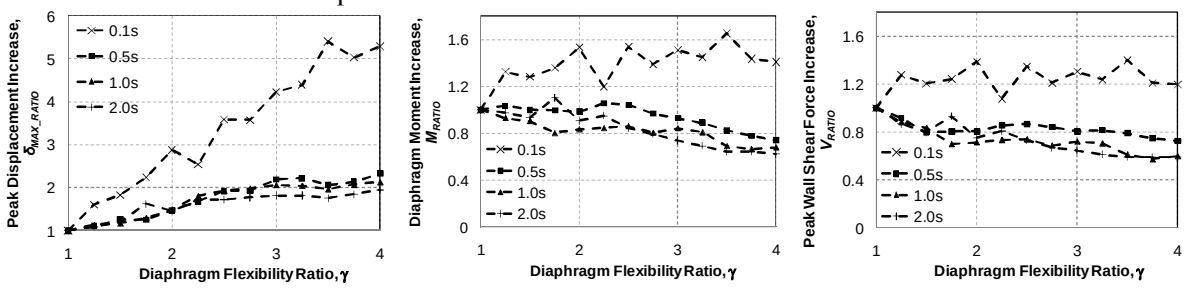


Figure 5. Non-dimensional demand parameters obtained due to diaphragm flexibility for selected rigid diaphragm structural periods.

Possible design methods (e.g period dependent or independent) for multi-storey structures with flexible diaphragms were also developed. The non-dimensional demand parameters obtained from applying such simple methods, were compared with those from time-history analyses. Based on the findings from this study, Equation 6 is formulated to provide the likely increase in displacement response due to diaphragm flexibility.

$$\text{Displacement demand} = (\text{Regular structure displacement demand}) \times (1+2(\ -1)/3) \qquad (6)$$

4 CONCLUSIONS

Designers often require complex analysis techniques to be used for building design if certain code regularity limits are not satisfied. These limits are based on engineering judgement and do not have rational justification. This paper outlined some of the recent findings obtained from studies on irregular structures. Both vertical and horizontal irregularities were considered. The studies involved developing simple methodologies to evaluate structural irregularity effects. The change in the seismic response due to irregularity was used to develop simple equations that can be used by designers to estimate the likely increase in demand due to irregularity. This study helps designers understand quantitatively the effects of irregularity on building performance so that they can mitigate their effects in the initial design phase. This rigorous study also provides a strong technical basis for revision of the regularity provisions in the present NZS 1170.5.

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