Highway cut made in a rock formation with precarious stability

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ABSTRACT
The paper describes the peculiar deformational behavior observed in the vicinity of a 60 m tall highway cut, where the natural slope of the surrounding ground is of about 33% (18°). A description of the observed behavior and comments about its stabilization are included.

RÉSUMÉ
L´article décrit le particulier comportement deformationel observé dans le contour d´une coupe de route de plus de 60 m de haut, où l´inclinaison naturelle de la pente où fut excavé est de l´ordre de 33% (18°). On inclu la description du comportement observé et les commentaires en ce qui concerne son stabilisation.

1 BACKGROUND

The transcendental mission of communication that since the beginning of the last century has been accomplished by the historic federal highway connecting the capital city of Mexico with the port of Tuxpan and the northern part of the state of Veracruz, crossing the states of México, Hidalgo, Puebla and Veracruz. This communication link is currently being upgraded through the construction of the new Mexico City-Tuxpan expressway road and once completed will be operated under the scheme of a concession granted in a bidding process by the *Secretaría de Comunicaciones y Transportes*, the highway branch of the federal government. Once in operation the improved highway will be reduced by 26 km to a total length of 300 km that presently have to be traveled to interconnect Mexico City with the port of Tuxpan, in the Gulf of Mexico.

With the new toll road, whose concessionaire is the consortium known as AUNETI (Autovía Necaxa-Tihuatlán), transportation of passengers and freight will be expedited to alleviate the existing federal highway with only two traffic lanes accommodated in an extraordinarily winding topographic alignment with frequent encounters of rain and fog.

After this new highway is completed, the traveling time between both extremes Mexico City and Tuxpan seaport, will be reduced from five hours to approximately two and a half.

The execution of the final sections of this new toll road, namely Nuevo Necaxa-Ávila Camacho and Ávila Camacho-Tihuatlán, will be the responsibility of the contracting corporation CONNET (Constructora Nuevo Necaxa-Tihuatlán).

In the first of these two stretches of the road, the so called Cut XV is located, in the vicinity of station km 845+250, whose behavior and stabilization constitute the main objective of the paper presented herein.

2 GEOLOGIC AND GEOTECHNICAL FRAMEWORKS

2.1 Regional geology

The area where the highway project is being developed is located at the boundaries of the geologic provinces known as *Eje Neovolcánico* and *Sierra Madre Oriental*. Outcroppings are found of sedimentary rocks from Upper Jurassic, Lower and Upper Cretaceous and Tertiary (Paleocene) constituting what it is known as "*Anticlinorio de Villa Juárez"*. The sedimentary layers and the main structures of the folding present a general NW-SE orientation dipping toward the SW and forming in general terms recumbent structures of asymmetric type.

The deposits from the Quaternary are associated to basaltic lave flows and to their pyroclastic components such as tuffs and breccias with the same composition. From the Recent age there exist talus and fluvial deposits appearing in low lying areas and occasionally covering important areas at hillsides whenever they have been produced by large landslides.

The main feature of the area refers to the largest part of the area that evidences an advanced and deep degree of weathering due to the climatic conditions that have endured and that still prevail. At some cliff zones there are important outcrops where sedimentary and volcanic rocks have been exposed due to the intense erosion produced by the streams running across this region, particularly that of San Marcos River. Streams and gorges in the area develop a quite irregular drainage network that follows a direction sensibly parallel and perpendicular to the strike of the stratification planes.

From a geotechnical point of view, it can be considered that the site being studied corresponds to the most difficult zone of the Mexican Republic to develop infrastructure works due to three main aspects:

- Type and lithological variety that is encountered in the area.
- Climate, including high rainfall rates.

- Abrupt orography.

2.2 Generic stratigraphic profile

The rocks and soil deposits outcropping in this region are listed in Table 1.

Table 1. Rock outcrops found in the region

Age	Formation	Symbol	Rock
Recent, Q	Residual Soil	Sr	A
	Alluvial deposits	Qal	B
	Terrace deposits	Qte	C
	Talus deposits	Qt	D
Tertiary	Chicontepec	Pchi	E
Upper Cretaceous, Ks	Méndez	Ksm	F
	San Felipe	Kssf	G
	Agua nueva	Ksan	H
Lower Cretaceous, Ki	Tamaulipas superior	Kit_s	I
	Tamaulipas inferior	Kit_i	J
Upper Jurassic, Js	Pimienta	Jsp_g	K
		Jsp_d	L
	Tamán	Jst	M
	Santiago	Jss	N

Description of local rocks:

- Sr: Layers of clay-type soil and highly weathered rock, coming from volcanic and sedimentary rocks.
- Qal: Gravel and sands of fluvial origin.
- Qte: Gravel, sands and silts of fluvial and colluvial origin.
- Qt: Soils with variable composition and grain size distribution found at the foot of hillsides or resulting from landslides.
- Pchi: Fine grained calcareous sandstones and laminated gray and greenish clay shale from 2 to 5 cm in thickness.
- Ksm: Gray clay marl and limestone 20 to 30 cm in thickness.
- Kssf: Greenish gray laminated limestone with clay shale and interstratified bentonite and nodules of hematite, 20 to 30 cm thick.
- Ksan: Light gray limestone and clay limestone 15 to 25 cm in thickness, with banded black flint stone 4 to 5 cm thick.
- Kit_s: Light gray and cream limestone in 30 to 50 cm thick strata, with nodules and bands of flint stone occasionally presenting laminated clay limestone and clay shale in layers 5 to 10 cm in thickness.
- Kit_i: Dense fine grained light gray limestone in undulated strata with 20 to 70 cm thickness, with nodules of white flint stone.
- Jsp_g: Dark gray and black limestone in medium thick strata from 14 to 60 cm, with very thin interstratifications of carbonated clay shale.
- Jsp_d: Clay limestone in thin strata with thickness ranging from 10 to 12 cm, with interstratified thin carbonated clay shale.
- Jst: Black calcareous clay shales and dark gray clay limestone, with thin stratification smaller than 10 cm and occasionally lenticular strata. Disseminated pyrite is also found.
- Jss: Dark gray clay limestone in undulated and laminated strata with thickness from 2 to 60 cm, and black calcareous and carbonated clay shale from 2 to 15 cm in thickness. It shows calcareous nodules and concretions with diameter ranging from 15 to 30 cm.

At the zone of Cut XV (Figure 1) rocks of the Méndez formation are found being in contact with Jurassic rocks of the Pimienta formation due to the inverse regional fault that lies immediately to the south.

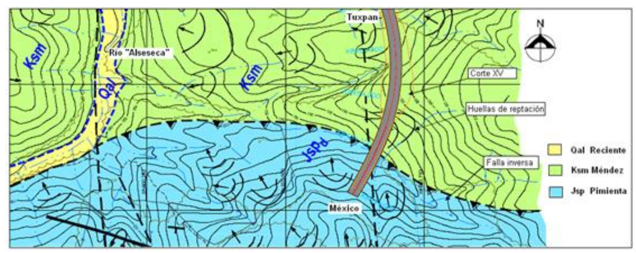

Figure 1. Topographic location of Cut XV

2.3 Underground hydraulic conditions

The region under study, being located in a zone with high rainfall rate, evidences a generally high phreatic level (NAF) that follows, at a certain depth, the general topography of the hillsides, gradually flowing down until reaching its intermediate base level. The NAF shows seasonal fluctuations, subsiding in the dry season and raising rapidly in the wet season. In spite of being a zone with abundant calcareous rocks, karsticity is not a process that governs the phreatic level in the subsoil because this characteristic is generally focused on the rocks of the Upper Cretaceous that are topographically located in high zones, whereas, as mentioned in section 2.2, the stratigraphic sequence include older rocks from the Jurassic.

In the area of Cut XV the underground water level was not detected during borings drilled at the hillside because these bore holes were relatively shallow with respect to the topographic differences in elevation that are found in the region.

During the rainy season temporary seepage is expected to flow through the discontinuities of the rock massif at the cut, but it gradually vanishes as the season progresses.

2.4 Geotechnical peculiarities of the area

2.4.1 Seasonal displacements of the hillside due to rock flowage

The topography in the area of the cut is characterized by the presence of a mountain range with elevations ranging from 1100 to 1650 msnm (meters above mean sea level), with medium to strong sloping of the ground, varying between 30º and 45º. These topographic elevations are found in the sedimentary rocks from Cretaceous and Jurassic, being strongly folded and tectonically faulted. They show a rounded shape typical of their calcareous nature; cliff zones also exist with great height where the sedimentary and volcanic sequence becomes exposed.

Climate has contributed to a large degree in the morphology of the region and in the geotechnical characteristics of the soils and rocks, because during most of the year continuous rains fall provoked by moisture retained and accumulated coming from the Gulf of Mexico that induces in the sedimentary deposits a strong erosion and an accentuated degree of weathering, with residual soils having thickness ranging from 7 to 10 m.

Deforestation, the topographic gradient, and the great thickness of the residual soils generally saturated by rain have led to the development in all of this area of a slow by constant process of flowage at the superficial layer of the ground. Occurrence of flowage and of faulting of the residual soil is evidenced by a morphology represented by short steps and terraces where rain water easily concentrates propitiating constant seepage into the subsoil.

2.4.2 Foliated and deformed rock resulting from an intense tectonic activity

The rock that was excavated from Cut XV corresponds to the Méndez formation from Upper Cretaceous and it is constituted by clay-type light gray marl and limestone forming layers with thickness ranging 20 to 30 cm.

The limestone rock was subjected in the geologic past to intense deformation and folding during the mountain-forming era of the Tertiary. The presence of an inverse-type regional fault that was produced by the same tectonic process affects to a large degree this zone and crosses in the vicinity of the area of the cut, and connects the sedimentary formations of the Jurassic with those of the Cretaceous.

The intense tectonic deformation experienced by the sedimentary rocks induced the development of a structure known as foliation that is characterized by the generation of systematic breakage planes in the rock mass, to such a degree that occasionally the planes of stratification disappear or are difficult to distinguish. The orientation of the foliation planes is similar to that of the stratification planes but they differ in what refers to the direction of dipping. Another important feature inherent to foliation is that its planes show a serous (thin and watery) surface because new laminated minerals were created (chlorite and mica) with low shear strength. Actually, it represents a sedimentary rock with incipient metamorphism induced by a dynamic-metamorphic process.

3 NEW STRETCH NECAXA-ÁVILA CAMACHO

This stretch under construction along the new Mexico City-Tuxpan toll road with a length of close to 37 km, crosses a very abrupt mountain area where very high stiff cliffs mix with hillsides of similar height but with low gradient. The topographic elevation of the alignment varies between 1265 and 378 msnm, with an average value of 822.

To accommodate the alignment of the road in compliance with the high specifications required to keep a significant operative speed, close to 40 cuts are being excavated with heights exceeding 30 m, as well as six twin tunnels and 12 bridges, with lengths varying between 310 and 1382 m in the former and spans from 30 to 850 m in the latter. Complementary works for the highway project include 10 PIV transversal viaducts with the toll road crossing below.

Among those bridges, the San Marcos stayed bridge is worthy of note which crosses its namesake river at an approximate height of 225 m above the river bed. It is worth observing that its Pier No. 4, built at the right bank of the river, will have a height similar to the value mentioned above, therefore ranking it as one of the highest in the world.

Strong weathering of the rock formations at the site, whose folding give an idea of the intense tectonic forces that have occurred at the site, together with the intense phenomenon of erosion that permanently affects the area, lead to the idea that the natural slopes of mountains and hills found in the vicinity of the alignment, maintain a precarious stability, with safety factors very close to one, or even smaller in certain seasons of the year, therefore making them “crawl” (flowage), as evidenced by numerous bent tree trunks that can be observed in the zone.

4 HIGHWAY CUT XV

4.1 Location and geometry of Cut XV

Cut XV, with a length of almost 180 m in plan, is located on the right hand side of the freeway, between stations km 845+160 and km 845+340, a few hundred meters beyond the Necaxa tunnel. The ground surface of the hillside where it was excavated has a moderate slope, of about 25 to 33% on average, forming an angle of 14° to 18°, with respect to the horizontal.

According to the original project design, the cut should have been excavated with an inclination of 0.5:1, to reach a height of 44 m, measured at its shoulder. However, in reality it was excavated with an inclination of 1:1, and its height at the shoulder (chamfer) became equal to 57 m (Figure 2).

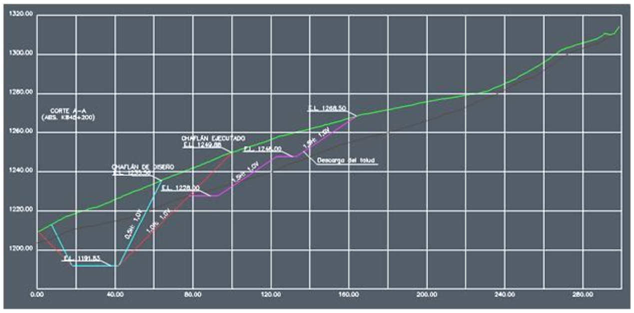

Figure 2. Cross section at Cut XV, at station km 845+200

4.2 Specific geomorphology of the area at Cut XV

The most important river close to the area of the highway cut is known as Alseseca, that rises following the direction of the inverse fault tectonic contact between formations Pimienta of the Upper Jurassic (Jsp) and Méndez of the Upper Cretaceous (Ksm), subsequently changing its strike to follow a trajectory that is perpendicular to the stratification planes. This river has caused deep erosion with differences in elevation exceeding 400 m, and with hillsides inclined toward its course with an average slope ranging from 35º to 40º, alternating with platforms of less grading.

The inverse fault is an important geologic structure because, in general, it induced a high degree of fracturing and foliation in the adjacent calcareous rocks and particularly in the rock mass constituting the mass of the cut analyzed.

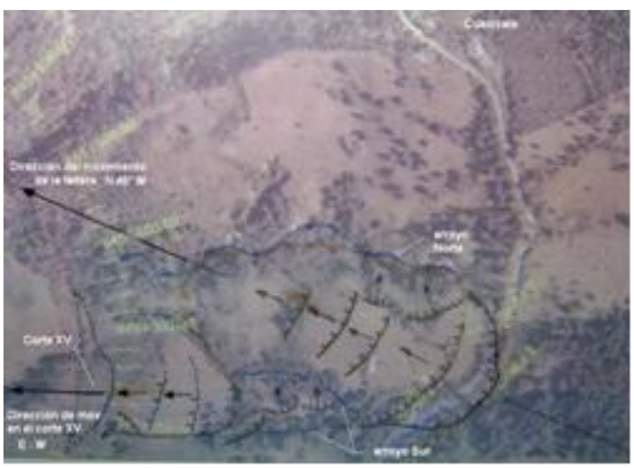

Figure 3. Aerial photograph of the site where Cut XV is located

Morphologically, the hillside is characterized for presenting undulations and stepping representative typical of quite accentuated crawling movements of the residual soil that covers the area and it is quite possible that part of the weathered rock is also involved in the flowage. At the northern hillside, adjacent to Cut XV, there exists another topographic feature that evidences important recent movements, prior to the excavations for the freeway, as shown in Figure 3.

4.3 Stratigraphic profile and geotechnical properties of the local materials

Figure 4 depicts the stratigraphic profile of the highway cut referred to that, according to INGETEC (2009) report, in its deepest part there is fractured clay-type marl and limestone of the Méndez formation (Ksm), whose stratification follows a slightly descending inclination towards the mountain itself and it is therefore favorable for the stability of the cut.

Overlying the Méndez formation, a deposit of fractured and weathered rock is found, having variable thickness, covered in turn by a layer of residual soil with thickness ranging from 7 to 10 m and constituted by reddish brown clay and silt, with low plasticity.

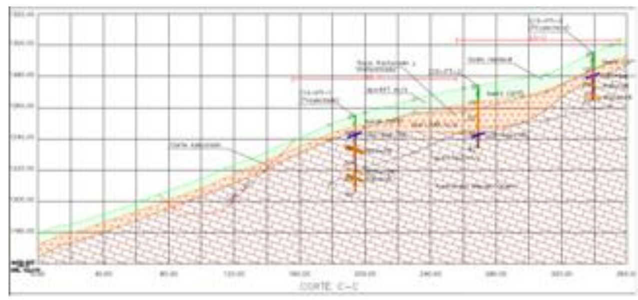

Figure 4. Stratigraphic profile of Cut XV

In none of the three exploratory borings carried out to define the stratigraphy at the site (C15-PT-1 to 3), the phreatic water level was detected. In addition, it should be mentioned that the drilling water was lost in the full depth explored.

For purposes of the stability analyses performed by INGETEC (2009), it was found that the materials encountered in the subsoil underlying the cut have the properties shown in Table 2.

Table 2. Parameters of the materials at the site

Stratum	γ kN/m^3	Su kPa	c' kPa	ϕ' °	q_u MPa
Residual soil	17.0	41	8	29	-
Weathered rock	25.0	-	0	39	-
Fractured rock	25.0	-	39±10	41±3	15±5

4.4 Sliding failure

The shear failure occurred when the elevation of the excavation to accommodate the freeway had already reached the fractured, but not weathered limestone of the Méndez formation. The first or initial failure took place in the southern side of the cut between stations km 845+160 and km 845+200, covering a height of approximately 50 m, and creating tensile cracks at a distance of 25 m from the shoulder of the slope.

The second failure encompassed a larger volume and it occurred 40 days after the first one, appearing a series of tensile cracks at the upper part of the hillside running to about 120 m behind the shoulder of the cut, between stations km 845+200 and km 845+260.

During the time elapsed between the first and the second slide, the excavation operations continued in the northern side of the cut.

In the pictures of Figures 5 to 7 some aspects of the failures can be observed.

Figure 5. Cut XV

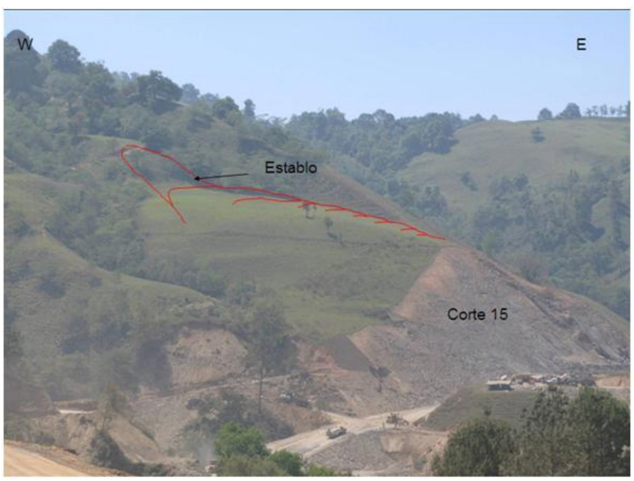

Figure 6. Cracks on the hill adjacent to Cut XV

Figure 7. Detail of cracks on the hill adjacent to Cut XV. INGETEC (2009)

The rate of displacement recorded at the instrumentation bench marks placed at the top and alongside the hill, at the beginning of the movement varied between 2 and 15 cm/day, depending on the location of each bench mark. It subsequently dropped to less than 0.04 cm/day, with a trend to become stabilized.

Figure 8 shows schematically the failures occurred.

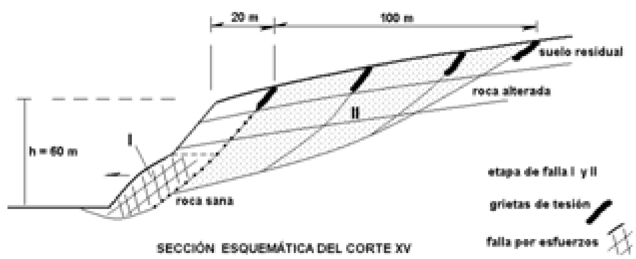

Figure 8. Schematics of the failures occurred in Cut XV

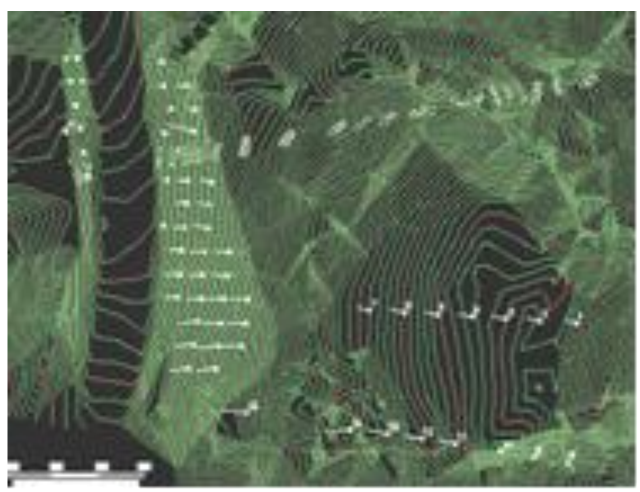

Figure 9. Vectors of the displacements observed at Cut XV

Recently, at the beginning of the month of July 2010, as a result of the occurrence of heavy rains the trend to movement of the cut reappeared at rates of about 1 to 2 cm/day, dropping again after 2nd August to values of 0.3 cm/day and once more with the trend to become stabilized.

Figure 9 shows schematically the displacement vectors observed in the instrumentation installed at the surface of the cut and at the adjacent hillside.

5 BEHAVIOR OF THE FAILURES

5.1 Theoretical explanation of the occurrence

When both shear failures referred to took place, there was no rainy season when the first one occurred in the rocky slope of the cut and when the second happened encroaching the hillside. It is therefore considered that the initial movement was to a certain degree independent of the presence of underground water.

The failure of the slope excavated in rock due to concentration of stresses is not common to happen. It is considered as a failure by compression of the ground at the toe of the slope; however, it is still a rupture mechanism governed by the acting shear stresses (induced by the excavation) that exceed the resisting stresses of the massif at that zone.

It is fairly well known the importance assigned to the discontinuities in what refers to the strength of the rock massif but little is known about the case histories of rock massifs with no discontinuities, massive and homogeneous that are characterized by their low inherent strength. In general, it is considered that just because rock is dealt with the ground shows an intrinsically high strength, without taking into account that other influencing factors exist, in addition to the existence of its discontinuities.

The failure of Cut XV and of two others in its vicinity that were excavated through the same rock represent an example of a case of failure due to stress concentrations whose forecasting was quite difficult to predict following the procedures for study and exploration established for cuts of such height in rock. It is considered that the cut was properly studied to be able to carry out its design, beginning with the definition of the cut slope and ending with the treatments for support, under drainage, drainage and superficial protection.

Attending the conditions of fracturing and foliation experienced by the limestone rock, cores were recovered from the exploratory borings that showed thin stratification planes (0.5 to 2 cm), when they were actually foliation planes. Unconfined compression strength tests performed on the cores showed neither low values (20 MPa, on the average) nor important differences that could help predict a problem of low strength of the rock massif.

The slope failure mechanism could be fairly explained considering the criterion of Hoek-Brown (1994) for rock massifs where it is assumed that the strength σ_{mr} of the ground is a function of the confining stress σ_3 to which it is subjected:

$$\sigma_{mr} = \sigma_1 = \sigma_3 + (m*\sigma_3*\sigma_c + s*\sigma_c^2)^{1/2} \qquad [1]$$

Where m and s are parameters defined by Hoek and Brown (1994), for various types of rocks.

The excavation with a height h = 60 m of Cut XV induced a maximum non confinement σ_3 equal to 4.5 kg/cm^2:

$$\sigma_3 = \sigma_h = \lambda*\gamma_r*h \qquad [2]$$

Where λ is the horizontal stress coefficient and γ_r is the unit weight of the rock.

At the toe of the cut slope the strength of the rock decreased from 4.5 kg/cm^2 to zero or nil confinement.

In most of the rocks this non confinement value is very low and has no major effect in their strength σ_{mr} as rock massif; however, in the case of Cut XV the limestone rock with strong foliation developed is indeed susceptible to this reduction of confinement.

When the acting stress σ_1 is very close to the resisting stress σ_{mr} of the ground, in general the failure process is not immediate but it rather transforms into a function of time f(t).

The initial shear failure developed at the toe of the slope with repercussion toward the upper part along a relatively very short distance (20 m) with presence of tensile cracks.

The second shear failure encompassed the whole hillside with the tensile cracks extending to a distance of about 120 m behind the cut (Figure 8). It is considered that this second failure was due to the fact that the upper part of the hillside is characterized by the presence of materials with smaller shear strength and it is constituted by layers of disturbed rock and residual soil.

The second failure mechanism corresponds to the classic circular approach that is generally developed in soils.

5.2 Actual conditions

As of this date (23th February 2011) the cut has been practically completed and the behavior of the unstable mass is being monitored by means of instrumentation installed for this purpose that includes bench marks and targets topographically controlled to find out the displacements in three directions as well as two inclinometers located at the toe of the cut to determine the zone of influence below the subgrade of the freeway pavement and its movement.

Just before the month of July 2010, the trend toward stabilization was quite evident; however, at the beginning of the month of June and apparently resulting from the presence of heavy rains, new displacements were recorded with rates ranging from 1 to 2 cm/day, that once again tried to stabilize at the beginning of August, with the rates dropping to 0.3 cm/day and with a clear trend to stabilization.

The inclinometers installed at the toe of the cuts indicate that down to a depth of 2.0 m below the subgrade the ground has been affected by the movements; as also indicated by the external instrumentation, the displacements recorded continue to be quite superficial with a trend to gradual reduction with the passing of time.

6 CONCLUSIONS

6.1 Lessons learned

Because it is not frequent to encounter rock massifs characterized by an intrinsic low shear strength (not due to weathering or to the presence of conventional discontinuities), it is difficult to predict problems associated to these types of materials.

When it is assumed that this characteristic will be detected in the rock massif, it will be always necessary to go into further detail with the geologic and geotechnical investigations so as to rule it out or to confirm it. It is required to carry out more exhaustive laboratory and field tests that in general fall outside the scope of the conventional methods adopted in most of the cases.

The loss of confinement induced by excavations in the open have always an effect on the natural stability of the hillside slopes due to the new distribution of stresses, shape and level of concentration; however, at sites with low shear strength of the subsoil material the effect will be more accentuated.

6.2 Possible solutions applicable to the visualized problem of instability

To allow the displacement of the hillside until the movements become stabilized. Monitoring is carried out by means of instrumentation placed at the cut including topographical measurements and inclinometers installed at the toe of the cut. Currently, the displacements measured are quite small.

Under present conditions found at the hillside of Cut XV, with a large number of tensile cracks due to the displacement produced, the potential effect of water infiltrating into the subsoil is going to be a major factor in the long-term stability and therefore the most important actions to be implemented will imply preventing seepage, the superficial channeling of rain water and the under drainage of the ground through drilling of long drains.

To prevent problems of local stability, the surface of Cut XV shall be reinforced with conventional anchors, protecting the surface with triple torsion wire mesh so as to prevent small blocks from affecting the pavement wearing surface and also leaving a wide sidewalk at the toe of the slope and a retrieving wall (collection box) to catch large rock falls.

7 REFERENCES

Hoek, K. and Brown, R.B. 1994. *Underground Excavations in Rock*, Taylor and Francis, Ltd.

INGETEC, Ingenieros Consultores. 2009. Proyecto carretero Nuevo Necaxa-Tihuatlán, Comentarios de la exploración complementaria del Corte XV, *Informe preparado para la constructora CONNET*.