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Geophysical exploration for a large terrace landslide

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Abstract

A very large landslide occurred in 2019 in the flank of a terrace in the West Cordillera in Colombia, blocking for several months the most important road to the eastern lands of the country. Over 120.000 m3 were removed to partially retire the landslide and restore road use. The scarp of the remnant landslide is some 240m high in fluvio - torrential deposits with some levels containing boulders with volume over 10 m3. The landslide affected a two lane road tunnel that had been recently completed at some 60m depth, 40m in horizontal direction from the slope face in the landslide zone.

The paper presents the geophysical campaign conducted to contribute to characterize the deposit in order to conduct stability and hydrogeological studies of the problem. The campaign included seismic measurements by means of Down Hole and Spatial Autocorrelation (SPAC) methods, resistivity by means of vertical soundings (EVS) and electrical resistivity tomography (ERT) sections, and system characterization by means of ambient vibrations measurements and vibration response modeling for the terrace along the zones affected by the landslide and in intact zones. The measurements allowed the identification of the soil stiffness profile at low strains, fundamental periods of vibration, contact to underlying rock at some points, the stiffness degradation around the tunnel and due to the landslide, the presence of groundwater, and the identification of the damage zone in the base rock associated to a fault zone. The geophysical information was contrasted with data from boreholes and the stratigraphic profile exposed in the landslide scarp.

The stiffness profiles and system characterization measurements showed high density and stiffness of the intact soils. Also, that the stiffness was significantly reduced around the tunnel and near the landslide. The resistivity and EVS confirmed piezometric measurements indicating a high water table in the terrace, and anomalies around the tunnel. Two inferred fault traces in the zone were studied by means of resistivity tomography. These measurements confirmed a resistivity anomaly interpreted as a fault damage zone with high water content in one of the traces and no anomalies in the other.

The geophysical information was useful for the development of the geotechnical model required for the analysis of the problem, and also to verify the effect of the construction of the tunnel and the slide on the stiffness of the terrace materials affected by these processes .

1 INTRODUCTION

An exceptionally large landslide occurred in 2019 in the flank of the Mesa Grande terrace in the west cordillera in Colombia, blocking for several months the Bogota – Villavicencio which is the most important road to the eastern lands of the country. Over 200.000 m^3 were removed to partially retire the landslide and provisionally restore road use. The scarp of the remnant landslide is some 240m high in fluvio - torrential deposits with some levels containing boulders over 10 m^3 in volume. The landslide affected a two-lane road tunnel that had been recently completed at some 60m depth in the landslide zone. Figure 1 shows an air view of the terrace and the landslide that occurred. The figure shows that the end of the terrace had been bisected by a natural drainage leaving two remaining ridges. In one of them occurred the process of instability that left an escarpment of some than 240 m in height with disaggregated and loose material on the surface, and a significant thickness of the terrace affected by the movement that was not removed. The escarpment is active, with a high slope and with loose material and permanent risk of falling rocks and soil. The geometric conditions greatly hinders access to perform any type of exploration activity directly in the area affected by the slide. The location of the tunnel portal is shown in the photo. on the left. The tunnel had its exit portal in the natural drainage to the right at the edge of the area affected by the slide. A bridge had been constructed in this site that was destroyed by the debris. The section of the tunnel matching the slide has had large deformations with displacements of more than 1 m, indicating that the affected mass extends at least to the level of the tunnel.

As part of the studies aimed at evaluating the instability process carried out by the Colombian Society of Engineers, (SCI, 2020), the use of geophysical methods was considered to complement direct methods of field exploration. This document shows a description of the activities carried out, the results of the measurements and the geophysical model of the Mesa Grande terrace carried out by Jeoprobe (2020), as part of the work of the Study by the SCI (2020).

2 GEOPHYSICAL EXPLORATION PLAN

Different geophysical methods were evaluated to complement the information needed for the models of stability, seismic response, and water flow in the field. These included seismic methods of surface wave scattering and down hole, resistivity methods, and environmental vibration measurements to perform analysis of identification of dynamic slope responses.

Figure 1. Overview of the study area on December 2019 (SCI, 2020)

The use of surface waves for land characterization has had a great development in recent years see Foti et al., (2011) as a reference. For the characterization of deep profiles, the method currently used is space autocorrelation (SPAC) with multidirectional arrays and wide spectrum sensors, preferably combined with measurements using low-frequency triaxial seismic sensors. Asten and Kakashi (2018) present an updated account of the application of these methods that began to develop from the mid-1990s (Arai and Tokimautsu, 2004, Cho et al, 2008). These methods are complemented by techniques based on the measurement of three-dimensional displacement fields and the analysis of the spectral relationships of the vertical and horizontal motion component, HVSR, (Nakamura 1989, 2000) that identify natural modes of ground vibration, usually surface waves, and which can be used to make inversion of the HVSR ratio, or combined with surface wave dispersion measurements to determine and/or bound the estimates of the profiles of Vs to great depths (Arai and Tokimatsu, 2004 Sanchez Sesma et al., 2010, 2011, Claprood et al., 2012). In Colombia, the use of these methods for characterizing deep soft soil profiles has been reported (Rodriguez and Azuaje, 2018, 2019).

Environmental vibration measurement is a technique related to the above, which can be used as a structural identification method for characterizing the terrain under complex conditions of geometry or depth (Cornou et al., 2007. Fah et al., 2008). In this case, environmental vibration records were taken in 3 components and at various sites using broad-spectrum seismic recording stations for long periods of time. These measurements show the response of the terrain in natural condition. For the interpretation, numerical models of the slopes and terrace were made with the stiffness profiles obtained from the SPAC and Down hole measurements, in order to calculate the natural modes of vibration and compare them with the measurements of vertical horizontal and periods of natural vibrations. In this way it is possible to verify the interpretation of the deep stiffness profiles obtained in geophysical measurements and allows to understand the natural form of vibration of the slopes which forms the basis of the seismic response of these slopes.

The possibility of using passive seismic methods of surface wave dispersion analysis with spatial self-correlation (SPAC) techniques was identified to obtain shear wave velocity profiles from the top surface and the MASW methods from inside the tunnel. These were complemented by down hole testing on the bore holes performed for the study. The purpose of the exploration is to obtain information that allows to estimate the stiffness of the terrace soils both in the areas that have not been affected by the slide and in the sector affected. This determination is difficult because the surface is not accessible to the slide area. The large extent and depth of the deposit also makes it difficult to apply surface geophysics techniques to characterize the terrain. In order to achieve the greatest exploration depth SPAC arrangements in the upper part of the terrace were deployed, as close as possible to the unstable area and in the middle part of the terrace where there have been no problems of instability. These measurements would serve as a reference for the natural initial condition of the terrace.

The stiffness of the terrain is necessary to be able to analyze stresses and deformations that are relevant to study the possible causes and mechanisms of evolution of the instability processes that have been presented in the slope. Seismic geophysical measurements offer a great advantage in studying the stiffness of granular materials in terrace deposits, given the difficulty of taking representative samples of sufficient size that maintain the structure of the terrain and to carry out tests to establish these parameters in the laboratory or by mechanical tests in the field. Geophysical measurements allow the measurement in the field of stiffness at low deformations in terms of the propagation shear waves through the material in place. For the landslide analysis the stiffness and strength degradation with strain should be considered. A detailed analysis of these processes and the evolution of the landslide mechanism including the effects of the tunnel construction was part of the studies carried out by the SCI, but this is outside the scope of this paper.

In addition, environmental vibration measurements were considered to complement information from other stiffness measurement methods as they allow direct measurement of the terrain vibration modes that are determined by the stiffness and geometry of the slopes that in this case are very relevant to the problem.

As a complement to seismic measurements, vertical electrical surveys (VES) and electrical resistivity tomography (ERT) were also performed, allowing for further defining stratigraphy and the presence of field anomalies. Resistivity is sensitive to the presence of water in the ground which is an important factor for the assessment of the stability of the terrace.

As part of the studies of the SCI (2020) an interpretation of ortho photos of the front of the slide was made to generate a stratigraphic two-dimensional profile of the front of the slide as shown in Figure 2. The layered profile exposed in the scarp was correlated with the geotechnical and geophysical information available to date to propose the geological model. This identifies several pulses of terrace formation with different sizes of metamorphic rock blocks embedded in a mainly sandy matrix. According to the size of the blocks found, it is clear that many of these pulses correspond to a very high energy deposition regime, with the presence of large blocks of metamorphic rock packaged in a sandy silt matrix, which reach fairly high stiffness values.

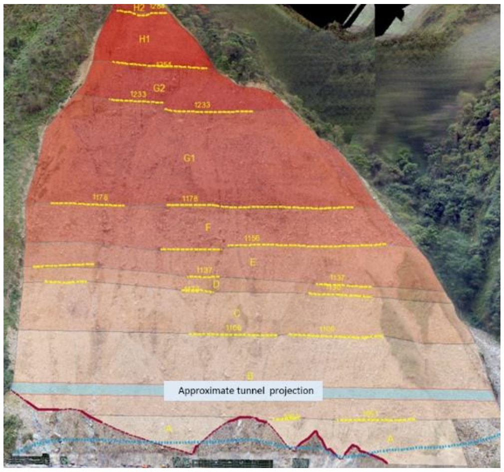

Figure 2. Vertical ortho photo of the slide front. Yellow lines show different terrace levels that were used to define the colored stratigraphic interpretation shown (SCI, 2020).

For effects of characterization using geophysical methods it is necessary that there is a significant contrast of the properties that are to be measured with the different methods in the field so that they can be identified in the measurements. The stratigraphic conditions of the terrace mean that it should be expected to identify contrasts of stiffness between levels that have progressively greater stiffness with depth. High stiffness values should be expected for granular sedimentary materials. The methods that can be used in this case are surface wave dispersion which allow to accurately identify the representative values of stiffness in an integral way but not in a detailed way and also do not have the possibility to identify strata with not very significant stiffness reductions especially with increasing depth.

The geophysical exploration campaign was carried out between December 2019 and January 2020, which included the following tests:

Three environmental vibration-SPAC measurement tests at the top of the Mesa Grande terrace. Two Vertical Electrical Probes (VES) on the terrace of Mesa Grande with AB/2 separations of up to 300 meters. Three down hole tests on the terrace of the Mesa Grande, in the S1, S2 and S4 boreholes, as well as a down hole test in the tunnel in the S3 borehole. Eight environmental vibration measurement tests-HVSR on the terrace and four tests on tunnel 13. Four electrical resistivity tomography (ERT), one on the Mesa Grande terrace, one inside the tunnel and two on the side of the Bogota - Villavicencio road. A seismic line inside the tunnel. The location of all geophysical exploration performed is presented in Figure 3.

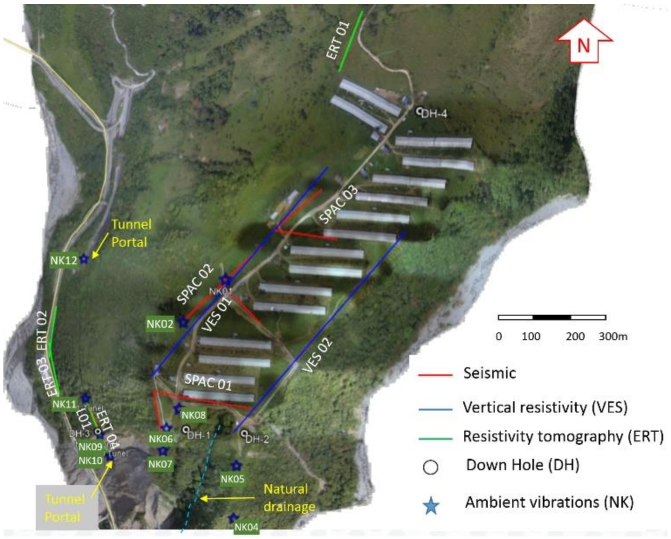

Figure 3. Location of geophysical tests performed.

3 RESULTS

3.1 SPAC Tests

Figure 4 shows the results of the three SPAC tests carried out on the Terrace of Mesa Grande. In general, a first layer with speeds of the order of 400 m/s is distinguished, corresponding to a surface alluvial material with thickness of approximately 7 meters. Underlying that layer, and up to a depth ranging from 23 to 43 meters in NE-SW direction, an increase in shear wave speeds is observed to an average of 600 m/s. Below this layer, another speed increase is seen that reaches an average of 850 m/s, and whose depth varies between 60 meters in SPAC 03, up to 106 meters in SPAC 02. Below that layer and up to the maximum scanning depth (150 meters), the speeds are greater than 1000 m/s. These profiles suggest the presence of very dense high stiffness deposits with large dense blocks and packaged in a matrix deposited under a very high energy regime.

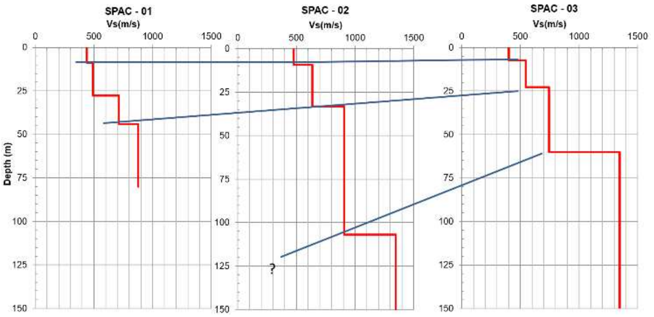

Figure 4. Shear wave velocity profiles resulting from SPAC tests.

3.2 Down Hole Tests

Figure 5 shows the shear wave velocity profiles obtained from Down Hole measurements. The tests DH 01 (50m) and DH 02 (40m) , carried out in the SW part of the terrace, show good correspondence with the SPAC tests, allowing to detail more precisely local variations of shear wave velocity. Down Hole 04, (45m) located in the NE area of the terrace, close to the mountain, allowed to identify contact with the rock at a depth of 40 meters. Down Hole 03 (27m), performed inside the tunnel, shows an area between the surface and 12 meters deep where the shear wave velocities are lower than expected for that stratum, corresponding to approximately 70% of the values recorded in SPAC measurements. This reduction in stiffness corresponds to a factor of 2, i.e. the stiffness around the tunnel has been halved from what was before the tunnel was built. This is attributed to the deconfinement effect caused by tunnel excavation.

In that test, the rock was identified at a depth of 27 meters.

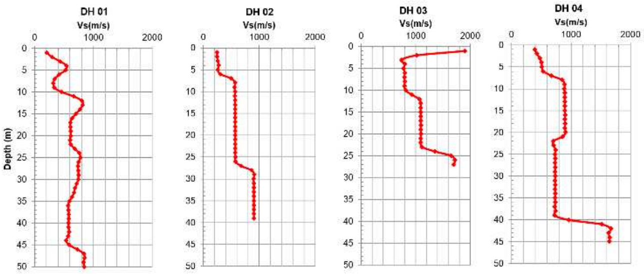

Figure 5. Speed profiles obtained from Down Hole tests.

3.3 Vertical electrical soundings

Figure 6 shows one of the resistivity profiles obtained from vertical electrical probes. These profiles allow to correlate the variations of the resistivity with the stratigraphic profile of the soil, observing a particularly good correspondence, as detailed in Figure 7. A significant reduction in resistivity is seen between 25 and 30 m deep, which corresponds to the water level in the field according to piezometer data from the boreholes. This information was used for a detailed hydro geological model in the SCI study considering the effects of the permeability contrasts, infiltration rates during wet and dry seasons, partially saturated zones and large topographical gradients and water level boundary conditions in the terrace.

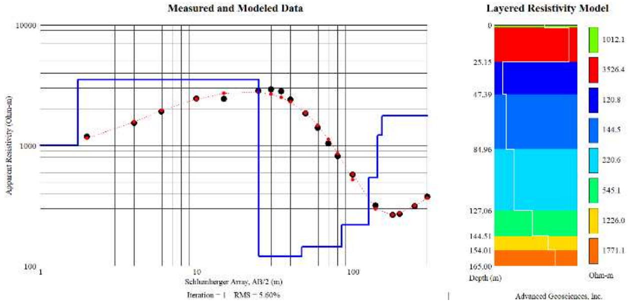

Figure 6. Resistivity profile obtained from vertical electrical probe 01.

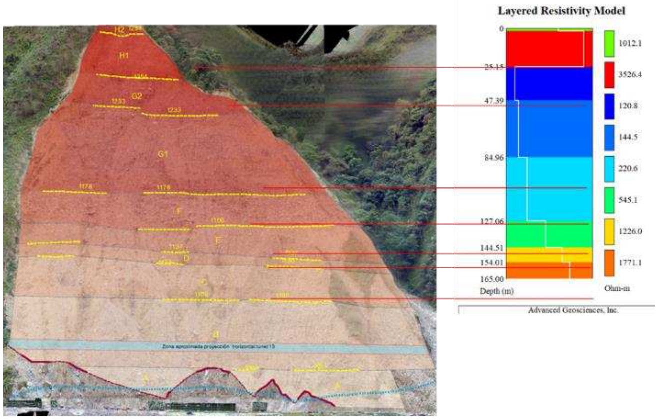

Figure 7. Comparison of VES 01 with the lithological profile observed in the ortho photo.

3.4 Resistivity electrical tomography.

Figure 8 shows the results of the ERT 01 electrical tomography, performed between the NE corner of the terrace and the mountain. The purpose of this scan was to determine the presence of the Mesa Grande fault. As shown in the figure, the contact between the residual soil and the alluvial terrace can be clearly identified. Likewise, the presence of the rock is observed. However, in the central part of the line, the presence of an anomaly, with lower resistance values is observed, which may be associated with an area of damage or greater fracture of the rock massif. In this area geologists have identified evidence of a geological fault or shear zone, which is consistent with what was obtained on the ERT.

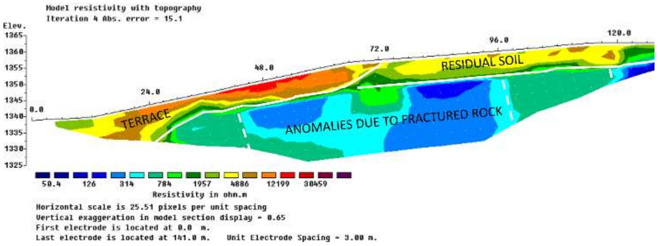

Figure 8. Resistivity tomography ERT 01.

Figure 9 show results of ERT 02-03 done along the road in the base of the terrace to examine the possible occurrence of a shear zone identified from morphological lineaments. No anomaly was observed in these measurements, ruling out the existence of the shear zone.

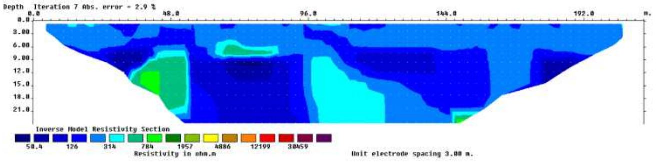

Figure 9. Resistivity tomography ERT 02 and 03.

Figure 10 shows the results of the ERT 04, which was performed inside the tunnel, just before the failed zone. The results of this tomography are quite homogeneous, showing two levels with different values in the terrace material. The first of these is approximately 0 to 15 meters and coincides with the de-confinement zone generated around the tunnel identified in surface wave measurements. The shear wave values of the seismic line performed in the tunnel are presented, which show a 70% speed reduction in the first 15 meters from the mean values in these materials in the terrace area , associated with the tunnel effect. Measurements are consistent and are interpreted as identifying the affectation zone of the terrace material by the effect of tunnel construction at a distance of the order of one diameter of the tunnel, which is a reasonable distance considering the construction process that was used in the tunnel.

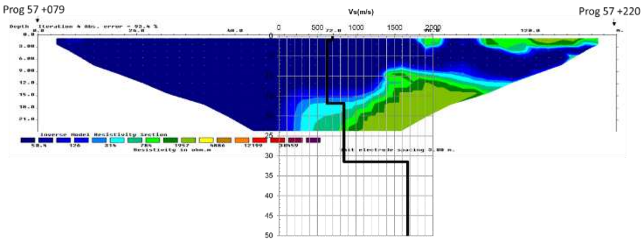

Figure 10. Resistivity tomography Inside the tunnel.

3.5 Environmental vibration analysis

Environmental vibration analysis is a technique used for the evaluation of structures and dynamic systems. It consists of measuring the natural modes of vibration of the structure that depend on its geometry and its stiffness. The principles of this method can be applied to earth structures and slopes to globally identify their overall stiffness conditions from actual measurements of the full slope behavior considering geometry and stratigraphy. These methods can be used to calibrate dynamic response models and verify stratigraphic and stiffness models at low strains under static condition. They are therefore useful for achieving a better understanding of the system and verifying the information obtained from other methods performed on the slope such as those described in the previous sections.

To complement the passive measurements type SPAC, HVSR (Horizontal to Vertical Ratio) records were made in order to obtain the spectral ratios of the horizontal and vertical components of the movement and to be able to identify the natural periods of vibration, This information can be supplemented to obtain, through different types of inversions combined with SPAC data and numerical field models, the stiffness profiles of the entire deposit. HVSR measurements were made along the terrace and inside the tunnel, resulting in data on the actual ground response under different conditions of geometry, stiffness, and soils thickness. In this way the spatial variability of the terrain can be evaluated.

From the Vs values measured using SPACs and Down Hole tests, stiffness values were obtained at low strains and finite element models were generated using the Plaxis program with elastic linear materials to simulate the response surface for the terrace area and for the area of the ridge where the slide occurred, as shown in Figure 11. For these models a displacement signal was applied at the base and the subsequent free vibration response was calculated which is compared to the surface response measured with ambient vibrations in terms of the Fourier spectra of the response signal in the horizontal and vertical direction, and the spectral ratio of HVSR components. Figure 11 illustrates vibration modes calculated for the area the terrace is wide of the ridges and with the ridges, in one case with the terrace material without reduction of stiffness by deformation effect, and another with a reduced stiffness material that would correspond to the condition in the slip area. The vibration response in each case is different. These differences can be sought from environmental vibration measurements to identify the vibration periods for each of the cases comparable to the results of the numerical models for the effects of calibrating the parameters.

Table 1 shows the properties used in the Plaxis model for materials located in the terrace without affectation by the slide.

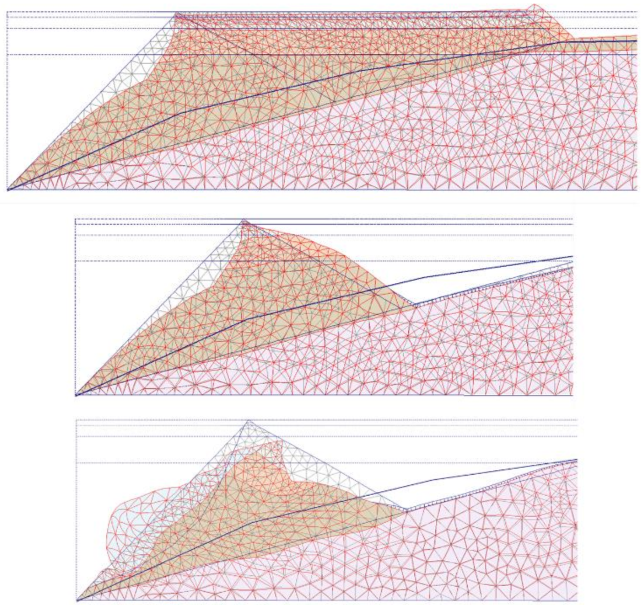

Figure 11. Numerical models of dynamic behavior.

Figure 12 shows a comparison between the surface signals obtained in the numerical model, with the signals measured at stations NK04 to NK08 (Terrace ridges zone), in terms of H/V spectral ratio. According to these curves, there is evidence of a difference in the signals of the NK07 station, which is located on the slide, which suggests a loss of stiffness of the materials in the vicinity of the escarp. On the other hand, the signals from the NK04 and NK05 stations correspond very well to the numerical model, which allows to conclude that the stiffness parameters obtained from the shear wave velocity measurements are valid for the numerical model in areas where the terrace has not been affected by deformation processes and decreased rigidity.

Table 1. Soil parameters terrace intact from top to bottom

ID	Vs (m/s)	Unit weight [kN/m^3]	Poison ratio	Elastic modulus at small strain [KPa]
1	400	20	0.2	800000
2	546	20	0.2	1500000
3	745	20	0.2	2750000
4	1000	20	0.2	4950000
5	1500	20	0.2	10750000

Figure 13 shows a comparison between the surface signals obtained in the numerical model, with the signals measured at NK01 to NK03 (Terrace Zone) stations, in terms of H/V spectral ratio. According to these signals, a good correspondence is observed between the measured values and the modeled values, thus validating the stiffness parameters and therefore the shear wave velocities obtained by the SPAC and Down Hole measurements. The measured response has additional high-frequency components which correspond to shallow local stratigraphic variations.

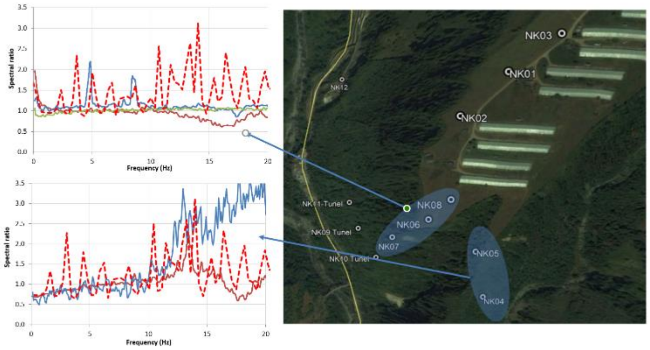

Figure 12. Surface response in the ridges area.

4 GEOPHYSICAL MODEL

Figure 14 shows an overview of the study area with the location of geophysical measurements performed. Figure 15 shows the geophysical data projected on a longitudinal section along the terrace.

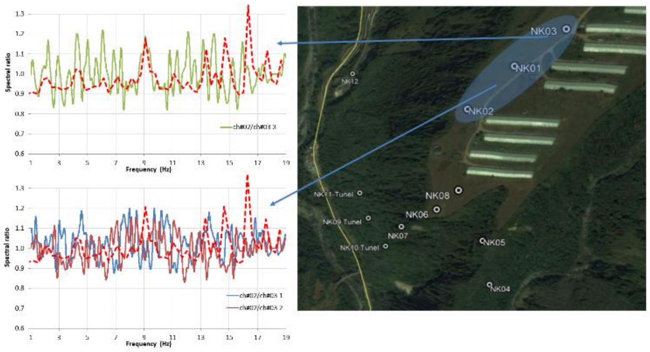

Figure 13. Surface response in the terrace area. The dashed red line corresponds to the values of the numeric model and the continuous lines to the measurements.

5 CONCLUSIONS

The geotechnical characterization of the terrace under study is difficult both because of the dimensions of the deposit, as well as because of its nature of very dense granular materials of large sizes. The geophysical techniques that were used were useful to complement the characterization and assist in the formulation of the geotechnical model of the area. Modern surface wave dispersion (SPAC) and environmental vibration measurement and analysis techniques were applied to identify the stiffness properties of the terrace at low strains at great depth. In addition, resistivity measurements were made that contributed to the delineation of stratigraphy and the identification of rock fracture zones associated with geological faults and water conditions in the terrain. The proper use of physical methods is a particularly useful and cost-efficient tool to complement geotechnical characterization especially in difficult-to-sample materials.

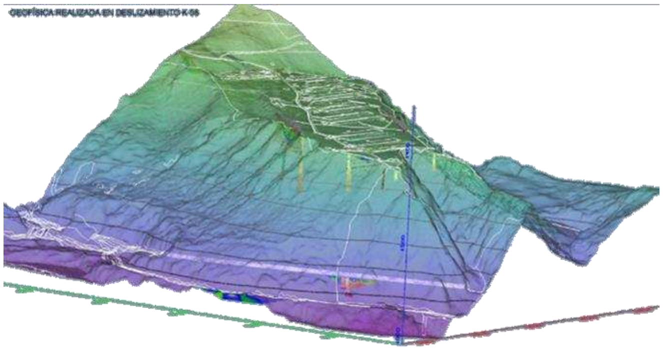

Figure 14. Front view of the study area with the results of geophysical measurements.

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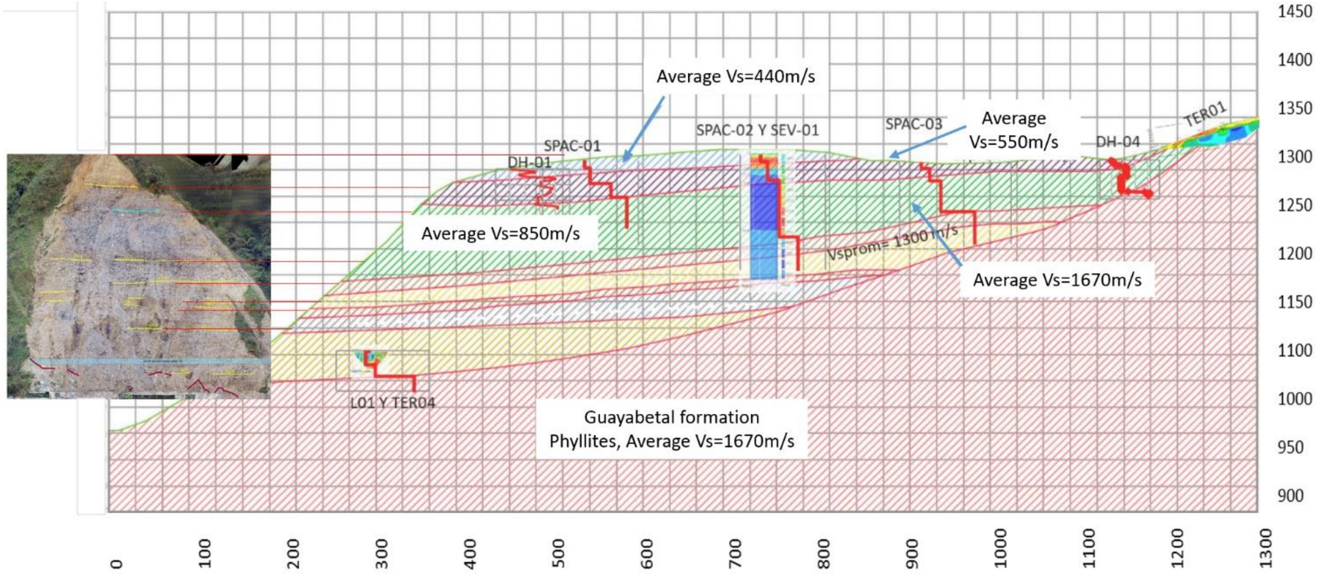

Figure 15. Results of geophysical exploration on the Mesa Grande Terrace. Succession of terrace levels over the Guayabetal formation.