SITE RESPONSE OF A DEPOSIT DYNAMICALLY CARACTERIZED USING CROSS-HOLE TESTS AND EMPIRICAL CORRELATIONS

MC. Madrigal [1], L. Osorio [2], C. Rosales [3], E. Botero [4], E. Ovando [5]

[1] *Geotechnical specialist, Instituto de Ingeniería, Universidad Nacional Autónoma de México, mmadrigalm@iingen.unam.mx*
[2] *Geotechnical specialist, Instituto de Ingeniería, Universidad Nacional Autónoma de México, losoriof@iingen.unam.mx*
[3] *Geotechnical specialist, Instituto de Ingeniería, Universidad Nacional Autónoma de México, crosalesf@iingen.unam.mx*
[4] *Researcher, Instituto de Ingeniería, Universidad Nacional Autónoma de México, eboteroj@iingen.unam.mx*
[5] *Researcher, Instituto de Ingeniería, Universidad Nacional Autónoma de México, eovandos@iingen.unam.mx*

Abstract

The dynamic properties of a soil deposit can be estimated from the shear wave velocity, V_s. This velocity profile can be obtained directly from field tests, such as cross-hole, down-hole or in-hole probe tests, or indirectly using empirical correlations. For sandy deposits, V_s is empirically correlated with the number of blows in the standard penetration test (SPT), whereas for clay deposits, V_s is empirically correlated with the tip resistance in the cone penetration test (CPT). A comparative analysis is presented in this paper for the site response of granular deposits characterized using directly and indirectly obtained V_s profiles.

Keywords: cross-hole, standard penetration test, site response, correlations, shear wave velocity

1. Introduction

The effects of soil-structure interactions depend mainly on the stratigraphic profile on which the structure is located, the dynamic properties of the soil deposit, the shear wave velocity V_s profiles, the frequencies of the input movement, and the type of foundation and structure.

Soil dynamic behavior is a function of the shear modulus, G, and the damping coefficient, ξ. The first property is a measure of the soil stiffness in response to disturbances, and the second property is a measure of the energy dissipation characteristics of the soil under cyclic loads. These dynamic properties can be estimated by measuring V_s along a stratigraphic profile. Thus, it is imperative to define this parameter properly and accurately.

Shear wave velocity profiles can be determined directly from field tests, such as cross-hole, down-hole or in-hole probe tests, and indirectly using empirical correlations based on the number of blows for the standard penetration test (SPT) or the tip resistance for the cone penetration test (CPT).

In this study, a site response analysis is performed on granular deposits that are dynamically characterized using V_s profiles obtained from cross-hole tests and compared with the response spectra calculated using an empirical correlation based on SPT blows, N. The effects of the V_s parameter on the site response are assessed.

1.1 Seismic cross-hole test

The seismic cross-hole test is based on ASTMD4428/D4428M-00 [1]. In this test, two or three boreholes are drilled at prescribed depths. One borehole contains a mechanical disturbance source, and geophones or triaxial accelerometers are placed in the other boreholes, which serve as receiving boreholes. The source is fired at a prescribed depth, and the time for seismic waves S and P to travel the distance between the seismic source and the geophones or triaxial waves accelerometers is recorded. During the test, all of the devices are placed at the same depth so that the generated wave follows a straight path through the surrounding medium. The arrival times of S and P and the distance between boreholes are used to determine the shear and the compression wave velocity (V_s and V_p).

1.2 Empirical correlations

Empirical correlations are used to determine the V_s profile along a granular soil deposit when direct field tests cannot be performed. However, the V_s values determined from the SPT test should be interpreted with caution because the results obtained from this test depend on the equipment and methodology used. In Table 1 and Fig. 1, some empirical correlations with the exponential form $V_s=AN^B$ in *m/s* are presented, where N denotes the number of blows in the SPT.

Fig. 1 shows significant dispersion and variability in the V_s values that are indirectly determined from these correlations based on N.

Table 1 – Empirical correlations

Author	Soil type	Correlation
Kanai (1966) [2]	All	$V_s=19N^{0.60}$
Imai & Yoshimura (1970) [3]	All	$V_s=76N^{0.33}$
Ohsaki & Iwasaki (1973) [4]	All	$V_s=82N^{0.39}$
Imai & Yoshimura (1975) [5]	All	$V_s=92N^{0.329}$
Imai et al. (1975) [6]	All	$V_s=90N^{0.341}$
Imai (1977) [7]	All	$V_s=91N^{0.337}$
Ohta & Goto (1978) [8]	All	$V_s=85N^{0.348}$
Imai & Tonouchi (1982) [9]	All	$V_s=97N^{0.314}$
Seed et al. (1983) [10]	All	$V_s=61N^{0.50}$
Yolota et al. (1991) [11]	All	$V_s=121N^{0.27}$
Jafari et al. (1997) [12]	All	$V_s=22N^{0.85}$

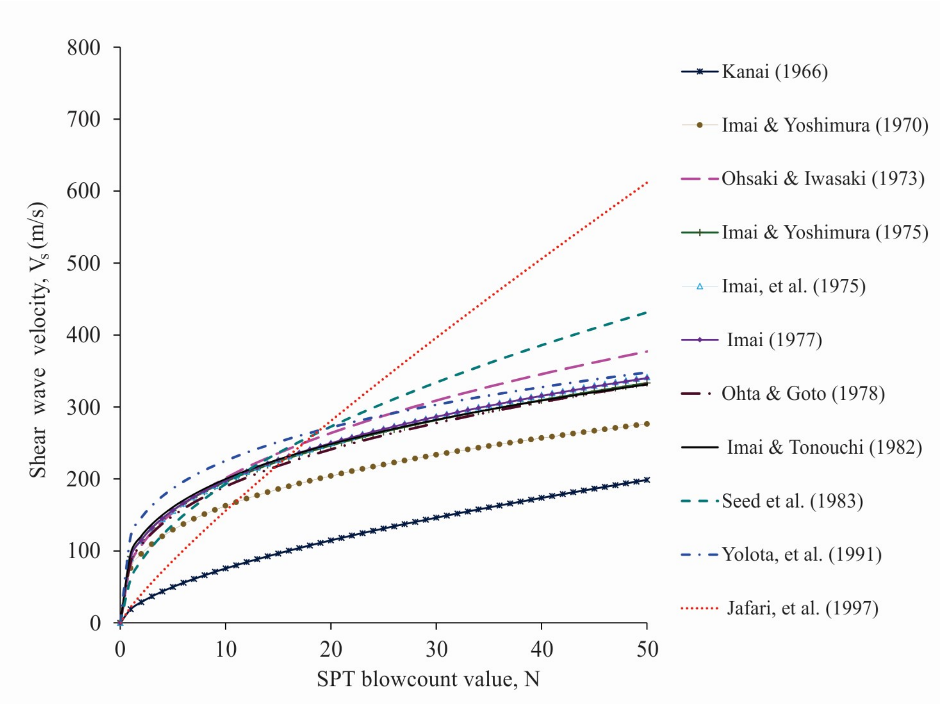

Fig. 1 – Empirical correlations for shear wave velocity as a function of the number of blows

The correlation developed by Seed et al. (1983) is frequently used in the field [10]. This correlation (Eq. 1) was proposed to assess the liquefaction potential of sandy deposits during a seismic event. In this equation, N is corrected for the energy and overload, and V_s is a function of the stress state of the soil deposit and does not depend on the strain level induced by a seismic movement.

$$V_s = 61N^{0.5} \tag{1}$$

This correlation is used in this study to dynamically characterize the sites and determine the V_s profile from N.

2. Geotechnical models

The sites of analysis are located in the Lomas area of Mexico City. Field exploration and laboratory tests were carried out to determine the stratigraphic profiles and mechanical properties of each stratum. The results were used to define the geotechnical models presented in Tables 2 to 4.

Table 2 – Geotechnical model site 1

Stratum	Depth [m]	γ [kN/m^3]	Description
1	0.0 to 1.8	22.1	Sand with gravel
2	1.8 to 8.0	14.9	Clayly sand
3	8.0 to 16.0	16.8	Silty clay
4	16.0 to 35.0	22.2	Sand with gravel
5	35.0 to 45.0	14.9	Clayly sand
6	45.0 to 50.0	20.0	Clayly sand with gravel

Table 3 – Geotechnical model site 2

Stratum	Depth [m]	γ [kN/m^3]	Description
1	0.0 to 5.0	18.8	Highly compacted clayly gravel
2	5.0 to 14.5	19.4	Medium compacted clayly sand
3	14.5 to 28.0	19.2	Highly compacted clayly sand
4	28.0 to 50.0	20.3	Highly compacted gravel

Table 4 – Geotechnical model site 3

Stratum	Depth [m]	γ [kN/m^3]	Description
1	0.0 to 4.0	17.0	Fill
2	4.0 to 8.0	19.4	Highly compacted silty sand
3	8.0 to 20.0	23.4	Highly compacted silty sand and gravel
4	20.0 to 30.0	22.0	Highly compacted silty sand
5	30.0 to 50.0	23.7	Fractured andesite rock

3. Characterization of seismic environment

The seismic environment of the study area was characterized by identifying the closest seismological station within the area and selecting three records as seed earthquakes with magnitudes Ms greater than 6.5 (Table 5). The objective was to generate three synthetic accelerograms with spectra that were compatible with the design response spectrum for the Lomas area (Zone I), as defined by the 2017 Construction Regulations for the Federal District [13].

Synthetic signals were obtained using RSPMatch 99 [14]. This program implements the Lilhanand & Tseng algorithm (1987, 1988) [15, 16] to modify the history of accelerations in the time domain and make this history compatible with the specified reference spectrum. Fig. 2 shows the response spectra obtained from a spectral adjustment of the seed seismic records.

Table 5 – Seismic events registered at station UI21

Event	Date	Ms	Component	Maximum accelerations [gal]
Event 1	09/08/2000	6.5	NS / V / EW	5.02 / 2.07 / 5.19
Event 2	11/01/1997	6.9	NS / V / EW	9.12 / 3.99 / 9.21
Event 3	30/09/1999	7.5	NS / V / EW	14.78 / 7.80 / 16.33

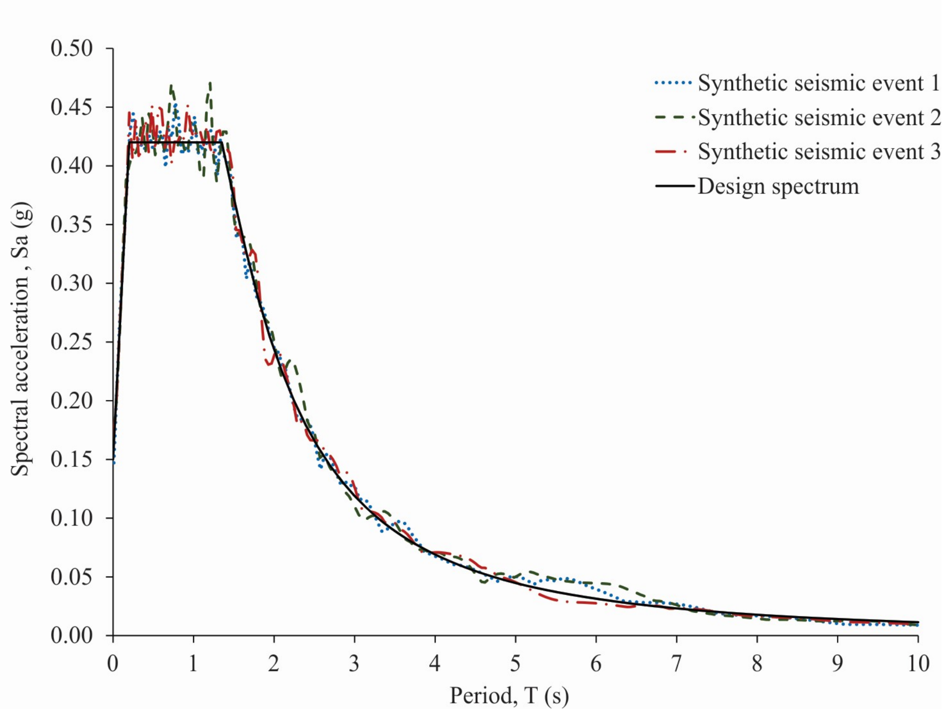

Fig. 2 – Response spectra in the rock of synthetic seismic events

4. Site response analysis

4.1 Shear wave velocity profiles

The dynamic responses during a seismic event of the three sites characterized dynamically using V_s profiles obtained from seismic cross-hole tests, and the correlation of Seed et al. (1983) [10] (Eq. 1) were determined and compared.

Fig. 3 presents a comparison between the V_s profiles obtained by direct and indirect methods for each study site. In this figure, the cross-hole tests identify low and high compaction strata that were not detectable by the SPT. The empirical correlation overestimated V_s for poorly compacted strata and underestimated V_s for most of the compacted strata, and at best, these V_s corresponded to an average of the cross-hole V_s values along the three stratigraphic profiles studied.

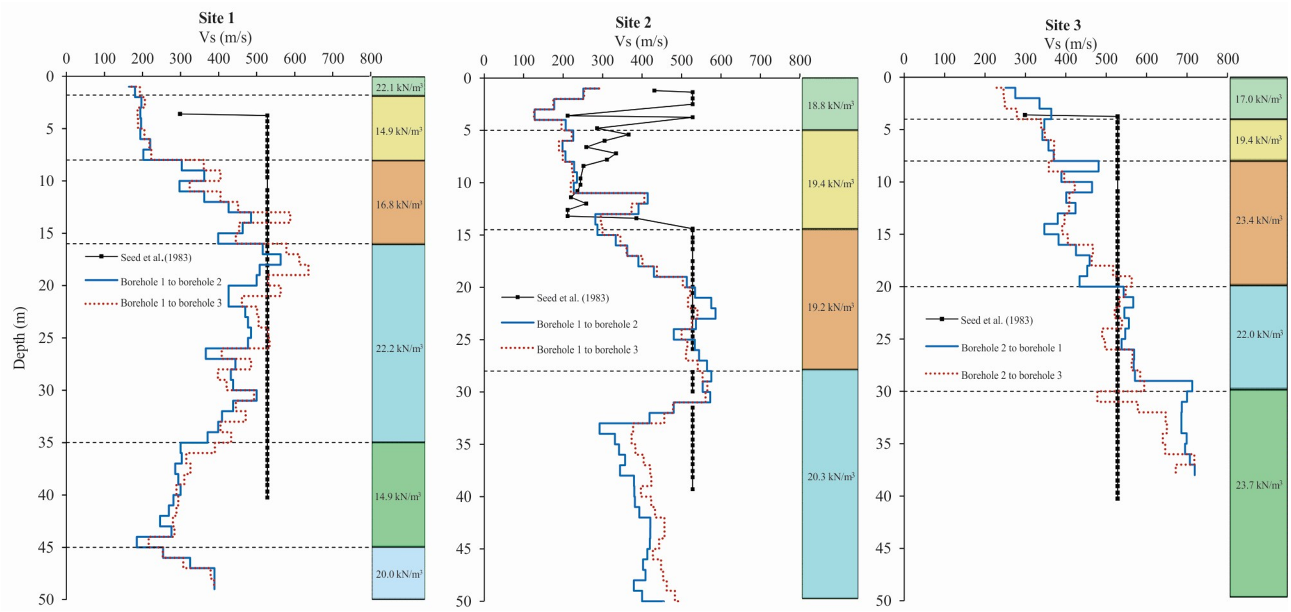
Fig. 3 – Shear wave velocity profiles

4.2 Dynamic properties

The SHAKE program [17,18] was used to perform a one-dimensional site response analysis of the soil deposits. The curves for G and ξ were used to consider the nonlinear effects in the soil and are presented in Fig. 4 and Fig. 5, respectively. Tables 6 to 8 present the curves used for each stratum of the sites of analysis.

Table 6 – Modulus degradation and damping curves used for site 1

Stratum	Depth[m]	Curves
1	0.0 to 1.8	Seed et al. (1986) [19]
2	1.8 to 8.0	Vucetic & Dobry (1/91) IP=30 [20]
3	8.0 to 16.0	Vucetic & Dobry (1/91) IP=30 [20]
4	16.0 to 35.0	Seed et al. (1986) [19]
5	35.0 to 45.0	Vucetic & Dobry (1/91) IP=15 [20]
6	45.0 to 50.0	Seed & Idriss (1970) [21]

Table 7 – Modulus degradation and damping curves used for site 2

Stratum	Depth [m]	Curves
1	0.0 to 5.0	Seed et al. (1986) [19]
2	5.0 to 14.5	Vucetic & Dobry (1/91) IP=15 [20]
3	14.5 to 28.0	Seed & Idriss (1970) [21]
4	28.0 to 50.0	Seed et al. (1986) [19]

Table 8 – Modulus degradation and damping curves used for site 3

Stratum	Depth [m]	Curves
1	0.0 to 4.0	Seed & Idriss (1970) [21]
2	4.0 to 8.0	Seed & Idriss (1970) [21]
3	8.0 to 20.0	Seed et al. (1986) [19]
4	20.0 to 30.0	Seed & Idriss (1970) [21]
5	30.0 to 50.0	Schnabel (1973) [22]

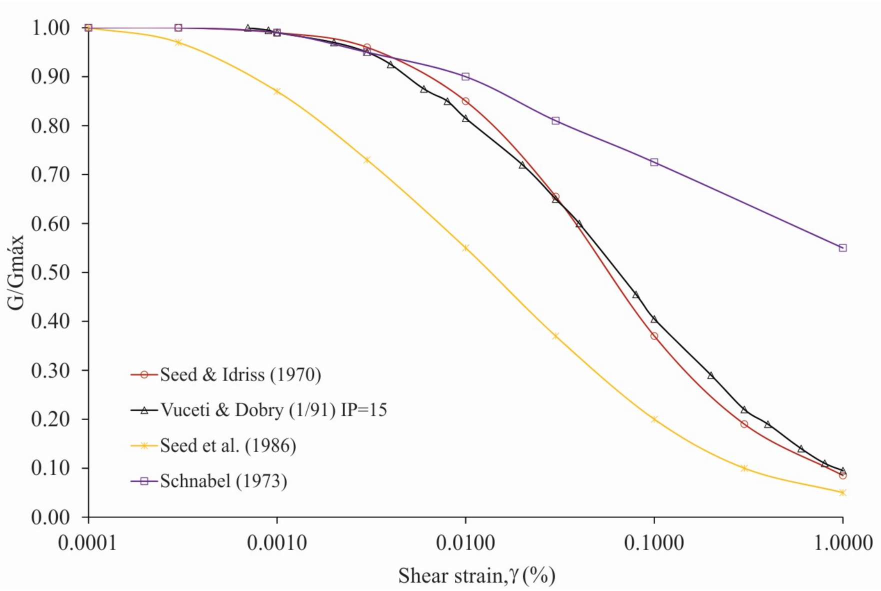

Fig. 4 –Modulus degradation curves

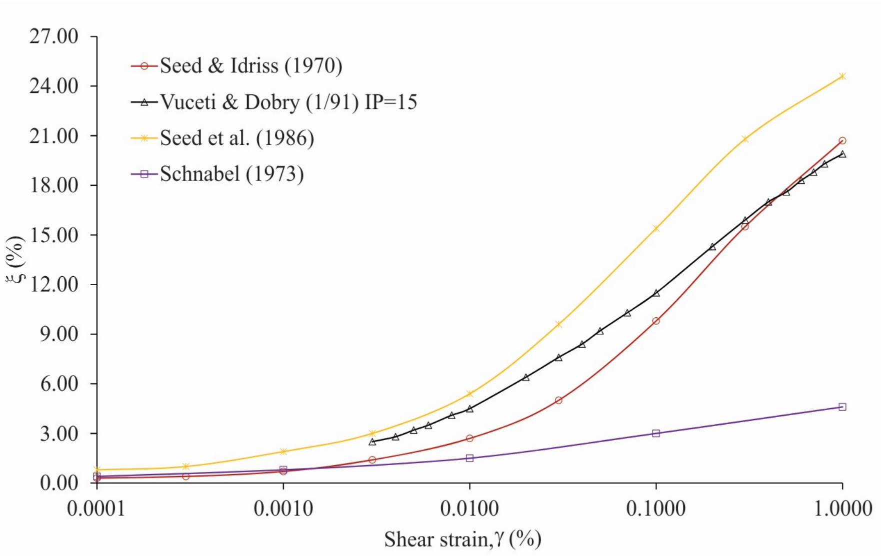

Fig. 5 – Damping curves

5. Results

Figs. 6 to 8 provide a comparison of the site response spectra obtained with the SHAKE program for each granular soil deposit. The dynamic properties of the geomaterials were determined using the directly and indirectly generated V_s profiles.

In Fig. 6 and 7, using the cross-hole V_s profile to characterize site 1 produces a soil period of approximately 1.40 s and a maximum ground acceleration of 0.21 g. The corresponding values for site 2 are approximately 1.20 s and 0.19 g. However, using the empirical V_s profile for site 1 produces a soil period of 0.70 s and a maximum ground acceleration of 0.25 g. The corresponding values for site 2 are 0.74 s and 0.24 g. Thus, the site responses of the soil deposits show that the dynamic properties determined from the cross-hole V_s correspond to a less competent deposit than the ones determined from the empirical V_s profiles

Note that there are no significant changes in the spectral ordinate for sites 1 and 2 when considering the, directly and indirectly, obtained V_s profiles.

Fig. 8 shows that using the cross-hole V_s to characterize site 3 results in a soil period of approximately 0.36 s and a maximum ground acceleration of 0.16 g. The corresponding results obtained using the empirical V_s are 1.20 s and 0.13 g. These differences are obtained because the cross-hole test can detect competent strata. At site 3, in particular, a stratum was found at a 30 m depth with V_s greater than 500 m/s.

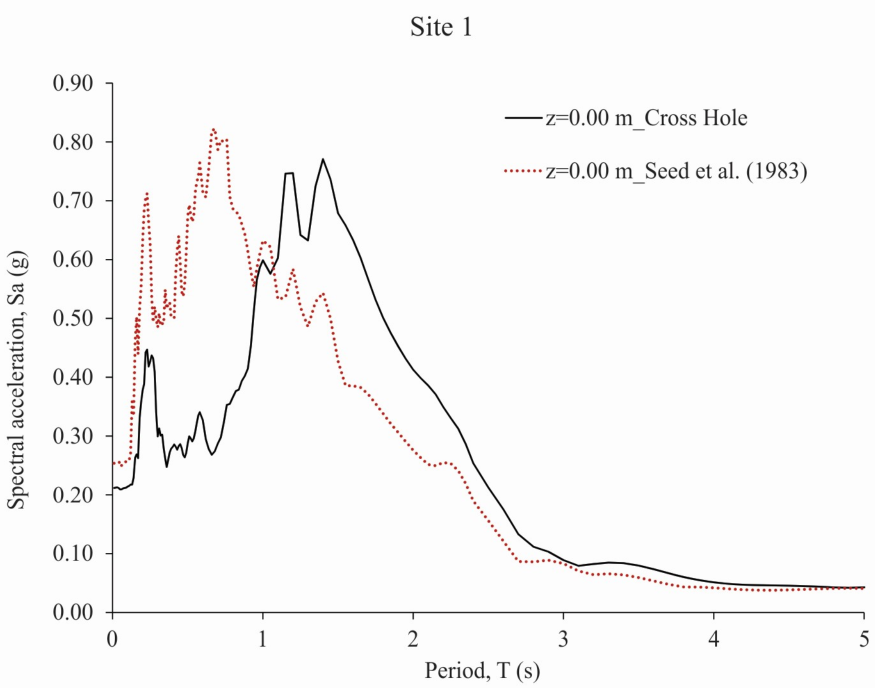

Fig. 6 – Comparison of surface response spectra for site 1

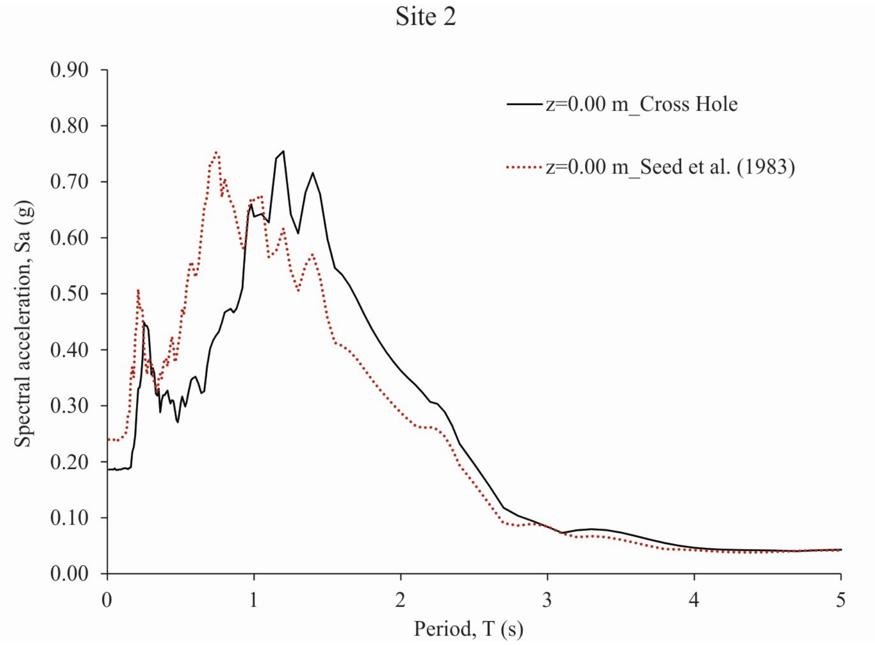

Fig. 7 – Comparison of surface response spectra for site 2

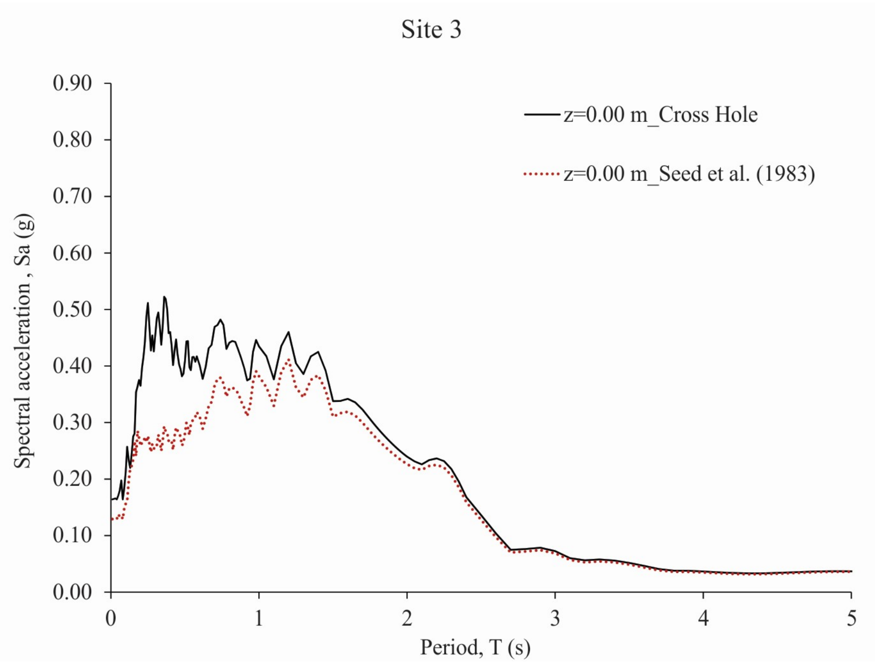

Fig. 8 – Comparison of surface response spectra for site 3

6. Conclusions

In this article, a comparative analysis is presented for the dynamic site response of three granular soil deposits in the Lomas Zone of Mexico City using two V_s profiles. One profile was obtained directly from cross-hole tests, and the other profile was obtained indirectly using a correlation by Seed et al. (1983) that is based on N in the SPT.

A comparison of the V_s profiles showed that the cross-hole tests identified low and high compaction strata in each study site, whereas the SPT did not. One-dimensional site response analyses using the SHAKE code showed that the response spectra of sites 1 and 2 characterized using cross-hole tests were more representative of a less competent soil deposit than those obtained using the empirical V_s profiles.

The surface response spectrum obtained for soil deposit 3 using dynamic properties obtained from the cross-hole tests was characteristic of geomaterials with significant stiffness. The capability of the cross-hole test to identify a competent stratum at a 30-m depth with V_s greater than 500 m/s is highlighted.

In conclusion, the V_s parameter influences significantly site response analysis and soil-structure interaction. Thus, it is essential to perform field tests that enable each of the strata of a soil profile to be properly identified and characterized. Incorrectly characterizing this parameter will significantly affect the dynamic behavior of the deposit and the structure under a severe seismic scenario.

7. References

[1] ASTM International (2000): Standard Test Method for Crosshole Seismic Testing. ASTM D4428/D4428M-00.

[2] Kanai K (1966): Conf. on Cone Penetrometer The Ministry of Public Works and Settlement (Ankara, Turkey) (presented by Y Sakai, 1968).

[3] Imai T, Yoshimura Y (1970): Elastic wave velocity and soil properties in soft soil. *Tsuchi-to-Kiso* **18** (1), 17–22 (in Japanese).

[4] Ohsaki Y, Iwasaki R (1973): On dynamic shear moduli and Poisson's ratio of soil deposits. *Soil Found* **13**, 61–73.

[5] Imai T, Yoshimura Y (1975): The relation of mechanical properties of soils to P and S-wave velocities for ground in Japan Technical Note OYO Corporation.

[6] Imai T, Fumoto H, Yokota K (1975): The relation of mechanical properties of soil to Pand S- wave velocities in Japan. *Proceedings of 4th Japan Earthquake Engineering Symp*. 89–96 (in Japanese).

[7] Imai T (1977): P and S wave velocities of the ground in Japan. *Proceeding of IX International Conference on Soil Mechanics and Foundation Engineering*, 2, pp. 127–132.

[8] Ohta Y, Goto N (1978): Empirical shear wave velocity equations in terms of characteristics soil indexes. *Earthquake Engineering and Structural Dynamics* **6**, 167–187.

[9] Imai T, Tonouchi K (1982): Correlation of N-value with S-wave velocity and shear modulus. *Proceedings of the 2nd European Symposium of Penetration Testing*, Amsterdam, pp. 57–72.

[10] Seed HB, Idriss IM, Arango I (1983): Evaluation of liquefaction potential using field performance data. *Geotechnical Engineering*, **109** (3): 458-483.

[11] Yokota K, Imai T, Konno M, (1991): Dynamic deformation characteristics of soils determined by laboratory tests. OYO Tee. Rep. 3, p. 13.

[12] Jafari MK, Asghari A, Rahmani I (1997): Empirical correlation between shear wave velocity (Vs) and SPT-N value for south of Tehran soils. *Proceedings of the 4th Int. Conf. on Civil Engineering* (Tehran, Iran) (in Persian)

[13] RCDF (2004): Reglamento de Construcciones para el Distrito Federal. Gaceta Oficial del Distrito Federal, México.

[14] Abrahamson N (1992): Non-Stationary spectral matching, *Seismol*. Res. Lett. 63, 30.

[15] Lilhanand K, Tseng WS (1987): Generation of synthetic time histories compatible with multiple-damping response spectra, *SMiRT-9*, K2/10.

[16] Lilhanand K, Tseng, WS (1988): Development and application of realistic earthquake time histories compatible with multiple damping response spectra, *Ninth World Conf. Earth. Engin*. (2):819-824. Tokyo, Japan.

[17] Schnabel P, Lysmer J, Seed H (1972): A computer program for earthquake response analysis of horizontally layered sites. Report EERC 72-12. University of California, Berkeley, USA.

[18] Idriss IM, Sun JI (1992): User's manual for SHAKE91: A computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits. Center for Geotechnical Modeling. Department of Civil and Environmental Engineering. University of California. Davis, USA.

[19] Seed HB, Wong RT, Idriss IM, Tokimatsu K (1986): Moduli and Damping Factors for Dynamic Analyses of Cohesionless Soils. *Geotechnical Engineering*, ASCE, 112(11):1016-1032.

[20] Vucetic M, Dobry R (1991): Effect of soil plasticity on cyclic response. *Geotechnical Engineering*, ASCE, 117: 89-107.

[21] Seed HB, Idriss IM (1970): Soil Moduli and Damping Factors for Dynamic Response Analyses. Report EERC 70-10, Earthquake Engineering Research Center, University of California, Berkeley, USA.

[22] Schnabel PB (1973): Effects of local geology and distance from source on earthquake ground motions, Ph.D. thesis, University of California, Berkeley, USA.

