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# Behavior of a Skirt-Type Foundation for a Metro Railroad Overpass on the Mexico City Soft Clay, During the $M_w$ 8.2 Gulf of Tehuantepec Earthquake, on September 7<sup>th</sup> 2017

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**Abstract.** Line 12 of the subway system (Metro) connects the southeast and the southwest zones of Mexico City. Along its length of 25 km different solutions were used such as tunnels, box-type foundations, superficial tracks and viaducts. The railroad overpass crosses a zone with soft clay subsoil having low shear strength and high compressibility. Some of the supports in this zone were founded upon using an innovative solution. It is constituted by four cast-in-place peripheral concrete walls with thickness of 60 cm and length of 10.5 m, forming in plan a square of 6.5 m on each side. These walls are connected to a prefabricated concrete footing-column monolithically cast to support the superstructure. This skirt-type foundation is locally known as “inverted glass” or “structured cell”. Description is made in this paper of the dynamic behavior of support ZP-16 having this type of foundation, based on its measured geotechnical variables and accelerations recorded during the  $M_w$  8.2 earthquake occurred on September 7, 2017, with epicenter in the Gulf of Tehuantepec. No damage occurred in the system. The time series of the geotechnical variables monitored during this earthquake indicate transient cyclic processes.

**Keywords.** Innovative foundation, dynamic measurements, very soft clay, skirt-type foundation, dynamic response.

## 1. Introduction

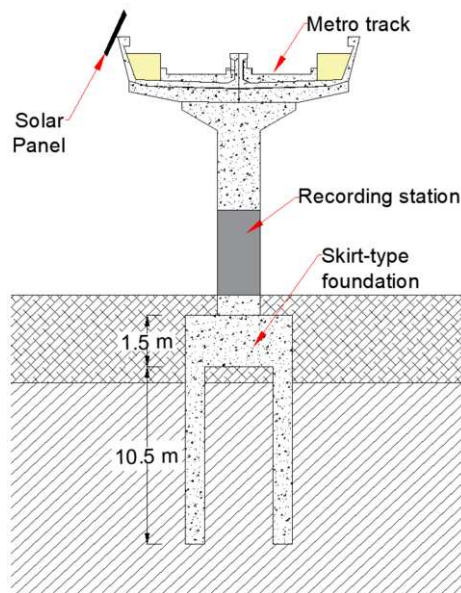
During construction of Line 12 of Mexico City subway system (Metro) recourse was made of tunnels, box-type foundations, superficial tracks and viaducts along its length of 25 km. It crosses the three geotechnical zones of the city: Hill Zone (*Lomas*), Transition Zone (*Transición*) and Lake Zone (*Lago*).

The Lake Zone is constituted by clay deposits of different thicknesses. This clay is identified by having low to very low shear strength and high to very high compressibility. Because of this, the earthquakes generated in the Pacific coast represent a serious hazard because the material referred to herein induces a very strong site effect.

Close to *Tláhuac* terminal station, in the supports built along a length of about 1.7 km of the elevated viaduct in the Lake Zone, use was made of an innovative solution locally known as structured cell or “inverted glass” [1]. This reinforced concrete

foundation is constituted by four cast-in-place walls with length of 10.5 m and thickness of 60 cm, forming in plan a square measuring 6.5 m on the side. These walls are attached with reinforced concrete to a precast element identified as a footing-column element, Figure 1. See additional details in a previous publication [2].

Because of the peculiarity of these foundations and to the very particular conditions of the soil where they were built, it was decided to measure some of the geotechnical variables and accelerations of a specific support founded upon this solution. For such purpose geotechnical sensors and accelerometers were installed at support ZP-16, which is located between *Zapotitlán* and *Nopalera* stations. The instrumentation includes total pressure cells placed under the footing-column, piezometers inside and outside the element and triaxial accelerometers embedded in the footing-column. All these sensors are connected to a dynamic data acquisition system electrically fed by a network of solar panels placed on top of the support.



**Figure 1.** Cross section of a support founded upon a structured cell.

## 2. Scope and objectives

This paper describes the dynamic behavior of a structured cell supported by clay deposits which was subjected to loadings imposed by the earthquake of September 7, 2017 with epicenter in the Gulf of Tehuantepec. Total vertical pressures under the footing, the variation of pore-water pressures at different depths, inside and outside of the inverted glass, and of the accelerations recorded at the top side of the footing are depicted.

The dynamic response of this type of foundation during passing of the Metro convoy has already been reported [2]. Work is now going on in its numerical processing to be able to develop a predictive tool of the state variables of this type of foundation and, based on it, anticipate its behavior when subjected to future seismic events and enhance its design with the data so collected.

3. Stratigraphy and geotechnical properties

The soil underlying support ZP-16 is constituted by a very soft clay deposit, interbedded with sand lenses of variable thickness. This clay is very thick, of about 60 m (Figure 2). It rests upon basalt rock with thickness ranging from 15 to 20 m.

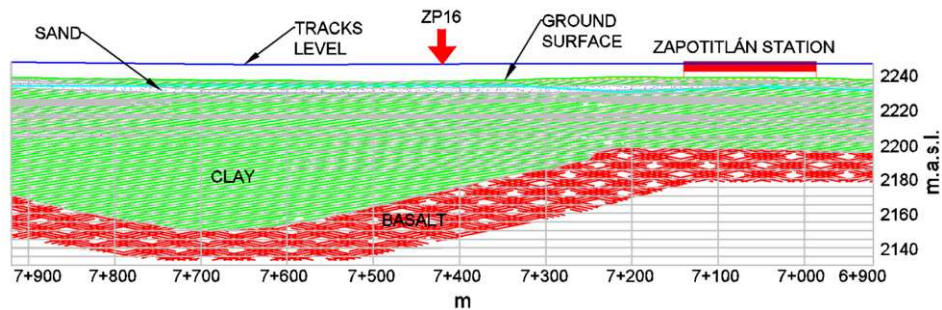


Figure 2. Stratigraphic profile along Line 12 of the Metro.

A cone test (CPTu) was performed at the site. Figure 3 shows some zones with low point-bearing resistance ranging from less than 1.0 to 1.5 MPa, corresponding to undrained shear strengths between 50 and 80 kPa for clayey strata. There are also some layers with high strength values belonging to sand lenses. Beyond a depth of 30 m, point-bearing resistances for clayey soils of up to 3 MPa can be observed. No dynamic properties are available at the site, and there is not an accelerographic station in the near field.

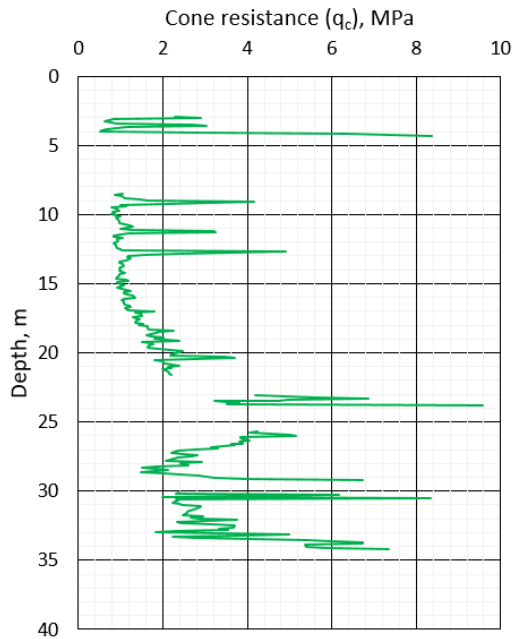


Figure 3. Electric Cone Test (CPTu).

4. Geotechnical and seismic instrumentation

Following the recommendations of Peck [3] and of Dunnicliff [4], among others, instrumentation of the foundation was designed to find answers to specific questions posed by the likely behavior of the foundation. According to this approach, a decision was made to measure the geotechnical and acceleration variables that could explain that behavior. To this end, geotechnical sensors of the resistive type were installed, capable of responding suitably when subjected to dynamic loadings.

To measure the total pressure at the bottom of the inverted glass, six (6) total pressure cells were installed just at the footing-soil contact. In addition, pore-water pressures were measured with five (5) piezometers placed at different depths outside the inverted glass and one (1) inside it; location of these instruments is presented in Figure 4. The accelerations acting on the foundation are monitored with a triaxial accelerometer embedded in the footing. All of them are connected to a dynamic data acquisition system with sampling rate of 100 data per second, which is triggered for an acceleration threshold of 3 cm/s<sup>2</sup>. If this happens, signals of all sensors are recorded during the seismic event, with 60 seconds of pre-event and 80 seconds of post-event. The installation of the instruments and further details are given in Mendoza *et al.* [2].

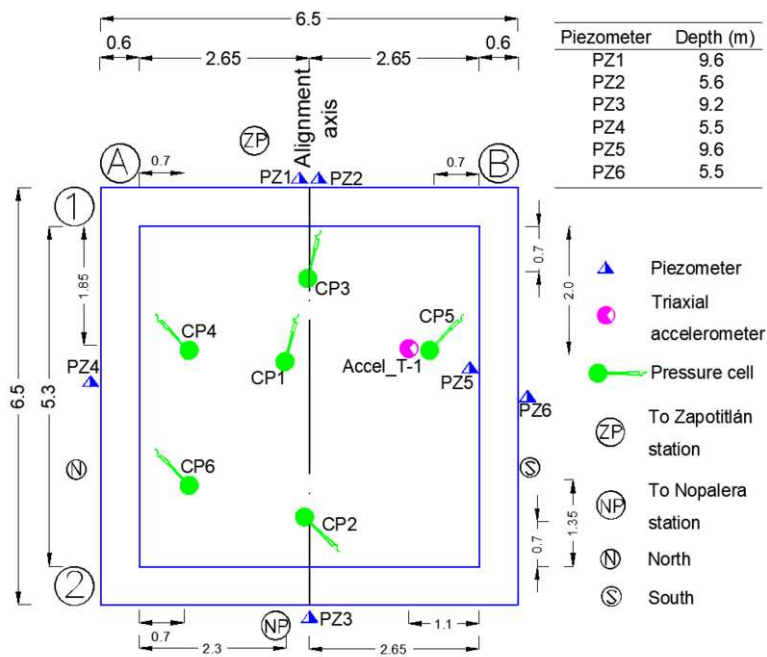


Figure 4. Location of instruments in plan.

5. Instrumentation measurements during the earthquake of September 7, 2017

The earthquake with magnitude  $M_w$  8.2 occurred September 7, 2017 with epicenter at the Gulf of Tehuantepec at an approximate distance of 133 km to the southwest of the town of *Pijijiapan*, State of Chiapas and 730 km far from Mexico City. The epicenter

was located at geographic coordinates  $14.761^\circ$  latitude North and  $-94.103^\circ$  longitude West, at a depth of 45.9 km [5]. According to the accelerations measured in the Valley of Mexico, its duration was a little longer than three minutes. The nearest free field accelerographic station on soft soil was 4.35 km away. The peak horizontal acceleration was  $62.22 \text{ cm/s}^2$ , and the peak vertical acceleration was  $12.88 \text{ cm/s}^2$ .

### 5.1. Accelerations at footing

Measured accelerograms at the foundation of support ZP-16 are depicted in Figure 5, which include the pre- and post-event recorded values. Mention should be made that the peak acceleration (PA) was equal to  $17.93 \text{ cm/s}^2$  and it was measured along the direction of the alignment axis (East-West direction). The maximum acceleration in the vertical direction was  $11.06 \text{ cm/s}^2$ , thus representing 61 % of the PA. In the transverse direction to the axis, the maximum value was  $14.77 \text{ cm/s}^2$ , i.e. 82 % of the PA. It could be expected that the PA would occur in a direction perpendicular to the axis because of the rigidity imposed by the superstructure; however, the opposite occurred.

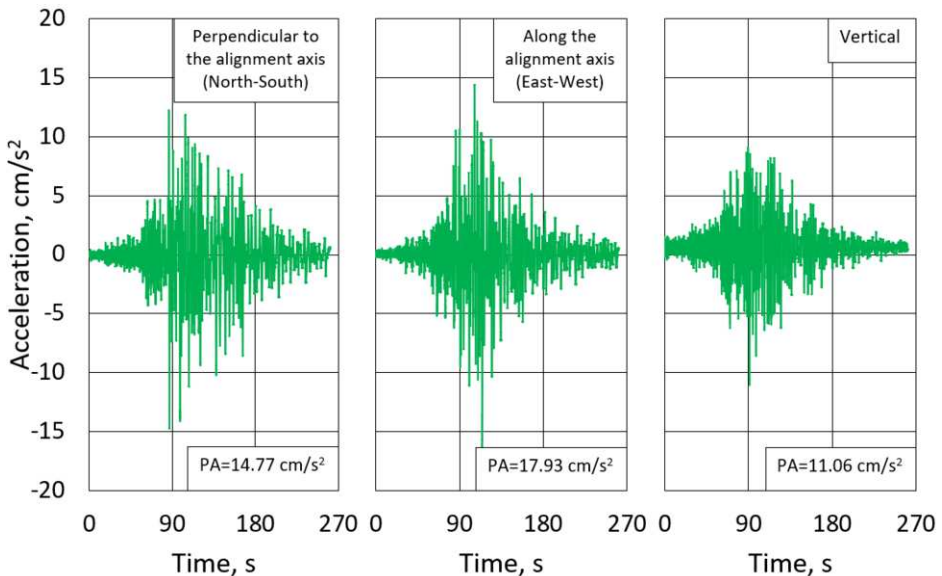


Figure 5. Acceleration measured at the instrumented foundation.

### 5.2. Total pressures under the footing-column element

Total pressures measured below the footing are shown in Figure 6. Their values recorded under static conditions evidence a large dispersion. This effect seems to be determined by the presence of temporary stiffening elements used to accommodate and level the footing-column during erection. The pressure cell evidencing the largest variation corresponds to CP6, located very close to the provisional element used to level the footing-column; in this same cell the largest static pressure was registered, reaching a value of 64 kPa. From a dynamic point of view, it shows a variation ranging from 59 to 69 kPa, equivalent to 16 % of the initial static value.

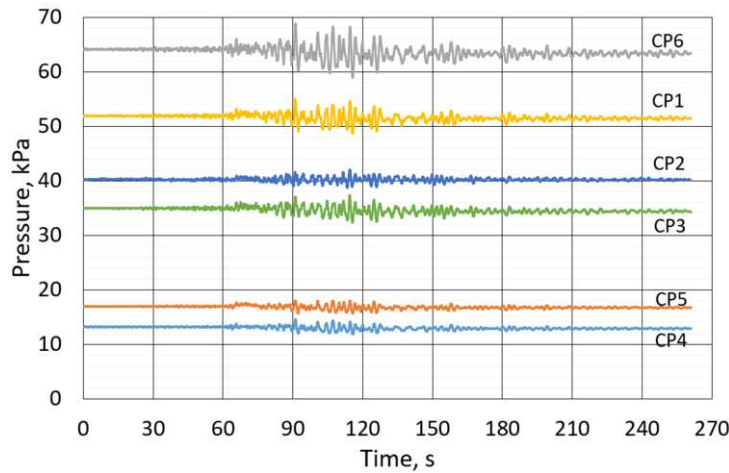


Figure 6. Total pressures measured below the footing.

Therefore, for this earthquake, the dynamic amplitude reached magnitudes varying between 8 and 23 % of the value corresponding to the initial static pressure.

5.3. Pore-water pressures

The static pressure corresponding to the deepest piezometers (PZ1, PZ3 and PZ5) range from 77 kPa to 82 kPa (Figure 7). These piezometers showed the least variation in the pressure measured during the seismic event, i.e. between 3 and 11 %. The inner piezometer PZ5 measured a lower variation than PZ1 and PZ3 which were installed at almost the same depth. This fact can be explained considering that the inner soil mass forms a single body with the structured cell.

For the shallow and outside piezometers (PZ4 and PZ6) located in the parallel faces to the alignment axis (North and South, respectively) the pore-water pressure measured statically was equal to 46 kPa. The dynamic variation of PZ4 ranges from 15 to 70 kPa, whereas the PZ6 varied between 16 and 76 kPa. On the other hand, piezometer PZ2 installed outside too and at the almost same depth, but in the perpendicular face (East) registered a static water pressure of 50 kPa, and a dynamic amplitude equivalent to 26 %. Figure 8 depicts the comparison of these measurements providing a clear evidence of the larger stresses experienced by the structured cell in its middle-upper zone, due to the inertia forces imposed by the superstructure in the transverse direction of the overpass.

6. Fourier's spectra

Vibrations induced by earthquakes contain movement components with a wide range of amplitudes, frequencies and phases. It is obvious that the peak accelerations mentioned above are a useful parameter but fail to provide complete information about the foundation response when subjected to a seismic event. Because of this, recourse was made of an analysis of the frequency contents to describe how the movement amplitude of the foundation is distributed among the very different frequencies involved in the seismic vibrations. One approach to analyze the seismic signals and their frequency

content is through the determination of Fourier’s spectrum. Fourier’s spectrum of amplitudes evidences the distribution of the movement amplitude within a wide interval of frequencies. For signal analysis use was made of software DEGTRA v9.3 developed at the *Instituto de Ingeniería*, UNAM.

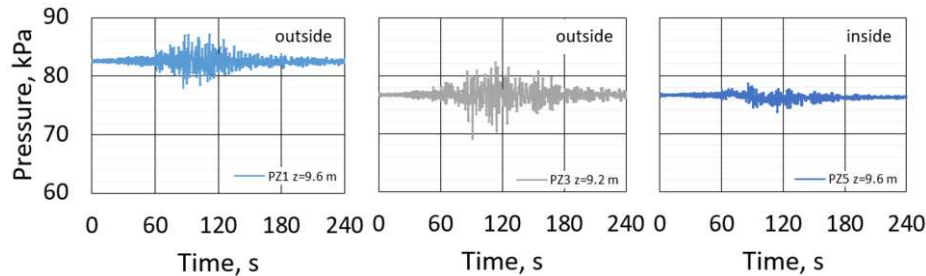


Figure 7. Pore-water pressures measured inside and outside the structured cell at depths of 9.6 and 9.2 m.

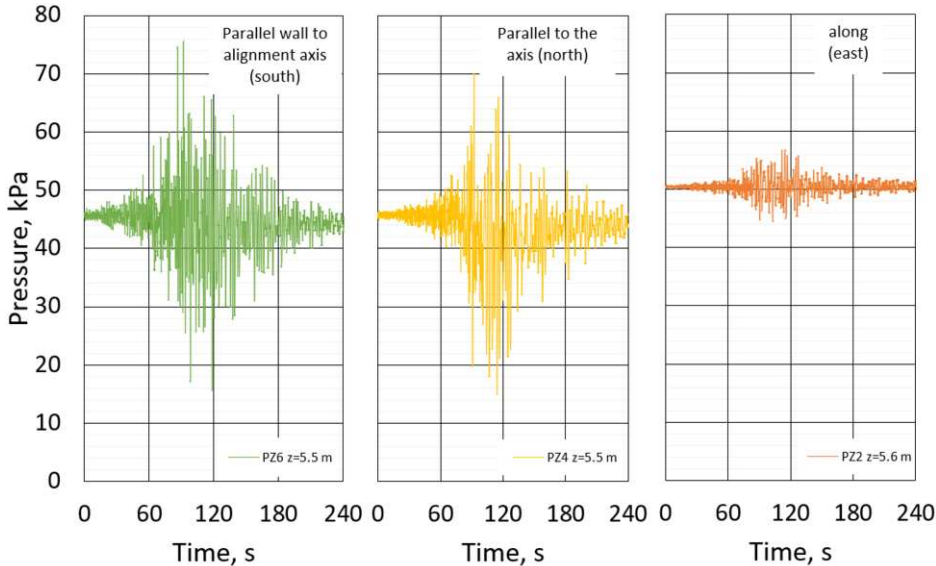
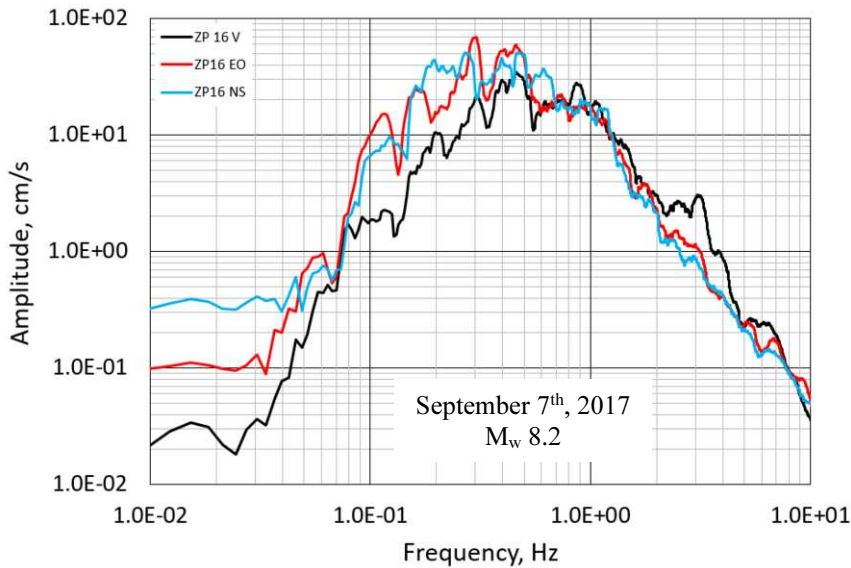


Figure 8. Pore-water pressures at outside faces of parallel and perpendicular walls to alignment axis.

Fourier’s spectra of the accelerograms in their three orthogonal components recorded at the supporting ZP-16 are shown in Figure 9. The spectral shapes of those three components of the acceleration amplitude became quite similar and special mention should be made that in the range of the largest responses the spectral ordinates in the vertical direction are comparable to the horizontal ones. Even in the range of high frequencies, the ordinates in the vertical direction are slightly larger than the horizontal ones. The wide range of low frequencies under which the system exhibits high spectral ordinates can also be observed, therefore indicating that the dynamic behavior of the foundation is fundamentally governed by the low rigidity of the soft clay soil underlying it; it can be assumed that the natural frequency of the site can be found in such interval. Unfortunately, there are no accelerogram data available of the nearby free field.



**Figure 9.** Fourier's spectra of the amplitudes of the accelerations recorded at support ZP-16.

As indicated before, the signals registered by geotechnical transducers during seismic events are quite similar to the accelerograph signals; therefore, and just like these, the maximum amplitudes of the vertical pressures under the footing and those of the pore-water pressures shall be complemented with information about the frequency content, as a point of comparison with the characteristics of movement of the soil-foundation-structure system. Therefore, Fourier's analysis has been used too to investigate the geotechnical signals. Figure 10 shows Fourier's spectra applied to the registries of the six pressure cells and their average value. Fourier's spectra corresponding to the registries of the piezometers are depicted in Figure 11, also including the mean value of their signals.

The spectral shape of the horizontal accelerations measured at the support and the mean value of the spectral amplitudes of the vertical pressures at the soil-footing contact are quite similar; the total pressures measured during the earthquake is in phase with the recorded horizontal accelerations. Similarly, the mean value of Fourier's spectrum of pore-water pressures and Fourier's spectra of the horizontal accelerometer signals have been plotted in Figure 12; it was found that their spectral shapes are practically identical, and their phases correspondingly match.

**7. Conclusions**

The following conclusions can be derived from the measurements registered of the pore-water pressure at different depths, of the total vertical pressure under the footing and of the accelerations, all of them measured at the supporting foundation ZP-16 during the earthquake of the Gulf of Tehuantepec. Neither damage nor visible deformations were observed in the foundation or superstructure. The Metro operation was resumed shortly.

The dynamic increase of the total vertical pressure at each of the sites monitored can be considered somehow proportional to the value of its initial static pressure.

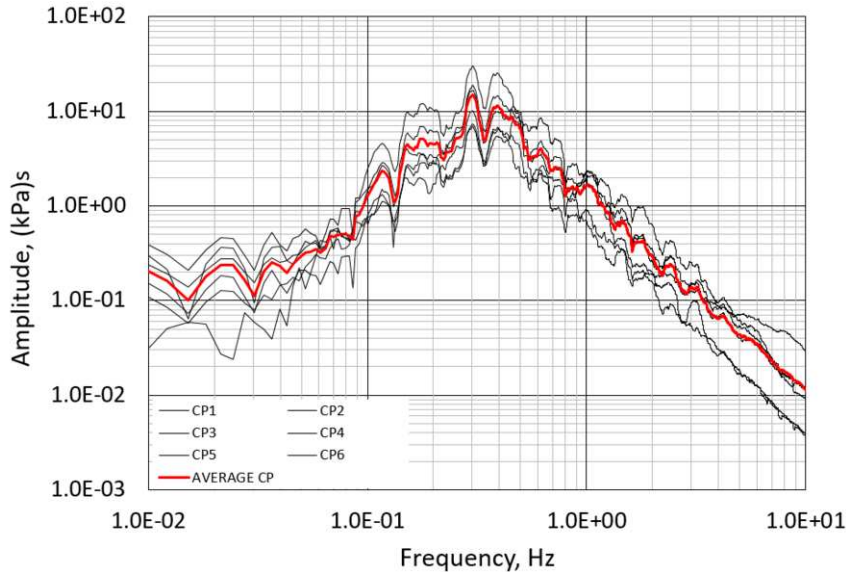


Figure 10. Fourier's spectra of amplitudes of vertical pressures under the footing.

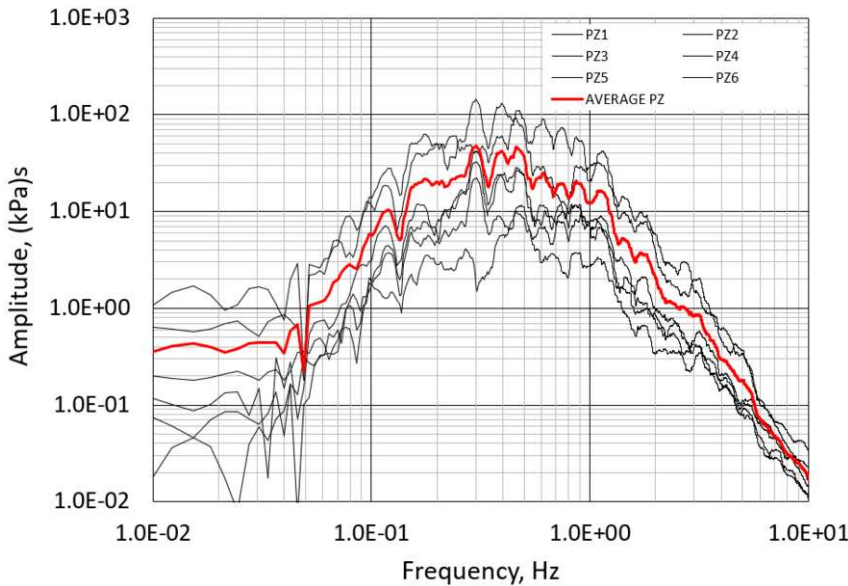
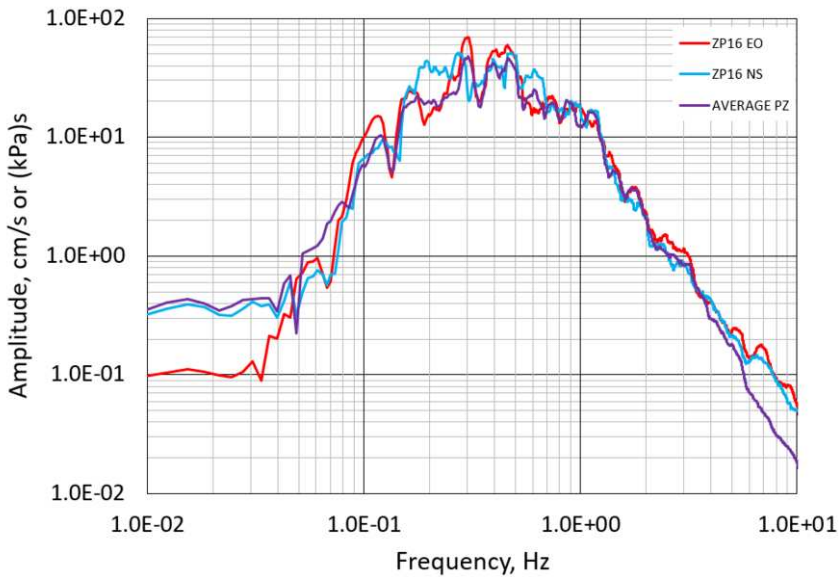


Figure 11. Fourier's spectra of amplitudes of pore-water pressures.

When pore-water pressures are considered, mention should be made that at a depth of 5.5 m of the foundation walls the increase of the dynamic pressure perpendicular to the alignment axis is 74 % higher than the increase sustained parallel to the axis.



**Figure 12.** Fourier's spectra of piezometers and accelerations.

At a depth of 9.6 m, the dynamic pore-water variation outside the structured cell is 62% higher than the increase occurred inside. That apparently indicates that the internal mass of soil practically displaces as a single unit together with the structured cell; in addition, the stress increases on the outside seem to reflect the rocking effect experienced by the foundation system during the earthquake.

Pressures applied under the footing as well as the pore-water pressures at the peripheral walls of the foundation exhibit spectral shapes just like Fourier's spectra of the horizontal accelerations. This indicates that the foundation accelerations and the geotechnical state variables defining its behavior are in phase. This finding has already been documented in a box-type foundation with friction piles built to support a bridge of *Impulsora* station of the Metro subway system [6, 7].

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