Sudden failure of an embankment resting on a clay soil that behaved as a fluid

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ABSTRACT
During construction of a high-specification highway section in a mountainous humid environment, when a side supported embankment was being built over the left side of a valley, a sudden failure of the supporting clay deposit occurred, causing a downhill sliding of the earth fill and of its clay foundation that behaved as a fluid.

RÉSUMÉ
Pendant la construction d´un tronçon d´autoroute de hautes spécifications dans une zone montagneuse humide, en être en train de conformer un terre-plein “en balcon” sur la pente gauche d´une vallée, se présenta une faille soudaine du terrain argileux où celui ci était appuyé, qui emporta dans son mouvement au cité terre-plein, en se comportant comme un liquide.

1 BACKGROUND

At the central eastern part of the Mexican Republic, crossing the states of México, Hidalgo, Puebla and Veracruz, the Mexico City-Tuxpan toll road is being built that after being completed will shorten by almost 26 km the total length of 300 km that at present has to be traveled along the federal highway connecting Mexico City with the important port of Tuxpan in the Gulf of Mexico.

Even more significant will be the reduction by almost 50% of the traveling time because the five-hour driving time required currently connecting both destination points will be reduced to two and a half hours.

Taking into account the different topographic zones crossed by such turnpike, it can be arbitrarily subdivided in five stretches, as shown in Table 1.

Table 1. Sections of the Mexico City-Tuxpan toll road.

Section	Name	End points
1	High plateau	Mexico City – Tejocotal Lagoon
2	Mountain	Tejocotal Lagoon – Nuevo Necaxa
3	Rugged sierra	Nuevo Necaxa – Ávila Camacho
4	Gentle hills	Ávila Camacho – Tihuatlán
5	Coastal plain	Tihuatlán – Tuxpan

As of to date (23th February 2011) the first two sections of the freeway have been completed and commissioned.

For purposes of construction of the third section, high cuts, road tunnels, viaducts and the long stayed bridge of San Marcos are being built. The fourth section is under construction with additional cuts, embankments and bridges, having moderate heights. Finally, the fifth section will be developed in predominantly flat terrain.

The federal highway that has connected since the beginning of the past century Mexico City with the port of Tuxpan passing by the historic hydroelectric power plant of Necaxa, has constantly endured serious traffic problems because there are only two lanes, one in each direction, and it follows an extremely winding alignment when crossing some mountainous stretches that are frequently covered by fog.

With the new freeway it is intended to expedite moving of persons and cargo between the port of Tuxpan and Mexico City and at the same time connecting in its path numerous zones of major relevance such as the important petroleum zone of Poza Rica.

2 SECTION TEJOCOTAL-NUEVO NECAXA

This stretch of the freeway that was recently commissioned has a total length of 17 km and a sustained downwards differential elevation of almost 800 m with a gradient close to 4%, linking the Tejocotal Lagoon, located at an elevation of about 2200 msnm (meters above mean sea level), in the state of Hidalgo, with the town of Nuevo Necaxa, not far from the city of Huauchinango, both of them lying at an elevation close to 1400 msnm, in the state of Puebla. Mention should be made that this section of the turnpike crosses a wooded area that receives heavy rainfall throughout the year and consequently several springs and water sources are generated.

Because of the rough topography encountered in this stretch, it was necessary to build several bridges and viaducts, in addition to high cuts and embankments.

An important point of note is the abundant source of water, the rough topography and the unfavorable geotechnical properties of the predominately clay and silt soils of the area were combined to give rise to notorious instability phenomena in the cuts that were excavated to accommodate the alignment, that had to be streamlined in some cases to achieve stability.

2.1 Geologic framework

As referred to by Herrera (2002) in its geologic report, the section being studied is located in the northern zone of the state of Puebla, between the boundaries of the physiographic provinces known as Eje Neovolcánico Transmexicano and the Sierra Madre Oriental.

It is a region where the heavy rainy climate gives origin to the source of important rivers that in their course toward the Gulf of Mexico carve deep gorges due to the high potential energy delivered by the head of water running through them added by a rapid dropping of the topographic elevations of the region.

The rocks outcropping in the area are deposits of volcanic origin constituted by flows of basalt and andesite, alternated with pyroclastic materials, breccias and tuffs. At the surface and sometimes to a depth of 30 m, these rocks evidence heavy weathering giving origin to residual soils that often preserve the original structure of the rock from which they originated (saprolites).

In the last six kilometers of the road section, just before arriving at the town of Nuevo Necaxa, the freeway has been cut through the left hillside of a canyon through which the Mazantla River runs with a low flow rate.

According to the report prepared by RVO y Cía. (2006), at the left bank of the canyon aforementioned there exist materials of volcanic origin such as basalts and tuffs in addition to residual soils resulting from weathering of the former. There are also breccias, agglomerates and talus deposits that include earth materials and rocky blocks of basalt.

On the other hand, the right bank of the canyon is characterized by Cretaceous limestone with thin to medium stratification that is overlain by more recent volcanic deposits.

Mention should be made that the left bank, with a differential elevation of about 100 m between the Mazantla River and its divide form an average angle of close to 16° with the horizontal plane, whereas the right bank, with a differential elevation of about 500 m, between equivalent references, describes an average angle of approximately 23 degrees.

2.2 Geotechnical environment

The materials of volcanic origin found at the left bank of the canyon, particularly the tuffs classified by RVO y Cía., (2006) as "free falling", after being subjected to an intense degree of weathering, have converted into residual soils, that can be geotechnically classified as silts and clays, with high and low compressibility, respectively.

Also heavily fractured basalts encountered there might be considered as predominantly granular soils, with large size blocks. Mention should be made that in the vicinity to this highway stretch clay-type residual soils of basaltic origin have been found, preserving the structure of the rock that originated them.

2.3 Presence of underground water

Understandably, as a result of the abundant rainfall occurring at the zone and of the large differential elevation in the topography of the area it is common to find springs and other water sources, particularly after excavating the high cuts that were required to accommodate the alignment of the new highway. It should be observed however that in general the flow rates of such underground water sources are not significant.

The presence of thin sand strata within the predominately clay deposits can be considered as insufficient to induce important hydrostatic pressures internally.

2.4 Historical records of instability at the cuts made to accommodate the alignment of the toll road

It should be also mentioned that during the excavation of the major cuts that were required to accommodate the alignment of the roadway, important geotechnical problems of instability were present together with a curious problem of plastification detected during handling and disposal of the excavated clay or silt material.

This paper does not focus on the particular problem of stability of the major cuts which could be the topic of a further technical paper. However, the topic of handling and disposal of the excavated material constitutes an interesting precedent to the subject matter discussed in this paper and therefore a brief description of the problem is as follows.

2.5 Behavior of the excavated material

Since the very beginning of the excavation of the large cuts in such stretch with maximum heights of 30 m or more and an inclination of 45° through primarily residual clay soils of volcanic origin, it could be observed that the material resulting from the excavation showed an obvious change in its consistency, a fact that attracted the attention of the contractors because they had to modify the whole planning related to the handling and disposal of such material.

In principle, the clay or silt material of the site showed an appreciable strength before being excavated; however, when dumped into trucks for transportation to the disposal pits, its strength was lost and it behaved as a thick syrup when at the end of the trip it was dumped again on top of materials previously piled up, creeping several dozen meters along them.

Similarly, the free surface of the dump yards, assumed inclined during the planning stage, showed a direct trend towards the horizontal, as it naturally corresponds to a fluid.

Mention should be made that for its placement in the dump yard, push tractors with wide crawlers such as those used at marshy terrain were available at the site.

Frequently there was evidence of slides in the clay-type muck inside the dump yards and it was necessary to build low stone levees protected with a geotextile fabric, similar to those used for tailings dams to retain the excavated material thus preventing it from flowing downhill due to the action of gravity, even when sliding along gentle slopes.

These clay-type materials, that originally had sufficient shear strength to maintain the stability of the cuts made through them, had an unusual geotechnical peculiarity, only appreciated in the clay deposits of Mexico City: its natural water content, ranging from 50 to 70%, was in many cases equal to or higher than its liquid limit. In other words, they are materials where pore water pressure is sufficient to convert them into a fluid when they are remolded, an effect that happens when they are excavated, loaded into a truck and transported to a dump yard.

3 PROBLEM OF INSTABILITY BETWEEN STATIONS KM 134+800 AND KM 134+940

One of the most conspicuous problems of instability that developed during the construction of the highway section referred to before occurred when shaping a side supported embankment (Figure 1), located at the left bank of the canyon where at its bottom the Mazantla River flows. Such embankment, with a length of about 200 m and crest width of 15.5 m, slope inclination of 1.7:1 (close to 30°) and designed to reach a maximum height of about 42 m, with respect to the toe of its right slope, suddenly failed when reaching 75% of the total height.

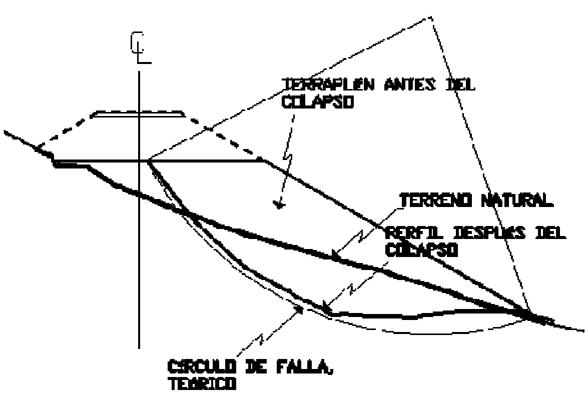

Figure 1. Cross section of the side supported embankment after failure took place. From RVO y Cía. (2006)

According to the description of the reported failure by the staff at the job site, it occurred at about 01:30 hours in the early morning of 29th April 2006 and a volume of nearly 100,000 m^3 was suddenly displaced with no previous development of any crack whatsoever and with no other symptom of instability having been detected in advance. There were no rains neither on the date of occurrence of the failure nor in the 60 days that preceded it.

As a result of the failure and activated by its potential energy that was converted into kinetic energy, the material, converted into a viscous fluid flowed downhill and it crashed frontally against the right bank of the valley, located at a distance of almost 100 m from the toe of the embankment, and afterwards it turned to the left in the direction of the running grade of the Mazantla River, where it became displaced an additional distance of approximately 200 m.

At the end of its travel, the failed material covered an area of almost 2 hectares in the shape of a "jester shoe" having a remnant superficial gradient, along the direction of the river flow, of about 6% (Figure 2).

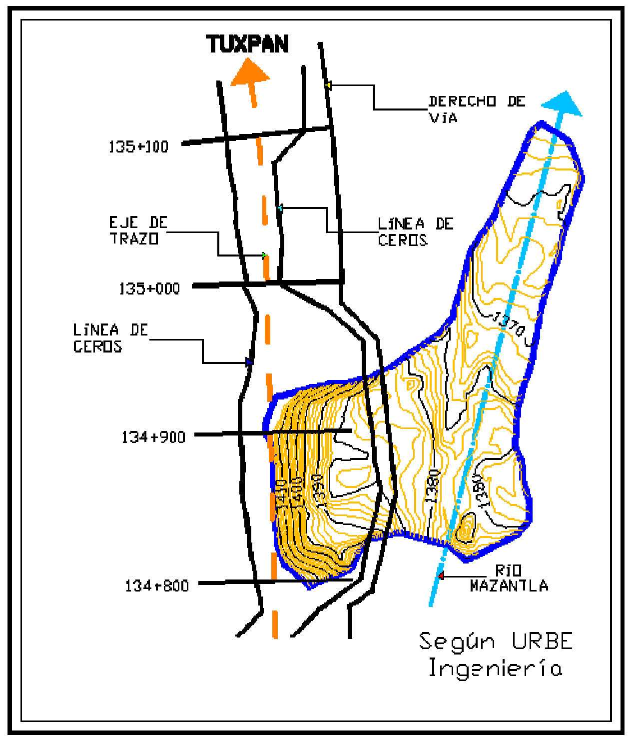

Figure 2. Topographic configuration of the failed material that was deposited in the Mazantla river bed. From URBA Ingeniería (2006)

Mention should be made that when the material was deposited in the Mazantla river bed it obstructed the flow and this made it necessary to excavate a relief trench that regulated the flow of the river.

In the pictures corresponding to Figures 3 to 5, some aspects of the failure occurred are shown.

Figure 3. Remnant escarpment of failure seen from the right bank. From RVO y Cía. (2006)

Figure 4. Remnant escarpment of failure (at left) and flow of the failed material toward the river bed (at right)

Figure 5. Truck carried away by the failed material

Figure 6. Traces of the splash against the right bank of the failed material that flowed like a fluid

Figure 7. Tree dragged by the failed material

In the pictures of Figures 4 and 5 the presence of a trapped dump truck can be observed after being carried away by the flow of the material. On the other hand, a tree dragged by the avalanche of materials can be appreciated in Figures 6 and 7 as well as the presence of the relief trench being excavated by the contractor to reinstate the flow of the Mazantla River that was blocked by the slide.

During the visit paid to the site by one of the authors of this paper, 80 hours after the major event had occurred, a small slide took place carrying a volume of about 8,000 m^3, also constituted by predominantly clayey material that has been estimated to have displaced close to 50 m at a rate of about 5 meters per second.

3.1 Stability analysis of the failed embankment

According to the recommendations of RVO y Cía. (2006), numerous direct and indirect exploratory works were carried out at the site and it was possible to develop the stratigraphic model that is depicted in Figure 8, together with the most critical failure circle resulting from the stability analysis performed by RVO y Cía. (2006), taking into account the “undrained” shear strength of the local materials, having obtained a minimum safety factor of about 0.92.

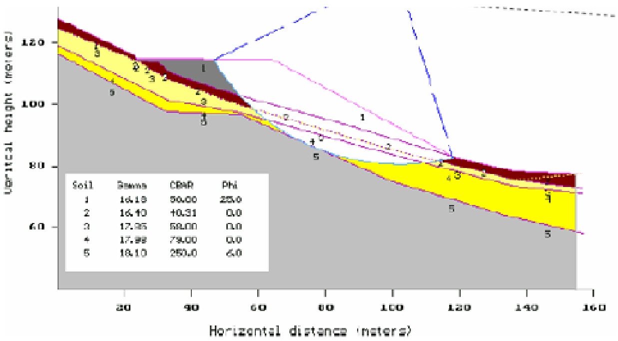

Figure 8. Stratigraphic profile of the site

Table 2 contains the following soil parameters: classification according to SUCS, natural water content (w), liquid limit (LL), unit weight (γ) and the strength parameters *c* and ϕ, determined from triaxial compression tests carried out under three criteria, consolidated-drained (Triaxial CD), consolidated-undrained (Triaxial CU) and not consolidated-undrained (Triaxial UU), of the soils sampled in the failure zone. All of this information was obtained by RVO y Cía. (2006).

Table 2. Soil properties corresponding to the failure zone.

U	w	LL	γ	c_{cd}	ϕ_{cd}	c_{cu}	ϕ_{cu}	c_{uu}	ϕ_{uu}
-	%	%	kN/m^3	kPa	°	kPa	°	kPa	°
U1	-	-	162	-	-	-	-	35 to 79	25 to 27
U2	48	59	164	51	12	54	7	40	0
U3	45 to 69	42 to 54	179	55	27	72	18	58	0
U4	-	-	180	90 to 135	27 to 30	98 to 120	18 to 20	79	0
U5	-	-	181	-	-	294 to 400	>30	250	6 to 34

Where the stratigraphic units U are defined as:

- U1: Material of the embankment, GM, SM
- U2: Residual clay soil, with high plasticity, CH
- U3: Residual silty soil, with low and high plasticity, ML and MH
- U4: Residual silty soil, with low and high plasticity, ML and MH
- U5: Fragments of rock and gravel, packed in a silty matrix.

Using simple formulas of volume and gravimetric relationships of Soil Mechanics, it is easy to verify that the clay and silt materials, whose shear strength values are shown in Table 2, have a degree of saturation close to 100%.

3.2 Geotechnical comments of the observed behavior

When analyzing in detail the geotechnical information mentioned before, as well as certain peculiarities offered by RVO y Cía. (2006), the following comments can be made in what refers the clay and silt soils of units U-2 and U-3:

- In Figure 8, the crust of stratum U-2, depicted with a different color, seems to correspond to a disturbed zone, associated to the growth of vegetation. The mechanical properties of this crust are not apparently playing a relevant role in the stability of the failed embankment.
- The maximum shear strength of the soils included in the units mentioned before is reached at very low strains ranging from 1 to 3%.
- Their residual strength is of about 72% of the maximum shear strength.
- The natural water content of these materials is similar to their liquid limit and in some cases, higher. In other words, these soils have sufficient water in their pores so that their behavior resembles more closely that of a fluid rather than a solid.
- The sensitivity of these soils varies between 30 and 50. It can be then deducted that their shear strength can be seriously diminished in case of being remolded. Even more, if their natural water content is similar to their liquid limit, it can be inferred that upon remolding these materials practically become a fluid.

The last four peculiarities listed above are shared mostly with the clay deposits found in the Valley of Mexico, with certain exceptions, such as for example the natural water content of the clays in Mexico City are many times higher whereas their sensitivity ratio is not so high.

As mentioned by Terzaghi (1967), soils whose natural water content is similar to their liquid limit and that additionally show a high sensitivity value, exceeding 16, can be considered as *quick clays*, because under certain conditions they can be suddenly converted into a liquid that flows, and this phenomenon in our specialty is known as “*solifluxión*” (soil flowage).

Observing the geometry of the failure, as shown in Figure 1, and reasonably confirmed by means of the circle of failure plotted in Figure 8, it can be estimated that close to 45% of the materials that flowed corresponded to clay or silt materials belonging to units U-2 and U-3. This represents close to 45,000 m^3 of the total volume of 100,000 that flowed and, if it is considered that the area covered by the failed material was of almost 2 hectares, it can be deducted that the cover of liquefied soil above which the embankment material flowed had an average thickness of 2.3 m.

3.3 Solution to the problem

After occurrence of the failure different alternatives of solution were analyzed for the roadway under construction, some of them based in the reconstruction of the failed embankment and the alternative, that was finally selected, was the construction of a viaduct bypassing the failed zone, which can be observed in Figure 9.

Figure 9. Solution based on a viaduct, applied to the section failed

4 REFLECTIONS ON THE PHENOMENON OBSERVED

This peculiar stretch of the Mexico City-Tuxpan toll road is showing to the Mexican geotechnical engineers what can be regarded as one of the first recorded cases of "clay flowage" in the country.

Mention should be made that the relatively high value of its natural water content, similar to its liquid limit, is more typical of soils with sedimentary origin rather than those with residual background. Attention is attracted to the geotechnical similarity of these soils with the clay deposits in the Valley of Mexico, in this case of lacustrine sedimentary nature.

Although it is acknowledged that at the subsoil of the job site suggests evidence of the presence of phreatic water, which is manifested through springs and other water sources, it is not reasonable to think that the flow of clays observed can be explained by the presence of them.

At first sight the results of the slope stability analyses based on the geometry of the failed embankment and in the mechanical properties of the supporting materials seem to be reasonable because the geometry of the failure surface was confirmed and the mechanism developed to affect the foundation material. However, there is no theoretical tool available currently to be able to identify the unfavorable phenomenon of "clay flowage" such as that occurred.

Considering the observed phenomenon as a first-time occurrence in Mexico, it is interesting to approach the recommendation of carrying out a more comprehensive geotechnical investigation on the peculiar behavior of clay and silt materials pertaining to units U-2 and U-3 of the site for the purpose of identifying future behaviors that could be unfavorable as applicable to the cuts and/or embankments found along the freeway referred to.

5 CONCLUSIONS

The phenomenon of instability discussed in the paper presented herein demonstrates evidence to an interesting behavior of clay and silt soils found at the area crossed by the highway section Laguna del Tejocotal-Nuevo Necaxa of the Mexico City-Tuxpan turnpike, that displayed the ability of being converted into a viscous fluid that flowed along hundreds of meters, as mentioned in this paper.

The social and economic importance taken on by the highway section recently completed and commissioned leads to the recommendation of performing more precise investigations of the clay and silt materials found at the site for purposes of developing protection measures as deemed necessary to maintain the sound performance of the roadway being studied.

6 REFERENCES

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