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Shear-wave velocity profile at the Texcoco strong-motion array site, Valley of Mexico

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RESUMEN

Se presenta un perfil de velocidades de ondas S obtenido en el sitio de la Red Sísmica de Texcoco, México. Se empleó el método de Penetrometría de Cono Sísmico (SCPT) hasta una profundidad de 39 metros bajo la superficie. Se encontró la capa dura a 28 metros y se perforó hasta 29 metros para continuar con el penetrómetro a profundidades mayores. Los resultados se comparan con los obtenidos en sísmica de reflexión y refracción, y con datos de inversión de microtemblores. Todos los estudios disponibles concuerdan entre sí, hasta llegar a la capa dura, pero hay algunas diferencias en cuanto al perfil a mayores profundidades. Las profundidades de las discontinuidades concuerdan con las reportadas en perforaciones de pozos.

PALABRAS CLAVE: Texcoco, SCPT, penetrometría, velocidades sísmicas, ondas S.

ABSTRACT

The shear-wave velocity profile at the Texcoco strong motion accelerograph array site was evaluated down to 39 m using Seismic Cone Penetrometry (SCPT). The hard layer from 28 m to 29 m was drilled to allow penetration to greater depths. The results are compared with those obtained from shear-wave reflection/refraction, and from the inversion of microtremor data. All the studies agree on the depth and shear-wave velocity above the hard layer, but diverge below it. Depths of discontinuities are in accordance with drillhole data.

KEY WORDS: Texcoco, SCPT, penetrometry, shear-wave velocity.

INTRODUCTION

The Texcoco strong motion array (TXC, Figure 1) was established after 1995 to investigate the role of soft soils in structural damage during earthquakes. Downtown Mexico City is vulnerable to large earthquakes from the Cocos Plate subduction zone, at an epicentral distance of 300 to 500 km (Singh *et al*., 1988). The city was founded in 1325 by Aztecs on a shallow layer of soft mud from a large lake which was gradually drained after it fell to a Spanish force in 1519. Damage in large earthquakes is strongly correlated with site effects related to this mud layer.

Observation of a presumed Rayleigh wave with a phase velocity of 160 m/s, recorded by strong-motion accelerographs of the Texcoco array (Stephenson, 2002) suggested the presence of a ~160m/s layer underlying the very low-velocity lacustrine materials at the ground surface, and that this layer controls the velocity of the coupled wave. A layer, possibly with these properties, has been widely described as the "hard layer", a marker at a depth of 25 to 40 m below the surface. As the velocity structure of the upper layers was not well constrained a shear-wave velocity profile was conducted in order to explore the depositional sequence of lake sediments in the depth range of zero to 28 m and beyond. The study was conducted in 2002 using the seismic cone penetration technique (SCPT).

GEOLOGY OF THE VALLEY OF MEXICO

The Valley of Mexico has not been extensively explored in terms of geology. A general geological interpretation is due to Mooser (1987).

The Valley of Mexico is a closed topographic basin of about 50 by 80 km horizontal extent, located in the volcanic plateau of central Mexico at an elevation of 2240 m. All rocks and sediments are of volcanic origin. Tertiary to Recent volcanics are underlain by Cretaceous limestones at sea level. The floor of the basin was occupied until recently by a large, brackish, shallow lake. Mooser proposes that the shallow layer of soft clay was formed by alteration of windblown volcanic ash which settled in the water. The lacustrine mud layer consists of a highly organic, sensitive clay with a density of 1,100 kg/m^3 and a Poisson's ratio of 0.49. Mooser distinguishes a consolidated top layer about 2 meters thick of Holocene soils and caliche—a hardpan produced by the capillary rise of brackish ground water.

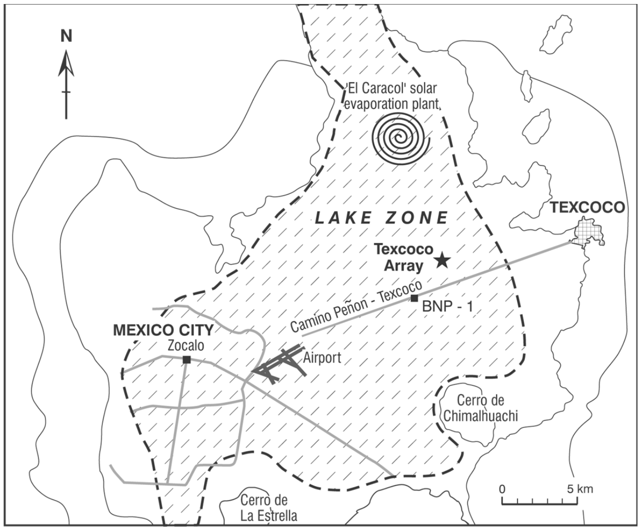

Fig. 1. Location of the Texcoco site in the Valley of Mexico.

The lake mud consists of 25 to 50 meters of very homogeneous soft clay with some interspersed thin soil layers. Mooser believes that this layer was deposited during the Wisconsin glacial period, from 10 000 to 80 000 years before present. The hard layer below this, at an average depth of 30 meters, has a thickness of about three meters and contains a reddish tuff attributed to soil formation during the Sangamon interglacial period (80 000 to 100 000 years b.p.). Beneath the Sangamon soils Mooser finds about 30 meters of very hard clays, tuffs and conglomerates with some rare pumice layers, corresponding to the upper Illinois glacial period. At the bottom of this sequence there are pyroclastics from a major eruption which must have occurred around 160 000 or 170 000 years b.p. It might be the great eruption of San Miguel Caldera, which produced the spectacular blue sands found over the larger area. Mooser does not identify other major eruptions within the upper 65 m of lake sediments. Rather, he believes that the hard layers in the sedimentary sequence are caused by climate change. The Illinois-age sediments continue down to a depth of at least 100 meters.

The lake was always shallow, so the small streams that fed the lake never formed any substantial delta deposits. Instead, sediments coming down from the hills tended to accumulate at the foot of the slope, where they can be found interfingered with mud layers and glacial deposits.

Murillo and García (1978) described some drilling logs obtained in the area of the Texcoco Array. They found a 28m thick layer of lacustrine volcanic clays overlying a hard soil layer of sandy silts, sands and silts of up to 3.5 m thickness. This is the Sangamon tuff described by Mooser. Below the hard layer are more lacustrine volcanic clays, and finally, below 42 m depth are the deep deposits of highly consolidated silts and fine silty sands, which Mooser attributed to the Illinois glacial period.

THE SCPT TECHNIQUE

While methods of obtaining shear-wave velocity profiles involving seismic refraction or the inversion of Rayleigh wave dispersion curves are attractive because they are non-invasive, they lack depth resolution, so that sudden velocity transitions with depth may not be detected. On the other hand, the standard downhole and crosshole methods are expensive to implement. Between these two techniques the seismic cone penetration test (SCPT) described by Robertson *et al*. (1986) fills a gap.

A miniature geophone is inserted in the penetrometer cone, and its signals are recorded at the ground surface. The sensor is easily deployed at depth by pushing the penetrometer rod into the soil, and shear-wave signals generated at the ground surface are detected by the sensor and transmitted by cable to a recorder at the surface. Thus a shear-wave velocity profile may be quickly and economically obtained.

Figure 2 shows the SCPT arrangement used by the Institute of Geological and Nuclear Sciences, New Zealand, as employed for the Texcoco investigation. All its components are built with standard technologies in mind, so that only a minimum of equipment needs to be transported when a remote site is investigated. A locally-available cone penetration rig, laptop computer and shear-wave generator may be used, and only the seismic cone (with its inbuilt preamplifier), cables, and parallel port based A/D converter need be transported to the site. This equipment is easily carried as hand luggage on an aircraft.

SCPT INVESTIGATIONS

At the Texcoco array site, as elsewhere in the lake zone of the Mexico City basin, the existence of a hard layer of one to three meters thickness at depths of 25 to 30 m complicates any effort to measure the shear-wave velocity profile at greater depths. From a mechanical point of view, penetrometry, including the Seismic Cone Penetration Test (SCPT), is limited by the inability of the cone to penetrate the hard layer. Also, in geophysical investigations such as shear-wave refraction surveys, the hard layer tends to reflect downward-propagating energy back towards the surface, and any significant arrivals tend to be obscured by scattered waves.

Most of the upper Texcoco profile is amenable to penetrometry, so we decided to use a combination of SCPT and drilling. The penetrometer rod was withdrawn when the hard layer was encountered; then the hard layer was drilled,

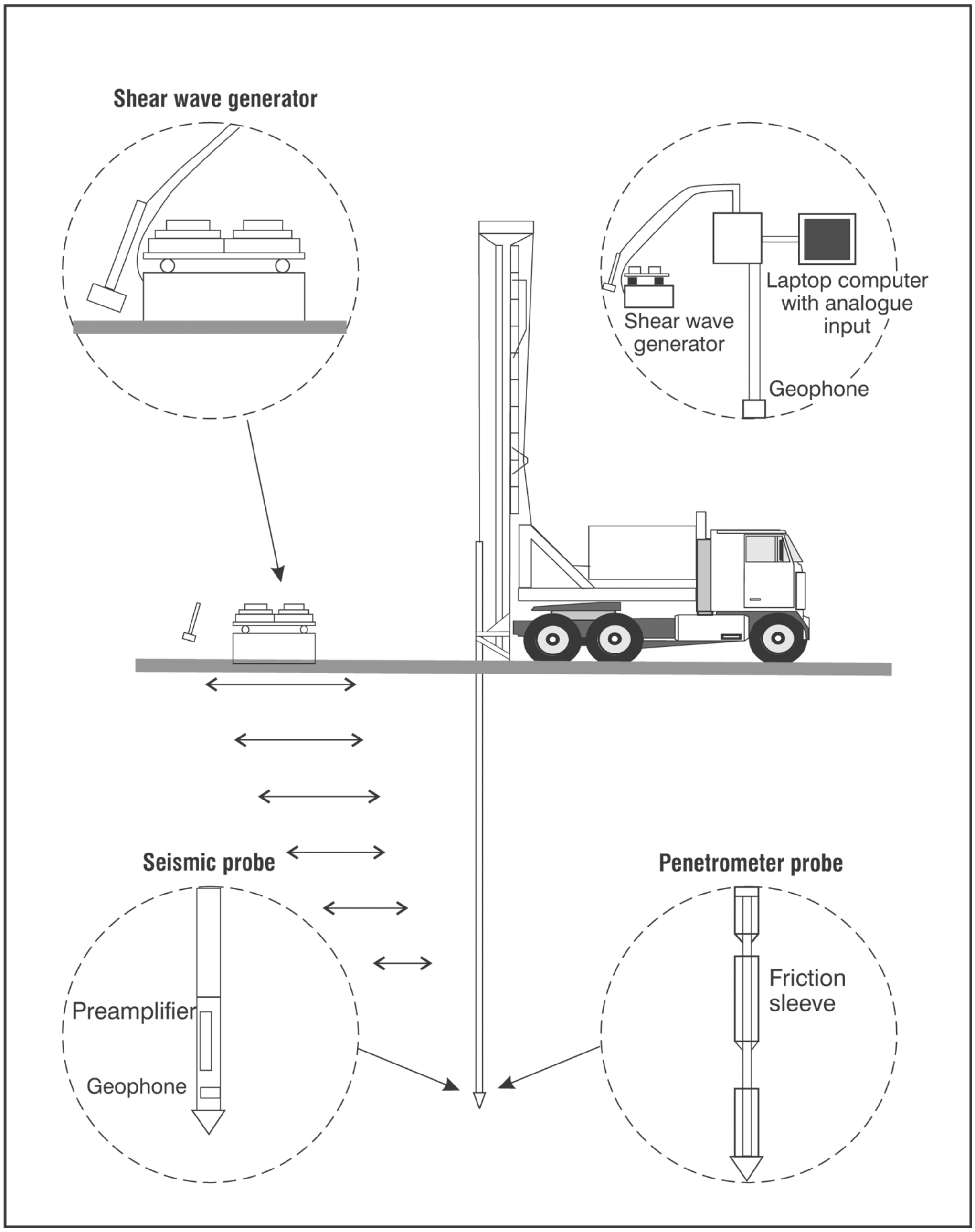

Fig. 2. SCPT equipment. Only the cone, cable, amplifier and adc converter need to be transported because a local shear-wave source and drilling rig may be employed.

and penetrometry operations were resumed. It was expected that the hard layer would reflect much of the incident energy back towards the surface, but the same would apply to noise, with the result that the signal should be observable at depth.

We used a 2-tonne penetrometer rig. In preparation for penetrometry we drilled a test hole through the hard layer in advance. This enabled us to assess the difficulties to be encountered during the SCPT investigation proper. Subsequently the drilling rig was moved a short distance, and the upper portion of the profile was investigated by the SCPT method. It was expected that the total profile would be completed in half a day. However the field operation was not as straightforward as we had hoped for two reasons: geotechnical difficulties and an unforeseen mismatch between the cone and the rods.

We encountered unexpected additional hard layers below the main one at 28 m. Some of these layers were sufficiently resistant that the rig was unable to advance the seismic cone. As a consequence it became necessary on two occasions to withdraw the seismic cone, drill a hard layer, and resume probing. This extended the time required for testing, and small gaps were introduced in the profile. Final refusal was encountered at 39 m. It was not easy to recover the cone from this depth because of dilatant behaviour at 39 meters. This behaviour also confirmed the presence of a change of material, suggesting that the depth of 39 m marks the bottom of a geological sequence (Murillo and García, 1978).

Finally, shear-wave generation and detection was carried out in the reverse direction, working upwards from 39 m at 20 cm intervals. At 29 m depth the signal was lost due to lack of coupling with the soil as the geophone entered the pre-drilled hole.

The incompatibility between the drilling equipment and the seismic cone equipment developed because although the cable connectors fitted inside the penetrometer rods, they were unable to pass through the rod joiners. This difficulty was overcome by cutting the connectors off from the cable and substituting direct soldered connections with improvised waterproofing. Thus we were unable to prevent some leakage of saline ground water into the preamplifier.

The combination of low signal, improvised waterproofing, leakage into the preamplifier, and a somewhat noisy electrical inverter, led to signal degradation. We were able to counter this to some extent by post-processing the geophone signals.

Field conditions at Texcoco are unusually adverse because of the aggressive saline environment. At depths greater than 29 m the amplitude of the geophone signal was very low and there was some noise from the hammer impact, presumably arising from cross-talk between the geophone circuit and the trigger circuit at the hammer. The problem can be overcome by ignoring signals that arrive earlier than the shear-wave.

Another source of noise was a 60 Hz hum from the inverter, especially on very low-amplitude geophone signals from depths greater than 29 m. This noise was removed by low-pass filtering the signal below 40 Hz. Raw and processed signals for a depth of 39 m are shown in Figure 3 to illustrate the improvements gained by post-processing.

When probing was resumed, this time working down from the ground surface at 20 cm intervals, leakage of the highly saline ground water into the geophone preamplifier package led to increasing noise. Below 16.6 m the shear-wave signal could no longer be detected despite repeated signal stacking.

The final plot of processed signals is shown in Figure 4, and also Figure 5 with geophone signals inverted. Note

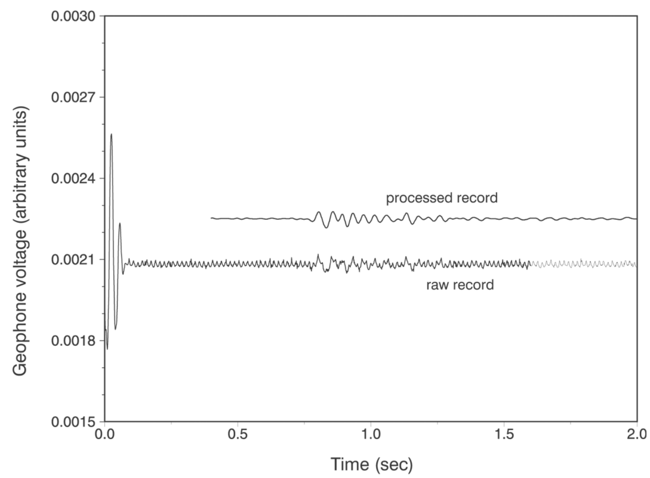

Fig. 3. Raw and processed (inset) geophone signals from 30 m depth. Processing has removed a 60Hz inverter-generated waveform, and an early hammer-generated waveform.

that there is a strong reflection from 5.6 m after 158 ms, implying a 1.6 Hz layer resonance. The shear-wave arrival at the bottom of the hard layer can be seen after 676 ms, if the signal at 662 ms is assumed to correspond to the top of the hard layer. By subtracting a guessed travel time in the hard layer, a natural period of 2.65 sec is found, in good agreement with the observed dominant period in seismograms. No reflection from the hard layer to the surface is seen (presumably it is lost in the noise). The shear velocity between the surface and a depth of 17 m is extremely low–between 30 m/s and 40 m/s. Between 17 m and 28 m (dotted line), the interpolated shear velocity is 50 m/s. We find a velocity of 130 m/s in the stiff material between 32 m and 35 m. Finally, a reflection is seen at a time of 1250 millisec, going upwards from a depth of 39 m. If a shear velocity of 475 m/s (to be justified later) is assumed below 39m this reflection may suggest the presence of a velocity discontinuity at 163m depth.

As an initial interpretation we assume that the arrivals in Figures 4 and 5 are produced by vertically propagating shear-waves, but in reality the waves are dispersive and the true first arrivals may be hard to determine. This uncertainty is compounded by the limited pattern-recognising ability of the human brain. Consistent alignments of arrivals are easily recognised, but such lines can be changed by simply reversing the polarity of the signals. The interpreted lines of first arrivals in Figures 4 and 5 represent a best effort to obtain a meaningful shear-wave velocity profile, but other interpretations are possible.

A minor error is introduced by the fact that the shear-wave source is offset horizontally by about 2 m from the point where the penetrometer rods enter the ground. As a consequence of this, at a depth of 2 m the actual travel dis-

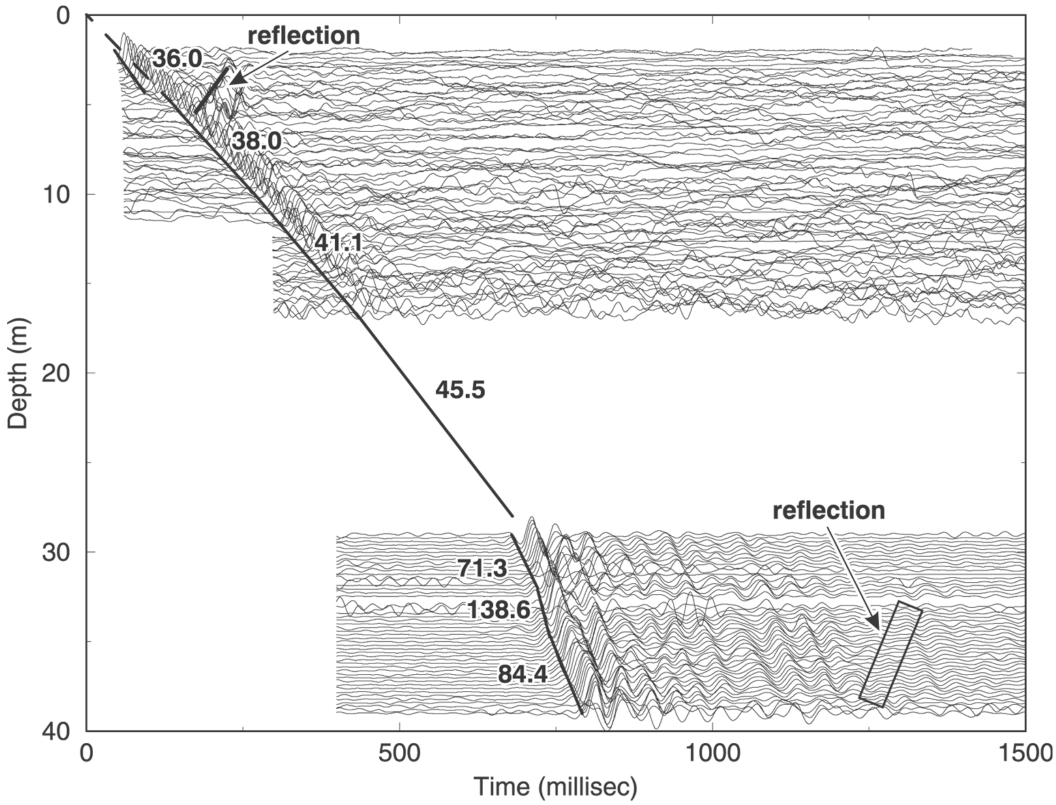

Fig. 4. Arrivals of hammer-generated shear-waves as a function of depth, together with an interpretation in terms of shear-wave velocity profile.

tance is $2\sqrt{2}$ m (assuming homogeneous velocity), which involves a distortion of the plot of arriving waveforms against time. We partly correct for this error by adjusting the time scale to allow for slanted propagation, but this can distort the lines of reflection, including the one at 150 ms (5.7 m depth), where the wave seems to have a greater velocity going up than going down.

In our proposed final shear-wave velocity profile for the Texcoco array site we have taken into account some information other than the SCPT traces. The BNP-1 borehole data and the cone penetration data down to the hard layer have been especially useful to compensate for lack of information about the thickness and shear-wave velocity of the hard layer, details of the shear-wave velocity between 17 m and the hard layer, and soil properties below 39 m depth.

Prior to installation of a vertical array of sensors at Texcoco, a penetration test was carried out to refusal at 28 m (Figure 6). This test further defined the depth to the top of the hard layer. In addition, SCPT signals were obtained at 29 m; thus the hard layer must be 1 m thick at the Texcoco array site. A credible Vs value for the hard layer itself should be at least 130 m/s, which is the velocity found for the layer between 32 and 35 m depth.

In Figure 6 we note increasing CPT tip resistance values with depth. This may indicate that between 17 m and 28 m the velocity is not constant as assumed, but that it increases with increasing depth.

On the basis of shear-wave refraction profiles conducted near the Texcoco Array site, Benjumea (2003, pers. comm.) assigned a velocity of 475 m/s to material immediately below 40 m depth. The BNP-1 well logs suggest that there is relatively homogeneous material between 40 m and 160 m.

In conclusion, our best evaluation of the shear-wave velocity profile is as follows.

Depth (m)	Shear-wave velocity (m/s)
0 - 7	30
7 - 17	40
17 - 28	50
28 - 29	150
29 - 32	75
32 - 35	130
35 - 49	75
49 – 160	475
> 160	>> 475

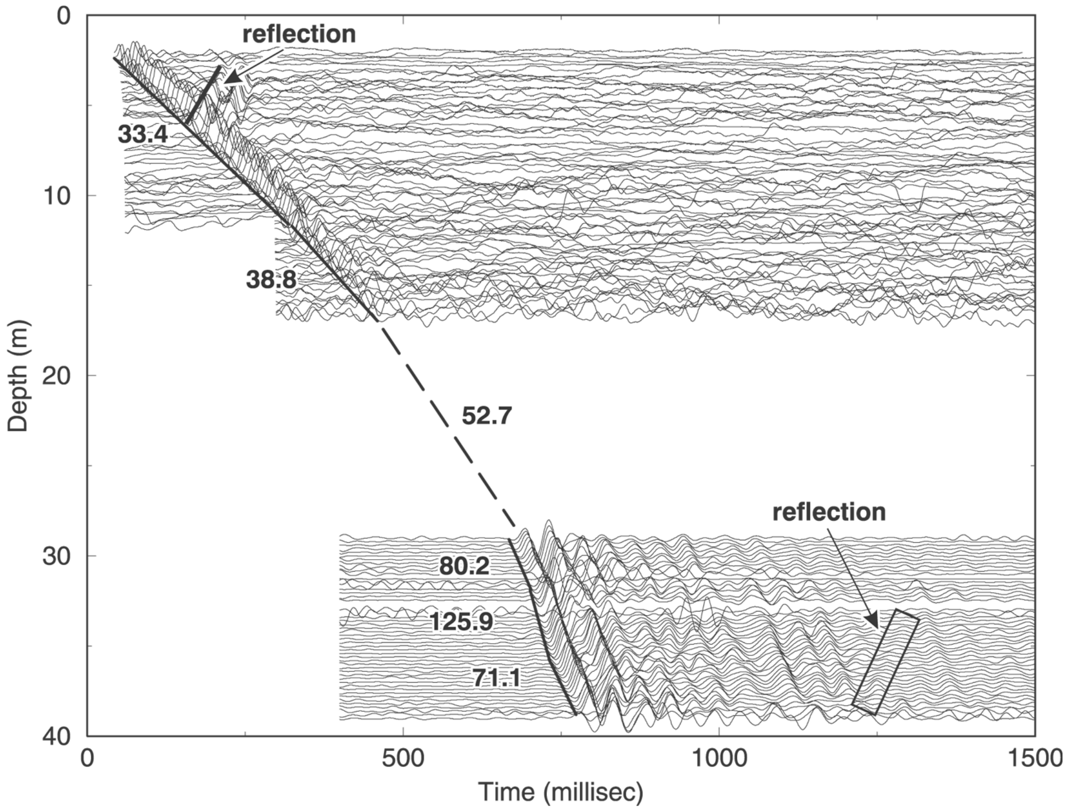

Fig. 5. Arrivals of hammer-generated shear-waves as a function of depth, together with an interpretation in terms of shear-wave velocity profile. Inverted traces.

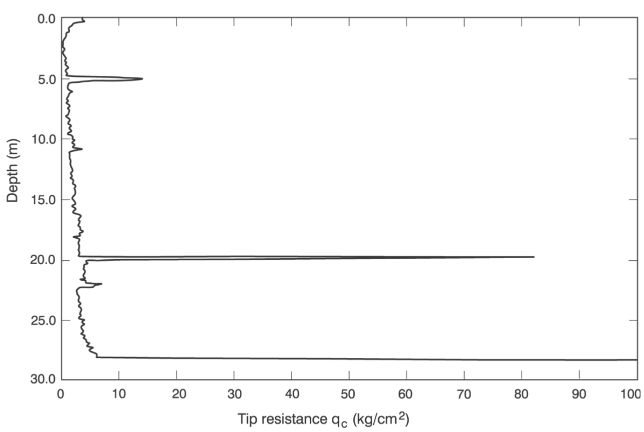

Fig. 6. CPT profile at the Texcoco array.

DISCUSSION

Aguirre *et al.,* (2001) deployed Guralp seismometers in 4-instrument arrays with apertures of 15 m, 62.5 m, 250 m and 100 m, at the well site P01, some 5 km northwest of the Texcoco array, but on much the same material. Using the SPAC technique (Aki, 1957) they obtained a dispersion curve for the phase velocity of Rayleigh waves which they were able to invert into a shear-wave velocity profile. Flores-Estrella (2004) obtained additional microtremor data near the Texcoco site and constructed a dispersion curve by combining the theoretical curve based on SCPT with the experimental curve based on SPAC. Inverting the resultant dispersion curve gives a shear-wave velocity profile which is intended to provide accurate values at depth. Naturally it agrees with SCPT near the surface. The various velocity profiles are summarised in Figure 7.

Benjumea (2003, pers. comm.) carried out seismic shear-wave reflection and refraction profiles at the Texcoco array site. Her results are generally in agreement with our values: shear-wave velocities from 40 m/s to 60 m/s in the top 35 m, generally increasing with depth, and a shear-wave velocity of around 475 m/s below 40 m. The latter velocity may be associated with the material in which the SCPT cone became stuck. With hindsight, it should have been possible to measure this velocity as part of the SCPT probe by using a “walk away” recording of our shear-wave source. Benjumea’s shear-wave refraction results are also shown in Figure 7.

Other geotechnical information from nearby locations is consistent with our results. Water content in clays is an indicator of shear-wave velocity. From a 120 m core extracted at borehole BNP-1 (see Figure 1), close to the Texcoco

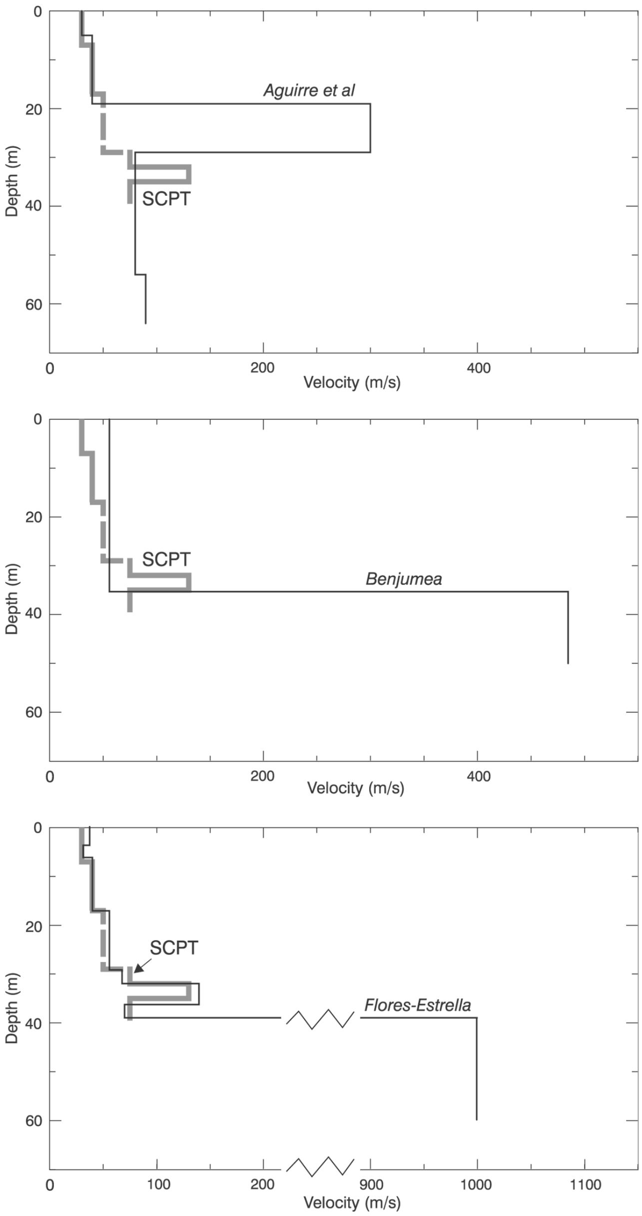

Fig. 7. Comparison of the SCPT-derived, refraction-derived and SPAC-derived shear-wave velocity profiles. (a) SCPT compared with SPAC (Aguirre *et al*, 2001. (b) SCPT compared with shear-wave refraction (Benjumea, 2003). (c) SCPT compared with a hybrid of SPAC and SCPT (Flores-Esrella, 2004). Note that shear-wave refraction studies gave a shear-wave velocity of 475m/s below about 40m, whereas the SPAC results gave 1000m/s, being influenced by deeper material.

array, the water content fell from around 300% in the top 28 m of lacustrine clays, to 30% between 100 m and 140 m, and to 25% below 160 m (Marsal and Mazari, 1990) The value of 25% implies a stiffer layer.

CONCLUSION

The use of SCPT has enabled us to evaluate shear-wave velocities in the crucial depth range between 29 m and 39 m with good depth resolution. We find a 3 m thick layer with a shear wave velocity of 130 m/s at a depth of 32 m. This feature may control the 160m/s wave previously observed by Stephenson (2002). It also suggests a velocity for the hard layer between 28 m and 29 m. However, other explanations of the slow wave must also be sought.

The SCPT shear-wave velocities down to a depth of 39 m, together with implied velocities of 475 m/s down to at least 160 m (Murillo and García, 1978) may provide a good foundation for additional studies. Obvious candidates for future research include the use of flexural waves in the hard layer, and of Rayleigh-wave dispersion in the Texcoco soil column.

The results of the SCPT investigation confirm and extend what has been known about the subsurface conditions at the Texcoco array site. We present a shear-wave profile down to 28 m that implies a natural period of 2.56 sec for the layer of lacustrine clay, in agreement with spectra for earthquakes recorded by the Texcoco array. The reflection seen at 1.25 seconds from 39 m depth, when combined with the velocity of 475 m/s measured by Benjumea, implies a site period of 4s for a depth-to-reflector of 163 m. The underlying reasoning is that at 39 m the down-going wave appears at 0.74 sec and the up-going wave at 1.25 sec. Therefore the reflector must be at 1 sec. Propagation down to 39m takes 0.74 sec, and the remaining 0.26 sec would be accounted for by 124 m of material with a velocity of 475 m/s, for a total depth of 163 m. While the Texcoco array does not fall within the area for which Lermo and Chávez-García (1994) presented contours of equal period, a value of 3 to 4 seconds for the natural period at the Texcoco array seems likely.

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