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Assessment of soil cracking mechanism in the south-east area of Mexico City based on deep geotechnical exploration

Détermination du mécanisme de fracturation du sol au sud-est de Mexico à partir de sondages profonds.

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ABSTRACT: This paper presents an interpretation of the results of a deep geotechnical exploration campaign carried out at several sites, in the south-east area of Mexico City. The purpose was to identify the mechanism of generation of the cracks in the soil that have affected this area during the last decades. The stratigraphic characteristics and the subsoil properties correspond to an abrupt transition zone between lacustrine soft clays and firm soils or volcanic rocks found in this area of Mexico City. Cracks can thus be attributed to the uneven consolidation of the lacustrine clays affected by drawdown of pore pressure due to deep pumping of water in local aquifers. Some remedial and mitigation measures that have been implemented in the area are presented.

RÉSUMÉ : Cette communication présente les résultats de travaux de reconnaissance géotechnique profonde réalisés sur plusieurs sites au sud est de Mexico. Le but de cette exploration était d´identifier le mécanisme de formation des nombreuses fractures que l´on peut observer dans le sol de cette zone depuis plusieurs décénies. Le profil et les propriétés des matériaux rencontrés correspondent a une zone de transition abrupte entre les argiles molles et les sols durs ou les roches volcaniques de cette zone de la ville de Mexico. Les fractures peuvent être donc être attribuées a la consolidation non uniforme de la zone lacustre affectée par l´abattement des pressions interstitielles du au pompage d´eau dans les aquifères. Les mesures prises dans la zone pour atténuer les conséquences des fractures sont décrites.

KEYWORDS: cracks, soft soil, subsidence, mechanism, mitigation.

1 INTRODUCTION.

Soil cracking in Mexico City constitutes an important risk factor that must be evaluated to define the protective and coexistence measures required to avoid, or at least reduce, the damage that cracks may cause to existing roads, buildings and public services, and to be able to take into account its real or potential presence in the design of new constructions.

The phenomenon of soil cracking can manifest itself as a consequence of any condition that generates significant tensile or shear stresses in the soil (Auvinet, 2010; Auvinet *et al.,* 2013, 2015). However, the most important and destructive cracks are a direct consequence of the regional subsidence that occurs in the Valley of Mexico due to the pumping of water from deep aquifers. This type of cracks has been extensively studied in recent decades (Auvinet *et al*., 2017).

It has also been observed that earthquakes can modify the geometry of existing cracks and generate additional discontinuities. The cracking of the soil observed in the periphery of *Santa Catarina* range, attracted the attention of the media after the earthquake of September 19, 2017. It was necessary to clarify that most of the cracks existed previously to the earthquake and that they had only undergone geometric changes (opening, increase of escarpment), some of them significant (Figure 1) during this event.

To understand the generation and propagation of cracks in the ground, it was considered necessary to know in detail the stratigraphic characteristics and properties of the subsoil. A detailed geotechnical exploration and instrumentation campaign was undertaken at several sites affected by cracks and considered representative of the different zones of abrupt transition between soft and firm soils in the south-east zone of Mexico City (Auvinet *et al*., 2019).

Figure 1. Activation of a pre-existing crack during the earthquake of September 19, 2017 (Deportivo Cananea, Alcaldía Iztapalapa).

2 DEEP GEOTECHNICAL EXPLORATION CAMPAIGN

The geotechnical characteristics of the area of interest are known in certain detail from the numerous geotechnical borings performed for different constructions in the area, especially Lines "12" and "A" of the subway system. This information has been documented in different thesis works (Flores-Tapia, 2000; Aguilar-Ortega, 2001; Morales de la Cruz, 2001; Barranco-Eyssautier, 2016) and summarized in Auvinet *et al*. (2017).

Figure 2 shows the geotechnical zoning of the south area of Mexico City, based on the above information and included in the Complementary Technical Standards for Design and Construction of Foundations for Mexico City (NTCDCC) published in December 2017. The areas corresponding to zones I (Lomas), II (Transition) and III (Lacustrine) are indicated.

Figure 2. Geotechnical zoning of Mexico City south area (NTCDCC, 2017).

In order to advance in the understanding of the large-scale soil cracking phenomenon, as well as to obtain useful data for numerical modeling focused on evaluating its medium and long term evolution, a detailed geotechnical exploration and instrumentation campaign was performed at four sites considered as representative of the affected area.

The deep exploration program included mixed borings (SM) with recovery of disturbed and undisturbed samples to define the local stratigraphy, electric cone tests (CPTu) with pore pressure measurement and pore pressure dissipation tests to determine the piezometric profile, one deep level bench (BNP) down to the deep deposits below the lacustrine clay soils, and one suspended probe test (SVs) to define a profile of the shear wave velocity. The geotechnical exploration and instrumentation were carried out by four different companies. Figure 3 shows the plan location of the borings and instrumentation with respect to the cracks.

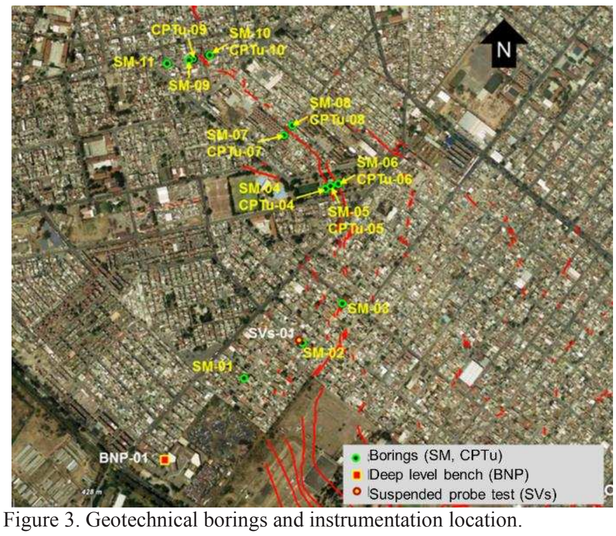

Figure 3. Geotechnical borings and instrumentation location.

3 INTERPRETATION OF THE RESULTS OF THE RECONNAISSANCE CAMPAIGN

3.1 *Colonia Del Mar site*

At the *Colonia Del Mar* site, borings SM-01, SM-02 y SM-03 with maximum exploration depth 74.8, 83.0 and 83.0m, respectively, were performed, as well as three electric cone tests with pore pressure measurement CPTu-01, CPTu-02 and CPTu-03, with maximum depth 57.78, 63.0 and 39.28 m, respectively. Figure 4 shows the location of borings.

In Figure 5, a cross section of the subsoil at this site is presented. A difference of approximately 25m in clay thickness can be observed between the deep level benchmark (BNP) and boring SM-01. The thickness of clay increases towards the southwest. Likewise, the clay thickness between wells SM-01 and SM-02 is approximately constant but between borings SM-02 and SM-03 a difference of 32m is observed due to the presence of a buried basaltic flow.

Figure 4. Location of borings, *Colonia Del Mar* site.

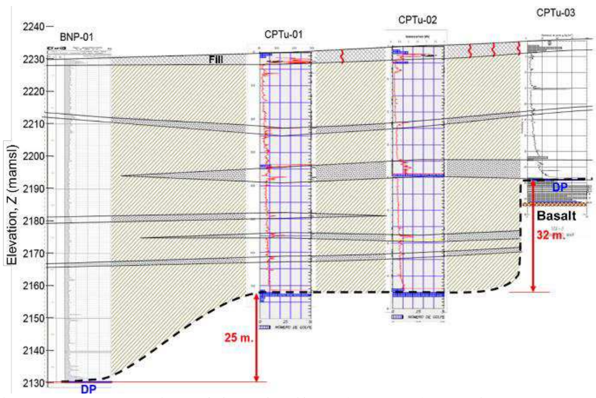

Figure 5. Cross section of the subsoil, *Colonia Del Mar* site.

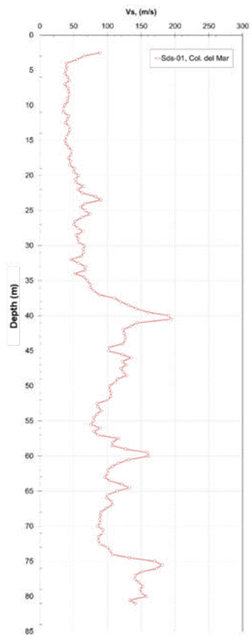

Figure 6. Profile (Vs) in the subsoil, *Colonia del Mar* site.

In order to complement the deep geotechnical exploration, II-UNAM performed one suspended probe test (*Sds*) in *Colonia del Mar* site, to measure the propagation speed of shear waves (*Vs*) in the subsoil (Flores-Castrellón and Flores-Guzmán, 2019, Figure 6). The low *Vs* values observed are typical of Mexico City lacustrine clays.

3.2 *Deportivo Cananea site*

At the *Deportivo Cananea* site (Figure 7), borings SM-04, SM-05 and SM-06 with a maximum exploration depth of 74.8, 83.0 and 83.0 m, respectively, were performed, as well as three electric cone tests with pore pressure measurement CPTu-04, CPTu-05 and CPTu-06, with a maximum depth of 57.78, 63.0 and 39.28 m, respectively. Additionally, two observation tubes TO-04 and TO-05 were installed to monitor the groundwater level.

Figure 8 presents a panoramic view of the site. Separation between the main cracks is approximately 23 m; the central zone presents a subsidence (graben) of the order of 0.70 m.

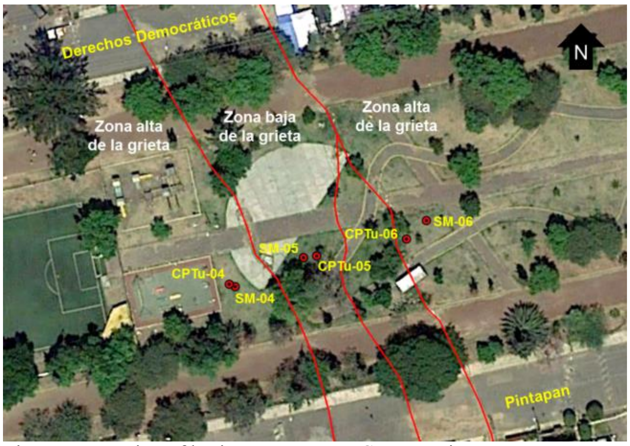

Figure 7. Location of borings, *Deportivo Cananea* site.

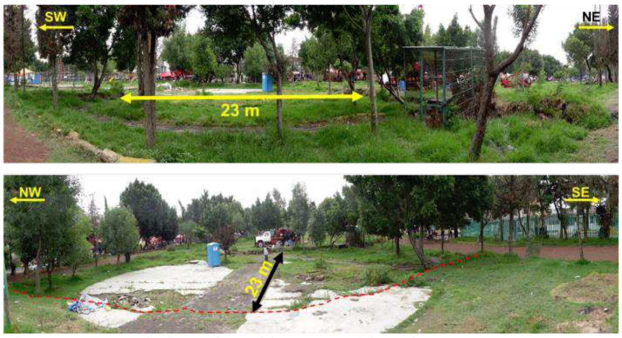

Figure 8. General view of cracking area with graben, *Deportivo Cananea* site.

Figure 9 presents a geotechnical section of the superficial subsoil. A predominantly sandy silt-type fill with a thickness of up to 0.60m, overlays a stratum of sandy clay and clayey sand that, together with the fill, form a rigid superficial crust (CS) affected by cracks with two parallel steps approximately 0.70 m high.

In Figure 10, a cross-section of the subsoil is presented down to the depth reached by the borings. It can be observed that the thickness of the clay layer, with interbedded sand lenses, is smaller in boring SM-04 than in borings SM-05 and SM-06. With these borings it was possible to roughly define the configuration of the deep deposits. Comparing borings SM-04 and SM-05, the difference between the depths to the resistant materials is of the order of 8 m.

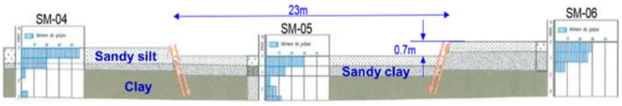

Figure 9. Superficial cross-section of subsoil, *Deportivo Cananea* site (InGeum, 2019).

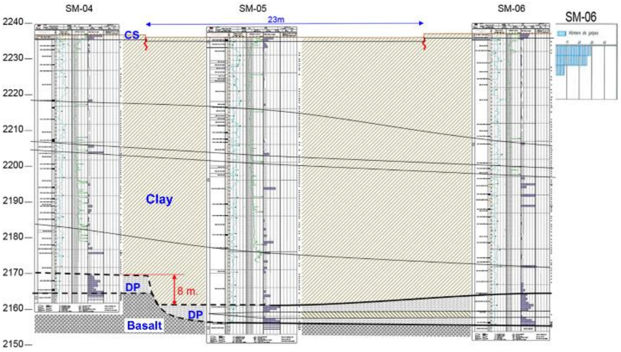

Figure 10. Cross section of subsoil, *Deportivo Cananea* site.

3.3 *Colonia La Planta site*

At the *Colonia La Planta* site (Figure 11), borings SM-07, SM-08, with a maximum exploration depth of 61.5 and 55.9 m respectively, were performed as well as three electric cone tests with pore pressure measurement CPTu-07 and CPTu-08 and CPTu-03, with a depth of 57.78, 63.0 and 39.28 m, respectively. Additionally, two observation tubes TO-07 and TO-08 were installed to monitor the groundwater level.

Borings SM-07 and SM-08 are located at an approximate separation of 33 m, on both sides of a crack that presents a step of the order of 1.0 m (IEC, 2019). Figure 12 presents a view of the crack.

Figure 11. Location of borings, *Colonia La Planta* site.

Figure 12. Crack with step, *Colonia La Planta* site.

Figure 13 presents a cross-section of the subsoil. On the surface, silty sand-type fill materials with a thickness of up to 2.5 m are found overlaying a stratum of fine black sand 1 to 2 m thick. The thickness of the main clay layer, with interbedded sand lenses, is 48 m for SM-07 and 40 m for SM-08. The deep deposits and basalt flows were found at a depth of 56.5 m in SM-07 and 48.7 m in SM-08, a difference of approximately 8 m.

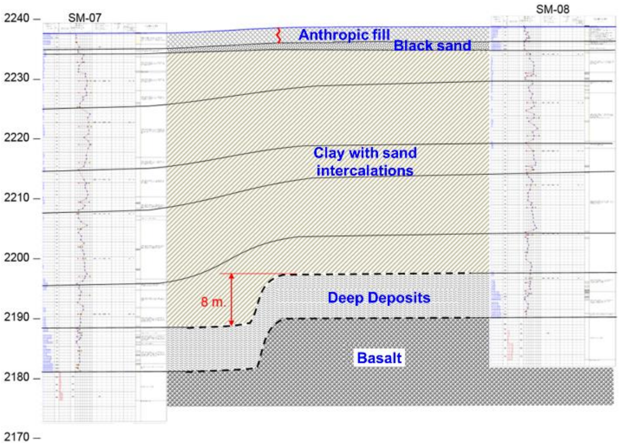

Figure 13. Cross section of the subsoil, *Colonia La Planta* site.

3.4 *Colonia El Molino Tezonco site*

At the *Colonia Del Mar* site (Figure 14), borings SM-09, SM-10 and SM-11, with a maximum exploration depth of 68.3, 66.0 and 100.2 m respectively, were performed as well as three electric cone tests with pore pressure measurement CPTu-09 and CPTu-10, with a depth of 58.14 and 55.86 m respectively. The borings are located along a 55 m long axis (GEOVISA, 2019).

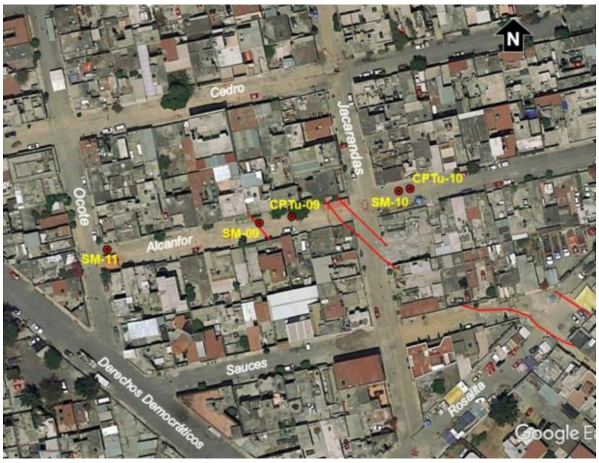

Figure 14. Location of borings, *Colonia El Molino Tezonco* site.

Figure 15 shows a cross-section of the subsoil. Below a predominantly silty sand-type fill of variable thickness (up to 2.5 m), a layer of fine black sand with a thickness of 1.0 to 2.0 m is found. Under this sand layer, there is a layer of clay, with interbedded sand lenses, with a thickness of approximately 56.0 m (SM-09 and SM-10) and 90 m (SM-11). The deep deposits and basalt are found at an approximate depth of 63.0m in the SM-09 and SM-10 borings, and 95.0 m in the SM.11 boring. Basalt was found only in boring SM-09 at a depth of 65.0 m. It is observed that between the SM-09 and SM-11 borings the step in the resistant materials is of the order of 35 m.

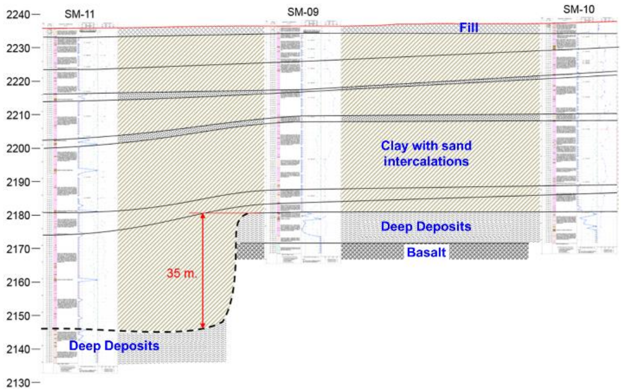

Figure 15. Cross section of the subsoil, *Colonia El Molino Tezonco* site.

4 MECHANISM OF CRACKING

The results of the deep geotechnical exploration presented confirmed that the main cause of the soil cracking in the area is the abrupt variation of the thickness of the lacustrine clay in the transition between the lacustrine zone and firm materials such those surrounding the Santa Catarina range. The consolidation process of the clay under these geometric conditions leads to pronounced differential settlements and to the generation of tensile and shear stresses in the soil and to cracking. This mechanism can be reproduced by finite element analysis (Figure 16) and corresponds to the mechanism defined as Type II by Auvinet *et al*. (2017. p. 108 and Figure F.25).

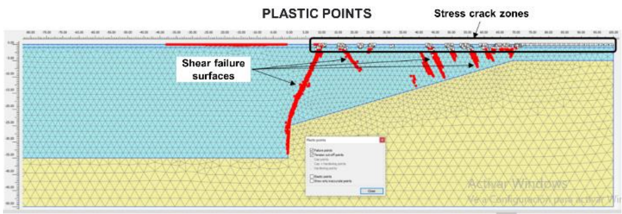

Figure 16. Numerical modeling of the consolidation of a clayey layer of variable thickness.

The generation and propagation of cracking for this site could be modelled using fracture mechanics (Pineda and Auvinet, 2021). The condition of Figure 5 (*Colonia Del Mar*) as representative of those existing in the area. On the other hand, the seismic behavior of the cracked soil has been analyzed for the conditions prevailing at this same site (Martínez *et al*., 2021). It was concluded that ground acceleration is strongly amplified by the presence of cracks and that permanent displacements in the cracks such as those observed on Figure 1 can appear during earthquakes.

5 PREVENTION AND MITIGATION MEASURES

Cracking of the soil in Mexico City induces serious damage to streets, buildings and public services. This phenomenon puts the well-being of the population at risk and causes significant maintenance costs. Preventing soil cracking due to uneven subsidence of the ground is a complex and difficult task. Suspending the pumping of water that induces subsidence cannot be considered since the local aquifer is the main source of potable water for the city. Actions have thus been focused on implementing robust solutions to prevent and mitigate damage.

5.1 *Pavements*

Many streets in Mexico City are affected by soil cracking. The presence of steps makes it difficult for vehicles to transit and some the streets must be closed to traffic (Figure 17).

Figure 17. Examples of crack with step on streets in *Iztapalapa* municipality.

A mitigation measure called "angular strain dissipative trench" (Auvinet *et al.*, 2019) has been proposed and implemented on more than 1000 cracks. This trapezoidal trench is excavated on the trace of the crack and filled with a clean sand that cannot transmit tensile stresses. In case of evolution of the crack step, the sand dissipates the angular strains induced within the superficial soil, avoiding direct damage to the pavement.

The geometry of the dissipative trenches must be adapted to the different conditions found on the site (Figure 18). The depth, h, of the granular fill must be chosen to keep the slope of the surface below the maximum allowable value for an acceptable time. The design was based on parametric studies performed using a model based on the discrete element method.

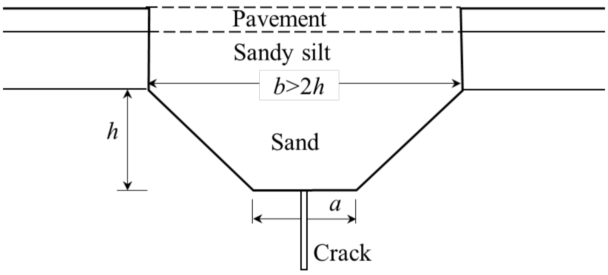

Figure 18. Geometry of dissipative trench.

5.2 *Foundations*

After the 2017 earthquake, the Commission for the Reconstruction of the Government of Mexico City began repairing the damage caused by the presence of cracks in the ground in the municipalities of Iztapalapa, Tláhuac, Xochimilco and Milpa Alta in the south-east part of Mexico City.

The construction of buildings on soil affected by cracks requires special attention. In the case of cracks with a step larger than 10cm, it should not be considered as acceptable to build over the crack. The project must then be adapted (Figure 19). If the above is not possible, it should be considered that the land is not suitable for construction.

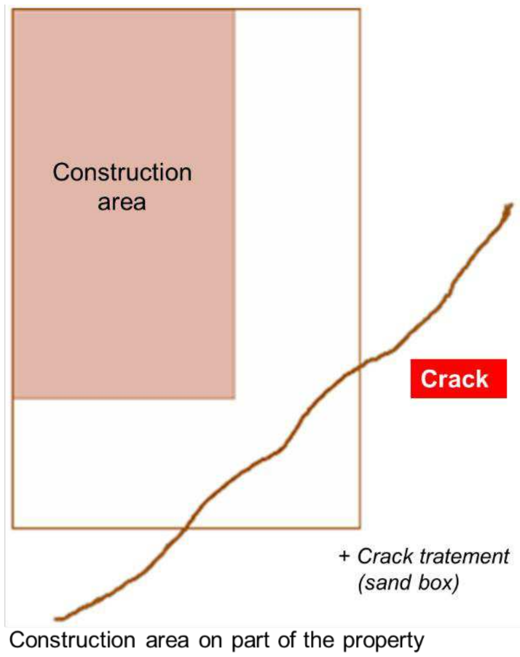

Figure 19. Adaptation of architectural design to the presence of a crack.

The proposed foundation solution for a site without a visible crack is shown in Figure 20. A protective layer of sand or *Tezontle* (a local volcanic slag) is placed on the soil before the raft foundation is built.

In the case of cracks with a step of less than 10 cm, it can still be considered acceptable to build over the crack provided that a trench of granular material is placed on the trace of the crack as shown in Figure 21.

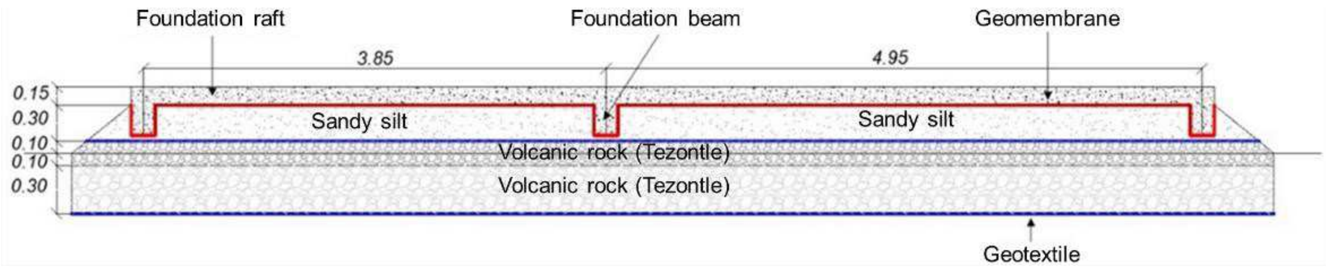

Figure 20. Foundation design for subsoil without cracking.

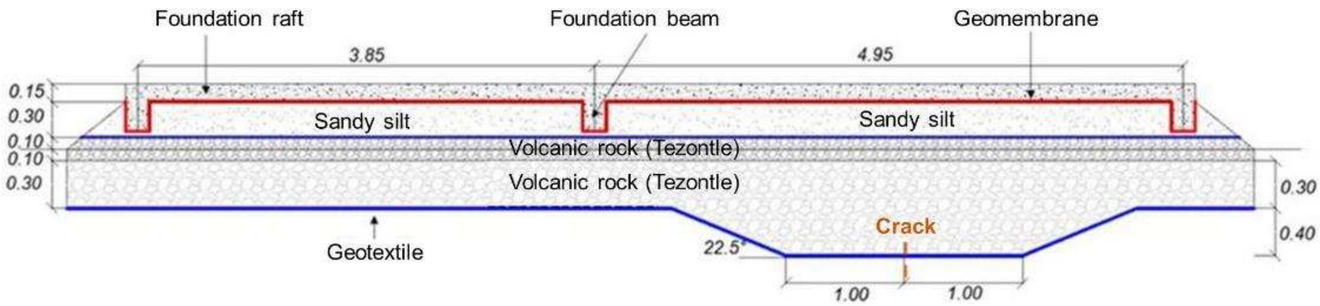

Figure 21. Foundation design for subsoil with cracking.

5.3 *Public services*

A similar strategy has been adopted to protect public services such as potable water or drainage utilities. Pipes and culverts are protected by sand in order to avoid direct interference with the cracks (Figure 22).

Figure 22. Protection of culvert in area affected by soil cracks.

6 CONCLUSIONS

The results of the deep geotechnical exploration carried out in several sites of the municipalities at the south of Mexico City, allowed to establish that the generation of cracks in the superficial subsoil of this zone should be attributed to the differential settlements that the clay formation presents during its ongoing process of consolidation due to abrupt changes of thickness.

The basic principle of the prevention and mitigation measures presented in this paper consist of interposing a granular material between the cracks and the construction to be protected. The granular material does not transmit tensile stresses and allows dissipation of the angular strains induced in the soil by cracks.

7 ACKNOWLEDGMENTS

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