A study on stability of natural cliffs with seismic effects

Etude sur la stabilité des pentes naturelles avec effets sismiques

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SYNOPSIS A description of the boulders, gravel and sand cliffs that are located in the littoral of the urban area of Lima-Peru is made, considering its geological, seismic and geotechnic characteristics and, making an evaluation about its behaviour, specially with respect to the actions of the earthquakes that are frequent in this area. The results of the theoretical evaluation of the cliffs stability is exposed, applying the most appropriate method of calculation and establishing for the studied area the actual conditions of static and dynamic stability for usual and probable load effects; as well as for earthquake intensities that could occur in the future. In conclusion, the zonation obtained, based on the theoretical analysis carried out, will coincide with the stability conditions previously reported and represents an adequate criterion of design for the future.

INTRODUCTION

The littoral of the urban area of Lima in Peru, is strongly cut by cliffs that reach up to 70.00 meter height, estimating variable gradients from 50° to 90°of slope in the most of cases. The development of the city, become to be a cause of the construction of buildings and important engineering projects, close to the top of the slopes that means a considerable surcharge that in same cases has affected the adyacent slopes stability (Fig. 1).

In general, the predominant material in this cliffs is the "conglomerate" of Lima, which is a material that has a good resistance to the shear strength due to the cementation of the fine soils mixed with calcium carbonate and to the well joint of gravel between themselves. However, some slides have occured in different zones of the Lima littoral, becouse different factors between which we can mention the follwing:

The seismic force, as an important factor to be considered in the stability analysis of the cliffs, due to the fact that Lima is locatted in a highly seismicity zone and the earthquakes that had previously occured, had notably affected the city; specially those occured in 1940, 1966, 1970 and 1974 (Carrillo, 1979).

The presence of stratum of either fine or loose materials is also an instability factor. We must mention that in certain zones, where stratum of materials appear in the top parts of the cliffs, sliding have occured, whose surfaces through the upper stratum and a portion of the conglomerate

Fig. 1- General view of the actual conditions of the cliffs

Another cause of the produced landslides, has been the effect of the water infiltration in the materials that compose the cliffs. In many zones of the sea-land contact the flow water are produced due to damages occured in the water and sewerage pipes or because of the intensive irrigation in the top of cliffs, this can modify the strenght parameters of the materials that compose such cliffs making it unstable.

With respect to the underground waters, the water table have notably decreased due to the exploitation of approximately one thousand water wells and an evidence of this, is the presence of dead vegetation along the cliffs, besides the water sources have decreased in number and in volume of flow.

The dynamic action of the sea is also another important factor in the stability of this cliffs.

Some studies about such phenomenon in which it is indicated that the dynamic action of the sea is intense in the north part of the studied area, disminishing slowly to the southern part.

GEOLOGICAL SETTING

This granular coarse-grained soil is a part of a big debris cone of Rimac river, constitued by carried material by such river on a very long geological time during the Quaternary period.

From the petrographic point of view it is a sedimentary soil, of uniform aspect that can be classified as a conglomerate of boulders, gravel and sand, well jointed. The aggregates that constitute this conglomerate, are totally igneus.

The studied soil until the corresponding geologic upper Cretaceous period, has been under the sea, emerged from this period over the sea level with a deep erosion and refilled of the actual material by the Rimac river on the Quarternary period forming the coastal zone that underwent active erosion by means of rivers with depot of carried materials constituting the actual debris cone (Carrillo, 1981).

That cone which has a front size wider has underwent a sea erosion and has formed the actual cliff of the coast as a vertical erosion in the sea-land contact that conforms the fluvioalluvial plain where the most engineering structures are settled in Lima city.

GEOTECHNICAL CHARACTERISTICS

The heavy stratum of conglomerate at the central part of debris cone that exceed 400 mts. in depth, this sedimentary material, in some cases, have the presence of lenses of silty sand, fine materials, calcareous crusts, gravel and fine gravel in a dense and dry state. Therefore, it is possible to establish the following physical and mechanical parameters for "Lima conglomerate":

Dry unit weight (γ) 18 kN/m^3 to 22 kN/m^3.

Density index ranged between 70% to 95%

Effective diameter (D_{10}) of 0.15 to 0.45

Uniformity coefficient (c) of 10 to 130.

Average cohesion (c) ranged between 40 kPa to 80 kPa, and

Angle of internal friction (ϕ) ranged between 36°to 42°.

In many of these studied cases it has been found that generally appear two tension craks; the first one nearer to the slope edge that normally appear between 2.00 mts. and 4.00 mts., and originates the first material sliding, detecting in the majority of cases a second tension crack located between 10.00 mt. and 20.00 mts., from the upper part of the slope, generating a wedge that penetrates under the first wedge and originates a heave at the lower part of the cliff slope (Carrillo, 1982).

SEISMOLOGICAL CHARACTERISTICS

The Lima city is located in the seismic zone of the Southern Pacific; and, in accordance to the seismic statistics carried out in Peru, it can be considered for the urban area that approximately every twelve years a seismic of MM VI grade or more will occur, according to the modified scale of Mercalli intensities. Earthquakes of greater intensity up to MM IX degree, have been registered since approximately 1578, every one hundred and thirty years and from this time there has not been registered any epicenter in the area of metropolitan Lima.

The earthquakes records will only be useful as a reference data, because for estimating the seismic force, the typical acceleration of the earthquake must be considered. Taking into consideration the accelerations registered in the last four severe earthquakes occured in Lima in 1940, 1966, 1970 and 1974, maximum acceleration of average recurrence of 0.25 g. can be estimated, 0.15 g. as an average acceleration for frequent earthquakes and 0.10 g. as a minimum acceleration (Carrillo, 1977).

EVALUATION PRODEDURE

From the different methods existing to analyze the slope stability, to elect the most appropiated method to analyze the cliffs stability of Lima, becomes to be difficult due to the fact that in accordance to the different references, each one recommends a different method and in some cases coincide with another same method.

By other hand, the slidings of different magnitude that have occured in the cliffs, have showed mon-circular slip surfaces.

From the methods that do not restrict its analysis to a circular slip surfaces, the most recommendable methods are those that satisfy all the equillibrium conditions, so that the results to be obtained will present a lower rate of insecurity (Jambu, 1973; Sarma, 1973).

However, the most recommendable action was to use one of the rigorous methods, and between them, the most simple, even sonsiderating the inertial forces generated by an earthquake.

If we consider the problem of the earthquake, between the Janbu and Sarma methods, the last one resulted to be more simple. The proposed method by Sarma is developed in order to obtain below a simple iterative fact, the corresponding seismic acceleration for an assumed safety factor and to obtain a factor of safety curve versus seismic acceleration with approximately three iteractions, from which, we can obtain the respective safety factor for each seismic acceleration; as well as the static safety factor, when the seismic acceleration is equal to zero; and, the critical seismic acceleration that will be required in order that the factor of safety become to be equal to one (Sarma, 1975).

The advantage of this method is that there are mon-convergence problems that sometimes appear in other iteratives methods. This simple method is as safe as the Morgenstern - Price method as it presents similar values in a similar problem. However, the obtained solutions by Sarma method, as well as occur with other methods, were verified in their physical acceptability before to be adopted; it is, the internal forces obtained with the solution must not modify the failure criteria and the tension must not be implicit in the soil mass.

The slopes stability analysis of the Lima cliffs were developed using many programs supported by a IBM - VM / 370 computer, installed in the Computation Center of the National Engineering University and also with assitance of the Hewlett - Packard HP 41-CV

Taking into consideration this point of view, the analysis was developed by zones. All the coastal area was divided in thirty zones, according to their characteristics and a representative section was obtained in each one with the respective stratigraphy and dimensions (Fig. 2).

With respect to the geometrical configuration of the sections, these were obtained through measurements with topographycal equipment.

The conglomerate of Lima was the predominant material in the most of cases, and many of them were intercepted by stratum of silty-clay material.

To effect the stability analysis when the thickness of the fine material stratum has not been significant, it was considered as a homogeneous slope, this is, as if the slope were only composed of conglomerate. It had been possible to observe that the thickness of fine material performs a significative influence in the results when this reaches the 10% of the total height of the analised slope.

Up to five slip surfaces were tested in each representative section, indicating as a critical shear surface that in which the lowest values were obtained for the static safety factor and the critical seismic acceleration.

RESULTS AND DISCUSSION

The zones were classified by two pints of view, in accordance with the obtained results from the respective stability analysis: static and dynamic.

In order to classify the zones in accordance with the safety factor found; the static point of view was considered to determine certain criteria:

Class 1, probably unstable or critical: factor of safety lesser or near to 1.00

Class 2, medium stable: factor of safety between 1.10 to 1.20.

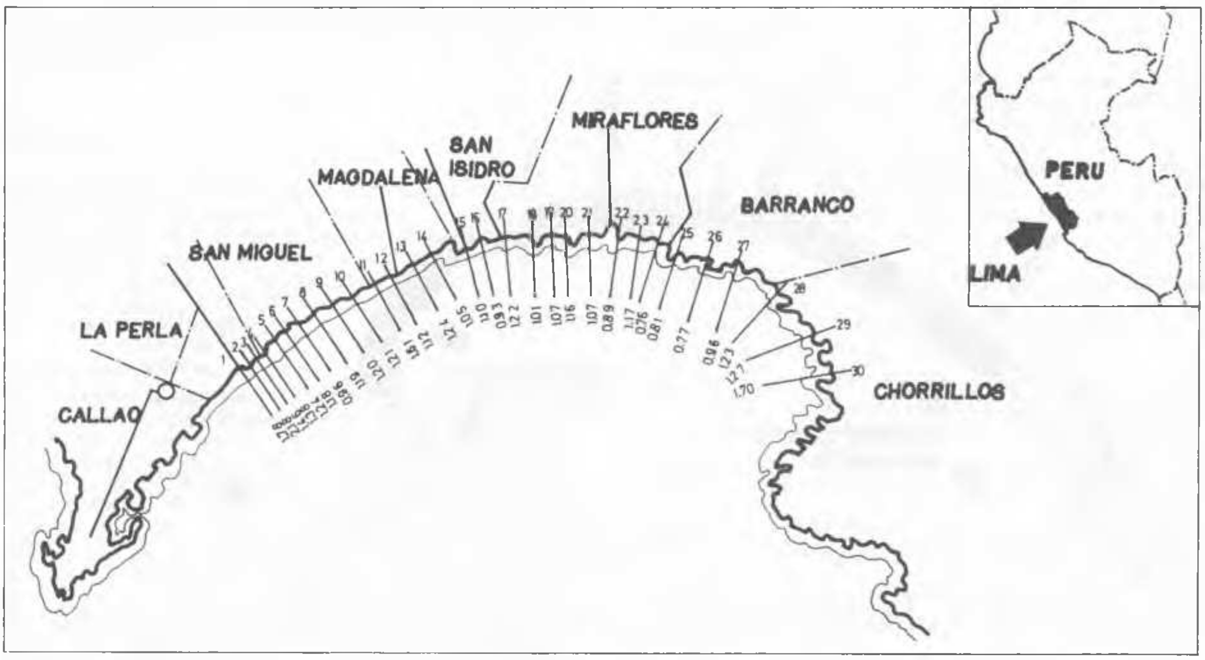

Fig. 2- Location of the studied area and its factor of safety

Class 3, stable: factor of safety between 1.20 to 1.40.

Class 4, very stable: factor of safety greater than 1.40

This criteria, although arbitrary, is a product of the author experience from the development of studies in the soils and cliffs of Lima during many years.

In Figure 3, the studied zones were arranged based by the static safety factor determining the stability of the zones.

It was established that for certain slopes, some safety factors, lesser than the unit were found and even so, the slope did not fail. This is probably due to the reason that the stability analysis was developed with the average values from the material strength parameters, however, each zone can present different values to these averages. Otherwise, we must mention that all the slopes that presented this incongruence are totally composed of conglomerate, material that has a good strength due to the cementation of its particles, this is a property that can not be measured with the conventional laboratory tests. May be this is the principal reason that allows the higher slopes still firmly stay, although they must have fault as indicated in the calculated safety factors.

We can also observe that in the most of cases in which the safety factor is lesser than 1.0, the solution does not fullfill the conditions establish for the method and in accordance with the theory this implies that the assumed critical shear surface was not appropiated for the given conditions.

Consequently, the new factor of safety would be greater than the calculated, therefore those results considered as unacceptable, have been considered as true, and will give us a certain margin of validity.

From the dynamic point of view, we can clasify the studied slopes in three types, according with the calculated critical seismic acceleration.

The classification criteria had been established based on the seismic acceleration records and on the observed earthquakes. Then, three types of slopes have been established:

- Type I : It can fail when seismics of MM III or MM IV grades of intensity occur, in the modified Mercalli scale, and has a lower critic seismic acceleration than the minimum acceleration registered (0.10 g.)
- Type II : Susceptible to fail when earthquakes of MM V or MM VI grades of intensity occur and that have a closer critical seismic acceleration registered (0.15 g.)
- Type III : Those whose critical seismic acceleration is close to the maximum seismic acceleration value registered, 0.25g., these slopes can fail when seismics of grade MM VI to MM X or more occur.

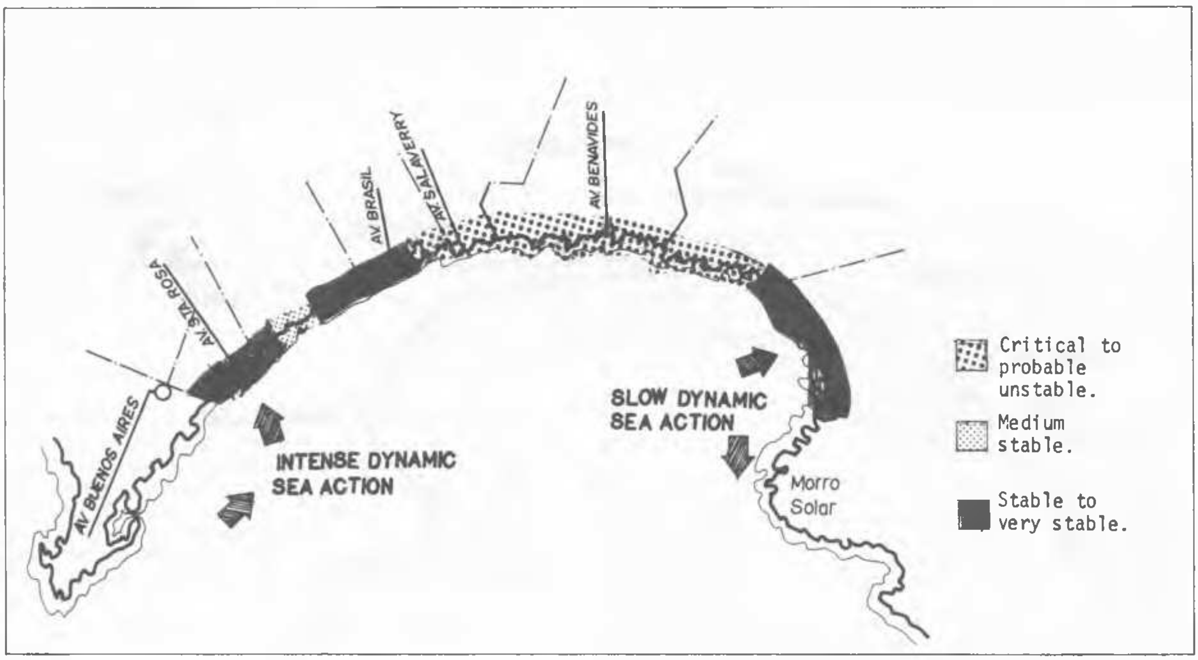

Fig. 3- Static stability conditions of the Lima-cliff

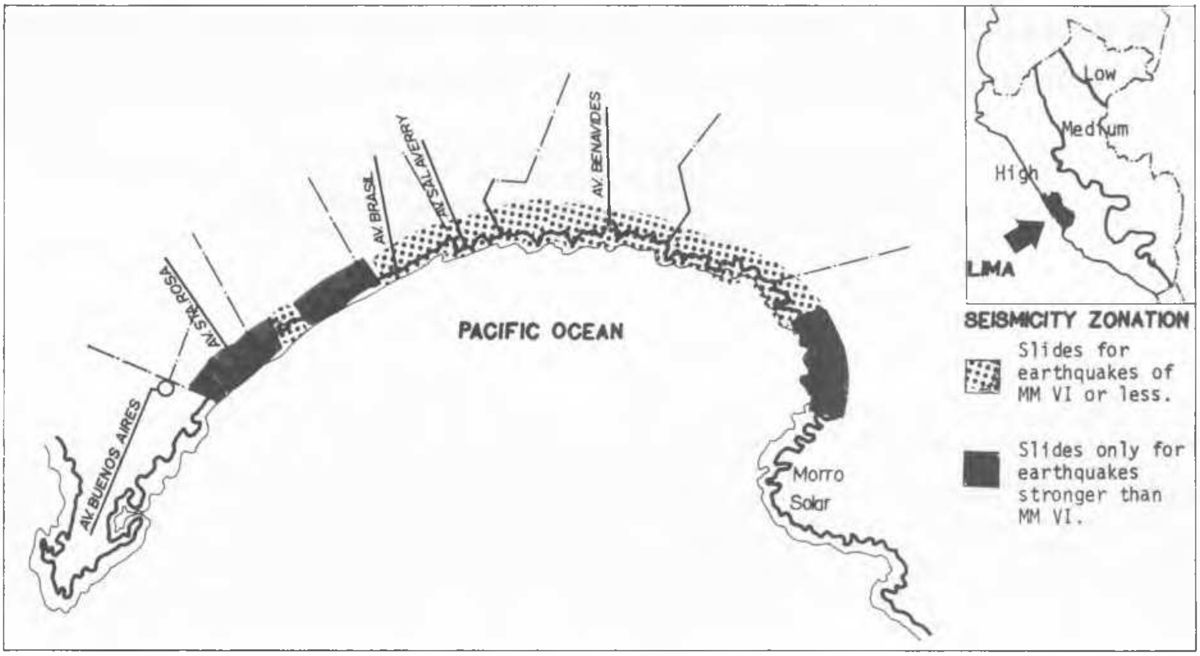

Fig. 4- Dynamic stability conditions of the Lima-cliffs

In Figure 4, the studied zones, based on its calculated critical seismic acceleration, have been ordered, finding out that zones with critical seismic acceleration with negative values, appear. The interpretation of a null critical seismic acceleration, means that these slopes are in equillibrium state, and could fail with a slight earthquake.

However, it is posible that this does not occur in the reality, due to the reason that the above mentioned factors increase the shear strenght of the material.

CONCLUSIONS

1-The evaluation method used for establishing the stability of these specific slopes, composed by coarse grained soils have resulted acceptable for getting an adequate static-dynamic zonation, inside the necessary limitations to fullfill the minimum equillibrium conditions and their boundaries characteristics.

2-In some cases, due to the special characteristics of these materials, incongruencies in the results of theoretical evaluation have appeared, since slopes with lower safety coeficients than the unit of negative critical seismic acceleration even stay stable. However, after an adequate interpretation of these cases, its incidence have been generalized untill getting the indicated zonation, which allow to take measures of security during the construction of buildings in those areas of the Lima city, given that its results allow to establish the stability characteristics that mantain a close relation with the local conditions found in case of slidings that have previously occured.

3-The unstable areas a cause of a dynamic action, have resulted more extensive than their similars from the static point of view; consequently, it is established that for these slopes, the action of the earthquakes must be considered as a very important factor in the analysis of the slopes stability and in the engineering design.

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