Amplification Effects of Thin Soft Surface Layers: A Study for NBCC 2015

W.D. Liam Finn and Francisco Ruz

Abstract The seismic response of shallow soft surface layers is of concern in developing the seismic section of the National Building Code of Canada for 2015. The response of such layers is studied using recorded data from the 2011 Tohoku earthquake. Fourteen sites have been studied in detail so far that had soft, shallow surface layers. At each site two records were available, one at the bottom of the borehole at a depth of the order of 100–500 m and one on the surface. Site response analyses were conducted to determine the ground motion at the top of the rock underlying the surface layer, so that the amplification of the soil layer itself relative to the rock surface could be determined. These analyses were conducted using the program SHAKE. The properties in SHAKE were calibrated to get a good match between the measured and computed surface motions for the recorded input at the bottom of the rock.

Keywords Site response · Shallow site amplification factors · Amplification correlations with V_{s30} · Tohoku 2011 data

Introduction

The soil conditions at a site are a major factor in determining the damage potential of incoming seismic waves from bedrock. The softer surface soils amplify the motions from bedrock as they pass to the surface. Damage patterns in Mexico City from the 1985 Michoacan earthquake provide a vivid example of this effect. Peak accelerations in the incoming rock motions were generally less than 0.04 g and had predominant periods of around 2 s. Many clay sites in the dried lakebed on which the original city was founded had site periods of around 2 s also and were excited into resonant response by the rock motions. As a result, the bedrock motions were

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amplified about 5 times as they passed through the clay layers. The amplified motions in turn excited resonant response in buildings with periods of about 2 s with devastating effects. In the 1989 Loma Prieta earthquake, major damage occurred on soft soil sites in the San Francisco—Oakland region where strong motion spectral accelerations were amplified 2–4 times compared to adjacent rock sites and caused severe damage, (Housner 1989; Idriss 1990).

In the current Canadian building code (NBCC 2010), the amplification potential of site conditions are quantified by the use of foundation factors. All site conditions are classified into one of five classes (A–E) based on the average shear wave velocity in the top 30 m, V_{s30}, and a set of short and long period amplification factors are assigned to each site class. Problems arise with this approach, when the surface soils on the rock are less than 30 m thick. Prior to NBCC 2010, sites with soft soil thicknesses less than 30 m were classified using V_{s30} even if that meant incorporating some rock to make up the thickness, with the caveat that this process was not allowed to move the site into one of the rock categories, A, B. This was a matter of practice and was not incorporated in the code. NBCC 2010 directed that the appropriate Site Class for the shallow surface deposits should be based on the average properties of the softer surface materials. There was little evidence to support this development. The 2011 Tohoku earthquake in Japan has provided many recordings on soft shallow sites and this data is being studied to get an insight into the ground motion amplification potential of these sites and to provide a sound basis for classifying these sites for NBCC 2015.

Theoretical Basis of Amplification

The basic mechanism of site amplification (Finn and Wightman 2003) is best illustrated by examining the effect of an uniform surface layer on incoming bedrock motions. Consider the elastic undamped layer shown in Fig. 1 which is characterized by a thickness, H. a shear wave velocity, Vs, and a density, ϱ.

Okamoto (1973) has shown that, if bedrock motion is a harmonic wave with a period equal to the period of the elastic surface layer ($T = 4\ H/V_s$), then the amplification factor $AF = a_t/a_r$ for undamped motion at the surface is

$$AF = 2/\kappa \quad (1)$$

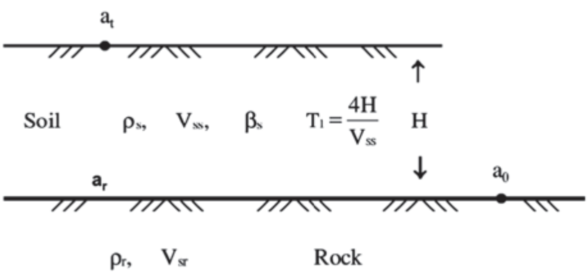


Fig. 1 Elastic layer on elastic half space

where, the impedance ratio, is $\varrho_s Vss/\varrho_r Vsr$, a_t is the surface acceleration, a_r is the incoming bedrock acceleration to the upper layer and $\varrho_{s,}$ ϱ_r are the soil and rock densities respectively. The factor 2 in Eq. 1 is due to wave reflection from the surface of the soil layer. If damping is considered

$$AF = 2/\left(\kappa + \beta_s\ \pi/2\right)$$

where β_s is the equivalent viscous damping ratio in the soil.

The acceleration, $a_{r,}$ is rarely available. Therefore ground motions for seismic design are determined by first selecting appropriate rock or stiff soil outcrop motions, a_o, and using these as input to a nonlinear or equivalent linear site response analysis that accommodates the split between up-going and down-going component motions at the interface between soil and rock or stiff soil. In this case the amplification is estimated as $AF = a_t/a_0$ where a_0 is the outcrop motion. Since a_0 is also a surface motion, the amplification factor is now given by

$$AF = 1/\left(\kappa + \beta_s\ \pi/2\right) \tag{2}$$

These theoretical results show that the important parameters controlling ground motion amplification are (i) the relationship between the periods of the incoming motions from bedrock and the predominant period of the surface layer, (ii) the impedance ratio between the bedrock and the surface layer and (iii) soil damping (Finn and Wightman 2003).

Analyses of Tohoku Borehole Sites

The amplification of ground motions passing through shallow soft surface layers is of concern in developing design motions for the National Building Code of Canada for 2015 (NBCC 2015). The response of such layers is being studied using recorded data from the 2011 Tohoku earthquake obtained from KiK-net at http://www.kyo-shin.bosai.go.jp/. Data from a total of 30 Tohoku sites will be studied ultimately. Fourteen sites have been studied so far with soft surface layers less than 18 m in thickness with 2 exceptions. Details of these sites are shown in Table 1. The PGA at the top of rock was calculated using SHAKE analysis as will be described later.

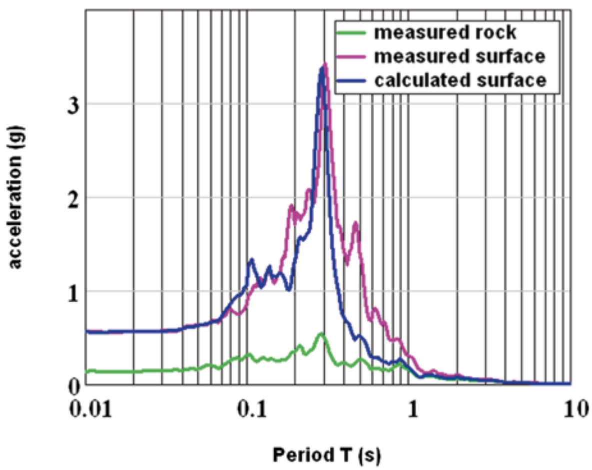
Ghofrani et al. (2012) made a careful, detailed study of all Tohoku borehole data and studied the amplification effects of the surface layers in a very interesting paper. They defined amplification with respect to the motions recorded at the bottom of the borehole, assuming that negligible amplification would occur between the bottom and the top of the rock column. In practice, amplification is usually related to motions on a stiff soil or rock layer directly underlying the surface layer. Therefore in the present study the ground motions at the top of the rock column were calculated and the amplification of the surface motions was defined relative to the top of rock motions.

Table 1 Details of instrumented boreholes

Site	Name	PGA surface	PGA top rock	PGA base rock	Downhole depth (m)	H soil (m)	Vs30 (m/s)
1	MYGH04	0.70	0.41	0.12	100	4	850
2	MYGH12	0.53	0.31	0.16	102	6	748
3	IWTH27	0.75	0.38	0.11	100	4	670
4	IBRH16	0.51	0.28	0.12	300	12	626
5	FKSH09	0.43	0.25	0.10	200	10	585
6	TCGH13	0.56	0.41	0.14	140	4	584
7	IBRH18	0.45	0.29	0.16	507	15	559
8	FKSH17	0.28	0.18	0.07	100	6	544
9	FKSH10	1.08	0.48	0.18	200	16	487
10	IBRH15	0.60	0.25	0.10	90	5	450
11	SITH11	0.20	0.06	0.02	106	14	372
12	SITH06	0.23	0.10	0.06	200	50	369
13	FKSH19	0.61	0.31	0.13	100	18	360
14	FKSH18	0.58	0.19	0.10	100	30	307

At each site two records are available, a rock motion at depths of the order of 100–500 m and on the surface. The objective of this study was to estimate the amplification of motions between the top of bedrock and the surface of the soft layer. This entailed site response analyses to determine the motions at top of rock. These response analyses were conducted using the program SHAKE (Schnabel et al. 1972). The properties in SHAKE were calibrated to get a good match between the measured and computed surface motions for the recorded input at the bottom of the rock. Typical results are shown in Figs. 2, 4 and 6. Comparisons between recorded and calculated spectra suggest that the SHAKE analyses are good enough to give

Fig. 2 Recorded and computed response spectra at site TCGH13



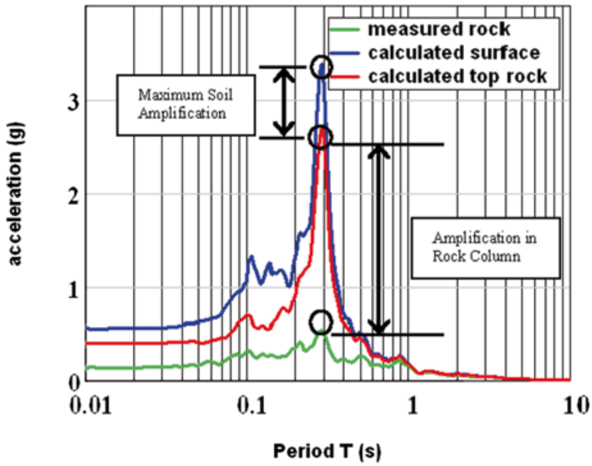


Fig. 3 Recorded and computed response spectra at site TCGH13

useful estimates of the amplification of motions by the soft surface layers. The amplification of spectral acceleration at the top of the rock column with respect to that at the base of the rock column is shown in Figs. 3, 5 and 7 which also shows the spectral amplification at the top of the soil layer with respect to the top of the rock. It appears that variable but significant amplification can occur in the rock column. The amplification in the rock column is also indicated by a comparison of PGA values at the top and bottom of the rock column in Table 1.

The average amplification factor for the response spectrum at the surface relative to the top of rock was calculated for each site and is plotted against V_{s30} in Fig. 8. There is a good correlation ($R^2=0.80$) between average amplification of spectral acceleration and V_{s30}. The standard deviation is $\sigma=0.5$. The mean correlation is given by

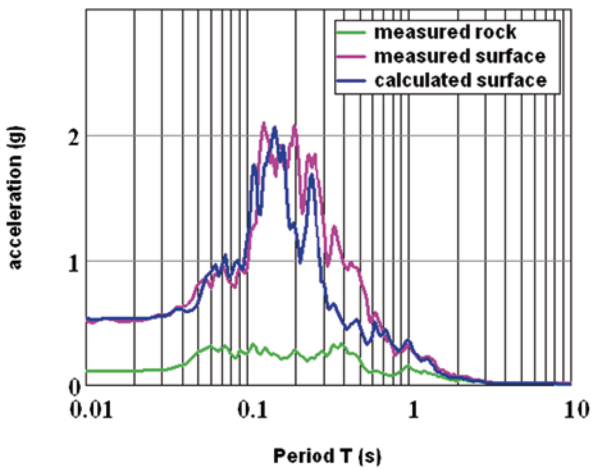


Fig. 4 Recorded and computed response spectra at site IBRH16

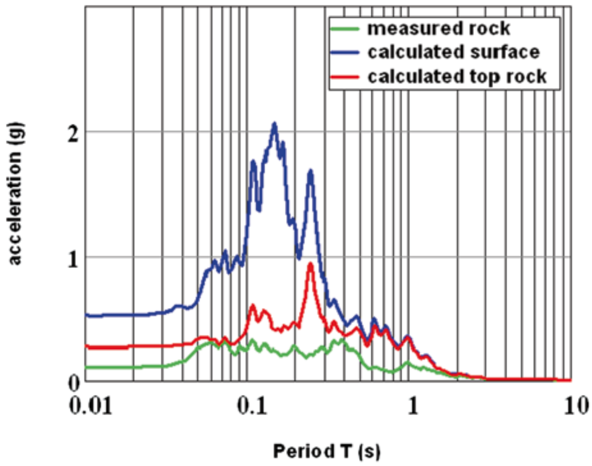


Fig. 5 Recorded response spectra at site IBRH16

$$\text{Mean AF} = 167.66\, V_{s30}^{0.719} \tag{3}$$

where AF is the amplification factor.

NBCC 2010 recommends that the classification of shallow sites for site amplifications should be based on the properties of the sites in particular Vs. In Fig. 9 average spectral amplifications are plotted against Vs. There seems to be very little correlation between the average spectral amplification and the velocity of the surface layer in contrast to the strong correlation between mean spectral amplification and V_{s30}. It would seem that the recommendation in NBCC 2010 regarding classification of the surface layer needs to be reviewed critically.

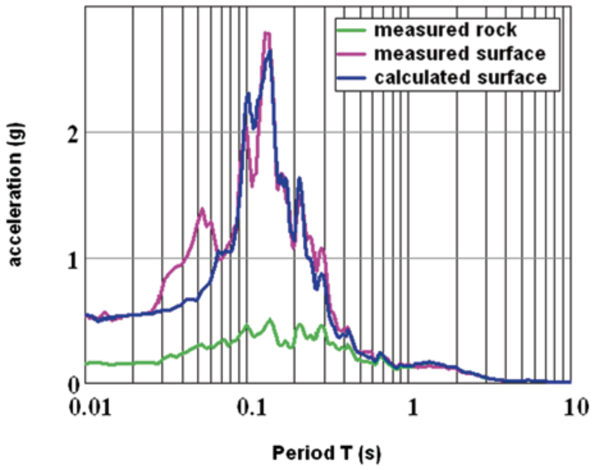
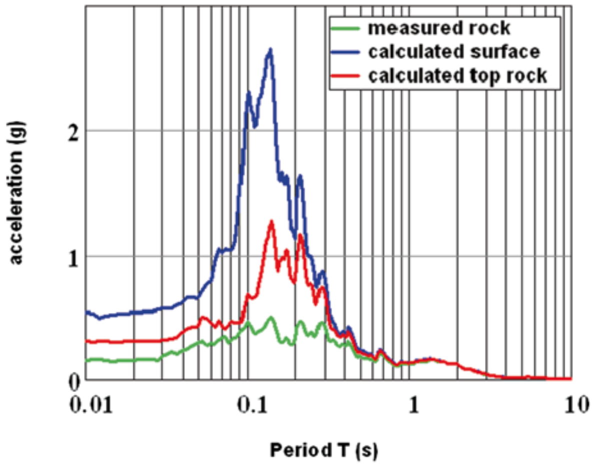


Fig. 6 Recorded and computed response spectra at site MYGH12

Fig. 7 Recorded response spectra at site MYGH12



It is clear from examination of Figs. 2–7 that the seismic response of the surface layers is a narrow band short period response, typically in the period range T = 0.1–0.3 s. Therefore the maximum spectral amplification may be more important than the mean. The maximum peak spectral amplification is shown in Fig. 10 as a function of $V_{s30.}$ There is a considerable scatter in the data and the correlation V_{s30} with $R^2 = 0.36$. The defining equation of the correlation is

$$Max\ AF = -0.0091\, V_{s30} + 8.6893 \tag{4}$$

This type of scatter is typical of field response data as shown in Fig. 11, where Borcherdt (1994) shows field data for the period range T = 0.4–2.0 s. The data shows a scatter band of 2 standard deviations about the mean.

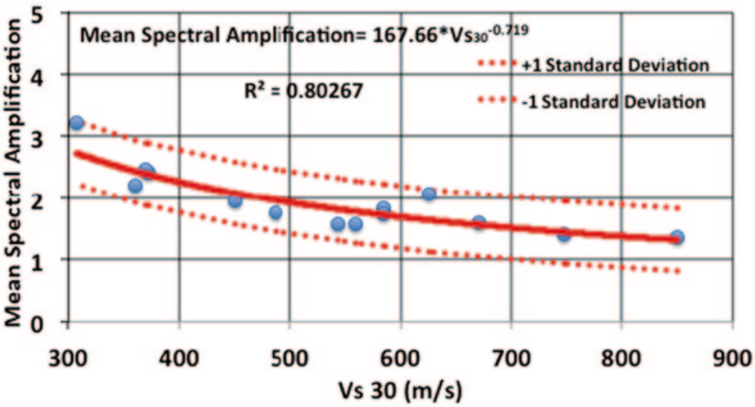


Fig. 8 Average spectral acceleration as a function of V_{s30} with ± one standard deviation (0.5)

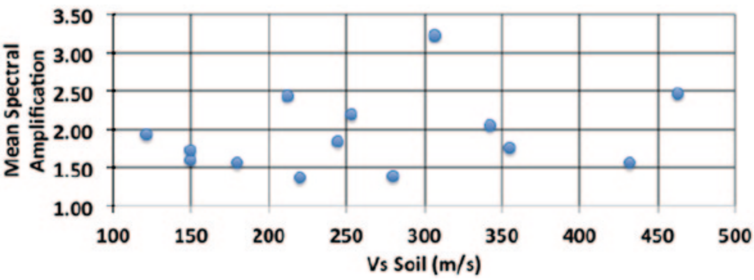


Fig. 9 Mean spectral amplification vs Vs_soil

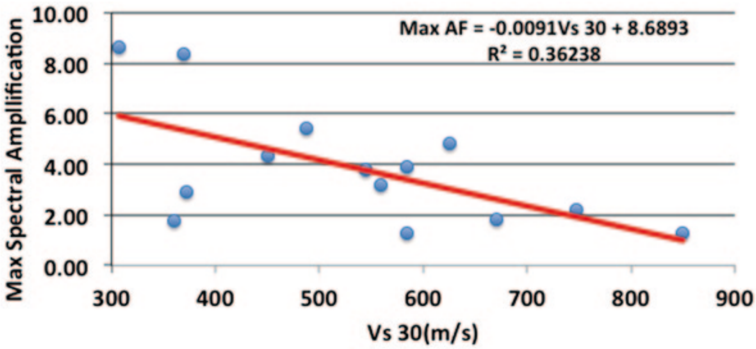


Fig. 10 Maximum spectral acceleration as a function of V_{s30}.

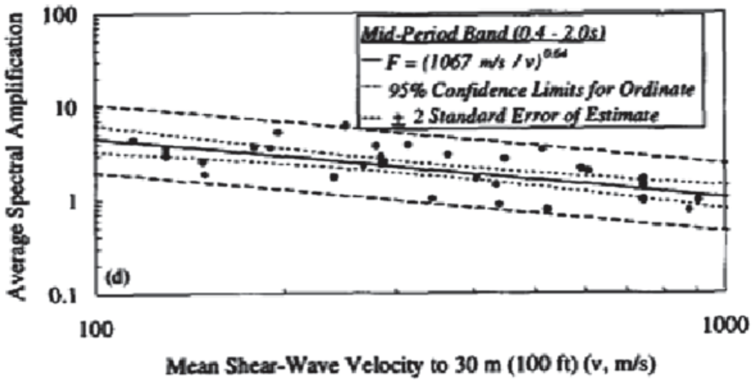


Fig. 11 Mid period band amplification-(0.4–2.0 s), Borcherdt (1994) used by permission of the Earthquake Engineering Research Institute

Fourier Spectra Amplification Factors Based on Site Period

The amplification factors currently used in US and Canadian codes are based on the pioneering work of Borcherdt (1994). He developed continuous amplification factors based on Fourier amplitude ratios for specific period ranges as a function of V_{s30}. His findings are summarized in Fig. 12. For periods greater than T=0.5 s, the amplification factors are not very sensitive to period but are much greater than the short period amplification factors for periods less than T=0.5. These results led to the recommendation to adopt 2 sets of amplification factors; one for short periods and one set for longer periods.

Period dependent Fourier amplitude spectra were developed in the present study for the same period ranges as used by Borcherdt (1994). The results are shown in Fig. 13. For the Tohoku borehole sites, the amplification factors in the short period range T=0.1–0.5 s are much higher than the longer period amplification factors in contrast to the findings by Borcherdt (1994) for Loma Prieta data which was recorded on much thicker deposits. The curves representing the three longer period ranges (Fig. 13) are not as close as in Fig. 12 but the amplifications given by all three curves could be reasonably represented by the mid-period curve, indicating a certain lack of sensitivity to differences in the longer period ranges.

The role of site period is investigated further by relating the fundamental period of the soft soil surface layer, T=4 H/V_s, where V_s is the average shear wave velocity in the soil layer, to $V_{s30.}$ A remarkable correlation between the period of the surface soil layer and V_{s30} is evident in Fig. 14 with R^2=0.95. The defining equation of the correlation is:

$$Log\left(f_0\right) = 1.62Log\left(V_{s30}\right) - 3.62 \quad (5)$$

Ghofrani et al. (2012) conducted a similar study on all available Tohoku data but based their site period on the total depth of the borehole. Their equation is:

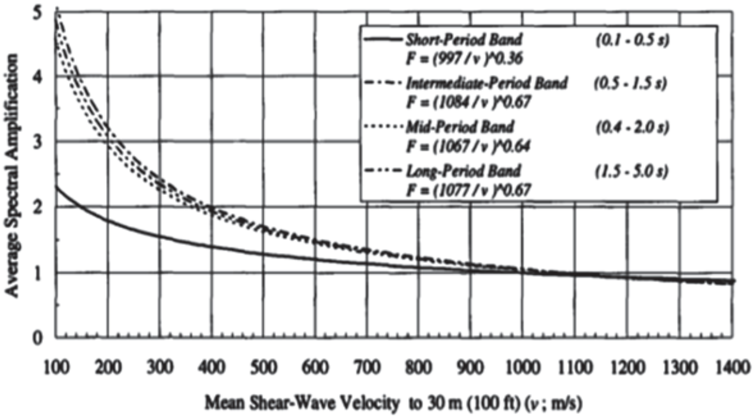


Fig. 12 Short and long period amplification factors for Loma Prieta response data (Borcherdt 1994), used by permission of the Earthquake Engineering Research Institute

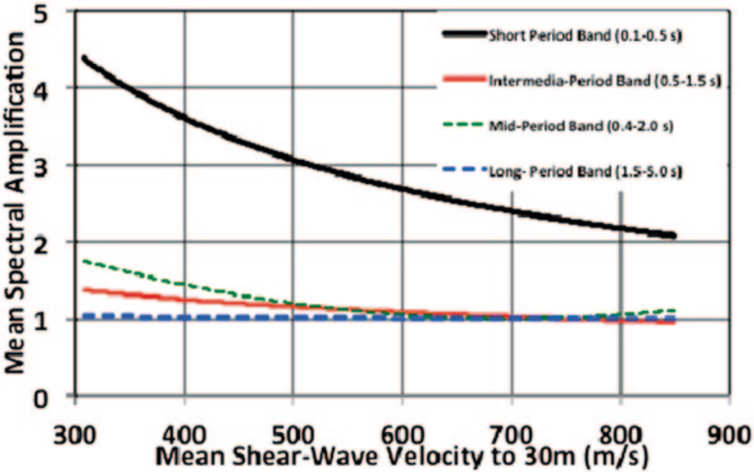


Fig. 13 Fourier spectra amplification factors as a function of shear wave velocity

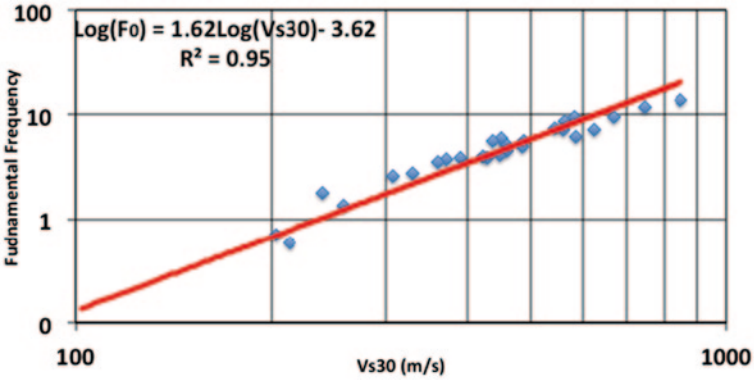


Fig. 14 Fundamental site frequency vs mean shear wave velocity in the top 30 m

$$Log\left(f_0\right) = 1.33Log\left(V_{s30}\right) - 2.92 \tag{6}$$

It is surprising how similar the correlations are and in both cases it is difficult to explain why the different periods correlate so well with $V_{s30.}$

Regional Site Amplification Factors

The average amplification factors for sites with Vs_{30} of 300, 400 and 800 m/s respectively are shown in Fig. 15. The average spectral amplification was calculated for each site characterized by shear wave velocity and the resulting spectral http://www.springer.com/978-3-319-10785-1

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