Suggested Reference

Derakhshan, H., Ingham, J. M., & Griffith, M. C. (2010). Effects of unreinforced masonry wall slenderness ratio on out-of-plane post-cracking dynamic stability. In Jason Ingham (Ed.), *Proceedings of the 2010 NZSEE Annual Conference* (pp. 1-8). Wellington. Retrieved from http://www.nzsee.org.nz/db/2010/Paper55.pdf

Effects of unreinforced masonry wall slenderness ratio on out-of-plane post-cracking dynamic stability

2010 NZSEE
Conference

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ABSTRACT: A large number of time-history analyses were performed on several unreinforced masonry (URM) walls that had different slenderness ratios, and the viability of adopting wall slenderness ratio as a criterion for seismic assessment was investigated. Several combinations of three wall properties were assumed to cover most walls found in New Zealand URM buildings, and 30 representative time-history records were used to perform analyses. Walls were either two-leaf thick with no overburden load applied or three-leaf thick having an overburden load applied equal to the weight of a typical second-storey two-leaf URM wall. Wall behavioural data was obtained based on a previous laboratory based study, and each wall was subjected to ground motion scenarios with increasing peak ground acceleration (PGA). The ground motion record PGA that caused the wall to undergo a displacement limit equal to 60% of wall instability displacement was identified, and the sensitivity of the obtained PGA to wall slenderness ratio was studied for all the used records. It was shown that increasing wall slenderness ratio resulted in the wall being more vulnerable.

1 INTRODUCTION

Unreinforced masonry was one of the most common construction materials in New Zealand prior to the 1931 Hawke's Bay earthquake (Dowrick 1998). The popularity of this form of construction has resulted in approximately 3800 URM buildings remaining throughout New Zealand (Russell 2010), with these buildings forming a large proportion of New Zealand’s heritage structures (Goodwin 2009). These buildings have not been designed to resist seismic forces, and pose a high level of earthquake risk to society. The heritage importance of these buildings, together with New Zealand legislation regarding building standards (DBH 2004), has prompted seismic evaluation and retrofit projects being undertaken throughout the country.

Reports of past earthquakes have revealed that a high level of seismic risk is associated with existing URM walls when subjected to out-of-plane excitations. Wall out-of-plane collapse has been one of the most common forms of building damage observed during past earthquakes, and such damage jeopardizes the gravity-load carrying capacity of the building (Bruneau 1994). Blaikie and Spurr (1992) reported the impact of seven earthquakes on buildings and concluded that out-of-plane failure of URM building components was the most prominent form of building damage in the majority of events.

The New Zealand Society for Earthquake Engineering (NZSEE) guidelines for seismic evaluation of structures (NZSEE 2006) proposes a procedure for out-of-plane assessment of one-way URM walls on the basis of the cracked wall “dynamic stability”. A previous study (Derakhshan et al. 2009) by the authors has shown that a certain combination of parameters used in the aforementioned procedure leads to erroneous results over a range of practical wall slenderness ratios (S), such that increasing S can significantly improve the wall assessment results. In contrast to the NZSEE approach to wall out-of-plane assessment, ASCE (2007) recommends wall slenderness ratio as the appropriate criteria for assessment, and suggests that wall stability generally decreases with increasing wall slenderness ratio.

ASCE (2007) recommends maximum acceptable wall slenderness ratios based on the seismicity of the region in study and the wall location within the subject building. The proposed slenderness ratio limits are based a study by ABK (1981), and was shown to be conservative in a separate study based on mechanics of rigid bodies (Sharif et al. 2007). Direct time-history analyses are performed using a variety of representative ground motions and wall characteristic behaviour to study the effects of parameter S on wall out-of-plane stability.

2 WALL PROPERTIES

Russell (2010) identified one and two-storey buildings as the most prevalent forms of masonry construction in New Zealand, and suggested wall heights that ranged from 3000 mm up to 7000 mm, with the median height being 4000 mm for single storey buildings and 6000 mm and 5000 mm, respectively for lower storey and top storey of two storey buildings. Thirteen combinations of 3 wall properties (height, thickness, and overburden) as listed in Table 1 were selected based on the aforementioned study, with the wall thickness assumed to be 230 mm in the top-storey and in single-storey buildings and to be 350 mm in the lower storey of two-storey buildings. An overburden ratio (defined as the ratio of overburden to wall self-weight) of 0.7 was considered for three-leaf walls based on this assumption that the top storey walls of two-storey buildings are two-leaf thick, and zero overburden was conservatively assumed for two-leaf walls, ignoring the building parapet and roof weight. The masonry density was assumed to be 1800 kg/m^3.

Table 1. Wall combinations

Wall	Nominal thickness (mm)	Clear height (mm)	Height-to-thickness ratio	Overburden ratio
1	350	4000	11.4	0.7
2	350	4300	12.3	0.7
3	350	4600	13.1	0.7
4	350	5000	14.3	0.7
5	350	5500	15.7	0.7
6	350	6000	17.1	0.7
7	350	6500	18.6	0.7
8	230	3000	13.0	0
9	230	3400	14.8	0
10	230	3700	16.1	0
11	230	4000	17.4	0
12	230	4300	18.7	0
13	230	4700	20.0	0

3 NUMERICAL MODEL

Calculation of the seismic response of simply-supported one-way out-of-plane URM walls connected to rigid diaphragms involves solution of the following equation of dynamic motion (Doherty 2000):

$$a_m(t)+\frac{3}{2}\left(\frac{4g}{h}\left[\frac{t}{\Delta(t)}-1\right]\right)\Delta(t)=-\frac{3}{2}a_g(t) \qquad (1)$$

The above equation assumes that the wall is pre-cracked at mid-height, and that the wall behaviour is characterised by rigid-body rotations of the wall halves about pivotal points at wall ends and at crack height. Variable $\Delta(t)$ is the time-dependent relative displacement of the wall at mid-height, $a_g(t)$ is the ground excitation, and $a_m(t)$ is the relative acceleration component within the system.

Doherty (2000) details that the term in curved parentheses is the static bilinear force-displacement relationship of the cracked wall divided by the wall mass, and that the equation corresponds to an equivalent single-degree-of-freedom (SDOF) system with unit mass. The equivalent system is subjected to 1.5 times the ground acceleration applied to the out-of-plane wall, and has stiffness properties that are 1.5 times higher than the stiffness of the out-of-plane wall being studied, in order to correctly account for distributed mass being treated as equivalent lumped mass for the upper and lower halves of the out-of-plane responding wall. A 5% damping ratio and a unit mass were assumed in the SDOF analyses performed, and the above-mentioned considerations with respect to the wall stiffness and the applied ground acceleration were made in a numerical model constructed in SAP2000® (2005).

A multilinear elastic link element was used to replicate the wall nonlinear stiffness characteristics, which has previously been reported in Derakhshan et al. (2010). The proposed trilinear behavioural models (Figure 1a) improve the conventional bilinear rigid rocking models by including the effects of masonry crushing, which results in a wall maximum resistance, F_i, less than the predictable rigid resistance, F_0, being obtained. The trilinear defining parameters were calculated for walls listed in Table 1, and the results are summarised in Table 2. Figure 1b shows the relationship between the uniformly applied force per unit wall height and the wall displacement, with the force calculated for unit wall length.

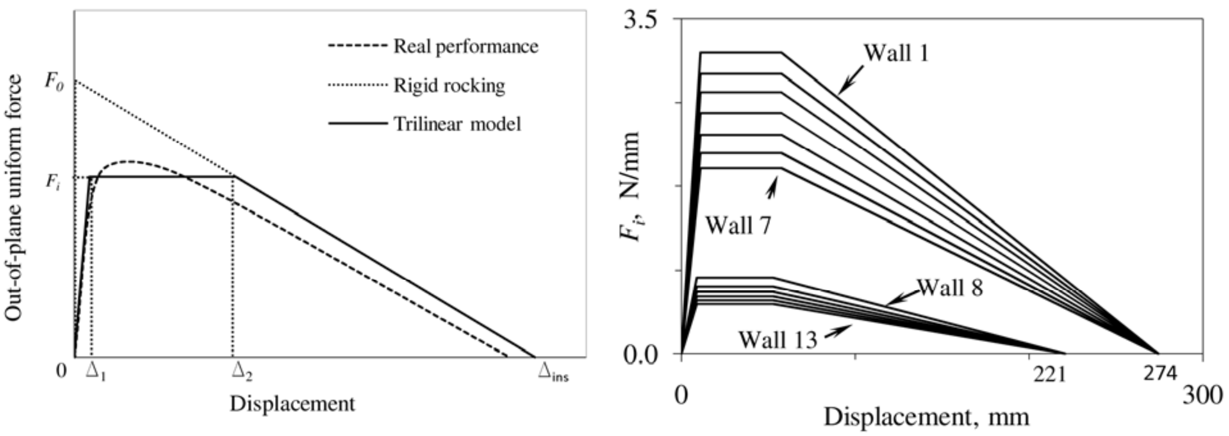
Table 2. Trilinear defining parameters

Wall	$_1$ (mm)	$_2$ (mm)	$_{ins}$ (mm)	F_i (N/mm)
1	11.0	57.5	274.3	3.15
2	11.0	57.5	274.3	2.93
3	11.0	57.5	274.3	2.74
4	11.0	57.5	274.3	2.52
5	11.0	57.5	274.3	2.29
6	11.0	57.5	274.3	2.10
7	11.0	57.5	274.3	1.94
8	8.8	52.8	220.8	0.80
9	8.8	52.8	220.8	0.71
10	8.8	52.8	220.8	0.65
11	8.8	52.8	220.8	0.60
12	8.8	52.8	220.8	0.56
13	8.8	52.8	220.8	0.52

4 NUMERICAL ANALYSIS

Thirty ground motion records (Table 3) consistent with New Zealand seismic characteristics were acquired from Oyarzo-Vera et al. (2008). Each time history was incrementally scaled and several analyses were conducted to observe the wall maximum displacement when subjected to each excitation. With three variants of ground motion records (30), walls (13), and the number of incremental PGA increase (45), nearly 18,000 analyses were performed and a database was created, which included the wall maximum displacement for each analysis.

Figure 2 and Figure 3 show the dependency of the calculated wall displacement on the PGA for record 01, plotted on the same scale for two-leaf and three-leaf walls. Analyses showed that wall deformation beyond a certain limit dramatically increases with increasing PGA.



(a) (b)

Figure 1: Out-of-plane wall behavioural models; (a) general; (b) walls 1 to 13

Table 3. Ground motion records.

No	Ground motion record	Date	No	Ground motion record	Date
01	Arcelik, Kocaeli, Turkey	17-Aug-99	16	HKD085, Hokkaido, Japan	26-Sep-03
02	Bear Val. #5, Loma Prieta, USA	18-Oct-89	17	Joshua Tree, USA	28-Jun-92
03	Bovino, Camp. Lucano, Italy	23-Nov-80	18	OTE Bldg, Kalamata, Greece	13-Sep-86
04	Caleta de Campos, Mexico	19-Sep-85	19	La Union, Mexico	19-Sep-85
05	Calitri, Camp. Lucano, Italy	23-Nov-80	20	Lucerne, Landers, USA	28-Jun-92
06	Chihuahua, Victoria, Mexico	9-Jun-80	21	Managua, Nicaragua	23-Dec-72
07	Convict Creek, USA	25-May-80	22	Matahina Dam D, NZ	2-Mar-87
08	OTE Bldg, Corinthos, Greece	24-Feb-81	23	Tabas, Iran	16-Sep-78
09	Delta, Imperial Valley, USA	15-Oct-79	24	TCU046, Chi-Chi, Taiwan	20-Sep-99
10	Duzce, Turkey	12-Nov-99	25	TCU 051, Chi-Chi, Taiwan	20-Dec-07
11	El Centro Array#6, Imp. Valley	15-Oct-79	26	CHY101, Chi-Chi, Taiwan	20-Sep-99
12	El Centro, Imp. Valley, USA	19-May-40	27	KAU001-IV, Chi-Chi, Taiwan	20-Sep-99
13	Erzican, Turkey	13-Mar-92	28	Takarazu, Kobe, Japan	16-Jan-95
14	Fortuna, Mendocino, USA	25-Apr-92	29	Superstition Hill, USA	24-Nov-87
15	Gisborne, New Zealand	20-Dec-07	30	Yarimka YPT, Kocaeli, Turkey	17-Aug-99

The critical displacement limit beyond which point the wall displacement dramatically increased was observed to be on average 60% of the wall instability displacement (132.5 mm for 2-leaf walls and 164.6 mm for 3-leaf walls), and the PGA required to induce this displacement was regarded as the “instability PGA”. Although instability PGA is not regarded as the best characteristics of a ground motion that can describe its capacity to induce wall instability, PGA is used here to perform a qualitative study with respect to the effects of wall slenderness ratio on walls general behaviour.

The instability PGA for a certain wall was observed to significantly differ for different ground motions. Figure 4 shows this variation and details the maximum (1.3g for record 20) and minimum (0.3g for record 13) PGA that caused wall 01 to reach the displacement limit. The ratio of the maximum instability PGA to the minimum was approximately 500% for wall 01. The difference observed in the instability PGA for different records is attributed to other features of the ground motion histories such as frequency content and the duration of excitation, and could potentially be explained by soil conditions at site where different ground motions were recorded.

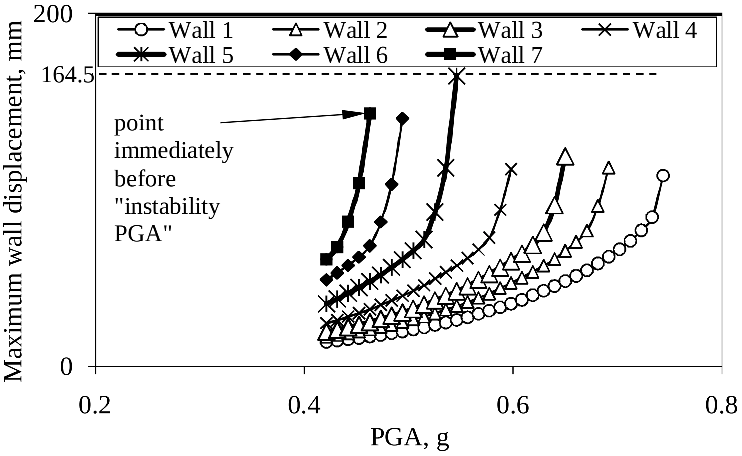


Figure 2: Dependency of wall displacement on PGA (Rec01); three-leaf walls

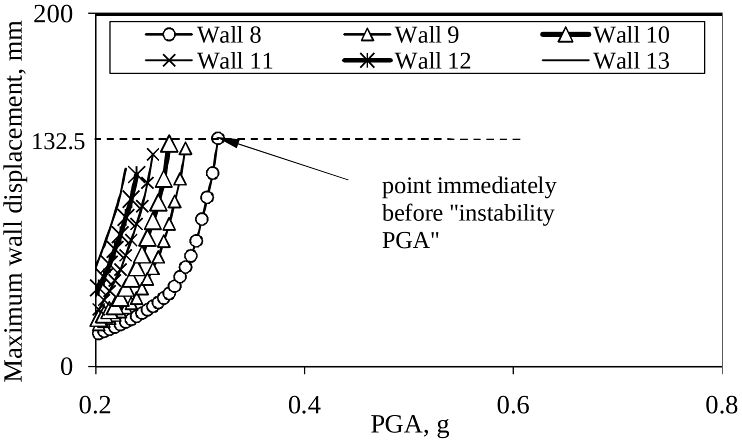


Figure 3: Dependency of wall displacement on PGA (Rec01); two-leaf walls

Based on the instability PGA variations observed for a certain wall and among different records it can be concluded that the results from a single record are not conclusive in wall seismic evaluation. An average value from a suite of records can instead be used, as recommended in ASCE (2007, p.67). The high variation observed in Figure 4 suggests that the higher the number of ground motions records considered, the more accurate the overall result is. While the aim of the current study is to investigate the overall effects of wall slenderness ratio on instability PGA by incorporating 30 different records in the time history analyses, individual suites of 7 records, proposed by Oyarzo-Vera et al. (2008), are used at a future study to develop wall assessment data for respective seismic regions in New Zealand.

Figure 5 shows that the wall behaviour was governed by the wall slenderness ratio, although the ground motion records were different in nature. The instability PGA consistently decreased with increasing wall slenderness, but this trend was occasionally not observed due to the wall behaviour being highly unpredictable at wall displacements closer to the instability displacement. Figure 6 shows average results from all records and confirms that walls with higher slenderness ratios reached their displacement limit at lower PGAs. Based on Figure 6, the average instability PGA was nearly 0.23g higher for a three-leaf wall with slenderness ratio of 11 compared to a wall with the same thickness but with a slenderness ratio of 19, with this difference being significant in a typical earthquake. For two-leaf walls, the average instability PGA was nearly 0.12g higher for a wall with slenderness ratio of 13 compared to a wall with the same thickness but with a slenderness ratio of 20.

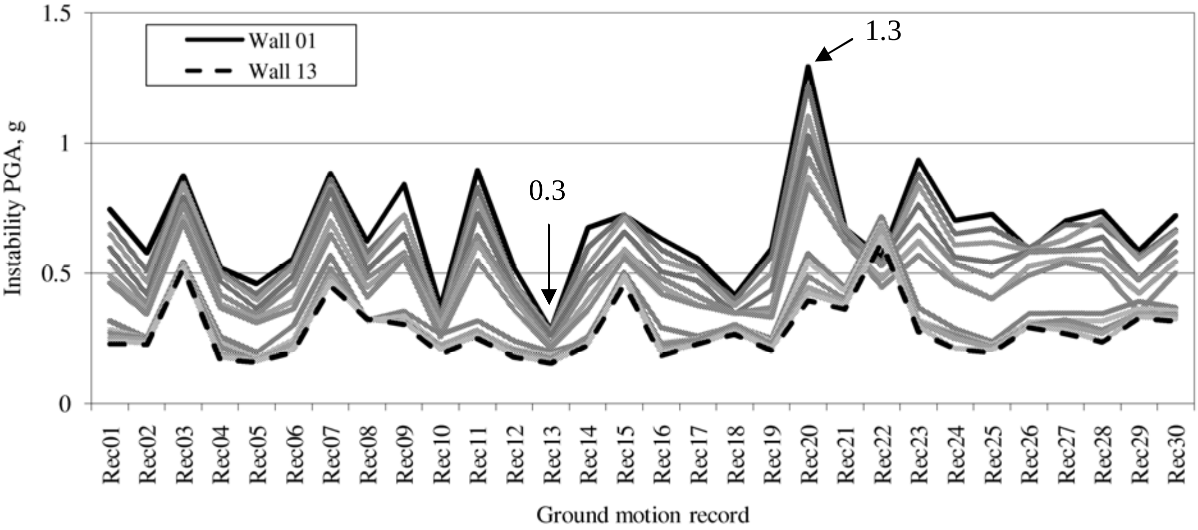
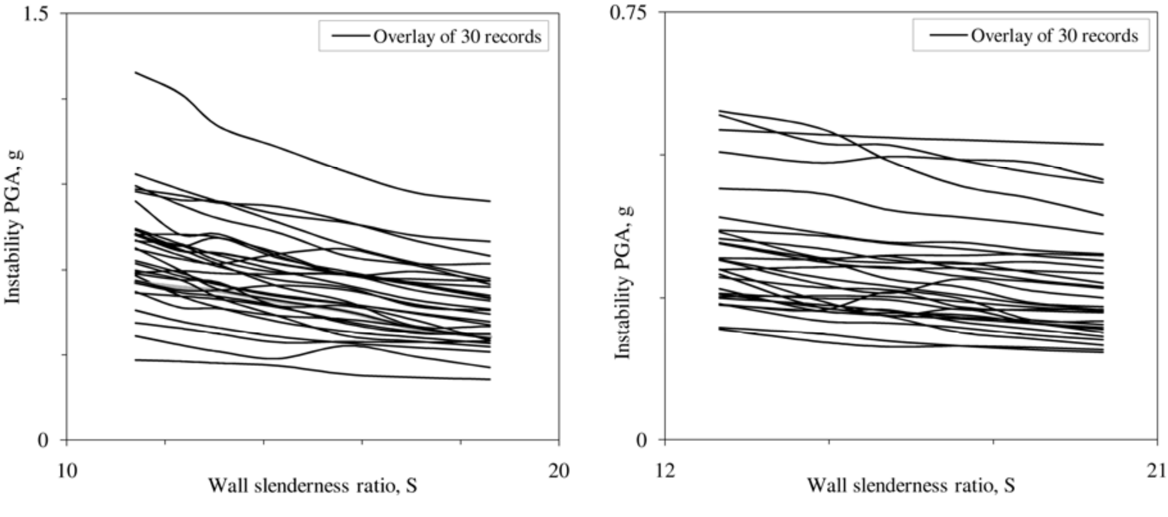


Figure 4: Instability PGA for different ground motion records

The observed trend in Figure 6 suggests that wall evaluation methods such as that proposed in ASCE (2007), which recommends a maximum allowable wall slenderness ratio, are an acceptable means of out-of-plane wall seismic assessment. A similar trend was observed in a study by Sharif et al. (2007), which used theories of rocking mechanics to predict out-of-plane stability of URM walls. Figure 6 further supports the conclusions of a previous study by the authors (Derakhshan et al. 2009), which identified the NZSEE (2006) wall evaluation method to be erroneous, as the procedure occasionally produces more favourable assessment results for walls that have higher slenderness ratios. The results of the current study will be used within reasonable timeframe to propose allowable wall slenderness ratios in New Zealand.



(a) (b)

Figure 5: Dependency of instability PGA on wall slenderness ratio; (a): 3-leaf walls, (b): 2-leaf walls

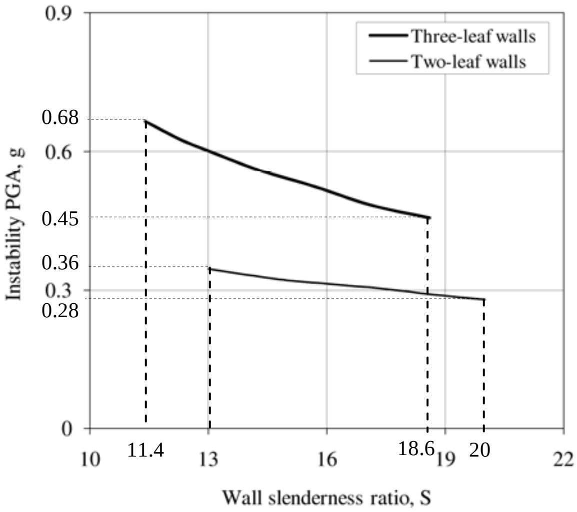


Figure 6: Effects of wall slenderness ratio, average from all records

5 CONCLUSIONS

A set of time-history analyses were performed to investigate the effects of wall slenderness ratio on overall out-of-plane seismic behaviour. Wall behavioural data was obtained based on a previous laboratory based study, and 30 ground motion records were used in analysis scenarios with increasing peak ground acceleration. It was shown that wall slenderness ratio governed the wall behaviour, although the ground motion records were different in nature. Wall slenderness ratio resulted in the wall being more vulnerable, and the results confirmed that a wall evaluation method based on wall slenderness ratio is a viable option for the prediction of the out-of-plane stability of cracked walls.

Peak ground acceleration that would cause instability in a certain wall was observed to vary significantly among different ground motion records, with a maximum difference of approximately 500%. It was concluded that an average value from a large number of ground motion records should be used as a basis for wall evaluation.

6 ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support provided by New Zealand Foundation for Research, Science, and Technology (FRST). The authors also wish to thank Ken Elwood for his invaluable feedback to this study.

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