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Pioneer application of a dynamic penetrometer and boroscope in archeological prospecting

Application pionnière d’un pénétromètre dynamique et d’un boroscope dans la prospection archéologique

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ABSTRACT: This paper presents a pioneer application of a geotechnical technique in archaeological prospecting. A light dynamic penetrometer, georadar and geo-boroscope were applied to determine the superficial stratigraphic profile at the Cacaxtla Gran Basamento archeological zone, in Mexico, in areas where walls and floors present important cracks. From the geotechnical point of view, the Gran Basamento is an artificial platform conformed by heterogeneous fills (mainly tuff rock fragments, silty and sandy soils) where pre-hispanic structures were built (from 450 bC to 900 aC). There is an important lack of knowledge about the mechanical characteristics and position of the soil deposits or buried archeological structures. The interpretation of the results shows that it is not only possible to obtain a very good idea of the characteristics and distribution of the superficial soil deposits, and to evaluate the origin of cracks and their mechanisms to avoid slope and wall instabilities, but that it is also possible to identify stages of construction of the pyramid for the hypothetical reconstruction of the layers and structures that conform this archeological monument. Based on the geotechnical information, pre-hispanic floors at different construction stages were correlated with high dynamic cone resistance and very loose granular material with low dynamic cone resistance, which was a risk condition in slope stabilization. Both conditions were verified visually with a geo-boroscope.

RÉSUMÉ: Cet article présente une application de pionnier d'une technique de prospection archéologique en géotechnique. Un pénétromètre dynamique, le géo radar et géo-endoscope ont été appliquées pour déterminer le profil superficiel stratigraphique du Gran Basamento à Cacaxtla, au Mexique, dans les zones où les murs et les planchers présentent des fissures importantes. Du point de vue géotechnique, l'Gran Basamento est une plate-forme artificielle conformé par hétérogène comble (surtout des fragments de roche de tuf, limoneux et les sols sableux) où préhispaniques structures ont été construites (à partir de 450 avant JC à 900 AC). Il ya un manque important de connaissances sur les caractéristiques mécaniques et la position des dépôts de sol ou enterrées structures archéologiques. L'interprétation des résultats montre qu'il est non seulement possible d'obtenir une très bonne idée des caractéristiques et de la répartition des dépôts superficiels du sol, et d'évaluer l'origine des fissures et leurs mécanismes pour éviter les instabilités de pente et le mur, mais qu'il est également possible d'identifier les étapes de la construction de la pyramide pour la reconstruction hypothétique des couches et des structures conformes de ce monument archéologique. Sur la base des informations géotechniques, préhispaniques étages à différentes étapes de la construction ont été corrélés avec résistance au cône dynamique élevée et très lâche matériau granulaire avec résistance au cône dynamique faible, ce qui était une condition de risque dans la stabilisation des talus.

KEYWORDS: archeology, geo-boroscope, dynamic penetrometer, georadar, geophysical prospecting.

1 INTRODUCTION

The *Gran Basamento* of the Cacaxtla archeological zone is, from the geotechnical point of view, an artificial platform of the natural terrain carried out with heterogeneous fills formed with fragments of tuff and soil, on which different types of structures were placed, from various pre-hispanic periods (450 b.C. to 900 a.C.) and using varied construction techniques, such as excavations or the construction of walls or columns made of adobe (Fig 1).

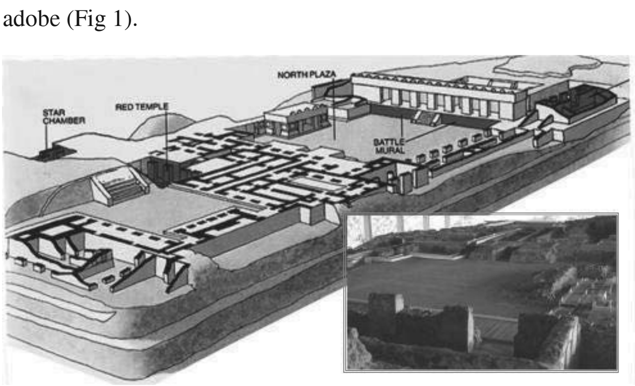


Figure 1. Cacaxtla’s Acropolis (National geographic, 1992)

Currently, the geometrical and mechanical characteristics of the fills that form the Gran Basamento are unknown, as well as position and composition of support material. Given the different construction stages, the use of each building that integrates this structure and the presence of walls and columns, the definition of the stratigraphic units is complex. On the other hand, the Gran Basamento has been and will continue to be subjected to the effects of environmental processes and human activity, which induce changes in its constitution, which in turn generate movements and a rearranging of the material that constitutes the platform and the structures that integrate it. The movements and rearrangements generated are shown through the superficial cracks of the structure, present on walls, floors and columns, but mainly on some of the valuable polychrome murals. Therefore, it is necessary to know their origin, describe their current condition and follow up their evolution to assess the stability and integrity of the platform in the short, medium and long terms.

To date, the cracking on some of the platform’s zones is at an advanced stage of development, but in others it remains incipient. In effect, there are cases where the cracking has provoked instabilities on walls, floors and cuts (fall of blocks, chipping, spalling, etc.), that could have contained or not important archeological elements, but we are in conditions to prevent these losses in the other areas.

In this work the results of the pioneering application of geophysical and geotechnical techniques are presented, which allowed constructing a preliminary vision of the platform's condition and origin and possible evolution of cracks.

2 GEOPHYSICAL-GEOTECHNICAL EXPLORATION CAMPAIGN

To define the Gran Basamento's geotechnical model, a geophysical-geotechnical non invasive campaign was carried out, oriented to determine the thickness and quality of the surface fills located at the zones where intense cracking is present. It is important to comment that due to the project's characteristics, it is not possible to use the traditional geophysical exploration equipment because it is necessary to diminish as much as possible damage to the structure. To that end, the penetration radar method (Barba 2006) was used, as well as an ultra-light dynamic penetrometer, PANDA, and a geo-boroscope, together with a geotechnical surveying of test pits, exposed cuts inside the platform, as well as a survey of the cracking observed on surface (inGeum 2005).

Through radar prospecting it is possible to obtain a general idea, and on occasions a detailed one, of the location of the various geological units. With the penetrometer, the thickness and quality of the fills can be determined, and with the geo-boroscope one can appreciate the granulometry of the materials and their structure. Upon combining the information obtained with the radar, the penetrometer and the geo-boroscope, the geophysical exploration is calibrated and the geotechnical one is extrapolated, to thus obtain a better image of the subsoil's conditions, with minimum damage to the archeological structure.

A total of 12 radar lines were carried out at the Gran Basamento, 35 dynamic penetration soundings, 4 geo-boroscopes in places where the dynamic penetration was carried out, and 4 shallow test pits (Fig 2; inGeum 2005 and Barba 2006)).

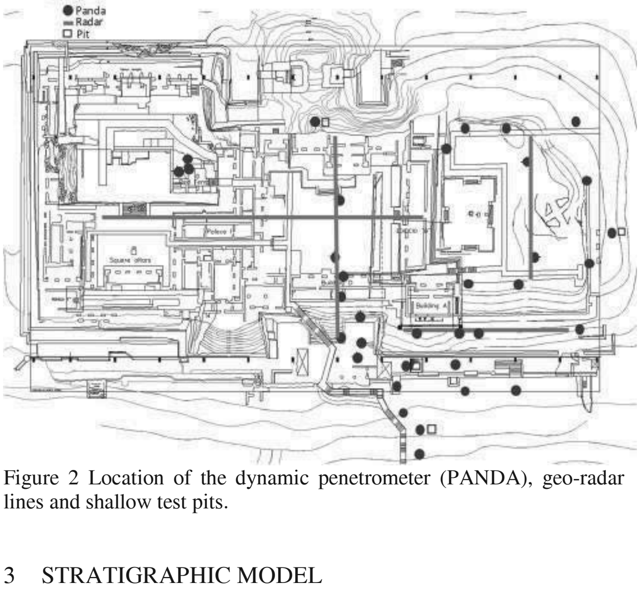
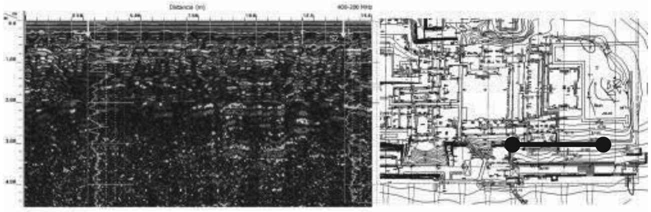


Figure 2 Location of the dynamic penetrometer (PANDA), geo-radar lines and shallow test pits.

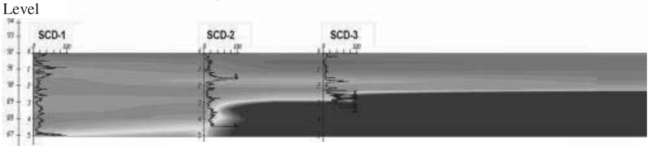
3 STRATIGRAPHIC MODEL

Figure 3 shows the profiles obtained with the radar techniques and the penetrometer along the slope located at the northeast zone of the platform (Fig 3b), where the lateral variation of the subsoil's quality and hardness is seen (Figs 3a and 3c). Here the surface fill's thickness diminishes toward the north and dynamic resistance to penetration of cone q_d increases also in this direction (in Fig 3c the dark color indicates a high dynamic resistance, and the light a low dynamic resistance). Also, Fig 3a shows a comparison between the results of the georadar-penetrometer techniques, where it is possible to observe a high correlation between both techniques. This result is valuable because the penetrometer is an additional tool that helps in the georadar's interpretation, and the latter can extrapolate the results obtained with the penetrometer, which offers punctual data, as mentioned previously. A detailed report on the use of these techniques in archeological exploration is presented in Barba (2006).

Additionally, a small geo-boroscope was used, which was introduced in the perforation left by the penetrometer, in order to observe the characteristics of the penetrated materials. With this tool various types of fill were observed, related to different construction stages of the pyramid. Fig 4 shows some photos taken with the boroscope, which show the various fills that were penetrated: a) sandy silt, b) silty sand, c) sandy silt with gravel and d) fill with archeological remains.



a) Georadar and penetrometer data b) Location of the section



c) Isoresistence curves from dynamic penetrometer

Figure 3 Typical results of the exploration with Georadar and Dynamic Penetrometer.

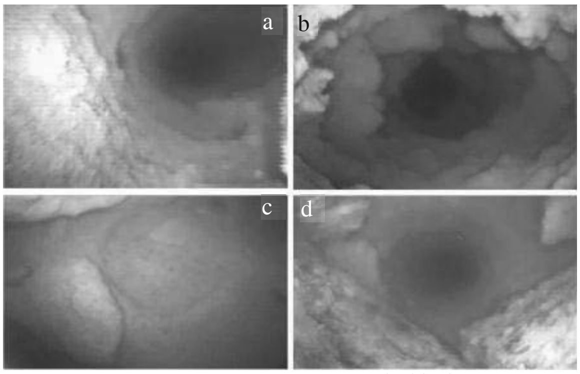


Figure 4. Photos taken with the geo-boroscope inside the penetrometer's perforation.

Derived from the geophysical-geotechnical exploration and preliminary information, a surface stratigraphic model was determined for the Gran Basamento. In synthesis, there are three surface geotechnical units (Fig 5):

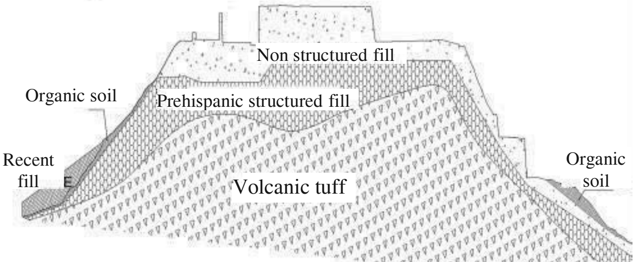


Figure 5 General stratigraphic model

Organic soils. Formed by loamy or silty soils with little sand and organic material. Their thickness is variable, from 0.2 to 1m. They are located mainly in zones with small slope.

Fills. They are materials deposited by man in different periods, with different types of constructive processes and materials. Mainly three types of fill are distinguished, named in terms of their origin and quality: recent, pre-hispanic without structure, and structured pre-hispanic. The first one is a silt of low plasticity with variable contents of sand, or silty sands on occasions with pre-hispanic scrap (sherds), roots and lenses of sand or gravel, with or without compacting, used in the construction of recent earth structures, such as the access platforms and protecting structures, with or without compacting. The pre-hispanic fill without structure is similar to the first in composition, but more erosive, and was used by pre-hispanic builders to finish the structures. This unit is characterized by being formed by loose to lightly compacted fills, with roots and voids, that on occasions form small tunnels where animal activity takes place. In general, they tend to be unstable in cuts, especially when the material degrades or saturates. This fill can contain pre-hispanic substructures, such as floors, walls, etc. Finally, the structured pre-hispanic fill is formed by fragments of tuff packed in a sandy loam or sandy silt matrix of low plasticity, with scarce cementing. This fill lies below the previous two and was the material used to over elevate the level of the natural terrain, create new construction levels, and build walls or various substructures, so its thickness is expected to be variable. When this fill occurs with little cementing it is unstable, and on occasions it presents local failures, such as chipping, which can give rise to failures or general sliding.

Volcanic tuff. It is a soft rock of light to dark brown color, on occasions with caliche and pumice lenses. It presents a slight semi-vertical fracturing and it is generally very stable in cuts, and impermeable and easily excavated. Given the good geotechnical quality of this unit, deep excavations are carried out frequently with no stability problems. In the soil mechanics study carried out by Diseño e Ingeniería Aplicada (1985), the tuff was observed to be at an average 5m depth on the periphery zone of the Gran Basamento.

Regarding the conditions of subterranean water, the phreatic water level is deep and there only are superficial leaks due to rain, or due to condensation water stored on the metal roofing, or due to leaks from the collection system.

4 SUPERFICIAL CRACKING AND PLATFORM MOVEMENTS

Based on a general mapping of superficial cracks (Rangel, *et al*, 2006, and Mooser 2005) and the geotechnical model, the position of the cracks is observed to be essentially peripheral, which indicates that they are linked directly to the Gran Basamento's slopes; also, cracking is produced toward the platform's central part (Fig 6).

The above suggests that under the central portion of the cracks and at some depth, there must be a local high, meaning a mound, or buried structures, which possibly form the monument's original base. This aspect is reinforced upon noting that the archeological wall is tilted toward the eastern slope. Analyzing various points, one can also note that the arrangement of the cracks often produces the formation of tiny pits and pillars that reveal a superficial state of tension.

There is another cracking system that develops in a concentric manner around columns or walls. This cracking is genetically associated to the subsidence of the structures (walls, columns, etc.) due to a deficiency in the supporting material's compacting. According to what was observed, this subsidence developed mainly during the construction of the pre-hispanic structures.

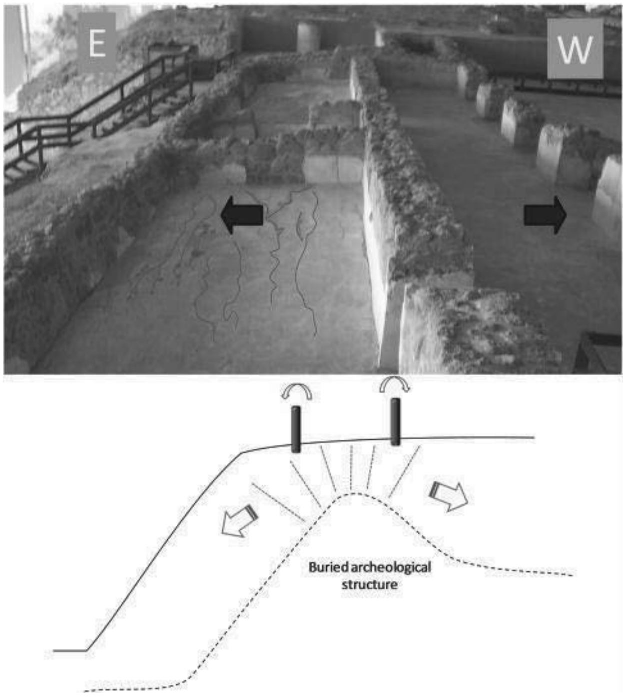


Figure 6 Cracking near slopes

The cracking observed is the result of the internal movement and rearrangement of the Gran Basamento. Although the movements are barely perceptible, with time they can generate important instability zones. In general, three types of movement of the Gran Basamento were observed (Rangel *et al* 2006), as follows: subsidence, lateral displacement, and a combination of both.

The subsidence observed originates from the presence of loose fills placed by the ancient inhabitants where structures rest, whereas the lateral displacements are mainly due to the subsoil's small shear resistance at the point of contact between the badly compacted fill and the compact or natural soil; any change in the slope, whether by doing a cut or applying a surface overload, causes the fill to slide along that frontier.

At the lower part of the platform the trees are seen to be slightly tilted, which suggests the existence of a slow displacement process or creep, associated to the excessive humidity that exists at the point of contact between the badly compacted fill and the natural terrain. This aspect was only observed at the fill zone, mainly the pre-hispanic one without structure.

The creep mechanism, the lateral displacement and the subsidence can locally cause mechanisms of rotational failure during their stages of great development.

There is cracking that is active, such as in Building A, the temple of Venus, the Red Temple, and the South Portico. This cracking is the product of the slope's instability, except for the Red Temple, whose causes are nearby excavations and soil altering processes.

Currently the active factors that importantly influence the generation of cracking are: excessive inclination of the slopes, subsoil increase of water content (infiltrations), excavations, abrupt temperature changes, overloads, vibration, and progressive soil alteration.

5 GEOTECHNICAL ANALYSES

In order to evaluate stability conditions on the Gran Basamento's northeastern slope, at the zone of Building A, where there has been important cracking, and also to know the instability mechanism in more detail, subsoil numerical models were carried out with the finite elements method, FEM, considering the geometrical and mechanical conditions measured. The section of analysis corresponds to the one known as Axis Section 10, where important cracking has been observed on the slope's crown.

Modeling. Fig. 7 shows the mesh of finite elements used in the analysis that represents in an approximate way the slope's condition as obtained with a topographical survey. It is a bi-dimensional mesh with triangular elements of 12 integration points. Inter-phase elements were placed between the platform's natural material and the fill.

To determine the slope's stability, a numerical process was carried out in which the strata's mechanical properties are reduced step by step, from the measured resistance, until producing a cinematically admissible failure mechanism. Parametric non linear analyses were made varying the resistance properties of the inter-phase elements to verify their influence on the stability. The results obtained are shown below.

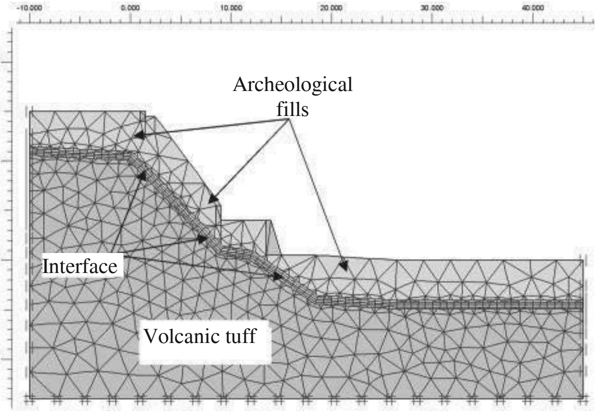


Figure 7 Finite elements mesh

Derived from the analyses described above, a probable failure mechanism was obtained, as shown in Fig. 8. The slope's failure is observed not to be rotational, but rather that there is a sliding or creep of the fill over the natural material of the Gran Basamento. Such sliding occurs at the point of contact between both materials, and it generates tension zones at the slope's crown, which in turn can produce cracking, such as is physically observed on the site, as well as a plastification zone at the point of contact between fill and platform.

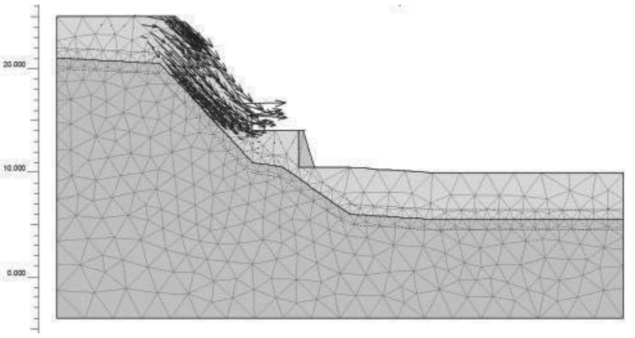


Figure 8 Mechanism of probable failure

For current conditions, the safety factor associated to this failure mechanism is only 1.2. This shows that although the slope is stable, the condition could easily deteriorate if current conditions change; for example, when doing a cut, applying a surface overload and/or when water infiltrates.

6 CONCLUSIONS

The Gran Basamento of Cacaxtla is an earth structure that in the last few years has presented cracking on the crown of the slopes and on the top platform, which has affected the main archeological structures, for example the walls of the Red Temple and the Venus Temple. If this cracking continues to develop, slope failures could occur. Therefore, it is necessary to learn the origin of this cracking. In first instance, the characteristics of the materials that form the pyramid must be known, but since it is an archeological monument, it is not possible to use conventional geotechnical exploration equipment because important damage would be induced, so indirect exploration methods have been used, such as the radar technique, and direct ones, as with the ultra-light penetrometer, where induced damage is small. Also, a geo-boroscope has been used, introduced into the drilling made by the penetrometer, in order to observe directly the characteristics of the materials penetrated.

The model of the materials that form the pyramid, obtained through these methods, consists of three basic units: organic soils, fills and volcanic tuff. Out of these materials surface fills stand out, consisting of sandy silt and/or silty sand that in some zones are loose, poorly compacted or of low consistency. Based on the results of the numerical analyses carried out, it was concluded that the frontier between these fills and the pyramid's natural material (volcanic tuff) is a marked sliding surface that is activated by the humidification that occurs in some of the pyramid's zones or when excavating on the slopes.

Also, with the results from the penetrometer and the geo-boroscope it was possible to determine different construction stages of the pyramid, when identifying the various types of fill and the compacting qualities of those fills. This characteristic serves as support to carry out archeological studies about the construction processes applied to the pyramid.

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