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MAPPING OF INELASTIC EFFECTS AND STRUCTURAL BEHAVIOUR FACTORS FOR EUROCODE 8: A CASE STUDY FOR ICELAND

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ABSTRACT:

The objective of this paper is to present a uniform probabilistic hazard representation of inelastic spectral ordinates and structural behaviour factors. The study area selected is the South Iceland Lowland. The analysis is performed within the framework of Eurocode 8. The data set applied are obtained from the ISESD data bank. It contains significant Icelandic earthquakes but is augmented by data from continental Europe and the Middle East. In all cases the selected earthquakes are identified as shallow strike-slip earthquakes. The site conditions dealt with are quantified as rock according to the Eurocode 8 definition. The probabilistic hazard study is carried out using a synthetic earthquake catalogue based on available instrumental and historic earthquake data for the study region. The time span of the historic catalogue is roughly 1,000 years, the instrumental catalogue covers 100 years and the strong-motion database covers about 25 years. The numerical results are presented in terms of inelastic uniform hazard spectra and corresponding structural behaviour factor for the study area. These results can be used as an addition to the zoning maps for Iceland presented at the 13WCEE.

KEYWORDS: Eurocode 8, uniform hazard spectrum, inelastic effects, structural behaviour factor, strong motion

1. INTRODUCTION

The application of Eurocode 8 (2003) requires that probabilistic seismic zoning maps are produced. These maps display the peak ground acceleration for an appropriate mean return period, usually corresponding to 475 years. In addition to these basic maps, it is desirable to produce maps showing the location and magnitude of the events contributing most to the design events, say, the 475 year event. Such maps are required for the generation of synthetic time series needed in inelastic analysis specified as a design option and design check in Eurocode 8. To further facilitate the probabilistic inelastic design analysis, a more thorough quantification of the inelastic properties is needed. This includes mapping of the inelastic response spectral ordinates, as well as structural behaviour factors represented as uniform hazard ordinates conforming to the Eurocode 8 requirements and specification.

The study area selected is Iceland and the Icelandic Region emphasising the major seismic zones, in particular the South Iceland Seismic Zone, and densely populated areas. The earthquakes in these zones can be characterised as shallow, moderate to strong, with a predominant strike-slip faulting mechanism. The fault planes of the largest earthquakes are in all cases close to vertical and the rupture typically propagates to the surface.

2. BASIC PRINCIPLES

According to Eurocode 8 the foundation of force-based seismic design for ductility is the inelastic response spectrum of a single degree-of-freedom system which has a perfectly elasto-plastic force-displacement curve under monotonic (increasing) loading. Such a system is defined in terms of the following parameters: undamped natural period (under small oscillations); critical damping ratio; yield force; and ductility factor. The inelastic response spectrum is within the framework of Eurocode 8 derived from the linear elastic response spectrum applying the so-called structural behaviour factor, q, defined by the following ratio:

$$q = \frac{\max|F_{elastic}|}{\max|F_y|} \tag{1}$$

Here, $F_{elastic}$ represents the force that would develop if the system behaved as linear-elastic and F_y is the yield force of the inelastic system. The corresponding peak displacement demand of the inelastic system is expressed in terms of the (global) ductility factor defined as:

$$\mu = \frac{\max|\delta|}{\delta_y} \tag{2}$$

where, δ_y is the yield displacement of the system, taken here as being positive, and δ is the induced (global) displacement. In Eurocode 8 the ratio q, the behaviour factor, is as a rule greater than one. In North America the same quantity is termed the *force reduction factor* or the *response modification factor* and commonly denoted as R. This ratio is used in Eurocode 8 as a reduction factor on the internal forces that would develop in the elastic structure with 5% critical damping. That is, of course, equivalent to applying it to reduce the seismic inertia forces that would develop in this elastic structure provided that the principle of superposition applies, at least approximately. According to this greatly simplified approximation the seismic internal forces for which the members of the structure should be dimensioned can be calculated through linear elastic analysis. However, the structure has to be provided with the capacity to sustain a peak global displacement at least equal to its global yield displacement multiplied by the displacement ductility factor corresponding to the value of q used to reduce linear elastic spectral ordinates to derive the inelastic spectral ordinates.

To be able to apply the above outlined methodology with confidence for the study area a uniform hazard spectrum of inelastic response should be obtained. The first step towards the uniform hazard spectrum is to derive proper strong-motion estimation equations for the inelastic systems to be applied with an appropriate earthquake catalogue.

3. STRONG-MOTION ESTIMATION EQUATIONS FOR INELASTIC SYSTEMS

The required inelastic spectral acceleration response was derived using the dataset based on the earthquakes listed in Table 3.1 (Ambraseys et al., 2004). The faulting mechanisms of the selected earthquakes were in all cases classified as being strike-slip and the site characteristics of the stations were classified as rock. Abbreviations used for country names in the table are: AR (Armenia), GR (Greece), IS (Iceland), IT (Italy), SL (Slovenia) and TU (Turkey). The data originate from ten earthquakes and consist of 55 records, altogether 165 time series. The majority of the records are from Iceland. However, they have been augmented with data from continental Europe and the Middle East. The structural model applied is, in accordance with Eurocode 8, an elasto-plastic single degree-of-freedom system characterised by an undamped natural period, critical damping ratio, ductility factor and yield strength. Furthermore, the systems are modelled in the following using constant ductility response spectra. The strong-motion estimation model suggested for the present study is a simplified version of the model applied by Ambraseys et al. (2005). It is given as:

$$\log_{10}(S_{inelastic}) = b_1 + b_2 M_w + b_3 \log_{10}\sqrt{d^2 + b_4} \tag{3}$$

Here the following notation is used: b_1 … b_4 are the model parameters obtained by regression analysis using the dataset outlined above; M_w is moment magnitude; and d is the distance from the site to the surface trace of the causative fault measured in km. The model parameters obtained are displayed in Figure 1 along with corresponding linear elastic spectral parameters. The data applied was a reduced dataset derived from Table 3.1 by omitting the records indicated with grey shading. Records from stations where the distance to fault was greater than 100 km were excluded. Furthermore, the recordings from the Umbria Marche were omitted. It is believed that these recordings are not representative for the study area. Finally, recordings from the Thjorsabru Bridge are disregarded due to potential structural influences and site dependent conditions. This gave 47 records from eight earthquakes. Only the bigger horizontal component is considered. The undamped natural period is log-spaced and the critical damping ratio is 5%. The derived strong-motion estimation equations apply only to moderate sized, shallow strike-slip earthquakes and for rock site foundations.

The obtained strong-motion estimation equations are displayed in Figure 2, as a function of distance to fault, illustrating systems with an undamped natural period equal to 0.2 s and 1.0 s, respectively, both with a critical damping ratio equal to 5%. The earthquake magnitude is taken as equal to 6.5 in both cases. It is seen that the linear elastic system response is significantly bigger than the inelastic strength demand, although this is not necessarily the case for the displacement demand.

The structural behaviour factor, as defined above, is a quantity required for transforming the linear elastic response spectral acceleration into an inelastic demand. This can be expressed in a simplified way for the elasto-plastic systems as follows:

$$S_{inelastic}(T,\lambda,\mu) = S_a(T,\lambda)/q(\mu,\lambda,T) \tag{4}$$

Here, $S_{inelastic}$ is the inelastic strength spectrum for the elasto-plastic system, S_a is acceleration spectrum for the linear elastic system, q is the behaviour factor, T is the undamped natural period of the linear elastic system, which is taken equal to the initial small amplitude undamped natural period of the inelastic system, λ is the critical damping ratio and μ is the ductility factor.

It follows that both the earthquake response spectra and the structural behaviour factor must be a function of site-to-source distance, site conditions, faulting mechanism and the selected hazard level. Figure 3 shows that the structural behaviour factor increases with increasing distance to source. Furthermore, almost in the entire range, except next to the fault, the structural behaviour factor is somewhat bigger for the system with an undamped natural period of 0.2 s than the flexible system with a 1.0 s natural period. The strong-motion estimation equations are displayed in Figure 4 (a) as a function of undamped natural period. The spectra have been smoothed by applying the Savitzky-Golay method. The corresponding behaviour factors are displayed in Figure 4 (b) as a function of undamped natural period.

Table 3.1 The earthquake data set used for inelastic analysis (Ambraseys et al., 2004).

Date	**Time**	**Country**	M_w	**Station**	**Distance** (km)
26.08.1983	12:52:09	GR	5.20	Ouranoupolis-Seismograph Station	15
26.08.1983	12:52:09	GR	5.20	Poligiros-Prefecture	42
16.12.1990	15:45:51	AR	5.48	Akhalkalaki	20
16.12.1990	15:45:51	AR	5.48	Toros	51
16.12.1990	15:45:51	AR	5.48	Stepanavan	70
16.12.1990	15:45:51	AR	5.48	Spitak-Karadzor	77
26.04.1997	22:18:34	GR	5.02	Kyparrisia-Agriculture Bank	26
16.10.1997	12:00:31	IT	4.39	Colfiorito-Casermette	1
16.10.1997	12:00:31	IT	4.39	Nocera Umbra-Biscontini	10
16.10.1997	12:00:31	IT	4.39	Nocera Umbra	12
12.04.1998	10:55:33	SL	5.70	Cerknica	88
12.04.1998	10:55:33	SL	5.70	Sleme	104
04.06.1998	21:36:54	IS	5.45	Hveragerdi-Church	6
04.06.1998	21:36:54	IS	5.45	Irafoss-Hydroelectric Power Station	15
04.06.1998	21:36:54	IS	5.45	Selfoss-Hospital	18
04.06.1998	21:36:54	IS	5.45	Oseyrarbru	18
04.06.1998	21:36:54	IS	5.45	Reykjavik-Heidmork	23
04.06.1998	21:36:54	IS	5.45	Reykjavik-Foldaskoli	27
04.06.1998	21:36:54	IS	5.45	Reykjavik-HusVerslunarinnar	32
17.08.1999	00:01:40	TU	7.64	Izmit-Meteoroloji	9
17.08.1999	00:01:40	TU	7.64	Gebze-Tubitak Marmara Arastirma Merkezi	47
17.08.1999	00:01:40	TU	7.64	Yapi-Kredi Plaza Levent	92
17.08.1999	00:01:40	TU	7.64	Istanbul-Maslak	93
17.08.1999	00:01:40	TU	7.64	Tokat-DSI Misafirhanesi	558
17.06.2000	15:40:41	IS	6.57	Flagbjarnarholt	5
17.06.2000	15:40:41	IS	6.57	Minni-Nupur	13
17.06.2000	15:40:41	IS	6.57	Thjorsarbru	15
17.06.2000	15:40:41	IS	6.57	Selfoss-Hospital	31
17.06.2000	15:40:41	IS	6.57	Selfoss-City	32
17.06.2000	15:40:41	IS	6.57	Irafoss-Hydroelectric Power Station	34
17.06.2000	15:40:41	IS	6.57	Ljosafoss-Hydroelectric Power Station	35
17.06.2000	15:40:41	IS	6.57	Hveragerdi-Retirement House	41
17.06.2000	15:40:41	IS	6.57	Hveragerdi-Church	41
17.06.2000	15:40:41	IS	6.57	Sultartanga-Hydroelectric Power Station	42
17.06.2000	15:40:41	IS	6.57	Hrauneyjafoss-Hydroelectric Power Station	61
17.06.2000	15:40:41	IS	6.57	Reykjavik-Heidmork	70
17.06.2000	15:40:41	IS	6.57	Reykjavik-Foldaskoli	72
17.06.2000	15:40:41	IS	6.57	Reykjavik-Hus Verslunarinnar	78
21.06.2000	00:51:48	IS	6.49	Thjorsarbru	5
21.06.2000	00:51:48	IS	6.49	Thjorsartun	6
21.06.2000	00:51:48	IS	6.49	Selfoss-Hospital	14
21.06.2000	00:51:48	IS	6.49	Selfoss-City Hall	15
21.06.2000	00:51:48	IS	6.49	Irafoss-Hydroelectric Power Station	20
21.06.2000	00:51:48	IS	6.49	Ljosafoss-Hydroelectric Power Station	20
21.06.2000	00:51:48	IS	6.49	Flagbjarnarholt	22
21.06.2000	00:51:48	IS	6.49	Hveragerdi-Church	24
21.06.2000	00:51:48	IS	6.49	Hveragerdi-Retirement House	24
21.06.2000	00:51:48	IS	6.49	Minni-Nupur	28
21.06.2000	00:51:48	IS	6.49	Reykjavik-Heidmork (Jadar)	53
21.06.2000	00:51:48	IS	6.49	Reykjavik-Foldaskoli	56
21.06.2000	00:51:48	IS	6.49	Sultartanga-Hydroelectric Power Plant	58
21.06.2000	00:51:48	IS	6.49	Reykjavik-Hus Verslunarinnar	61
21.06.2000	00:51:48	IS	6.49	Sigulduvirkjun- Hydroelectric Power Station	81
21.06.2000	00:51:48	IS	6.49	Blondustifla	149
23.08.2000	13:41:28	TU	5.53	Yapi-Kredi Plaza Levent	151

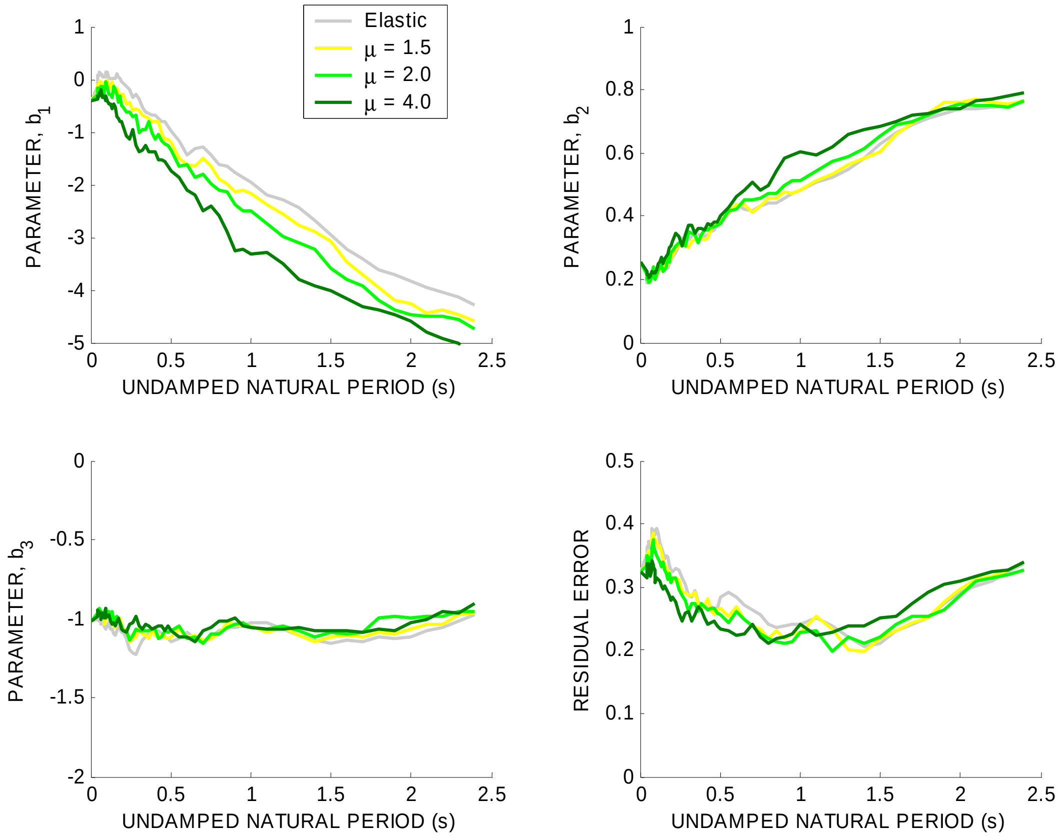
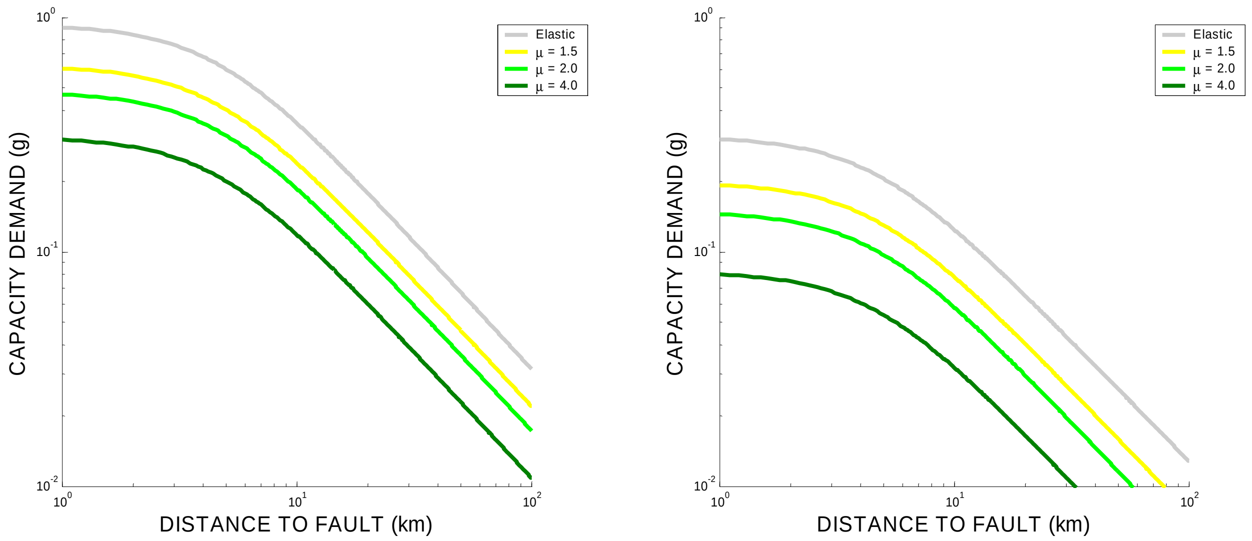
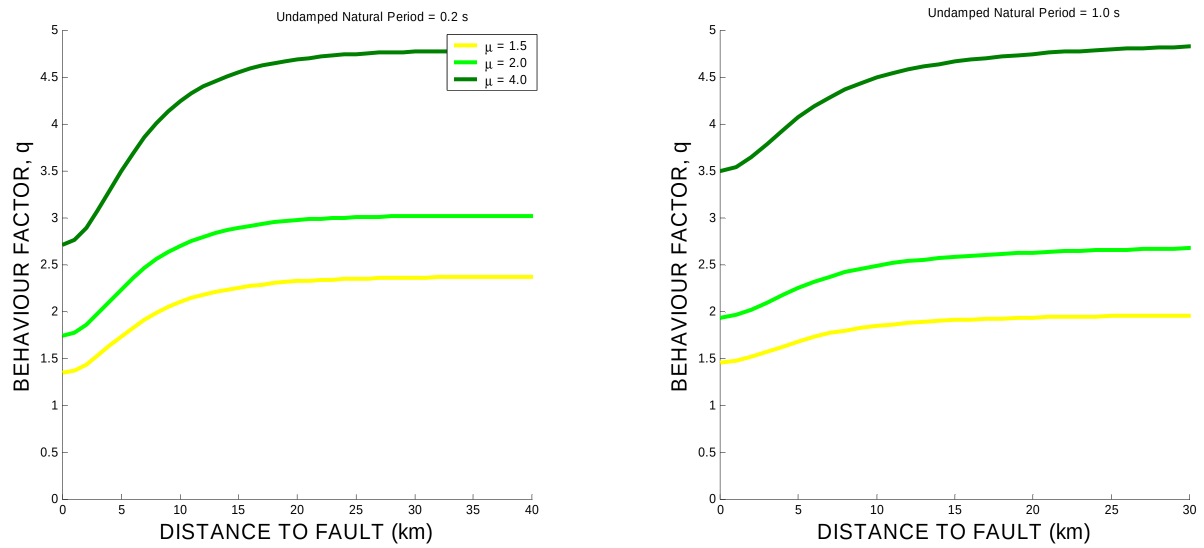


Figure 1 Model parameters for constant ductility earthquake response spectral ordinates (see Eqn. 3) for the bigger horizontal component. The critical damping ratio is 5% and b_4 = 4.5 km.



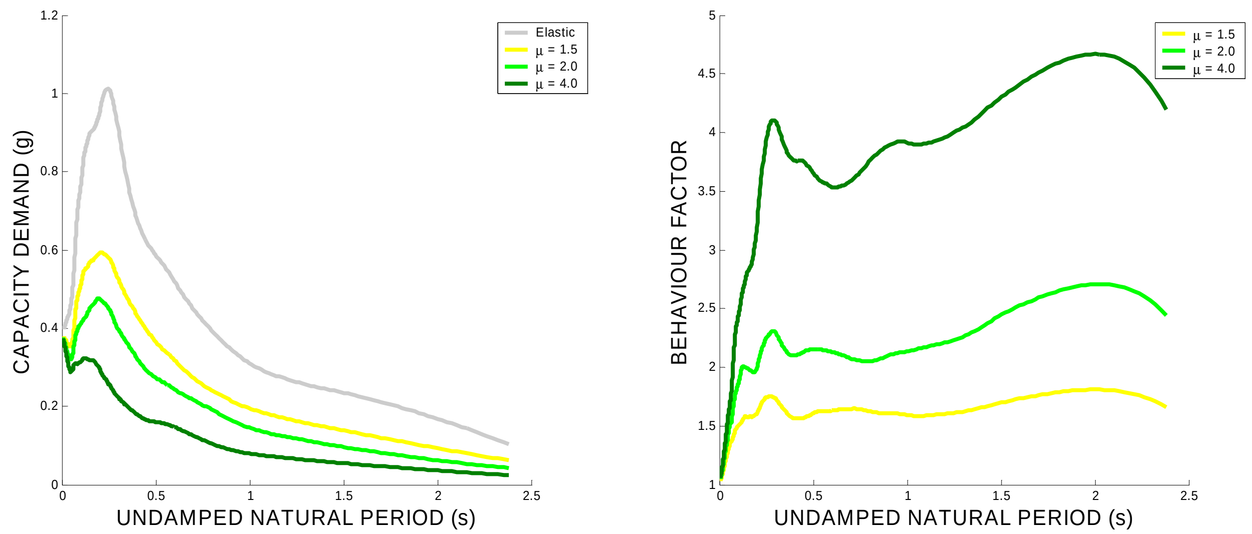
(a) (b)

Figure 2 Capacity demand as a function of distance from site to surface trace of causative fault. The response is induced by a magnitude 6.5 strike-slip earthquake. (a) Undamped natural period 0.2 s and (b) undamped natural period 1.0 s. Critical damping ratio equal to 5% in all cases.



(a) (b)

Figure 3 Structural behaviour factor for horizontal response relating the spectral acceleration of linear elastic systems to the strength of constant ductility elasto-plastic systems expressed as a function of distance to source. The response is induced by a magnitude 6.5 shallow strike-slip earthquake. Critical damping ratio is equal to 5%. (a) Undamped natural period 0.2 s and (b) undamped natural period 1.0 s.



(a) (b)

Figure 4 (a) Horizontal response spectrum, as a function of undamped natural period, for linear elastic and elasto-plastic systems with constant ductility factor. (b) Structural behaviour factor for horizontal response relating the spectral acceleration of linear elastic systems to the strength of constant ductility elasto-plastic systems expressed as a function of undamped natural period. In both cases the response is induced by a magnitude 6.5 shallow strike-slip earthquake. Critical damping ratio is equal to 5%. The distance to the surface trace of the causative fault is < 1 km. Smoothing has been performed applying the Savitzky-Golay method.

4. UNIFORM HAZARD SPECTRUM FOR CONSTANT DUCTILITY INELASTIC SYSTEMS

In this section the inelastic behaviour is further described through earthquake hazard curves and uniform hazard spectra for constant ductility derived by applying a synthetic earthquake catalogue. The study area selected is in the eastern part of the South Iceland Seismic Zone. The main parameters characterising the seismicity of the study site are taken to be the following: the Gutenberg-Richter parameters are α = 5.0 (referred to 100 years) and β = 0.61. Furthermore, the maximum magnitude is assumed to be 7 and the minimum magnitude applied is 4.

The hazard curves of the horizontal spectral acceleration response ordinates for an elasto-plastic system at the study site based on a synthetic parametric earthquake catalogue and assuming rock site conditions is shown in Figure 5 (a). The undamped natural period is 0.25 s, the critical damping ratio is 5% and the ductility ratios are equal to 1.5, 2.0 and 4.0, respectively. The presented hazard curves are obtained as the average of 100 sample curves each derived applying the same simulated earthquake catalogue. Also, in this case we see a significant reduction of the strength demand compared to the linear elastic system.

The uniform hazard spectra are displayed in Figure 5 (b) for the horizontal spectral acceleration response of constant ductility system. The ductility factors are 1.5, 2.0 and 4.0, respectively. The critical damping ratio is equal to 5% in all cases. The mean return period is 475 years. The presented curves are obtained as an average of 25 sample curves. The corresponding behaviour factor for the horizontal spectral acceleration response of constant ductility system is shown in Figure 6 (a).

The obtained results have been compared to the provisions given in Eurocode 8 (2003). This comparison is visualised in Figure 6 (b) where the straight bold lines are in accordance with the code recommendations. It is seen that the computed structural behaviour factors tend to overshoot the code recommendations especially for systems with low behaviour factor and low ductility. This is worth taking into account in the structural design.

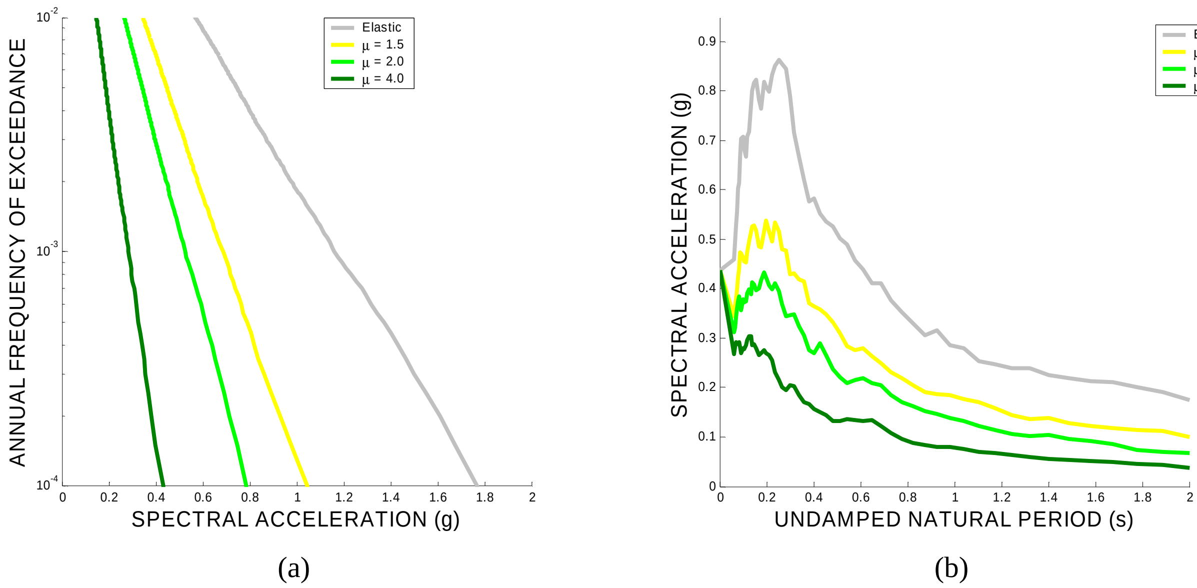
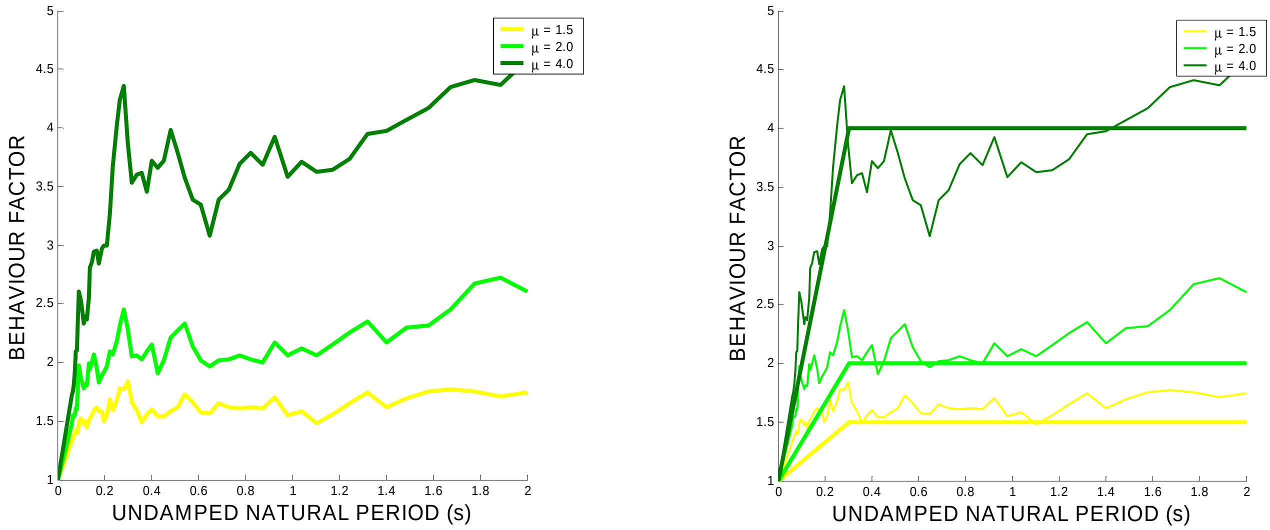


Figure 5 (a) Earthquake hazard curves for the horizontal spectral acceleration response. The undamped natural period is 0.25s and the critical damping ratio equal to 5%. (b) Uniform hazard spectra for the horizontal spectral acceleration response of a constant ductility system. Ductility factors are 1.5, 2.0 and 4.0, respectively. The critical damping ratio is equal to 5% in all cases. The mean return period is 475 years.



(a) (b)

Figure 6 (a) Behaviour factor corresponding to the horizontal spectral acceleration response of constant ductility system. Ductility factors are 1.5, 2.0 and 4.0, respectively. The critical damping ratio is equal to 5% in all cases. The mean return period is 475 years. (b) The bold lines represent behaviour factors according to Eurocode 8 while the slender lines are taken from Figure 6 (a).

5. CONCLUSION

The main finding of this study is that the behaviour factors overshoot the code recommendations, especially for systems with low behaviour factor and low ductility. This applies both to behaviour factor derived directly from the obtained strong-motion estimation model, as well as those derived from probabilistic hazard assessment carried out for the South Iceland Seismic Zone. These results can be used as an addition to the zoning maps for Iceland presented at the 13WCEE (Sólnes, Sigbjörnsson and Elíasson, 2004).

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