Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-2727

Influence of the surface layers on the site effect

L'influence des couches superficiels sur l'éffet

Ramón Verdugo
Department of Civil Engineering, University of Chile

ABSTRACT
To investigate the seismic amplification phenomenon on a layered ground, a borehole seismic array in Chile has been implemented in an area where important damage to houses an high accelerations during the 1985 Chilean earthquake were observed. Accelerometers at the bedrock, within the soil deposit and at the ground surface were installed in a soil profile consisted in a layered structure of saturated clay, silt, sand and gravel materials. Some seismic records presented notable differences in the horizontal peak accelerations at the bedrock, but unexpectedly, the accelerations at ground surface tend to be uniform, suggesting the existence of an important two-dimensional effect. Additionally, it is shown that the natural period computed from the recorded earthquakes is close to the one predicted by the classical one-dimensional theory of soil amplification considering only the upper softer 20 m.

RESUMÉ
Pour comprendre le phénomène d'amplification sismique due à éffet d'un sol estratifié, nous avons installé un reseau sismique dans la côte de la région central du Chili, où le dégas sur les édifications ont été les plus sévères à cause du seisme 1985. Des acceléromètres ont été installés en profondeur sur rocher, à l'interieur des sédiments et en surface, sur ces sédiments qui comprennent argile, lime, sable et grave. Les résultats montrent qu'il y a des differences rémarquables entre les accelerations maximun horizontals enregistrées dans le rocher, mais qui ne se manifestent pas en surface. Ces résultats sugèrent qu'il exist un éffet 2-D important. Finallement, on montre que la periode naturelle obtenu à partir des enregistrements c'est assez proche à celle qui la théorie classique 1-D prevois en considérant seulement les prémiers 20 m du sol.

1 INTRODUCTION

It is a well recognized fact that local soil conditions have a significant effect on the ground surface motions. Therefore, structures located on soil deposits of different geotechnical properties in the same seismic area can be subjected to seismic disturbance that can be quite different. In this respect, there is important empirical evidence indicating that the damages caused by earthquakes are normally concentrated in specific areas where it has been possible to identify particular unfavorable soil conditions (Duke, 1958; Borcherdt, 1970; Seed et al., 1969; 1988; Idriss, 1990; Dobry, 1991; Midorikawa et al., 1994). For example, during the 1985 Chilean earthquake of Magnitude 7.8, intensities ranging from 7 to 10.5 were observed at sites in close proximity just to north of the port of San Antonio as shown in Fig. 1. Clearly in this case is observed the existence of certain zone where the shaking effects were locally higher. In general, the analysis of the soil conditions consistently indicated that the major losses took place in saturated soil deposits of sandy silt, silty sand and soft clay.

According to all the experience gained through field observations and by the accumulation of valuable data provided by modern seismic stations, site effects are completely accepted and, therefore, explicitly incorporated in seismic codes to better account for amplification phenomena (Borcherdt, 1994; Dobry et al., 1999, 2000). Nevertheless, in spite of the recent advances generated by the earthquake geotechnical engineering there are still uncertainties to be elucidated and solved regarding the seismic amplification problem. Among these uncertainties is possible to include the depth of the soil profile that has to be considered for evaluating the profile of shear wave velocities that permit the estimation of the fundamental period of the ground and the seismic site response. This is especially important when there are several soil layers of different stiffness and thickness. Accordingly, new real data regarding the soil amplification phenomenon has been generated though the installation of the first Chilean seismic station with borehole accelerometers to permit measurements of seismic amplitudes from the bedrock to the ground surface. The location selected for the vertical array corresponds to an area that showed strong seismic amplification and heavy damage to houses during the 1985 Chilean earthquake. The recorder accelerations are analyzed and presented below.

2 LLOLLEO BOREHOLE ARRAY

This seismic array is located in a rather flat area close to the Pacific coast, west of Llolleo City, approximately 91 km west of Santiago as shown in Fig. 1. In this area quaternary alluvial soil deposits consist of sands, gravels, clays and silts, with a planar and horizontal stratification are found. Below the 45 m of depth, calcareous sediments consisting of shells can be found in soil layers of sandy and gravely materials. The observed sequence of soils and shells can be interpreted as an in-shore soil deposit, mainly controlled by sea action. Above this level, the soil strata are finer and consist mainly of silty and clayey materials, reflecting a change in the energy of deposition, which is likely associated with past sea level variations.

The upper part of the soil deposit consists of sandy and silty materials. A soil profile with the results of the site investigation is presented in Fig. 2, where it is observed in more detail the stratified soil structure consisting of different alluvial and marine sediments of variable thickness. The water level was found at a depth of 6 meters.

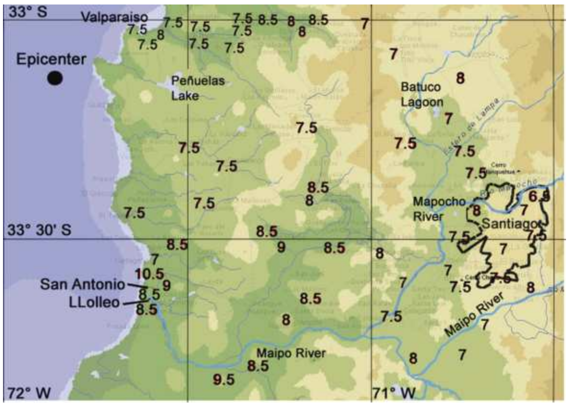

Fig.1 : Intensities of the Chilean earthquake 1985 (Astroza et al, 1993)

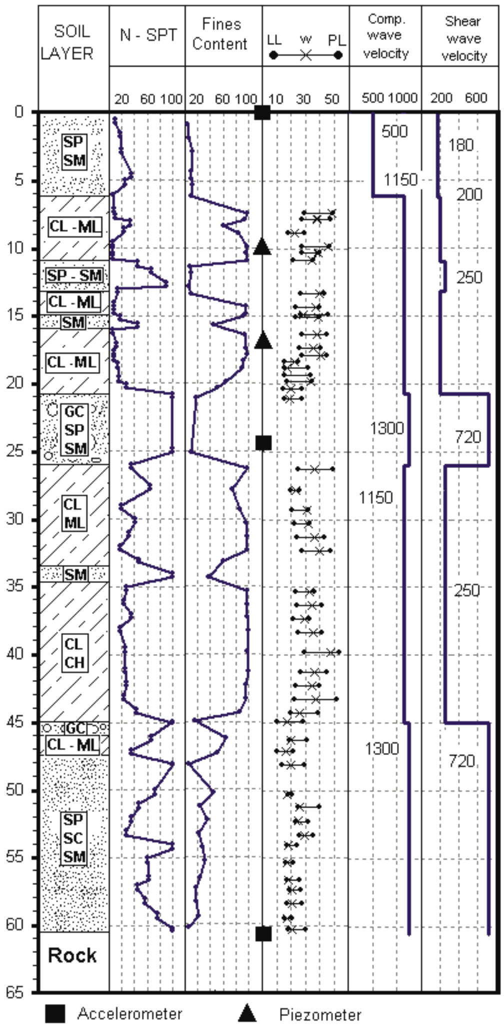

Fig. 2: Soil properties at Llolleo site

The seismic array consists of three force balance triaxial accelerometers SSA-320SS, two fast-response piezometers, and one GPS time receiver. The accelerometers were located at the ground surface, at 24 m depth, and at 62 m depth, respectively. The accelerometers installed at 62 m depth was placed on the bedrock, penetrating 0.5 m in granite. The horizontal components of the accelerometers were aligned with an electronic compass in the north-south and east-west directions. The piezometers were installed at depths of 9.6 and 17.4 m.

Each instrument was installed in a different borehole especially drilled and each instrument placed at the bottom of its borehole. The boreholes were separated from each other at a horizontal distance of about 3 meters. After placed, the accelerometers were surrounded and covered with uniform fine sand, while the piezometers were surrounded by medium sand and covered with bentonite pellets.

All instruments were connected to an A/D converter and then to a personal computer where the data are permanently read and stored. The hardware was designed and built by GeoSys in Switzerland, while a group of professionals from the Institute of Solid Earth Physics of University of Bergen, Norway, was responsible for the installation of the instruments as well as the software. Since 2004 a telephone line is used to retrieve the data from the seismic station to the University of Chile.

The data acquisition system continuously reads and stores the data coming from the 11 output channels associated with the three triaxial accelerometers and the two piezometers at a sampling rate of 50 readings per second. The hard disk of the computer is partitioned in two areas, so all the readings are continuously stored in one part of the hard disk in a ring buffer. When the total capacity of this part of the hard disk is exceeded, the new data are overwritten in the ring buffer from the beginning, so a continuous process of data acquisition is undertaken. The level of the horizontal accelerations registered by the accelerometer located on the ground surface is continuously checked throughout a time window and compared with a triggering acceleration of 0.001g. When this level of acceleration is exceeded, a file with a name corresponding to the date and time of the event is created. In this file all the readings are stored, considering a period of time starting 30 seconds before the triggering acceleration was exceeded and finishing 15 minutes after. This long period of 15 minutes allows measurements of the main part of the dissipation of pore water pressure, which is also an important parameter to be studied. The data files containing the seismic events are stored in another part of the hard disk where they cannot be overwritten. Approximately 20 seismic events can be stored before the memory capacity is exceeded.

3 AMPLIFICATION OF PEAK ACCELERATIONS

All the recorded seismic events clearly show a significant amplification of the acceleration amplitudes from bedrock to the ground surface. For the recorded earthquakes with a horizontal peak acceleration at the ground surface greater than 0.005g, the peak accelerations normalized by the peak accelerations at the bedrock are presented in Figs. 3, 4 and 5. It can be seen that the relatively weak motions are significantly amplified from the bedrock to the ground surface, being especially augmented near the surface. For the geotechnical conditions of the Llolleo site, and for the level of shakings that have been recorded, the amplification factor for peak horizontal acceleration is in the range of 1 to 7, for the sector going from the bedrock to a depth of 24 meters. This factor increases to the range of 4 to 16, for the total domain compromised between the bedrock and the ground surface. These results suggest that most of the phenomenon of amplification is developed near the ground surface, probably in the upper 20 m. Although this outcome may seem to hold valid only for the particular site conditions of Llolleo, it nevertheless agrees with recommendations provided by seismic codes in the sense that site effect is only characterized by the mean shear wave velocity of the top 30 m (Borcherdt 1994; Dobry et al., 1999).

Regarding the amplification of vertical acceleration, the measurements indicate a factor in the range of 2 to 4, for the deepest sector located between the bedrock and a depth of 24 m. For the total soil deposit, the amplification factor is in the range of 4 to 10. Again, the main part of the amplification takes place in the top 20 meters, but it is less pronounced than observed for horizontal accelerations.

4 COUPLED HORIZONTAL SOIL RESPONSE

Some recorded earthquakes presented a remarkable difference between the two components of the horizontal acceleration amplitudes arrived to the bedrock. Two examples of this situation, which are likely associated with the relative location and characteristics of the rupture of the seismic source, are presented in Figs. 6 and 7. In one case, the peak horizontal acceleration at the bedrock in the E-W direction is almost 2 times greater than the peak horizontal acceleration observed in the N-S direction. On the contrary, in the second case the N-S peak horizontal acceleration is 2.4 times greater than the E-W peak horizontal acceleration. Surprisingly, at the ground surface there is a sort of rotation in the direction of the maximum horizontal peak accelerations. For the first case, at the ground surface, the peak horizontal acceleration in the E-W direction is around 0.9 times the peak horizontal acceleration observed in the N-S direction. While in the second case at the ground surface, the N-S peak horizontal acceleration is approximately 0.8 times the E-W peak horizontal acceleration.

The variation of the horizontal peak accelerations with depth are presented in Fig. 8, where it is observed that well before the ground surface both components of the horizontal peak accelerations become rather similar.

In these cases clearly a 2-D analysis is needed, opening a question about the validity of the one-dimensional analysis.

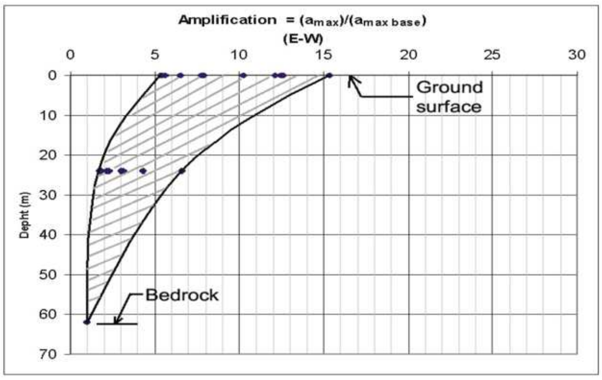

Fig. 3: Amplification of peak horizontal acceleration (E-W)

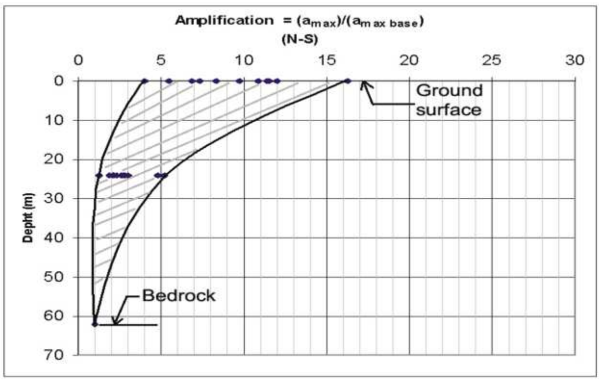

Fig. 4: Amplification of peak horizontal acceleration (N - S)

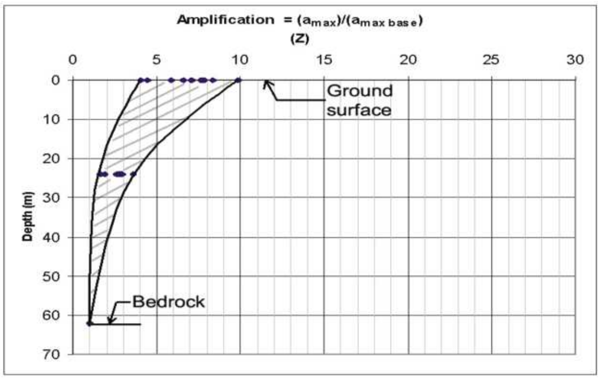

Fig. 5: Amplification of peak vertical acceleration

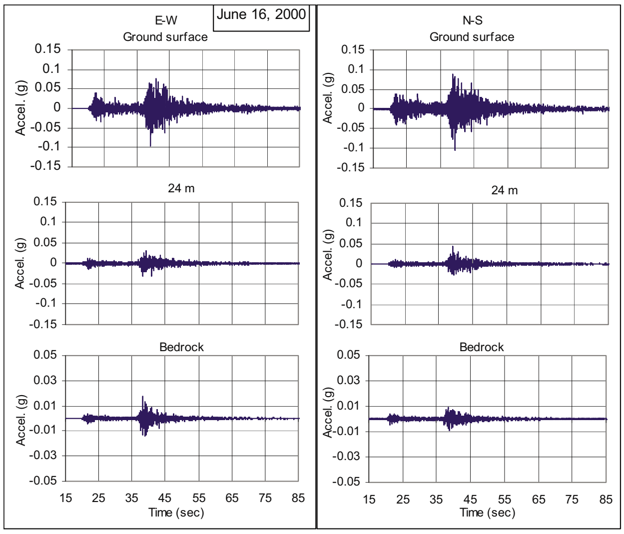

Fig. 6: Earthquake with different level of peak horizontal acceleration in the E-W and N-S components at the bedrock.

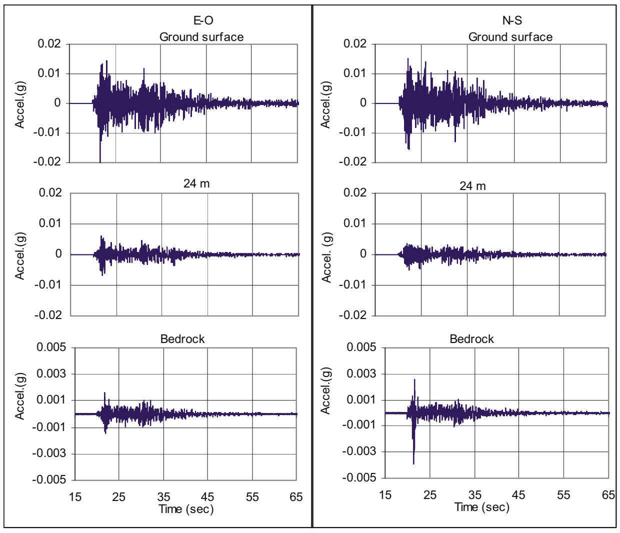

Fig. 7: Earthquake with different level of peak horizontal acceleration in the E-W and N-S components at the bedrock.

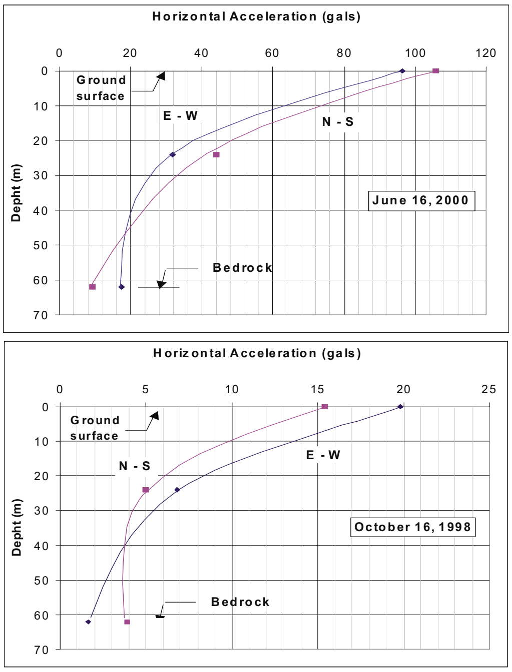

Fig. 8: Variation of the two peak horizontal acceleration.

5 TRANSFER FUNCTIONS

Considering vertically propagating waves and linear histeretic soil behavior, the resulting transfer function, surface to bedrock, is only a function of the soil properties and thickness of the soil layers, and therefore, it represents the site effect, regardless the characteristics of the shaking (Roesset 1977; Roesset et al, 1969; Kramer, 1996). However, it is important to bear in mind that shear modulus and damping ratio are strain dependent, and therefore, controlled by the shake intensity, which means that the transfer function should be also dependent on the level of the seismic event. Nevertheless, the available data represent small earthquakes where the non-linearity of the soil behavior should not appear.

Because response spectra are less sensitive to noise and peaks are easier to be identified, the transfer functions between surface and bedrock were computed using the ratio of the velocity response spectra instead of the Fourier transform. The average transfer function for the N-S and E-W components obtained from 11 recorded earthquakes is presented in Fig. 9. On the other hand, from a theoretical analysis for vertically propagating shear waves assuming linear elastic soil behavior for the soil properties shown in Figs. 2, the first natural period in shear has a value of T_{s1} = 0.74 sec and the second a value of T_{s2} = 0.27 sec.

It can be observed that the transfer function does not reproduce these theoretical natural periods. From the empirical transfer function seems possible to identify the first natural period of 0.43 sec, which can be associated with a natural period considering only the upper 20 m of the ground. Consequently, it is possible to indicate that in the case of a layered soil deposit, the weaker superficial layers tend to be more relevant in the seismic response at the ground surface. This statement holds valid at least for small to medium seismic events and to be conclusive for strong motions more field data are still needed.

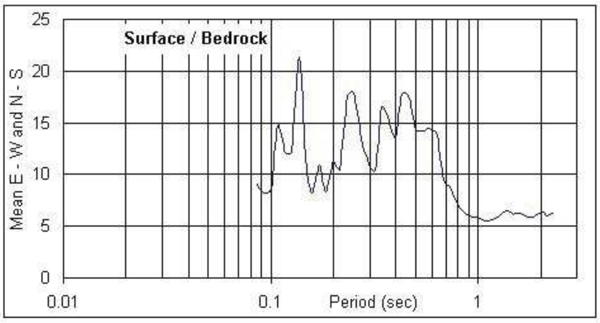

Fig. 9: Average Transfer Function bedrock to surface.

6 CONCLUSIONS

The acceleration amplitudes increase from the bedrock to the ground surface, with the largest increases occurring near the ground surface. The recorded earthquakes indicate that the main amplification takes place in the top 20 to 30 meters, which agrees with other studies that characterize site effect using the average shear wave velocity only of the upper 30 meters.

At the bedrock, the amplitudes of some recorded peak horizontal accelerations were significantly different in both directions, however at the ground surface the recorded horizontal accelerations were very similar in both directions. Therefore, a coupled seismic response in the horizontal plane takes place, which put a doubt about the total validity of the common one-dimensional analysis.

The average empirical transfer function surface-bedrock obtained from the recorded earthquakes does not show the theoretical natural period computed with the complete profile of shear wave velocities. However, it is possible to identify a natural period that coincides with the theoretical period computed only with the soil properties of the upper 20 m. These results obtained from small to medium seismic events suggest that, in the seismic response at the ground surface, the upper weaker soil layers are the most relevant.

ACKNOWLEDGEMENTS

The research project associated with the installation of the Llolleo borehole array has been only possible by the financial support provided by the Fondo Nacional de Investigación Científica y Tecnológica, FONDECYT, under the grant No. 1970440. The author also wants to thank the work done by the Civil Engineers, Karem de la Hoz and Carolina Vergara from University of Chile.

REFERENCES

Astroza, M., Monge, J. and Varela, J. 1993: "Intensities in the Metropolitan Region and Central Coast caused by the earthquake of March, 3 (in Spanish)," *Seismic Engineering, the Chilean earthquake of March, 3, 1985*. Edited by Rodrigo Flores.

Borcherdt, R. 1970: "Effect of local geology on ground motion near San Francisco Bay," *Bulletin of Seismological Society of America*, Vol. 60, No.1, pp. 29-61.

Borcherdt, R. 1994: "Estimates of site-dependent response spectra for design (methodology and justification)," *Earthquake Spectra*, Vol. 10, No.4, pp. 617-653.

Dobry, R. 1991: "Soil properties and earthquake response," *Proc. X European Conference of Soil Mechanics and Foundation Engineering*, Vol. 4, pp. 1171-1187, Italy.

Dobry, R. and Iai, S. 2000: "Recent developments in the understanding of earthquake site response and associated seismic code implementation," Key note paper. *Proc. International Conference on Geotechnical and Geological Engineering*, Vol.1, pp. 186-219. Australia.

Dobry, R., Ramos, R. and Power, M. 1999: "Site factors and site categories in seismic codes," Technical Report MCEER-99-0010. University at Buffalo.

Duke, C. 1958: "Effect of ground on destructiveness of large earthquakes," *Journal of Soil Mechanics and Foundations Division, ASCE*, Vol. 84, No. SM3.

Idriss, I. 1990: "Response of soft soil sites during earthquakes," *Proc. Symposium to Honor of Prof. H.B. Seed*, Berkeley.

Kramer, S. 1996:"Geotechnical Earthquake Engineering," Prentice Hall.

Midorikawa, S., Matsuoka, M. and Sakugawa, K. (1994): "Site effect on strong-motion records observed during the 1987 Chiba-Ken-Toho-Oki, Japan earthquake," *Proc. 9th Japan Earthquake Engineering Symposium*, Vol. 3, pp. E085-E090.

Roëset, J. 1977: "Soil Amplification of Earthquakes," Numerical Methods in Geotechnical Engineering, Edited by Desai and Christian, Chapter 19, 639-682, New York: McGraw Hill.

Roësset, J. and Whitman, R. 1969: "Theoretical Background for Amplification Studies," MIT Research Report No. R69-15.

Seed, H. and Idriss, I. 1969: "Influence of soil conditions on ground motions during earthquakes," *Journal of Soil Mechanics and Foundations Division, ASCE*, Vol. 95, No. SM1.

Seed, H., Romo, M., Sun, J., Jaime, A. and Lysmer, J. 1988: "Relationships between soil conditions and earthquake ground motions", *Earthquake Spectra*, Vol.4, pp. 687-729.