

ANALYSIS OF THE EFFECT OF WETTING ON THE STABILITY OF A SIDE SLOPE OF THE GRIJALVA RIVER, IN THE STATE OF TABASCO

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— Abstract—

During the rainy season in the Mexican state of Tabasco there are landslides over the rivers that flow through the state, being one of the most affected area *La Manga*. This paper presents the stability analysis evolution of the side slope due to changes over the soils saturation that forms it, going from safety condition to failure condition. In order to achieve this goal, a campaign of field exploration and laboratory tests was first carried out, which allowed obtaining the geometric characteristics of the river bank, as well as the soil properties that constitutes it. From the undisturbed samples obtained in the exploration field, triaxial compression tests were carried out, varying only the degree of saturation of the soil. With the information obtained and through the GeoSlope 2012 software, stability analyses were performed varying only the degree of saturation. The results show that as the degree of saturation increases, the stability of the bank decrease. It was found that exceeding 70% degree of saturation implies a slip hazard condition. Therefore, the monitoring of the soil degree of saturation that constitutes river banks allows to anticipate its failure and, consequently, makes it possible to establish prevention actions.

Keywords

River bank; cohesion; stability; safety factor.

Slopes, or hillsides, are inclined surfaces regarding the horizontal surfaces that the soil structures must adopt, either of natural origin or product of man activity during the execution of civil works (Juárez and Rico, 2005). Slopes are present in civil works such as dams, excavations, tunnels, river banks, sanitary landfills, etc. Historically, in Mexico there have been landslides of natural and artificial slopes more frequently during the rainy seasons and during seismic events. Geology, relief, the weathering, erosion and tectonic history are factors that condition the slippage of the slopes throughout the world. However, the wetting of the slope constituent material is perhaps one of the most important catalysts for the structural failures of the slopes. During rainfall events, the slopes are exposed to water advance inside their body due to excessive prolonged infiltration. As a consequence of this, the shear strength is rapidly reduced and the volumetric weight of the soil increases (Cho and Lee, 2001; 2002; Ching-Chuan *et al.*, 2008; Akay, 2016; Sun *et al.*, 2016). The structural slope failures that occur during rainy season do so regardless of the type of soil that composes them and their geometry. This is evidence that the wetting of the building material of the slope is one of the main factors that generate instability. Normally the landslides are shallow (Xie *et al.*, 2004). These types of failures are linked to regular rainfall but prolonged periods and can produce positive pore pressures in the body of the slope (Flores-Berrones *et al.*, 2003). The deepest failures are linked to decreased suction (Collins and Znidarcic, 2004) and are due to very heavy and prolonged rains (Casagli *et al.*, 2005). Much of the landslides occur in areas whose climate implies frequent rains during the year (Tohari *et al.*, 2007; Mora-Ortiz and Rojas-González, 2012; Sun *et al.*, 2017). Therefore, several researchers (Conte and Troncone, 2017; Wang *et al.*, 2018) have worked on methods that attempt to predict slope failures.

The state of Tabasco is located within the rainy tropical zone of the country, with the influence of tropical and northern cyclones. It has a warm humid climate with rains throughout the year being more abundant in the months of June to October (INEGI, s.f. ; García Payró, 2015). Tabasco is a flood plain where different rivers converge, among which Tonalá, Grijalva and Usumacinta stand out. The entity is located in the lower part of the Grijalva-Usumacinta basin, a basin that concentrates almost a third of the country's surface water. In the capital of Tabasco, Villahermosa, there are different areas that traditionally have instability of river banks during the rainy seasons. One of these areas is known as *Acachapan* and *Colmena*. This research intends to determine the effect of soil moistening on the instability of one of the river banks that passes through said area, specifically a board located in the *La Manga* 2nd section. It is desired to identify the degree of saturation for which the stability of this bank is at risk. The objective of this

article is to establish the first step to create an alert system of bank sliding on the rivers of Tabasco.

METHODOLOGY

The bank under study is located in Colonia *La Manga* 2nd section, municipality of Centro, Tabasco (Image 1). This area was chosen because it is in one of the sectors most affected by the instability of the banks, the so-called *La Manga* sector. Once the study area was chosen, it was necessary to have the bank's geometric characteristics and the properties of the soil that composes it. To achieve the above, a field recognition campaign was carried out where, using topographic equipment, the geometric profile of the bank was determined. To obtain the characteristics of the bank's constituent soil, three unaltered samples (20 cm cubes per side) were extracted by the Open Pit Mining (PCA) at a depth of 1.5 m following the procedure marked by the NMX-C- 416-ONNCCE-2003 standard.

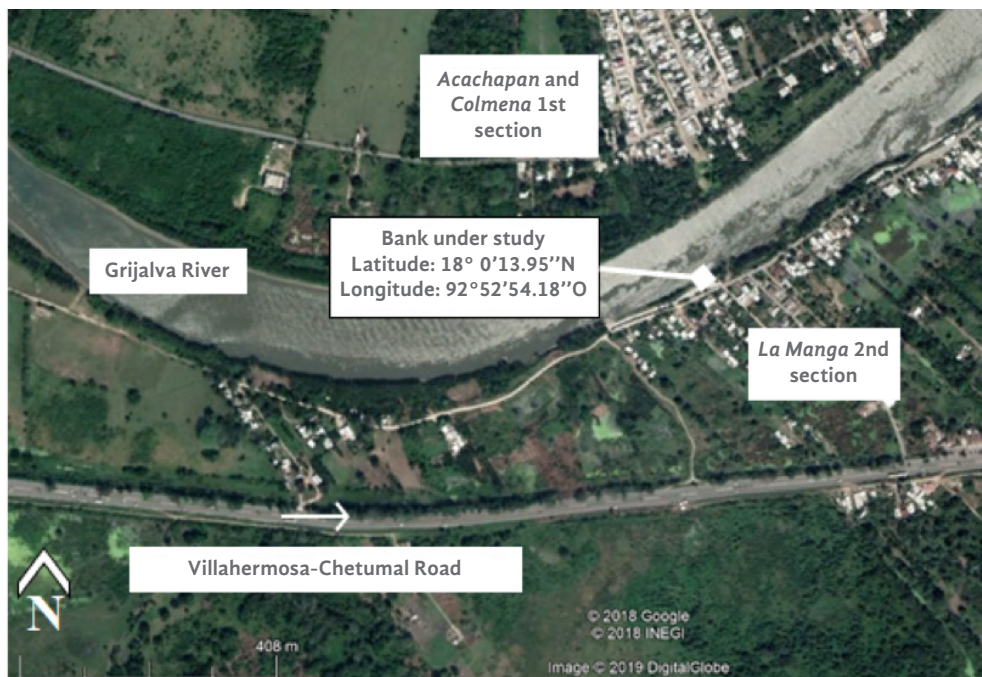


Image 1. Bank under study location

Table 1 shows the basic soil properties determined in the Soil Mechanics Laboratory of the Universidad Juárez Autónoma de Tabasco (UJAT). The liquid limit (LL) was determined with the Casagrande Method; the plastic limit (PL) with the Atterberg Method, the plasticity index (PI) with the arithmetic difference between the LL and the PL. The specific weights of

soil mass and relative solids were terminated with the laboratory tests that bear its name. All tests were performed following the procedure described in standard NMX-C-416-ONNCCE-2003.

Table 1
Basic characteristics and material classification

Liquid limit (LL)	76 %	Relative specific weight of solids	2.64
Plastic limit (PL)	41 %	USCS* Classification	MH (High plasticity slime with sand)
Plasticity Index (PI) = LL - LP	35 %	Degree of saturation (Sr)	42.20 %
Specific weight of soil mass (γ_m)	16.83 kN/m ³		0.77

* Unified Soil Classification System

As observed in Table 1, the soil has a high value of the plasticity index ($PI \geq 18$), which means in engineering terms that it is a material susceptible to decreases in resistance when wet.

The main parameters of the ground that govern the stability of a slope or bank are two: the angle of friction (ϕ) and cohesion (c). The magnitude of the latter is closely linked to the water content of the soil, so that at large water contents the cohesion values are minimal. That is, the more water the soil has, the lower the cohesion value and, consequently, the lower the stability of the edge. For all the above, monitoring the cohesion values and their respective impact on the stability of the slope allows identifying the critical value of this parameter for which the edge passes from a structural safety state to a fault condition. The best way to determine the values of cohesion (c) and friction angle (ϕ) is by the laboratory Consolidated-Drained Triaxial test following the classic procedure described by Juárez and Rico (2005).

Since it is desired to know the evolution of the stability of the riverside as the soil that constitutes it is moistened, it is necessary to know the changes in the magnitude of cohesion as the amount of water increases in the soil. For this, triaxial compression tests were performed on different samples of this soil, varying only its water content. Cylindrical specimens 38 mm in diameter and 76 mm high were carved from the unchanged samples that were extracted during the recognition campaign (Image 2). Sample processing is the process through which, using a minor tool such as knives and cutters, unaltered soil samples (20 cm cubes per side) are obtained from cylinder specimens, in order to perform a laboratory test.



Image 2. Processing of specimens for the triaxial test

To obtain the cohesion value corresponding to the driest state of the soil, three specimens were subjected to a progressive drying in the open air avoiding direct contact of the sun's rays to prevent cracking. Subsequently, a triaxial test was performed on the specimens. In this way the cohesion value for the dry state was obtained, which is reached during the dry season.

In order to know the variation in soil cohesion due to different water contents, specimens were carved and, starting from the dry condition (described above), they were moistened three by three by a slight spray of water with the help of an atomizer. To ensure the homogeneity of the moisture in the samples after wetting them, they were placed in sealed containers for 24 hours. At the end of this procedure, seven groups of three specimens were obtained, each group with a different degree of saturation (Table 2). From the driest to the wettest state, various triaxial tests were carried out, which allowed us to know the evolution of cohesion in the soil under study.

Table 2
Cohesion for different degrees of saturation

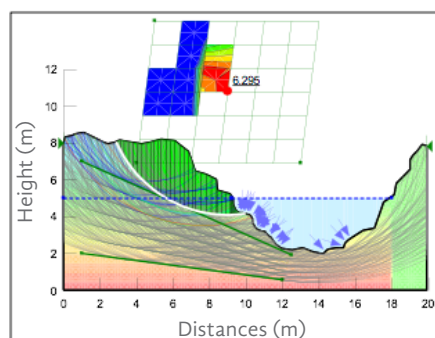
Groups of 3 Specimens	Degree of saturation (S_r)	Cohesion (kN/m^2)
1	8 %	57.45
2	14 %	48.77
3	22 %	33.41
4	41 %	25.68
5	67 %	9.27
6	83 %	3.98
7	95 %	0.48

To evaluate the stability of the edge, the Geo-Slope software (2016) was used. This is an international computer program used to assess the stability of

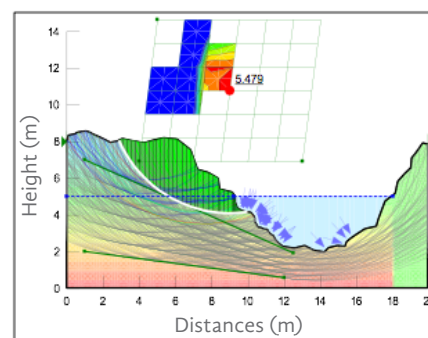
rock and soil slopes in different conditions of load and water table (Gofar *et al.*, 2009; Leung *et al.*, 2017; Munro and Mohajerani, 2018). The program requires as input data the geometry of the slope, conditions of the water table in the area, cohesion, the specific weight of the material constituting the slope (16.83 kN/m^3) and the angle of friction of the ground (24°). All this information was collected during the field exploration and through laboratory tests.

RESULTS

Once the edge's geometric information and the soil characteristics were collected, its stability was analyzed. This analysis consists in quantifying the forces that produce instability, as well as those that oppose the failure. The ratio between the forces that oppose the failure and those that cause it, is known as a safety factor (SF) (Juárez y Rico, 2005; Xiao, 2018). If the numerical value of this factor is less than one ($SF \leq 1$), the bank is considered to be in fault condition. On the other hand, if it is $SF \geq 1.5$, it is estimated that the bank is safe. If the SF is between the two limits mentioned above ($1 < SF < 1.5$) the edge is considered to be at risk. The method used in this investigation to calculate the SF was the Fellenius method (Juárez and Rico, 2005). This method has been extensively studied, and implemented in analysis of soil slopes, and has shown excellent performance. Image 3 shows the stability analysis of the edge for different cohesion values shown in Table 2. In each analysis a mesh is observed in which the minimum value of the SF is shown. According to Image 3, the highest safety factor corresponds to the highest cohesion condition, that is, to the driest bank. It can be seen that as the degree of saturation increases in the constituent floor of the bank, the safety factor decreases (Image.4). It can be seen, in the results obtained, that the stability of the bank is guaranteed ($SF \geq 1.5$) as long as the degree of saturation of the soil that composes it is less than 70% (Image 4).



Degree of saturation = 8 %
Cohesion = 57.45 kN/m^2
SF = 6.295



Degree of saturation = 14%
Cohesion = 48.77 kN/m^2
SF = 5.479

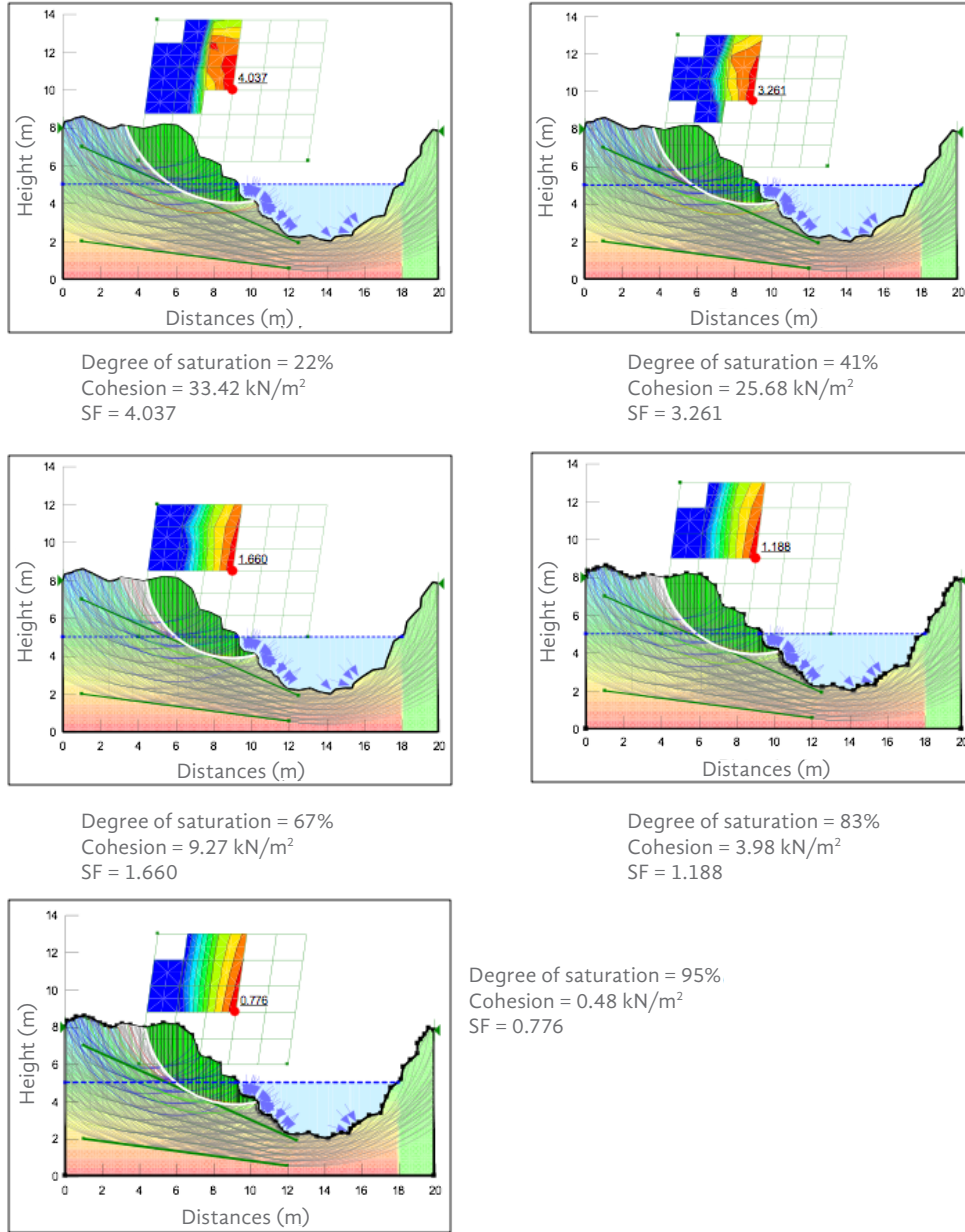


Image 3. Analysis of the bank's stability at different degrees of saturation

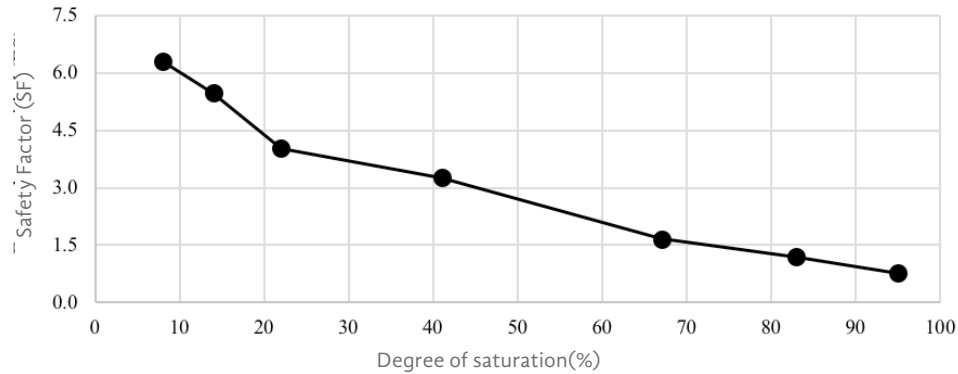


Image 4. Evolution of the safety factor with changes in the degree of soil saturation

From all of the above two conclusions are drawn:

- If rainfall is sufficient to place the soil's degree of saturation between 70% and 85%, the bank is in a situation of risk of failure ($1 < SF < 1.5$);
- If the dampening of the edge places the saturation level above 85%, the bank failure will occur ($SF \leq 1$).

DISCUSSION

Different factors influence banks' stability such as the type of constituent material, geology, weathering, erosion (by water or air), etc. However, in this study we have focused only on the dampening of the material that composes the bank. The above because the experimental evidence published by researchers such as Mora-Ortiz and Rojas-Gonzalez, 2012; Conte *et al.*, 2017; Sun *et al.*, 2017, to name a few, points to soil wetting as one of the main factors that cause instability in slopes located near or far from rivers. This work does not rule out the destabilizing effect of other agents, it simply aims to show that the saturation of the soil that makes up the bank under study alone is capable of causing the failure. A line of future research consists in incorporating into this analysis all the possible agents that contribute to river bank instability.

The results found in this investigation have shown that the progressive moistening of the constituent soil of the bank studied causes a decrease in the safety factor. After the flood in the state of Tabasco that occurred in 2007, it was necessary to repair 43 edges located only in the capital of Tabasco. The above represented an investment of 152.4 million pesos. The following year, after an intense period of rains (October-November), 53 edges were repaired, this time at a cost of 200 million pesos (Marí, 2009). The results obtained in this investigation show (at least for the bank under study) that when the soil reaches a degree of saturation greater than 85%, its stability is at risk. Achieving this degree of saturation in the state of

Tabasco is not difficult, since the entity is in the lower part of the Grijalva-Usumacinta basin (which, as already said, concentrates almost a third of the surface water of Mexico). Tabasco is also located in the rainy tropical zone of the country, with the influence of tropical and northern cyclones; there are rains throughout the year, the average annual rainfall being 2250 mm, although the most abundant rains occur during the months of June to October (INEGI, s.f.).

It is noteworthy that despite the data on banks' failures in the state of Tabasco there is no study today that allows to define the most prone to failure areas during the rainy season. That is to say, there is no danger map of bank sliding. Mexico City has maps of geological danger and hillside instability, and there are maps of geotechnical zoning and seismic zoning (Civil Protection, s.f.).

CONCLUSIONS

Due to its climatic situation in the state of Tabasco there are rains throughout the year, being more abundant during the months of June to November. During these rainy periods there have been consistently failures in the river banks that reach the capital of the state of Tabasco. The present investigation focused on analyzing the effect of soil moistening only on bank stability. It was found that for a bank located in the area known as *La Manga*, the wetting of the soil that makes up the bank is one of the main factors that cause instability. It was found that as the degree of saturation increases the safety factor (SF) decreases from a safe state ($SF \geq 1.5$) to a fault state ($SF \leq 1$). It was found that for the bank under study exceeding a saturation degree (S_r) of 70% represents a danger of failure condition. That is, by monitoring the rains and the degree of saturation of the soil that forms the slopes, it is possible to anticipate their failure. The present study shows a simple methodology that can be the basis for developing a map of danger of bank failure. Because all the bank change in their geometric characteristics and properties of the soils that compose them, it is necessary to repeat the process indicated here to all the banks that are to be monitored. The foregoing will allow the relevant authorities to take actions to ensure the integrity of people and structures close to the banks.

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