Experience in the design and construction of slopes on mountain roads

Marcelo ZEBALLOS[(1)]; Agustín BALBIS[(2)]; Joaquín RECHE[(1)], Juan Pablo CERUTTI[(2)]

(1) Universidad Nacional de Córdoba; (2) Abya Terra SRL

marcelo.zeballos@unc.edu.ar

Abstract

Geological and geotechnical research methods, and materials characterization tools, have had an important evolution in recent decades. This fact allows to establish the composition of the study campaign during the preliminary project and the project stages, with a high degree of precision. In the case of linear works, such as the construction of roads, the allocation of resources requires special attention. A detailed understanding of the geo-environment in which the work is located can be excessive, especially when the geology of the place has a high heterogeneity. In these cases, the project information can be used to generate the base models. These models must be permanently confronted, depending on the progress of the construction, with the information derived from a better observation of the site. This action, which constitutes the basis of the Observational Method, allows the validation of the hypotheses or their modification and adaptation for a better understanding of the problem.

The construction of a road in a mountain area in the Sierra Chica, in the Province of Córdoba, Argentina, has demanded the application of the work method indicated above. The road required the excavation of slopes in an environment of rock massifs, with a high level of possible failure and a high degree of weathering. Consequently, the initial project forecasts have been successively revised in the detailed engineering stages. Project reviews have been applied during initial construction, and also in subsequent stages of behavior reviews. The results obtained through the use of stability models, the auscultation and control actions applied in the partial failure stages, and the instability mitigation actions adopted as the final state of construction are shown.

Finally, recommendations are presented related to the control and auscultation requirements of the slope, and the need to perform maintenance tasks strictly linked to the stability of the slope.

1 INTRODUCTION

Treatment of slope instability problems is one of the basic components in the design and construction of mountain roads. The processes of characterization of materials, by means of field or laboratory tests, have undergone an important evolution in the last decades.

The characterization programs can be carried out with different scopes and degree of detail as the project stages evolve. In linear constructions, such as a road, the characterization of the affected geoenvironment is improved during the construction of the work. This action allows the validation of the originally formulated hypotheses or their revision. In the latter case, it involves the modification of construction actions or instability mitigation work.

The progressive improvement of the models used and the possibility of modifying the solution is very important when working on a site with large geological and geotechnical heterogeneities. The construction of a road over a mountain sector with large tectonic effects is a typical case of this heterogeneity. The experience of the authors in the excavation of slopes in a mountain road sector is presented. The slope shown, located on the Costa Azul Highway, pk 6 + 200, is characterized by a rapid variation of its properties due to the effect of weathering. The slope, after the recognition and the analysis of the behavior presented during the construction stage, was revised in its design. The new tasks performed showed significant improvements in stability, compared to the originally proposed cross-sectional profile.

1.1 Geological Environment

The work is located in the Province of Córdoba, Argentina. Its geological location corresponds to the western side of the mountain range called Sierra Chica. The location of the sector of interest is shown in Figure 1.

In the area of interest, geology is represented by “La Falda” Metamorphic Complex. According to Martino et al. (2011), this lithological complex is constituted, mostly, by paragneises with intercalations of tonalitic orthogneis. The first group of rocks occupies 80% of the total area.

The metamorphic basement is severely affected by the failure of the Sierra Chica or Punilla. The fault has a regional structure, it is of the inverse type, with an N-S orientation, in general, and an inclination to the E (between 35º-60º E). The fault is the main geotectonic feature of the construction site environment.

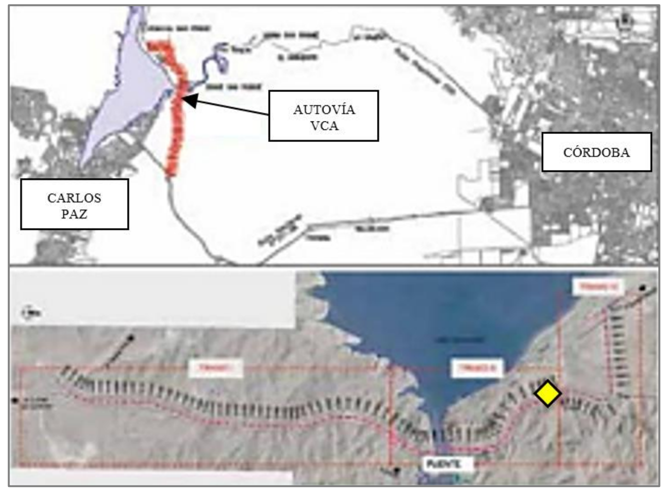

Figure 1. Location of the section of the road under study. The unstable slope position is indicated.

The metamorphic rocks that constitute the rock mass have low quality (medium to high degree of weathering) and have a well defined metamorphic foliation.

Olsacher (1930), indicates that the main discontinuities of the massif have predominant average directions. These directions are: N 5°, 30°, 110° and 125°. In general, the dip is subvertical, or variable between 40° and 75°, predominantly inclined east southeast. In the nearest areas of the Punilla fault, the pattern of discontinuities is distorted, with a random spatial distribution. These geological and structural conditions determine rocky domains with highly variable spatial geomechanical properties.

Figure 2 shows a view of the sector, in stages prior to its final conformation. The heterogeneity of the environment is appreciated.

Figure 2. General view of the slope (Pk. 6 + 200) with instability problems. Unstable sector is indicated in the box.

1.2 Description of the Problem

The designed road has the characteristics of a highway. It is formed by a road with four lanes and has partial lateral access control. The typical cross section has a crown width of 20 meters, which implies the execution of mid-slope profiles, with the formation of embankments and the excavation of slopes on the natural terrain.

Initial preliminary project evaluations defined the formation of an excavated slope with the following characteristics:

- Partial slopes: slope 1v:1h and height 8,0 m
- Berms: width 4,0 m.

The slope under study, in its highest elevation sector, has a greater height than 40.0 m and a total extension of 300.0 m.

In the stage of preliminary geotechnical studies, the sector was characterized by geophysical studies and surface studies. Evidence was obtained that demonstrated a significant decrease in the geomechanical quality of the massif of the sector, with respect to what was found in nearby sites.

During the development of the initial excavation, instability phenomena occurred. These facts demanded the review of the local characteristics of the affected materials, the installation of auscultation systems and the readjustment of the originally planned solution.

2 SITE CHARACTERIZATION

It has been indicated that the location of the structure is characterized by the presence of a rock mass with predominance of metamorphic formations, with a high degree of fracturing. Additionally, the basic components of the massif have a tendency to the development of accelerated weathering processes. The process is accelerated by the reduction of the confinement pressure and the contact with atmospheric agents. This review concludes with the modification of the resistance parameters and the stress and strain variables of the slope.

As a first approximation to the characterization of the affected rocky site, the Hoek & Brown failure model has been used. The parameters used have been defined based on values calculated in the initial surveys, which consisted of surface surveys and the execution of non-destructive tests (geophysics). These parameters have been applied in the transversal profile of the excavation indicated in previous paragraphs.

During the development of the construction, when the excavation was in its lowest sector, landslides of various sizes were observed. The failure mechanisms corresponded to a rotational kinematics. Characteristic elements of this type of movement were observed. Traction cracks were observed at the top. The settlements measured in the upper sector of the fault were several meters high. The settlements presented localized characteristics, which allowed for a retroanalysis. This allowed a review of the adopted geomechanical design parameters, and of the hypotheses applied. Table 1 shows a comparative between the design parameters adopted in the initial stage of design and those resulting from the retroanalysis. The observation of the slope, after the landslides, allowed us to conclude that part of the material initially considered as a low quality massif rock, should be considered as a deposit of clayed-silt soil, with the presence of gravel components.

Table 1. Resistance parameters Hoek & Brown (H&B) and Mohr-Coulomb (M-C).

Stage	H&B model				M-C model	
	GSI [-]	UCS_i [MPa]	m_i [-]	D [-]	c [kPa]	φ [deg]
Initial study	20	12	20	0.5	-	-
Back-analysis	15	4.5	10	0.7	5	28

One of the tasks performed to identify the triggers of instabilities, was the analysis of rainfall data from two meteorological stations located near the site. Those stations were used to evaluate the degree of correlation between seasonal precipitation events and mass removal phenomena.

The construction and its affectation during the period of rains, allowed to visualize water outcrops, at the level of the lower third of the slope. This situation allowed to improve the constitution of the simulation models.

Figure 3 shows an aerial view of the area with instabilities. The variation in the disposition of the local material is appreciated, and this fact allows the construction of the originally planned profile, a few meters from the unstable area.

Figure 4 shows a local view of the damage caused during construction.

Figure 3. Aerial view of the unstable area. Continuous line delimits the area.

Figure 4. View of fissures and settlements in the intermediate berm.

After the first landslide slope reconstruction, review of actions in the sector and topographic control points were arranged along the critical section of the slope (Figure 5).

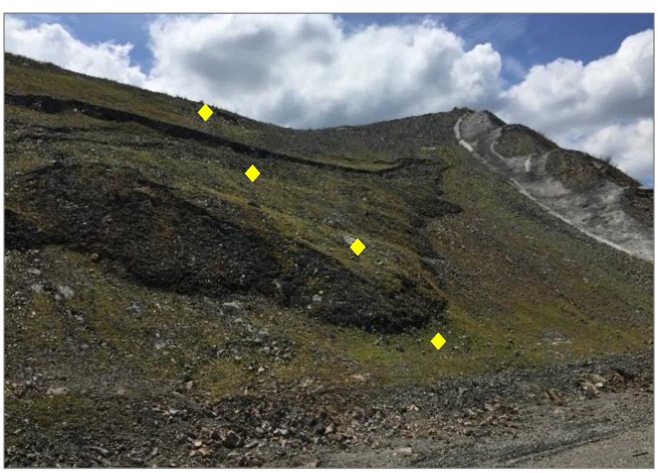

Figura 5. Provisional topographic control points (yellow) placed to monitor the progress of instability.

Those points allowed us to assess the magnitude and direction of the displacements, and their continuity over time (Figure 6).

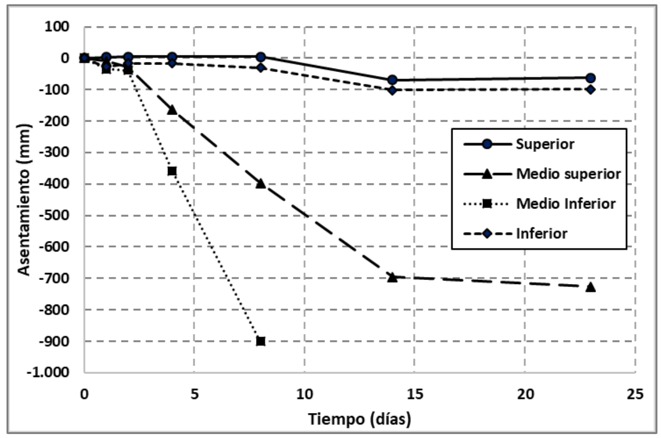

Figura 6. Settlement of topographic control points.

Points located at the upper and lower ends of the fault zone were not affected by the movement of the whole mobilized mass. However, the middle points show significant displacements over time. The magnitude of settlement is around 700 to 900 mm.

In addition, the results of displacement monitoring were correlated with rainfall records, in order to verify its influence on the evolution of instability. A marked reduction in the rainfall regime towards the end of February has been noticed. The tendency to slip was significantly reduced after this.

All this information has been very useful for the constitution of retro-analysis models based on the evolutionary behavior observed (Figure 7).

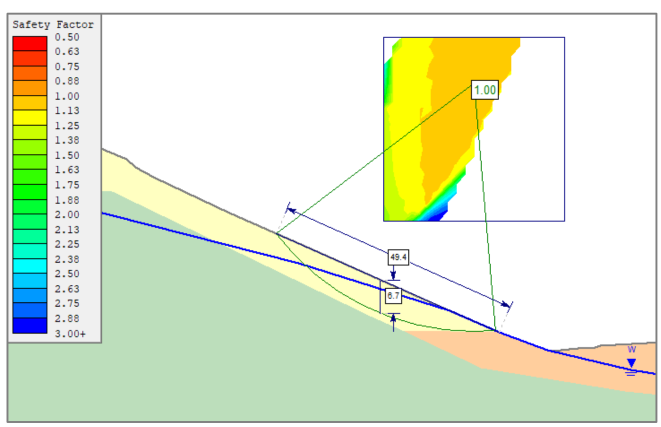

Figura 7. Retro-analysis model. Unitary safety factor under conditions of water table near the surface.

This new model allowed to consider other slope stabilization actions, in addition to excavation with a cross-sectional project profile.

3 STABILITY MODEL

After the first landslides occurred and for the purpose of adjusting the final geometric design of the slope, an analysis of its stability has been done. Despite the localized properties of instability, in all cases, the analyzes were performed using models based on the theory of limit equilibrium in two-dimensional sections. The definition of parameters and their estimated accuracy, concluded in the convenience of using simple methods for the calculation of safety factors, such as Bishop's method.

The evaluation scenarios were the following:

- Scenario 1. Usual operating condition. Global stability under conditions of self-weight of the backslope. The overall safety factor is 1.50.
- Scenario 2. Condition with high water table. Profile considered with a water table inside the slope. It is adopted a 1.10 admissible safety factor.
- Scenario 3. Earthquake action. Effects of a seismic action are included with a pseudo-acceleration of 0.07 g. The acceleration value used for this case, considers that slope material has undergone through a global degradation process, so its ductility has increased. In the future, this acts as an attenuator of the typical basal accelerations of 0.12g, considered in other sectors. An admissible safety factor of 1.10 is adopted for this scenario.
- Scenario 4. Combined earthquake and high water table action. Addition to the previous condition, the effects of a high water table (as in Scenario 2). This is an extreme condition with low probability of occurrence for which an admissible safety factor of 1.05 is adopted.

The modeled geometry consists of a uniform slope of around 25° (Figure 8). The geomechanical parameters used for the final design are those obtained from the retro-analysis model.

During the study stage of the new general stability in the sector, temporary actions were applied that proposed an improvement in local security factors.

4 RESULTS AND FINAL DESIGN

Table 2 shows the safety factors finally estimated for the analysis scenarios. In addition, Figure 8 shows a detail of the typical transverse profile applied.

Table 2. Calculated Safety Factors.

Calculations scenarios	FoS admissible	FoS calculated
E1	1.50	1.56
E2	1.10	1.11
E3	1.10	1.30
E4	1.05	1.10

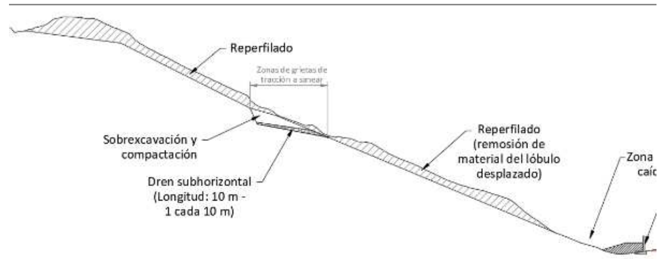

Figure 8. Projected mitigation actios shown on the transverse profile

As can be seen, the solution adopted maintains the initial design criteria through the execution of a hillside reprofiling, which implies the reduction of the height and the modification of the slope. This contributes to the reduction of the weight forces that act as destabilizers in the upper part. In addition, the conditions of visual impact are improved.

The sector where tensile cracks of several centimeters thick were developed, the surface material was removed, and compacted with the use of road equipment. The action carried out was intended to "seal" the fissures generated, in order to reduce potential water infiltration pathways. For this sector, a subsurface drainage system was projected. This consists of a mantle of draining material and perforated ducts separated every 10.0 m. The ducts act as collectors for local leaks. Finally, the coverage was made using fine soils, in order to act as a superior protection. A longitudinal slope towards the foot of the slope was formed, to allow efficient drainage.

In addition, the execution of a surface drainage control system was included. This is composed of ditches coated with shotcrete, which prevents the entry of runoff water into the treated slope.

On the surface, vegetation was applied through hydroseeding techniques. This tends to minimize localized surface erosions and restore local flora.

The solution was completed with the construction of a support wall at the bottom of the slope. It has a double function, on one hand a control structure against possible mass movements located in the lower level of the slope (high percentage of soils), and on the other hand, as a barrier of block fall control. The final solution adopted is presented in Figures 9 and 10.

Figure 9. Final solution materialized. General view of the area with a homogeneous slope.

Figure 10. Final solution materialized. Wall detail for block fall control.

5 CONCLUSIONS

Slope instability phenomena constitute a component of special interest in mountain road projects. Thereby, it is essential to understand the geomechanical behavior of the geological materials affected by the excavations, in order to optimize the construction designs and avoid economic consequences during the life of the project.

To satisfy the idea mentioned in the previous paragraph, it is necessary to constitute a geological-geotechnical model with a certain level of detail, which allows to predict the future behavior with greater certainty. In road projects, as is the case under study, it is difficult to achieve this knowledge in stages prior to construction (preliminary draft and design project stages), due to the strong limitations linked to the lack of geotechnical information of the subsoil. This fact, acquires even greater relevance, in sites with marked geological and geotechnical heterogeneities.

In cases like these ones, the geomechanical behavior model must be validated during the progress of the construction, with the information derived from a better visualization of the affected terrain. This action, which forms the basis of the Observational Method, allows the validation of the hypotheses or their modification and adaptation for a better understanding of the problem.

The case of instability under study represents an example in which the principles of the Observational Method are strictly applicable. The final design of the affected slope was implemented on the basis of the response of the rock mass to changes in natural equilibrium conditions. The application of back-analysis techniques based on events that lead the system to known behavioral conditions, allows to estimate more accurately the global resistant parameters of a material of heterogeneous characteristics, as well as the mechanisms that govern it.

According to the experience of the authors, it is considered advisable to carry out exhaustive geotechnical monitoring during construction and during the initial period of the work. This makes it possible to validate, adjust or reformulate the basic geological and geotechnical model and, therefore, improve the final designs and / or apply corrective measures early and effectively, minimizing the effects of slope instabilities during the period of operation.

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7 ACKNOWLEDGMENTS

The authors thank the technical staff of Empresa Concesionaria Vial Caminos de la Sierras S.A. and to the intervening Construction Companies, Chediack and Astori, for the contribution to the realization of these studies and the collaboration provided in the transfer of these experiences.