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COMPARISON OF RECORD SCALING METHODS PROPOSED BY STANDARDS CURRENTLY APPLIED IN DIFFERENT COUNTRIES

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ABSTRACT:

The New Zealand Standard, European Standard and the U.S. Standard follow different methodologies for scaling ground motion records according to site conditions when time-history is performed. The New Zealand Standard proposes that the spectrum of each scaled record should match the design spectrum over a range of periods related to the natural period of the structure investigated, and the energy of at least one of these record's spectra must exceed the energy of the design spectrum. The European Standard recommends that the average spectrum of the scaled records should be always larger than 90% of the design spectrum in a defined range of periods, and the value of the average spectrum at period equal zero should be larger than the value of the corresponding design spectrum. The U.S. Standard advises that in a defined range of periods the average spectrum of the scaled records should be 30% larger than the code spectrum.

This study analyses how these differences between scaling approaches affect the results of time-history analyses, and some recommendations for adequate application of record scaling procedures are presented.

KEYWORDS: Seismic standards, ASCE/SEI 41-06, Eurocode 8, NZS 1170.5, record scaling, time-history analysis

1. INTRODUCTION

The basic idea of finite elements time-history analysis is to reproduce the actual behaviour of a structure under the action of ground motions by considering their geometry and materials properties. Therefore an adequate set of ground motion records is fundamental to perform time-history analysis properly. There are two main sources where ground motion records can be obtained. Synthetic ground motion records can be generated using physical or numerical models (Boore, 2003; Vanmarcke et al., 1990), or real ground motion records can be obtained from databases of records of previous earthquake events (Consortium of Organizations for Strong-Motions Observation System, 1999; Earthquake Commission of New Zealand and GNS Science, 2004; Pacific Earthquake Engineering Research Center, 2005). In general, the second source of ground motions is preferred.

Considering that these actual records should have seismological characteristics similar to the expected earthquake for the considered site (magnitude, distance, fault mechanism and soil conditions), it is not an easy task to find records that satisfied simultaneously all conditions. Recently, a number of studies propose different ways for choosing set of records according to the seismological characteristics of the site (Baker and Cornell, 2006; Bommer and Acevedo, 2004; Cornell, 2005; Dhakal et al., 2007; Iervolino and Cornell, 2005; Oyarzo Vera et al., 2008). However, once the records are selected, the work does not finish. After the record selection, it is necessary to scale these real records to generate new scaled records (artificial records) that match the intensity of the earthquake expected for the site, that means, to adjust the ground motion records to the spectrum defined in the design code (target spectrum) for the site considered. However, as in record selection there are many criteria and no agreement has been made on how to choose a set of ground motion records properly, and there is no uniform criterion for record scaling. Consequently, a review of different seismic design codes reveals different methods for record scaling.

The aim of this study is to identify how different scaling procedures affect the results of time-history analyses. For this purpose, the response of a single-degree-of-freedom (sdof) system is analyzed under the action of seven ground motion records scaled according to the methods proposed in the European Standard (EC8), the U.S. Standard (USS), and the New Zealand Standard (NZS).

2. RECORD SCALING METHODS

The three methods presented here scale the magnitude of ground motion records using a multiplying factor, so that the response spectrum of the modified records fits the target spectrum defined in the corresponding design regulations. However, there are some differences in the procedure, which are described in the following section.

2.1. Eurocode 8

The EC8 (European Committee Standardization, 2004) recommends in section 3.2.3.1 that artificial records shall be generated from scaling real records. A set of at least three scaled records should be used in the time-history analysis. The average spectrum of the scaled records should be always larger than 90 % of the target spectrum in the periods between 0.2 T_1 and 2.0 T_1, where T_1 is the fundamental period of the structure in the direction where the excitation is applied. In addition, the value of the average spectrum at period equal to zero should be larger than the value of the target spectrum at period equal to zero. When less than seven records are used, the maximal response of the structure should be considered for design. However, when seven or more records are used, the average response of the structure can be used for design.

2.2. U.S. Standard

The USS (American Society of Civil Engineers, 2007) seems to be more simple, but more conservative, too. This standard refers to time-history analysis in section 1.6.2.2. It allows the use of sets of at least three artificial records generated by scaling real records. The average spectrum of the scaled records should be equal to 1.3 times the target spectrum in the periods between 0.2 T_1 and 1.5 T_1. When less than seven records are used, the maximal response of the structure should be considered for design; but when seven or more records are used, the average response of the structure can be used for design.

2.3. New Zealand Standard

The NZS (Standards New Zealand, 2004a and 2004b) presents the most elaborated method for scaling records, but also it includes in section 5.5.1 the most comprehensive explanation of the fundamentals and how to apply this method. The NZS recommends the use of at least three records scaled by two factors: the record scale factor (k_1) and the family scale factor (k_2). By scaling the records with the record scale factor (k_1) the response spectrum of the scaled records fits the target spectrum in a way that the function $\log(k_1 \cdot \mathit{Recorded\ Spectrum}/\mathit{Target\ Spectrum})$ is minimized in a least mean square sense over the periods between 0.4 T_1 and 1.3 T_1. The family scale factor (k_2) is applied to ensure that the energy in the spectrum of at least one record of the set exceeds the energy of the target spectrum. In addition, some recommendations are presented related to the values of k_1 ($0.33 < k_1 < 3.0$) and k_2 ($1.0 < k_2 < 1.3$). When these recommendations are not satisfied, the record that does not accomplish the requirement should be replaced. In all cases, the maximum response of the structure should be used for design.

3. NUMERICAL MODEL AND GROUND MOTION RECORDS

The study case presented in this article corresponds to the conditions of Wellington City (New Zealand), the populated area with the highest seismic hazard in the country. Shallow soil conditions are often found in Wellington's downtown. The ground motions selected for the analysis correspond to those recommended as default set of records for this kind of soil condition, that satisfied the seismological signature requirements (Oyarzo Vera et al., 2008). Three near-fault records are included in this list according to standard's requirement (Standards New Zealand, 2004a). The list of ground motion records and their characteristics are presented in Table 3.1.

Table 3.1 Ground motion records recommended for Wellington/Shallow Soil

ID	Record	Date	Magnitude	PGA (g)	
EQ1	El Centro (USA)	19-May-40	7.0	0.347	
EQ2	Llolleo (Chile)	03-Mar-85	7.8	0.646	
EQ3	La Union (Mexico)	19-Sep-85	8.1	0.163	
EQ4	Hokkaido (Japan)	26-Sep-03	8.3	0.283	
EQ5	Tabas (Iran)	16-Sep-78	7.2	1.041	Near-Fault
EQ6	Lucerne (USA)	28-Jun-92	7.3	0.778	Near-Fault
EQ7	Izmit-Kocaeli (Turkey)	17-Aug-99	7.5	0.215	Near-Fault

The structure analysed corresponds to a URM wall with 1000 mm high, 4240 mm long, 240 mm thick, and a total mass of 10000 kg. The compressive strength (f_c') and Young's modulus (E) shown in Table 3.2 correspond to the typical values for New Zealand stiff bricks with soft mortar (New Zealand Society for Earthquake Engineering, 2006).

Table 3.2 Material properties

	fc' (MPa)	E (MPa)
Soft Mortar	1	7000
Stiff Brick	12	12000

The wall was modelled with the software Ruaumoko (Carr, 2004) as a sdof system with structural properties according to the geometry and material characteristics (Figure 1), with a natural frequency of 2 Hz and a damping ratio of 15 %.

The nonlinear behaviour of the structure was represented by a Modified Takeda hysteretic model with parameters $\alpha = 0.4$ and $\beta = 0$. The yielding force of 22.8 kN is assumed for both directions, and the post yielding stiffness is 0.168 k_0 (Figure 2).

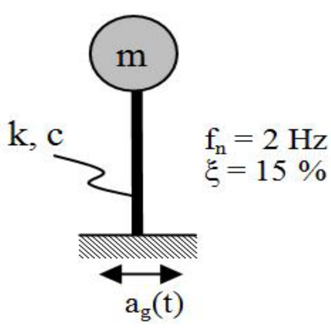

Figure 1: Sdof model

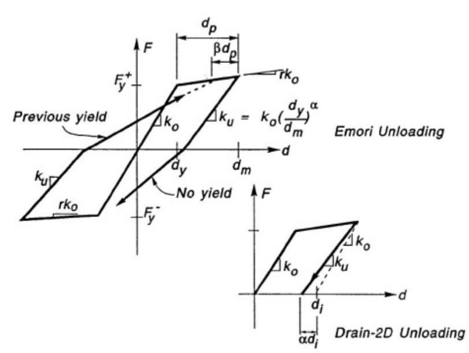

Figure 2: Modified Takeda hysteretic model (Carr, 2004)

4. RECORD SCALING FACTORS

The ground motion records were scaled according to the methods described in EC8, USS and NZS. The non-scaled and scaled spectra of these records are presented in Figures 3 to 6.

The first significant difference between the three methods is the range of periods considered for the scaling procedure. Since the natural period (T_1) of the considered sdof system is 0.5 sec, the periods recommended by EC8 are between 0.2 T_1 and 2.0 T_1 or between 0.1 sec and 1 sec; in the case of USS, the periods are between 0.2 T_1 and 1.5 T_1 or between 0.1 sec and 0.75 sec; and applying the NZS method, the periods are between 0.4 T_1 and 1.3 T_1 or between 0.2 sec and 0.65 sec. It is evident that the periods recommended by NZS are smaller than the others.

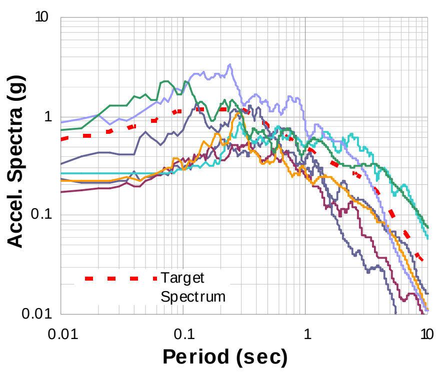

Figure 3: Non-scaled spectra

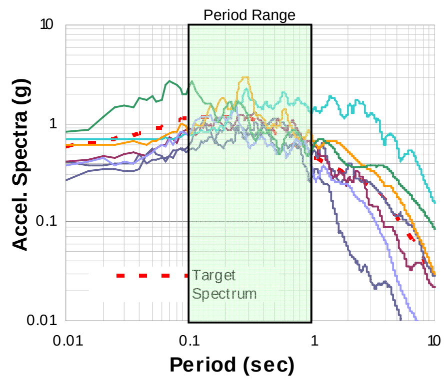

Figure 4: Scaled spectra according to EC8

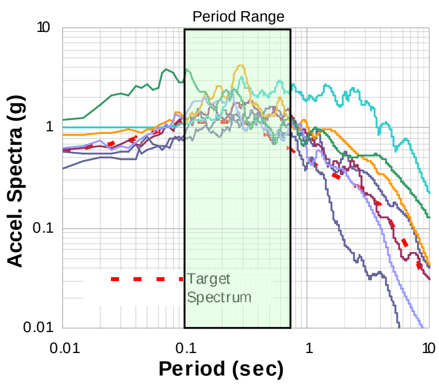

Figure 5: Scaled spectra according to USS

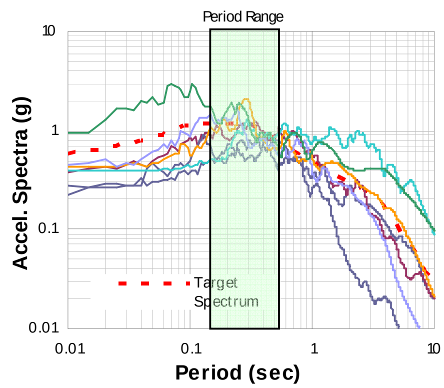

Figure 6: Scaled spectra according to NZS

The other significant fact is the value of the scale factors (Figure 7). In almost every record the NZS method provides the smallest scale factor, while the scale factor calculated according to USS is always the largest. The USS mean scale factor is 85% higher than the scale factor calculated according to NZS. The standard deviation of the scale factors calculated according to the NZS method is slightly lower (Table 4.1). Something similar happened with the PGA value (Figure 8). The USS average value of PGA is 72% higher than that according to the NZS. However, the PGA standard deviation is the opposite of scale factor standard deviation. The standard deviation of PGA extracted from records scaled according to NZS is larger than in the cases of EC8 and USS (Table 4.1).

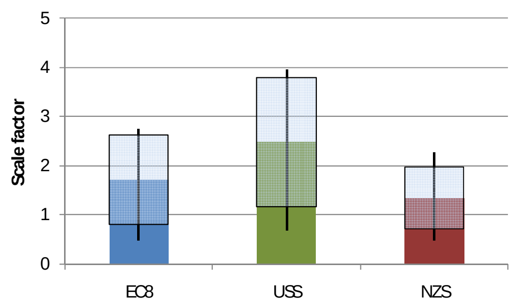

Figure 7: Scale factor

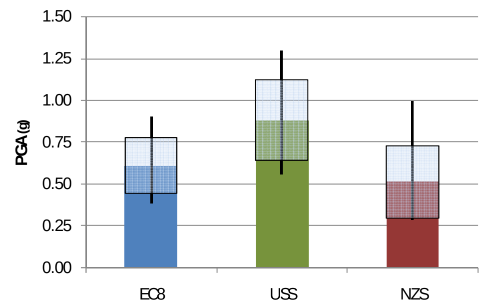

Figure 8: Scaled PGA

Table 4.1 Scale factors according to EC8, USS and NZS.

ID	Record	Scale Factor			PGA (g)		
		EC8	USS	NZS	EC8	USS	NZS
EQ1	El Centro (USA)	1.774	2.562	1.241	0.615	0.889	0.431
EQ2	Llolleo (Chile)	0.815	1.177	0.679	0.526	0.760	0.438
EQ3	La Union (Mexico)	2.410	3.481	2.257	0.393	0.567	0.368
EQ4	Hokkaido (Japan)	2.639	3.812	1.514	0.747	1.079	0.428
EQ5	Tabas (Iran)	0.493	0.712	0.505	0.513	0.741	0.526
EQ6	Lucerne (USA)	1.153	1.666	1.275	0.897	1.296	0.992
EQ7	Izmit-Kocaeli (Turkey)	2.724	3.934	1.926	0.586	0.846	0.414
	Average Value	1.715	2.478	1.342	0.611	0.883	0.514
		128%	185%	100%	119%	172%	100%
	Standard Deviation	0.911	1.316	0.628	0.166	0.240	0.216
		53%	53%	47%	27%	27%	42%

5. DYNAMIC RESPONSE AND DISCUSSION OF RESULTS

The response parameter considered in this analysis is the maximum displacement (u_{max}) recorded when the system is excited by each ground motion scaled according to one of the three methods. The results of this analysis are shown in Table 5.1. The same information is presented in Figure 9, but in this figure the collapse events are displayed as displacements equal to 100 mm, although they are actually larger.

In general, the u_{max} values obtained from ground motions scaled according to NZS are the smallest, followed by those obtained from ground motions scaled according to EC8, and the largest magnitudes of u_{max} correspond to ground motions scaled according to USS (Figure 9). This situation coincides with the observations made previously regarding the value of the scaling factor (Figure 7).

When the EC8 method is used to scale ground motions, a collapse of the structure is observed only for the Hokkaido record. When the ground motions are scaled according USS method, the El Centro, Hokkaido and Izmit-Kocaeli records induce a structural collapse. There is no collapse when the ground motions are scaled according to NZS.

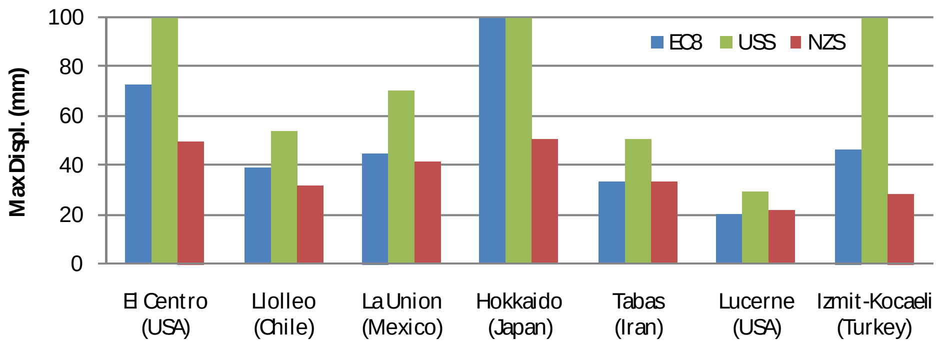

Figure 9: Maximum structural response

Table 5.1 Structural response of sdof system

ID	Record	u_{max} (mm)		
		EC8	USS	NZS
EQ1	El Centro (USA)	72.70	collapse	49.61
EQ2	Llolleo (Chile)	38.98	53.98	31.54
EQ3	La Union (Mexico)	44.84	69.97	41.35
EQ4	Hokkaido (Japan)	collapse	collapse	50.65
EQ5	Tabas (Iran)	33.26	51.01	33.59
EQ6	Lucerne (USA)	20.19	29.33	22.33
EQ7	Izmit-Kocaeli (Turkey)	46.89	collapse	28.27
	Maximum Value	72.7	69.97	50.65
		144%	138%	100%
	Average Value	42.8	51.1	36.8
		116%	139%	100%
	Standard Deviation	17.5	16.7	10.8
		41%	33%	29%

As Figure 10 illustrates and referring to the average value of u_{max}, the smallest value corresponds to the NZS scaling method. The value obtained from the EC8 and the USS scaling methods are 16 % and 39 % larger than the value of NZS scaling method, respectively. Regarding to the standard deviation, the smallest standard deviation corresponds to the NZS scaling method (29 %), followed by the USS scaling method (33 %) and, later, by the EC8 scaling method (41 %).

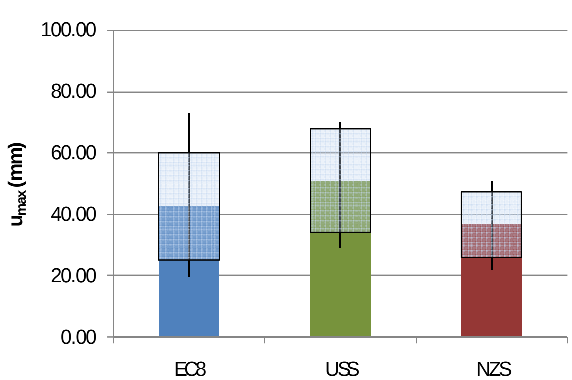

Figure 10 Average of the maximum responses

Finally, relative to the largest value of u_{max} (excluding collapse conditions), the largest value of u_{max} obtained according to the NZS scaling method (50.7 mm) is comparable with the average values of u_{max} obtained according to the EC8 (42.8 mm) and according to USS (51.1 mm) scaling method (Figure 11). This indicates that the requirement of NZS (use of the largest value of u_{max} for design and/or assessment) is equivalent to the requirements defined in EC8 and USS (use the average value of u_{max} for design and/or assessment), when seven or more records have been considered in the analysis. However, time-history analysis according to the NZS method can be strongly influenced by the response of a specific ground motion with particularly strong peaks. Considering this observation, the average response due to seven or more ground motions seems to be a better option, because it eliminates the influence of specific ground motions and offers a lower standard deviation in the response. Under this condition the NZS scaling method would become the less conservative. In the recent time some studies (Dhakal et al., 2007) support the idea of using the average response instead of the maximum response, when time-history analysis are performed using seven or more records scaled according to NZS method.

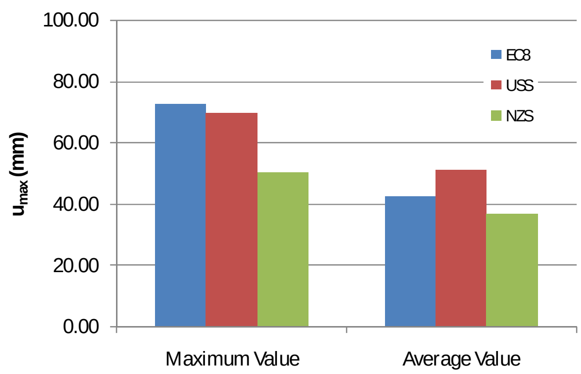

Figure 11 Maximum and average response

6. CONCLUSION

The NZS presents the most elaborated approach for record scaling, but at the same time, this is the most comprehensive method. This procedure offers the best matching to the target spectra, mainly because of the narrower range of periods considered in the fitting process.

Regarding the structural response, the most conservative scaling method is the method described in the USS, and the less conservative is the NZS scaling method. At the same time, the NZS method offers a lower standard deviation in the response.

The largest value of u_{max} obtained using the NZS scaling method is comparable with the average values of u_{max} obtained using the EC8 and USS scaling methods. This result indicates that the requirement of NZS (use the maximum value of u_{max}) is equivalent to the requirements defined in EC8 and USS (use the average value of u_{max}), when seven records have been considered in the analysis. The study reveals that the NZS scaling procedure is the less conservative method.

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REFERENCES

American Society of Civil Engineers. (2007). *ASCE/SEI 41-06. Seismic rehabilitation of existing buildings*, American Society of Civil Engineers, Reston, Va.

Baker, J., and Cornell, A. (2006). "Spectral shape, epsilon and record selection." *Earthquake Engineering and Structural Dynamics*, 35, 1077-1095.

Bommer, J. J., and Acevedo, A. B. (2004). "The use of real earthquake accelerograms as input to dynamic analysis." *Journal of Earthquake Engineering*, 8, 43-91.

Boore, D. M. (2003). "Simulation of ground motion using the stochastic method." *Pure and Applied Geophysics*, 160(3-4), 635-676.

Carr, A. J. (2004). "Ruaumoko – A program for inelastic time-history analysis." Department of Civil Engineering, University of Canterbury, New Zealand.

Consortium of Organizations for Strong-Motions Observation System. (1999). "COSMOS Virtual Data Center." [cited 01.Sept.2007]; http://db.cosmos-eq.org/scripts/default.plx.

Cornell, C. (2005). "On Earthquake Record Selection For Nonlinear Dynamic Analysis." *The Esteva Symposium*, August 2005, Mexico.

Dhakal, R., Singh, S., and Mander, J. (2007). "Effectiveness of earthquake selection and scaling procedure method in New Zealand." *Bulletin of the New Zealand Society for Earthquake Engineering*, 40(3), 160-171.

Earthquake Commission of New Zealand, and GNS Science. (2004). "GeoNet Strong Motion Data." [cited 01.Sept.2007]; ftp://ftp.geonet.org.nz/strong/processed.

European Committee Standardization. (2004). *Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings*, European Committee Standardization, Brussels, Belgium.

Iervolino, I., and Cornell, A. (2005). "Record selection for nonlinear seismic analysis of structures." *Earthquake Spectra*, 21(3), 685-713.

New Zealand Society for Earthquake Engineering. (2006). "Assessment and Improvement of the Structural Performance of Buildings in Earthquakes." *Recommendations of a NZSEE Study Group on Earthquake Risk Buildings*.

Oyarzo Vera, C., McVerry, G., and Ingham, J. (2008). "Ground motion records for time-history analysis of URM buildings in New Zealand – The North Island." *New Zealand Society of Earthquake Engineering Conference*, April 2008, New Zealand.

Pacific Earthquake Engineering Research Center. (2005). "PEER NGA Database." [cited 01.Sept.2007]; http://peer.berkeley.edu/nga/index.html.

Standards New Zealand. (2004a). *NZS 1170.5:2004 - Structural design actions. Earthquake actions.*, Wellington, New Zealand.

Standards New Zealand. (2004b). *NZS 1170.5:2004 - Structural design actions. Earthquake actions. – Commentary*, Wellington, New Zealand.

Vanmarcke, E. H., Cornell, C. A., Gasparini, D. A., and Hou, S.-n. (1990). "SIMQKE-I: Simulation of Earthquake Ground Motions ", Department of Civil Engineering, Massachusetts Institute of Technology., Cambridge, MA.