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Geotechnical characterization for a large urban excavation in Manizales, Colombia

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Abstract

The paper presents the geotechnical characterization for a large permanent excavation with some 400 m length and maximum depth of 40m required for the development of the Mall Plaza construction site in Manizales, Colombia. The site is in the middle of a highly populated area in a terrain with large topographic gradients. A regional fault with large displacements and its associated damage zone, some 100 m wide, crosses the site diagonally. The main rocks found in the site are graphitic schists. A diorite inclusion was found emplaced locally in the fault width zone. The terrain is overlaid by volcanic ash coverage from several eruptions of the Ruiz Volcano as well as colluvial deposits from quaternary earth flows and avalanches, common in the region. The zone has an average annual rainfall of 2000 mm, and is located near seismically active faults, capable of producing up to magnitude 7 earthquakes with recurrence within the design lifetime span of the project. Due to this adverse geological and environment conditions, the excavation have a high risk. Initial conventional wash borings and small diameter rotary drilling holes did not allow a reasonable characterization of the terrain. This required a detailed exploration conducted by means of high-quality boreholes with 130mm to 100 mm double core barrel continuous samples and geophysical methods to complete the designs. During construction, the ground conditions were carefully observed, and the geotechnical model verified and refined. The complex site conditions determined the support and drainage required for the project. The conditions at the site are representative of fault shear zones commonly found in the Colombian Andes. The most serious landslides occur in these areas. Geotechnical characterization of these areas is difficult. The experience gained in this site is useful for similar sites.

1 INTRODUCTION

The Andes in Colombia is divided into three main mountain ranges which have been formed in the last 12M years as a result of the recent orogeny in a predominant regime of east-west compression as a result of subduction of the Pacific plate, with additional influence from subduction in the Caribbean. These main forces generate thrusts on the blocks that make up the Andes mountain ranges against Guyana's shield to the east. Additionally, the geometric configuration of these mountain ranges implies strike slip components in the main fault systems that form the moving blocks. As a result, mountain ranges are demarcated by large systems of faults in the general north-east direction and other transverse systems. Many of these faults were formed in previous periods of orogeny and have been reactivated in the current regime of stresses different from the initial. This results in multiple and frequent shear zones along which there have been large displacements in different geological times. Under the current denudational processes the weaker shear zones control the development of valleys and the general morphology of the mountainous areas where the main cities and most of the country's population are located.

The effect of the damage zones gives Colombian mountains an exceedingly high susceptibility to landslides due to the shearing and subsequent weathering of the rocks affected by these faults. In addition, these shear zones control hydrogeological conditions, mostly forming preferential flow channels. These in turn favor reactive transport processes and deep weathering along these rock weakness zones that may have locally very deep soil profiles. Additionally, these faults are seismically active and generate a regimen of frequent strong, shallow, intra-plate-earthquakes that have a significant effect on the stability of slopes. The largest instability problems occur along the areas disturbed by the tectonic effects.

This article presents information on the detailed characterization of one of these areas that was required for the development of the project for the Mall Plaza shopping center which is the largest urban excavation carried out in the city of Manizales to date, Jeoprobe SAS, (2014).

The entire urban area of the city of Manizales has steep topography with slopes in residual soil profiles of metamorphic, volcanic, and intrusive rocks, covered by recent deposits of volcanic ash. In addition, due to the urban development of the city, there are frequent deposits of anthropic origin often without due technical control. All these surface soils are potentially unstable. The triggering factors are rainfall, that in the area is of the order of 2000 mm per year, with very intense rains in April-May and October-November, and frequent seismicity. This has resulted in frequent colluvial deposits originating in earth flows and shallow slides.

2 GEOLOGY

The geology of Manizales is described in Moreno-Sánchez et al. (2016) with an emphasis on tectonic shear zones occurring along high-angle reverse and strike slip faults in cretaceous metamorphic rocks as shown in Figure 1. The project site is indicated in the figure and corresponds to a location on the shear zone El Arroyo - Corinto in rocks of the Quebradagrande complex. This formation is locally composed of graphitic shale. These rocks typically develop a 5m thick weathering profile, made of clays and silts usually oxidized by water flow. The transition to sound rock occurs quickly in a saprolite stratum. The saprolite is fractured rock with high permeability and porosity, that holds and conducts water . This constitutes an aquifer layer along which water pressures can develop and act as an important agent of instability. In the shear zones the rock is fully fractured and distorted with abundant water flow, allowing it to be highly weathered to great depths. In these areas the occurrence of deep, large retrogressive rotational slips is common.

Figure 2 shows a slopes map of the project sector and indicates the limit of the shear zone that underlies most of the area. Contact with the shear zone is evidenced by a scarp in the northeast that delimits a strong change in topography. Towards the east of the escarpment fractured and folded but relatively sound schist is found. In the fault zone the material is totally disaggregated. Water outcrops were found and a rotational slide covering the fault was identified on the western side of the project lot as shown in Figure 3.

Superficially there are deposits of volcanic ash originating in various eruptive events of the snowy Ruiz volcano which is located about 29 km to the south east of the city. Due to the frequent instability phenomena caused by shallow slides in the ash cover and anthropic deposits, it is common to find earth flows deposits.

Figures 4 and 5 show photographic records of exploration drilling made during design studies, where the different materials found in the area can be seen. Figures 6, 7 and 8 show photographs of materials found during excavation for the project.

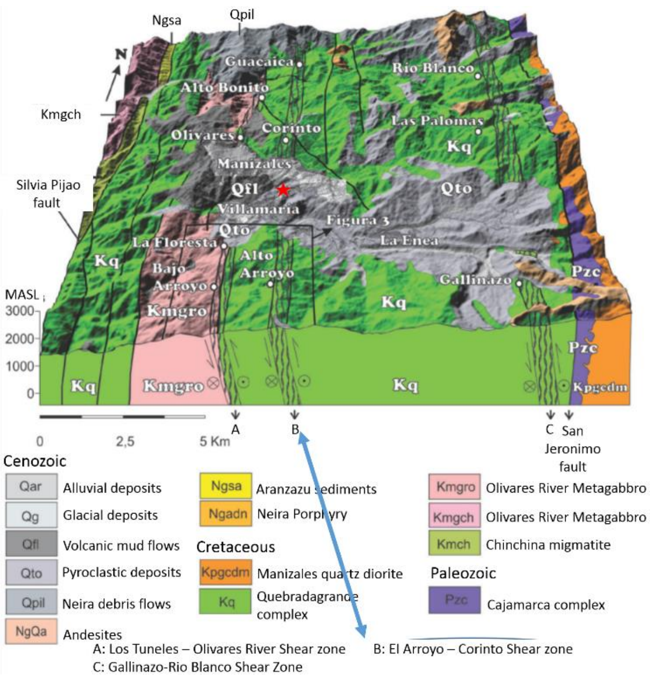
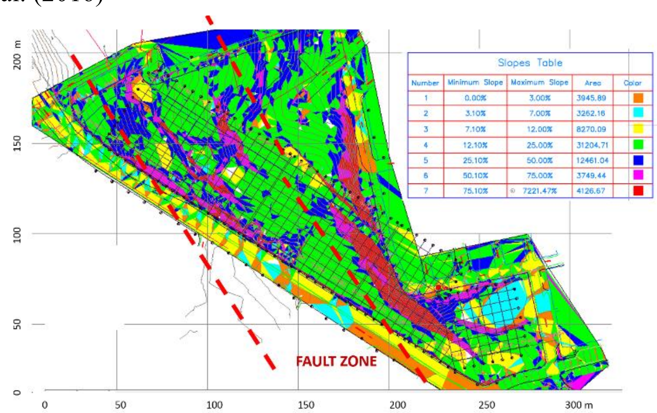


Figure 1 - Geology of Manizales and surroundings with emphasis on shear areas. Modified from Moreno-Sánchez et al. (2016)



Number	Minimum Slope	Maximum Slope	Area	Color
1	0.00%	3.00%	3945.89	
2	3.10%	7.00%	3262.16	
3	7.10%	12.00%	8270.09	
4	12.10%	25.00%	31204.71	
5	25.10%	50.00%	12461.04	
6	50.10%	75.00%	3749.44	
7	75.10%	7221.47%	4126.67	

Figure 2 – Slopes map of the project area showing the fault zone.

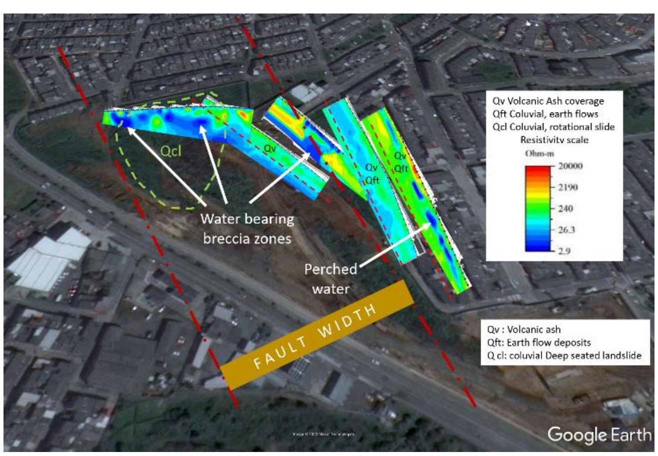


Figure 3 – Resistivity tomography sections.

3 GEOTECHNICAL CHARACTERIZATION

The geotechnical characterization of tectonic shear zones such as that found at the project site is difficult for several reasons. First, there is a strong variability of terrain conditions over short distances. Second, highly fractured rocky materials, shear zones and fully weathered rock are difficult to sample to obtain representative samples and even more difficult is to obtain unaltered samples for quantitative laboratory testing of stiffness and strength of these materials. In addition, a determining factor for geotechnical designs and hillside stability is groundwater conditions, controlled by localized fractured areas that are difficult to identify.

At the project site, a conventional geotechnical exploration campaign was initially conducted, used regularly for projects in the city, by means of percussion and washing drilling conducting standard penetration testing and rotation core drill sampling in small diameter boreholes. This exploration failed to obtain enough information to objectively identify the geotechnical conditions of the project site. Only shallow soil coverage thickness was established and the fault area was misidentified as a large colluvial deposit leading to an initial approach to excavation that was not consistent with real ground conditions.

Following a more detailed review, the existence of the fault zone at the project site was identified, and an additional exploration campaign was conducted with high-capacity drilling rigs using double-barrel, 110 mm diameter core drills with continuous recovery in both the surface soils and the underlying rocks profile. These boreholes allowed to objectively identify the different types of materials present at the site and their geological and mechanical conditions. In these perforations, Menard's pressuremeter tests were performed on the materials that allowed it.

Figures 4 and 5 show the photographic record of two of these bore holes. A continuous recovery was achieved in all the materials, which could establish an adequate geological description and geo mechanical classification of the rocks as well as perform tests on cores of unaltered material. The presence of a quartz diorite intrusion was identified along the shear area. It was also found that schists in the shear zone are completely disintegrated and weathered, giving place locally to a gravelly soil in silty matrix with clay gouge veins.

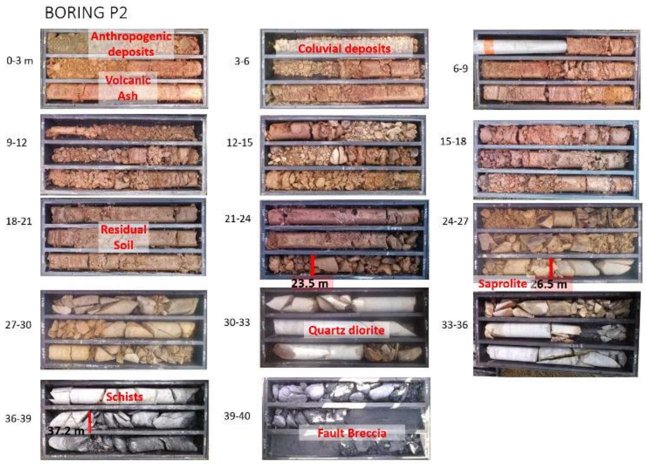


Figure 4 - Photographic record of P2 drilling located in the middle on the northern border of the project area.

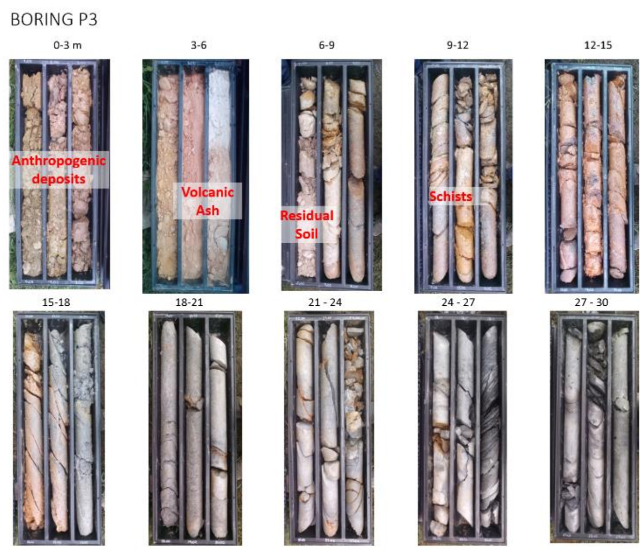


Figure 5 - Photographic record of P3 drilling located the fault zone in the central part of the project.

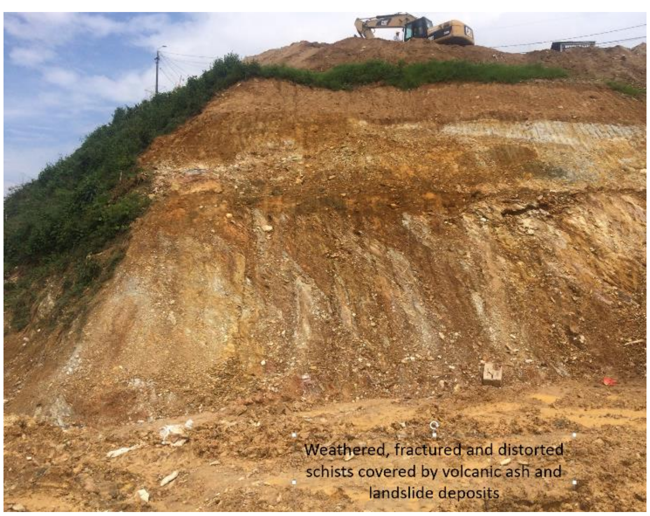


Figure 6 - Excavation slope in fractured schists and surface cover to the east of the fault zone.

Figure 7 - Excavation slope in the fault zone in the center of the project area.

Figure 8 - Excavation slope the western side of the project.

Geophysical methods were used that have the possibility of continuously covering longitudinal sections, as opposed to the local assessments that are carried out through drilling, to establish the variation of the subsoil and groundwater conditions at the site. Therefore, geophysical methods are an effective supplement in characterizing areas with complex stratigraphy and groundwater conditions such as those at the project site.

For the identification of water conditions in the field, a series of electrical resistivity tomography sections was made, the location and results of which are illustrated in Figure 3. The resistivity values obtained correspond well to stratigraphic conditions and allow to identify low resistivity areas associated with the presence of water in the terrain. These results show that outside the fault zone are perched water table levels in the surface deposits. In the fault zone are sectors where there is concentrated flow of groundwater. This corresponds well with the water outcrops that were initially found in the field and was an important information for water management during excavation by horizontal drains.

For the assessment of the mechanical conditions of materials in the field, seismic geophysical lines were taken with active and passive measurements that were interpreted by refraction analysis and surface waves dispersion. Refraction analyses allowed to delineate shallow soils thicknesses, and surface waves dispersion analyses provided shear wave velocity (Vs) profiles, that show the variation of ground stiffness at low strains. Figures 9 and 10 show the Vs profiles obtained along the northern perimeter of the area and along the central part in the northwestern direction. These sections allow to identify the surface soils, the fault area, and conditions of the schists outside the fault area, as well as the presence of the quartz diorite intrusion. This information was critical for the design of excavation support, both for static conditions and for the analyses required for seismic design.

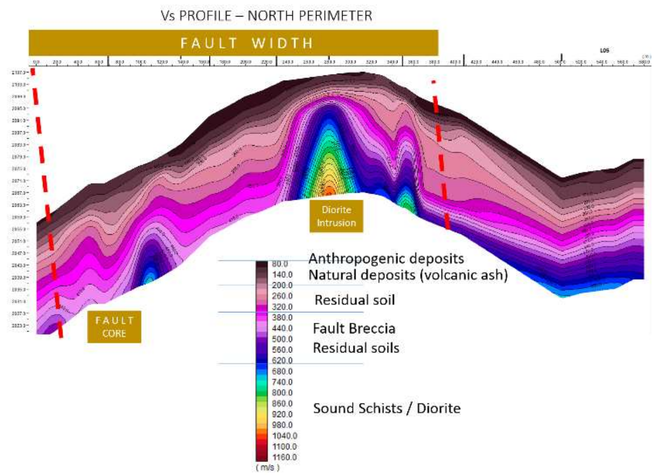


Figure 9 – Shear wave velocity profile along the project's north perimeter.

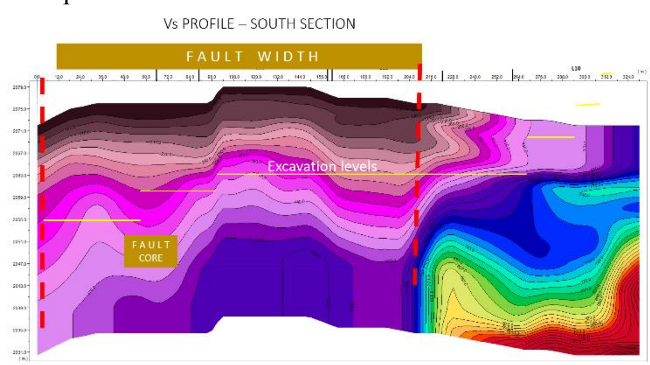


Figure 10 - Shear wave velocity profile through the central part of the project.

The information obtained through drilling and geophysical measurements was verified during construction, finding that it had been adequate to identify general terrain conditions. During the work, additional detailed measurements were made both through the construction records of all the elements used for the contention system, through detailed monitoring with deformation and piezometric instrumentation, and through additional geophysical measurements. This information allowed proper management of the excavation that was of high complexity and to detail the foundations works.

The sheared rock in the fault zone is an extremely poor material for slopes, but it is a moderate to competent material for bearing capacity. The presence of the fault core towards the west of the area was a medium stiff clay that required pile foundations for some of the project larger load columns. All the rest of the foundations on the sheared weathered rock were on shallow footings, some of them after a local replacement of loose or low stiffness soils at foundation level.

The basic concept of the containment system was the construction of excavated and cast in place piles, 80 cm in diameter 2.5 m apart between centers, completed by horizontal RC beams and active post-tensioned anchors.

The difficult terrain conditions required the implementation of an observational protocol during construction to confirm and supplement the information obtained during the design, and to make the adjustments that were necessary, particularly in the definition of the drainage system. This included keeping a detailed record of the construction of the piles and anchors that formed the wall, and the geotechnical assessment of the materials found during the excavation.

A complete instrumentation system was implemented by topographical control of bench marks in and around the wall, evaluation of wall movements using laser measurements of points located on the wall face as it was built, inclinometers, and piezometers in various perforations around the intervened area. Also, the rainfall was registered. In addition, the drainage flow of the horizontal drains installed in the wall was monitored. After construction, an automated permanent instrumentation control system with real time monitoring was left in place.

During the construction of the piles, the stratigraphy of each one of them was logged, which was contrasted with the geological model envisaged during the design. The same was done with the perforations for the anchors. In addition, a record of the grout injection volumes required for anchoring was kept. Figure 11 shows the pile length profiles that were constructed, the shear wave velocity profile along the north side of the site, and a map with the injection volumes required for the anchors. The embedment length of the piles was determined in the design by the need to support the base of the wall along the area, particularly along the fault breccia.

During construction, the length of the piles in some sectors was limited by the strength of the materials to the point that it was not possible to continue drilling with high capacity mechanical equipment for piling excavation. During the construction of the anchors it was identified that the shear zones, and the most permeable areas, had the highest consumption of grout during the construction of the anchors. The ground conditions were consistent with the design forecasts and allowed for a more accurate determination of stratigraphy throughout the wall before starting the excavation. During the excavation, the anchors were built, and the drilling records allowed to re-check the variations of the terrain conditions and identify water conditions that, as already said, occur in abundance but concentrated in limited sectors.

The results in Figure 11 show reflect the competence of the materials associated with the presence of materials affected by shearing, schists in relatively sound condition and quartz diorite intrusion. Therefore, all pile drilling and anchor construction were additional elements of ground characterization.

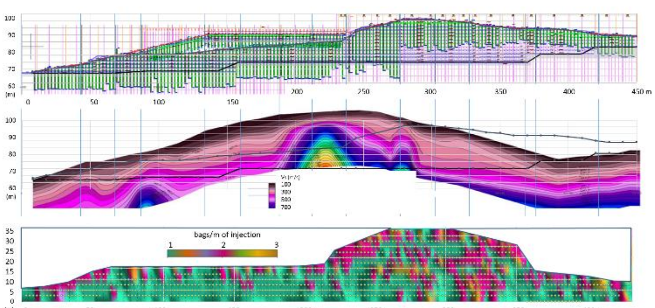


Figure 11 - Shear wave velocity profile through the central part of the project.

Figure 12 show the wall during construction in a view towards the west. The higher zone of the wall under construction can be seen to the right in the photo. The general extension and the context location of the urban excavation is shown in Figure 13.

4 CONCLUSIONS

Tectonic shear zones are quite common in the Colombian Andes and determine the occurrence of the main problems of instability that occur in the country. The characterization of these areas is difficult because of the variability, the state of the materials and the conditions of the water in the field.

Figure 12 – View of the excavation during construction.

Figure 13 – Air view of the excavation during construction.

This article presents a case that required a detailed exploration for the Mall Plaza Manizales shopping center that required a large urban excavation at a site along a fault breccia zone, being the most complex construction that has been made in the region. The large excavation required a retaining wall up to 40 m high and more than 400m in length.

The paper illustrates the methods used for ground characterization for design, including high-quality bore holes and geophysical exploration with seismic refraction and surface wave methods and resistivity electrical tomography. During construction the information was verified and supplemented by careful follow up and control of variables such as piles length and stratigraphy, anchor boring description, volume of injection required for anchor bulbs and soil conditions found during general excavations and excavations for footings.

Geotechnical instrumentation included piezometers, inclinometers, laser monitoring of wall front movements, topography measurements, pluviosity and fluviometric records of water drained from the wall, and field permeability tests, among others. These methods allowed the identification of a highly variable ground profile with abundant water localized along local shear zones and in perched water levels. The depth of the weathered zone, composed by medium to stiff clay gouge or silty gravel in the shear zone core was more than 40 m, while the regular weathered profile on undisturbed rock was less than 10m. The width of the shear zone was some 75m. These made the ground conditions in the project site highly variable in short distances.

Ground water conditions proved difficult to handle since there was abundant water, large variations of water levels with variation of cumulative pluviosity, and localized flow affected by the construction of anchors. The key to successful drainage of the wall was to precisely identify the location of the water bearing zones and to construct horizontal drains to those zones.

Due to the large extent and depth of the excavations, an adequate understanding of the ground conditions was a key factor for the success of the project.

5 REFERENCES

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