SOIL AMPLIFICATION BASED ON REGRESSIONS FOR COSTA RICA DATASET

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SUMMARY:

Amplification factors for two soil types and 23 periods were obtained using accelerographic records and their correlation with seismic parameters and soil condition for Costa Rica. The factors were obtained from regressions analysis between PSA for 5% damping as the dependent variable and three independent variables: magnitude. hypocentral distance, and soil type at each site, defined as S II (hard to medium soil) and S III (soft soil). It was assumed that the condition S I (rock) did not amplify. Factors obtained for S II show an almost constant value throughout the range of periods for the three different considered data sets (subduction. crustal or crustal + subduction combined) and compared with amplifications obtained by other authors, especially for Japan. For S III, amplification factors obtained in this investigation for the entire data set (subduction + crustal origin) are clearly higher mainly above period of 0.4 s.

Keywords: amplification, soils, earthquakes, inversions, Costa Rica.

1. INTRODUCTION

The results of a research conducted to obtain the amplification factors produced by seismic waves according to the predominant soil conditions and period-dependent are presented. Accelerograms obtained form Costa Rican earthquakes between 1990 and 2008 were used. Most of records came from digital instruments.

A dependent variable represented here by the PSA was correlated with a number of independent variables such as: the magnitude of the earthquake, distance and soil condition of the recording site. The latter term is estimated by regression using the least squares method.

It was assumed that the rock did not cause any amplification in the considered frequency range. This phenomenon will be estimated only for soil conditions.

2. METHODOLOGY

Based on the equation proposed by Boore & Joyner (1982):

$$Y = c_1 e^{c_2 M} \left[e^{c_3 D} / D^{c_4} \right] e^{c_5 S_1} e^{c_6 S_2} \tag{1}$$

Where the term ($c_1 e^{c_2 M}$) represents the source, ($e^{c_3 D} / D^{c_4}$) corresponds to the wave propagation (distance attenuation) and ($e^{c_5 S_1} e^{c_6 S_2}$) are the soil effects.

To carry out the regression, the equation 1 is linearized using base 10 logarithms on both sides and the following expression is obtained:

$$\log Y = c_1 + c_2 M + c_3 \log D + c_4 D + c_5 S_1 + c_6 S_2 \tag{2}$$

Where:

Y is the dependent variable, which in this case is the pseudo spectral acceleration (PSA) for 5% damping on the critic. Since there are two horizontal components, the following expression was used:

$$Y = \sqrt{PSA_L * PSA_T} \tag{3}$$

corresponding to the geometrical mean of spectral acceleration, according to their longitudinal (PSA_L) and transversal (PSA_T) components.

Each regression must be done to a value of Y that comes from each chosen frequency (in this case are 23 frequencies), in order to obtain a range of amplification factors as complete as possible.

The independent variables of equation 2 are the following:

- **Magnitude M:** is the magnitude of the earthquake associated to each record and corresponds to Mw (Moment Magnitude). For most of the earthquakes with Mw ≥ 5 it was directly obtained from the Global Centroid Moment Tensor (CMT, 2009). If the magnitude was smaller or missing from that database, it was obtained from the following correlations:

$$Mw = 2.27+(2/3)\ Ms \text{ (Okel \& Romanovicz. 1994)} \tag{4}$$

Where Ms is the magnitude obtained from surface waves. Furthermore,

$$Ms = -4.165+1.783\ M_D \text{ (Rojas et al., 1993)} \tag{5}$$

Where M_D is the magnitude based on duration. Combining these two equations:

$$Mw = -0.507+1.186M_D \tag{6}$$

- **Distance D:** is a measure of distance, for this work it's considered as the hypocentral (shortest distance to the hypocenter), because it's the only data available according to the consulted agencies. In this case it's used $D = \sqrt{r^2 + r_h^2}$, where r is the hypocentral distance and rh is a fictional term introduced to solve the problem of saturation of the ground motion in the near field (Dahle et al., 1995. García et al., 2005).

- **Soil Type:** S1 and S2 are binary variables that represent the local geology of the site and are obtained in the regression analysis. The soil variables operate as follows: $S_1 = S_2 = 0$ if the site is rock. $S_1 = 1$ and $S_2 = 0$ if the soil is hard or medium, and $S_1 = 0$ and $S_2 = 1$ if the soil is soft.

The term c_4*D of equation 2 corresponds to the inelastic attenuation due to imperfections in the materials. It has an important contribution when the distance D is large, over 200 km for example. However, for most of the available data D is smaller than that distance, so this term was not considered when making the regressions which yielded more stable results (Schmidt, 2010).

The accelerograms were filtered and baseline was corrected. Additionally, the criteria that the STA/LTA was between 3 and 5 were applied. This will achieve separation of ambient vibrations (STA/LTA less than 2.5) according to Atakan et al. (2004).

Regarding the classification of the soil, the procedure proposed by Zhao et al. (2006) was used. It consists on estimating the response spectral ratio for 5% damping for all the accelerograms recorded on the same site. Based on the average of the stations, it’s possible to identify the peak (in both period and amplitude) and apply the procedure suggested by that author.

This classification was presented in detail in Schmidt (2010). That publication assumed that soil types S III and S IV are grouped as a single category due to insufficient data for S IV. Then the three site types considered are: S I (rock), S II (hard to medium soil) and S III (soft or very soft).

Once the independent and dependent variables are calculated, the inversions for each of the selected frequencies were made. In this case, the method of least squares regression is used because it shows a more stable behavior for all frequencies, as compared to other ordinary two-step regression (Joyner & Boore, 1981) or the maximum likelihood method (Joyner & Boore, 1993).

Finally, the amplification factors (frequency dependent) are: 1.0 for rock or SI, 10^{C5} for S II and 10^{C6} for S III. The coefficients C_5 and C_6 represent the site effects according to Equation 2.

3. DATA USED

Soil classification corresponds to S I to S IV classes, which are equivalent to NEHRP classes as follows: S I is equal to (A + B), S II to C, S III to D and S IV equals E (Zhao et al., 2006).

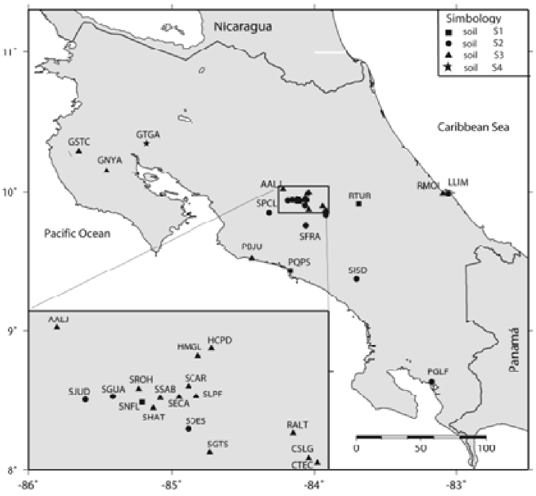
Table 1 shows the codes of the stations considered, as well as its latitude and longitude and soil type assigned according to Schmidt (2010). Very few stations are classified as S IV. In total 30 accelerographic stations are considered.

Figure 1 shows the location of the stations within the country. The majority are concentrated in the Central Valley. Some are located in the Nicoya Peninsula in the Central and South Pacific and Central Caribbean. Only 10% corresponds to SI and approximately 50% to S III and S IV combined.

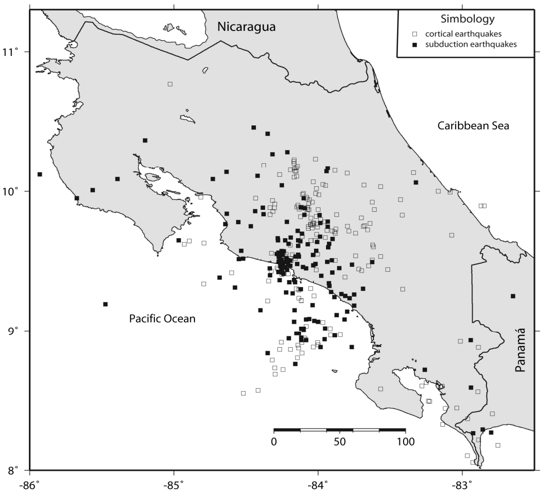
Table 1. Stations used in the study according to their code, coordinates and soil type

Station code	Latitude	Longitude	Soil	Station code	latitude	longitude	Soil
AALJ	10.02	-84.217	S3	RTUR	9.91	-83.69	S1
CCDN	9.834	-83.918	S2	SCAR	9.95	-84.064	S3
CSLG	9.864	-83.923	S3	SDES	9.899	-84.064	S2
CTEC	9.859	-83.913	S3	SECA	9.936	-84.097	S3
GNYA	10.148	-85.455	S3	SFRA	9.753	-84.058	S2
GSTC	10.284	-85.65	S3	SGTS	9.871	-84.038	S3
GTGA	10.349	-85.178	S4	SGUA	9.938	-84.152	S2
HCPD	9.995	-84.036	S3	SHAT	9.924	-84.105	S3
HMGL	9.986	-84.052	S3	SISD	9.373	-83.705	S2
LLIM	9.986	-83.056	S2	SJUD	9.934	-84.184	S2
PBJU	9.52	-84.435	S3	SLPF	9.938	-84.054	S3
PGLF	8.635	-83.171	S2	SNFL	9.931	-84.118	S1
PQPS	9.432	-84.166	S1	SPCL	9.85	-84.313	S2

RALT	9.894	-83.941	S3	SROH	9.947	-84.122	S3
RMOI	9.989	-83.095	S3	SSAB	9.943	-84.113	S2



graphic stations



the epicenters of
in this study.
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There are 349 events considered for this study. They occurred between 1990 and 2008. A total 55% of them are classified based on depth as local faulting and 45% associated to subduction process, according to criteria detailed in Schmidt (2010). There is an 80.5% with magnitude less than 5 Mw, 18.6% has magnitude between 5 and 7 Mw and only 0.9% has magnitude above 7.0 Mw.

Figure 2 shows the epicenters of the earthquakes considered and it's possible to note that the majority is located in the Central Valley and offshore in the Central Pacific.

The 349 events correspond to 770 records. Of them 49% is associated to local faulting and 51% to earthquakes originated by subduction.

Considering the soil type only 15% of the records correspond to SI, 36% of S II and 49% of S III + S IV. These percentages are similar to those observed in classifying the stations on the same soil types.

According to the range of magnitudes, only few records are available for Mw exceeding 7.0, since the data are concentrated in Mw below 5.0.

Most available records have associated hypocentral distances between 30 and 100 km and only a few exceed 200 km.

Table 2 shows the amplification factors obtained for two different soil conditions for 23 selected periods after inversion. These are obtained by separating the data according to depth: by subduction, by local faulting and by combining both sources. These results are plotted in Figs. 3 and 4.

Figure 3 represents the coefficients obtained as a function of period for soil condition S II (hard). Black dots show the factors which are interpolated by straight lines to obtain

intermediate values. The values obtained are similar in almost the entire range of periods. The case for combined earthquakes (local faulting + subduction) is about the average with respect to consider each case separately, even if the observed differences are not large.
Figure 4 compares the three sets of coefficients obtained for S III condition (medium to soft). In this case, there are remarkable differences above 0.24 s of period since the data generated by subduction shows higher amplification factors. The reason for this difference could be related to the type of source used. Subduction earthquakes have wider frequency content than cortical (local faulting) ones.

Furthermore, the hypocentral distance also influences the frequency content of the signal. For longer distance events, higher frequencies are quickly filtered than for shorter distances. In general, subduction earthquakes have hypocentral distances greater than those of local faulting and therefore have a lower number of higher frequencies.

Figure 5 compares soil amplification factors for S II for Costa Rica obtained by the present study (continuous black line corresponds to combined data) with those obtained by Takahashi et al. (2000) (gray line). Schmidt et al. (1997) (dotted line) and the spectral ratio S II / SI according to Zhao et al. (2006) (dashed black line), which represents the pseudo amplification factors obtained by Zhao et al. (2004).

We can observe the similarity between the four traces, being slightly lower the one obtained from H / V spectral ratio for Japan. However, those obtained through inversion using Costa Rica dataset (present study) and for Japan (Takahashi et al., 2000) are very similar.

When comparisons with the factors obtained by Schmidt et al. (1997) are made (which were obtained using data recorded in Costa Rica until 1997), it appears that those proposed by that study are almost constant for all period range (the amplification factor is close to 1.2 in almost all cases), but they were calculated for fewer periods. However, they show a similar trend for the other cases considered for hard soil (S II).

The same comparison for soil S III (soft soil) in figure 6 is presented. The solid black line represents the amplification factors for Costa Rica obtained in this research (combining subduction and local faulting), the dashed line corresponds the spectral ratio H / V according to Zhao et al. (2006), the continuous gray line shows the amplifications for attenuation models proposed by Takahashi et al. (2000) using the soil classification proposed by Zhao et al. (2006) and the dotted line corresponds to amplification factors obtained by Schmidt et al. (1997).

By comparing the factors obtained in this study with H / V spectral ratio for Japan, there is a good similarity between the two curves from 0.05 s to 0.4 s corresponding to high frequencies, but from 0.4 s to 3.0 s the curve obtained for Costa Rica is higher than that proposed by Zhao et al. (2006).

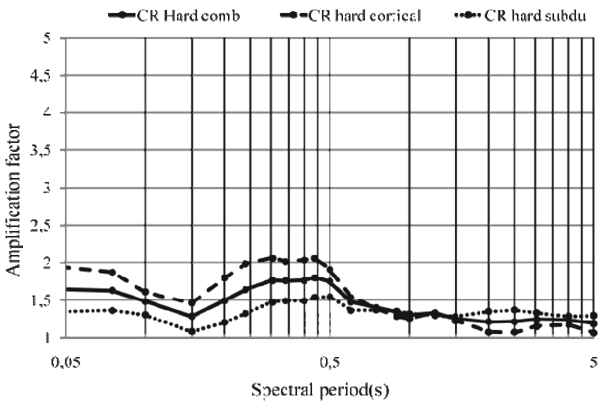
Comparing the results of this study with those obtained from inversions by Takahashi et al. (2000), it is possible to observe that the estimates for Costa Rica are higher in the whole range of periods. This becomes more evident for periods higher than 0.7 s where the spectral ordinates of Costa Rica exceed the ones obtained by Takahashi et al. (2000) in an approximately 50%. This can be associated to the fact that database used by Takahashi et al. (2000) covers a wider range of magnitudes with respect to Costa Rica data set. In the latter case small to moderate magnitudes (less than 5.0 Mw) predominates, recorded at short and intermediate distances (72% of the data corresponds to hypocentral distances between 0 and 100 km), then site effects appear to become significant over long periods.

The similarity in the trend between the curves representing the amplification factors obtained for different regions is remarkable. They increase from 0.15 s. reach a maximum at 0.4 s and then parallely decrease until 3.0 s.

By comparing the results obtained in this study with those proposed by Schmidt et al. (1997) for soil S III, it is clear that although in both cases the data were recorded in Costa Rica, the amplification factors obtained in this study are higher across the whole range of periods. This difference may be caused by the type of data used previous to 1997. That data has lower resolution because it is made of analog records. In addition, soil classifications used in 1997 are for on-site observations or interpretations of maps which provides very superficial layer information, therefore inaccurate.

Table 2. Amplification factors obtained for soil S II (solid) and S III (soft soil medium), for records of subduction origin, cortical or both combined, for 23 selected periods

	S II (hard) soil				S III (médium to soft) soil		
Period	Subduction	Cortical	Combinerd		Subduction	Cortical	Combinerd
0.02	1.31	1.86	1.59		2.28	2.03	2.21
0.04	1.34	1.97	1.65		2.21	2.03	2.17
0.075	1.36	1.87	1.63		1.99	1.87	1.98
0.1	1.30	1.61	1.48		1.79	1.69	1.78
0.15	1.08	1.46	1.28		1.79	1.65	1.77
0.2	1.20	1.79	1.49		2.04	1.92	2.03
0.24	1.32	1.98	1.64		2.58	2.37	2.53
0.303	1.47	2.05	1.76		3.80	3.12	3.53
0.34	1.49	2.01	1.76		4.19	3.29	3.81
0.4	1.49	2.03	1.76		4.48	3.66	4.16
0.44	1.53	2.05	1.80		4.89	3.85	4.47
0.5	1.55	1.91	1.75		4.97	3.79	4.47
0.6	1.36	1.54	1.47		4.46	3.50	4.06
0.752	1.37	1.38	1.40		4.29	3.10	3.75
0.9	1.35	1.28	1.34		4.14	2.77	3.49
1	1.31	1.25	1.30		3.91	2.64	3.30
1.25	1.30	1.34	1.33		3.38	2.62	3.03
1.493	1.28	1.22	1.26		3.37	2.47	2.92
2	1.35	1.07	1.21		3.39	2.14	2.73
2.5	1.37	1.07	1.22		3.08	2.02	2.51
3.03	1.33	1.15	1.24		2.75	2.06	2.38
4	1.28	1.17	1.23		2.37	1.93	2.13
5	1.29	1.07	1.19		2.06	1.68	1.85



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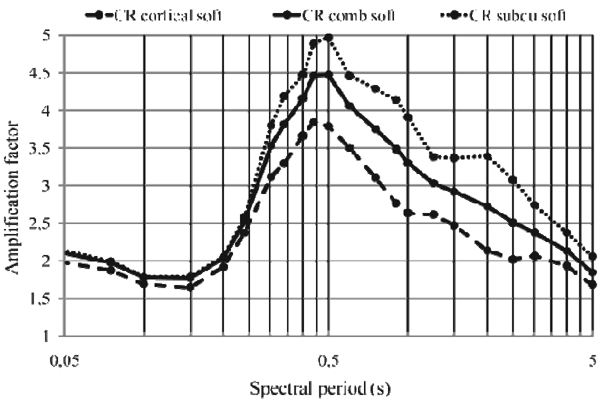

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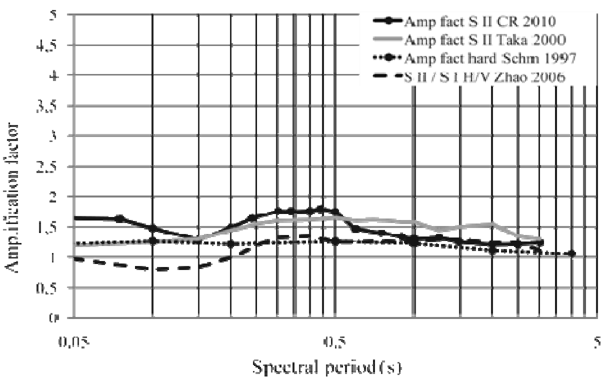

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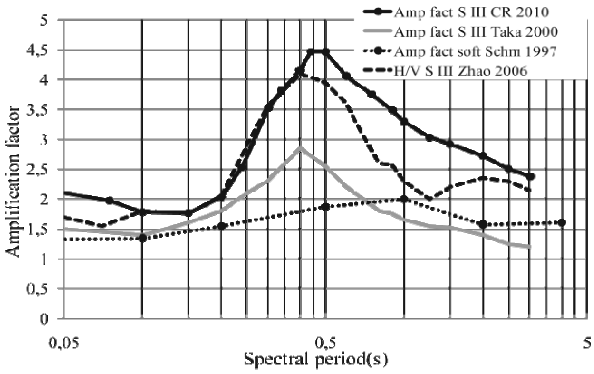

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4. CONCLUSIONS

Amplification factors for two soil types and 23 periods (23 frequencies) were obtained using accelerographic records and seismic data form Costa Rica.

Results were obtained from regressions between PSA for 5% damping as the dependent variable and three independent variables: the magnitude, hypocentral distance and soil type at each site, defined as S II (hard to medium soil) and S III (soft soil). It was assumed that S I condition (rock) does not amplify seismic waves in the range of periods defined.

The distribution of data used can be summarized as follows:

- Stations (locations): only few corresponding to SI and many for S III. Most sites are located in the Central Valley of Costa Rica.

- Earthquakes: the distribution is almost homogeneous according to their origin (subduction or cortical). However, regarding the magnitudes most correspond to Mw ≤ 5.0 and very little with Mw> 7.0.

- Accelerographic records: few obtained on S I site condition. Regarding the magnitudes, the majority of data corresponds to Mw ≤ 5.0. According to hypocentral distances, the majority of data corresponds to short and intermediate distances (between 30 km and 100 km).

From the results, the amplification factors for S II show quite similar values throughout the range of periods, varying between 1.19 and 1.65 for the case for the whole combined data set (using records subduction and cortical data mixed). being the amplitudes slightly higher for low periods (between 0.24 s and 0.5 s). For low periods, the amplitudes are slightly higher (between 0.24 s and 0.5 s).

With respect to the factors obtained for S III, it is possible to observe remarkable differences in the three cases (records associated to subduction, crustal, or both combined) above 0.24 s. The reason could be the fact that subduction earthquakes have associated longer hypocentral distances then high frequencies are filtered and significant amplification at low frequencies (long periods) is obtained.

When the results obtained in this investigation (subduction + crustal) are compared with those proposed by other authors, it is clear to note that amplification factors for S II soil are very similar across the whole range of periods. However, when making comparisons to soil S III, it is possible to note a great similarity with factors obtained from the ratio H / V for Japan to 0.4 s (high frequencies) but the amplitudes of this study exceed the Japan ones in long periods (low frequencies).

This high magnification shown by the factors obtained for Costa Rica becomes more evident when they are compared with the case of amplifications obtained from attenuation models for Japan over the entire range of periods, probably due to different soil conditions prevailing in both countries. In general, Costa Rican geology is younger than Japanese one, because of that, Costa Rican soils should be less consolidated than those in Japan making them more susceptible to the phenomenon of amplification.

However, it is remarkable the similarity in the trend between the curves which represent the amplification factors obtained for both regions to soil S III: both of which increase from 0.15 s, reach a maximum at 0.4 s and parallely decrease up to 3.0 s period.

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