Journal of Coastal Research	SI 39	629 - 632	ICS 2004 (Proceedings)	Brazil	ISSN 0749-0208

Failure Mechanisms of a Coastal Cliff in Rio Grande do Norte State, NE Brazil

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ABSTRACT

SANTOS JR., O. F.; AMARAL, R. F. and SCUDELARI, A. C., 2006. Failure mechanisms of a coastal cliff in Rio Grande do Norte State, NE, Brazil. Journal of Coastal Research, SI 39 (Proccendigs of the 8th International Coastal Symposium), 629 - 632. Itajaí, SC, Brazil, ISSN 0749-0208.

Part of the coastline of Rio Grande do Norte State is bordered by an escarpment of about 90° and 20 to 40 m high. This cliff is composed by beds of tertiary sediments of sandstone and conglomerate (Barreiras Formation). Six kilometers of sea cliff was selected as the subject of this study, with view to the changes brought about by the tourism industry, especially concerning the land use with the building of hotels and restaurants, in the last decade. This paper describes an investigation of failure mechanisms that has caused coastal cliff erosion in this area. Laboratory studies were carried out on twenty disturbed samples obtained along the cliff. Direct shearing and unconfined compression tests on undisturbed block samples were carried out to obtain geotechnical properties of the sediments. The effects of the saturation on the cohesion and the friction angle were also investigated. Field works were conducted to identify the causes of slopes failures. The result of the tests showed that the sediments consist mainly of clay sand with low plasticity. An expressive loss of strength when the soil is saturated was also noted. Three types of rupture were observed in the area of study: gullies due to superficial run off at crest of the cliff, sliding at the upper and middle parts of the slope and fall of material due to undermining of the base of the cliff.

ADDITIONAL INDEX WORDS: *Coastal erosion, sea cliff, slope stability.*

INTRODUCTION

The mountainous coastline of the State of Rio Grande do Norte, in the Northeast of Brazil, is distinguished by the cliffs and sand dunes, associated to sandy beaches. Beach rocks are also commonly found in the form of reefs, usually close and parallel to the shoreline. This sequence is interrupted by river beds that flow into the ocean.

Recently the occurrence of coastal cliff erosion has been studied at some sites of the shoreline of the Rio Grande do Norte State (AMARAL, 2001; SANTOS JR. *et al*., 2001). The retreat of the coastline towards the continent probably results from natural processes such as the medium sea level rise associated to the instability on the sedimentary balance by antropic interferences.

Studies on the mechanism of sea cliffs retreat indicate that the retreat rate depends on the hydrodynamics factors (BRAY and HOOK, 1997; WILCOCK *et al*., 1998; LIZARGA-ARCINIEGA and FISHER, 1998; PERATH and ALMAGOR, 2000; KIRK *et al*., 2000), continental climatic factors (HAPKE and RICHMOND, 2002; DUPERRET *et al.,* 2002) and geological factors (HUTCHINSON *et al*., 1981; BUDETTA *et al*., 2000).

The area object of the present work is located at the eastern coast of the Rio Grande do Norte State, about 60 Km to the south of Natal, the State capital city (Figure 1). It comprises an extension of approximately 6 km in the municipality of Tibau do Sul (located between the municipality seat and Pipa beach), characterized by sea cliffs varying from 20 to 40 meters high. Regarding the occupation and land use the tourism industry has put a great pressure on this area by building vacation resorts. According to the Tourism State Secretariat (SETUR, 2002) the local tourism sector of Tibau do Sul is among the ones which have experienced greater development in the country. However, coastal cliffs erosion has been observed in this area thus causing a retreat in the shoreline. This fact represents a hazard to the tourism industry since most hotels; restaurants and bed and breakfast accommodation have been built very close to the cliff border line. Consequently, they are at risk of collapsing as a result of retreating of the coastline.

As it could be seen, the need to study the coastal cliff erosion processes in this region as a subsidy to the policy of land use and occupation is of the utmost importance. Studies on the retreat of coastal cliffs have been developed at national and international levels, based either on aerial photographs or surveying/mapping at different times. Generally, rates of average retreat are obtained which can be used for planning of a certain region. However, the retreat of the cliffs occurs abruptly as a result of the falling of a slope. Thus, it is important to be aware of the failure mechanisms which cause the sliding of the slopes.

The present work is intended to make a contribution on this matter by identifying the failure mechanisms which are associated to the retreat of the cliffs existing between Tibau do Sul and Pipa beach. Based on the identified mechanisms in the area under study, conceptual models of cliff retreat forms are proposed.

STUDY AREA

Tibau do Sul is limited to the north with the south border of the Guaraíras lagoon; to the east with the shoreline of the Atlantic Ocean where the cliffs are located; to the south with the canal of the Catú River and to the west with an invisible line that connects the region of Barracas at the point of bifurcation of the Catú River to the western limit of the Guaraíras Lagoon.

AMARAL (2001) drew a map of the coastal zone of Tibau do Sul and sub-divided it into three sections (Figure 2): north, central and south. The northern section goes from the border (bar) of Tibau do Sul to the Ponta do Madeiro. The central section starts at the Ponta do Madeiro and continues up to the Pedra do Moleque. The southern section starts at the Pedra do Moleque and ends at the mouth of the Catú River.

The main factors which exert influence on the climatic characterization of this area are related to its geographical location. The climate of the region as a whole is classified as sub-humid with an annual average temperature of about 26ºC and an annual average humidity of about 74%. The heavier rainfalls range from April to July (SETUR, 2002).

At the coastal area of Tibau do Sul the identified relief comprises the coastal mesas (plateau with altitudes between 40 120 meters high), the coastal plain land (low areas), the coastal cliffs (oceanic borders of the mesas surface), the dunes and the beach rocks (blocks of ferruginous sandstone and reefs). These forms found in the whole coastline of the Rio Grande do Norte

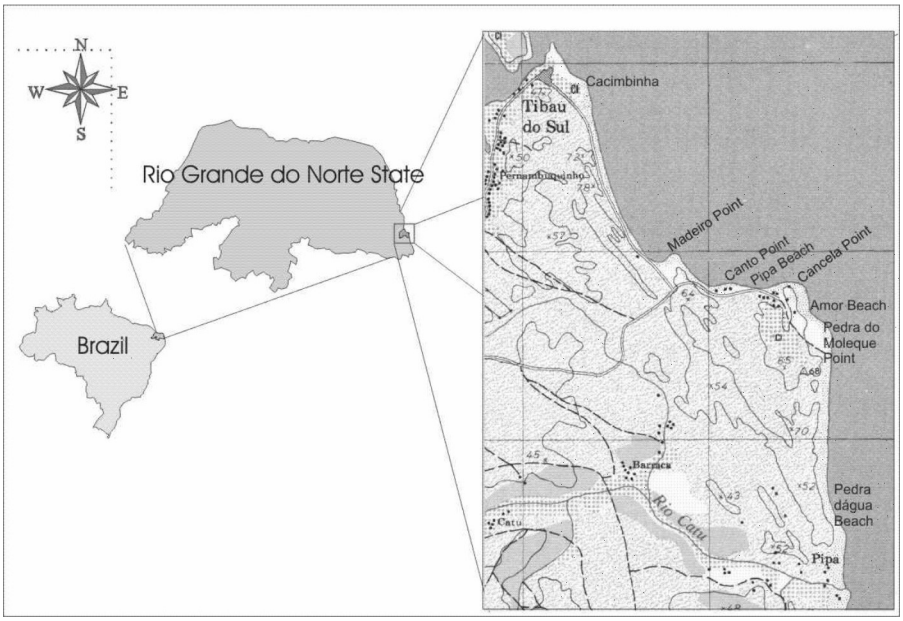

Figure1. Site of the studied area.

State as well as in most of the northeast coastline of Brazil.

The coastal mesas correspond to the low plain type of relief and their altitude does not reach 150m. They are located near the seaside but are hardly touched by the sea water. The coastal plains consist of sand beaches between the sea and the coastal mesas. The escarpments between the coastal mesas (barren sand-table) and the coastal plains form what is called coastal cliffs. These are present along the whole of the Northeastern coast. They are very steep descending slopes made of pre-Quaternary sediments of clay of Formação Barreiras, near the sea, and sometimes are separated from the sea by recent sedimentary formation (retreated cliffs), but they can also be in direct contact with the sea water (live cliffs). They indicate a recess (retreat), towards the continent, of the present coastline. The reefs have been submitted to a high level of use, and it is common to find residential homes and tourism resorts at their borders. In some sections mix raised shore line (debris brought by the sea or the wind) could be found at the reef base.

The dunes are well defined high land or sandy crest created by the sand brought by the wind which exist regardless the local topography. They are located at the seaside, considered as recent primary dunes without vegetation, as well as in the continent, on the surface of the Mesas, initially as parabolic dunes without vegetation, and then as parabolic dunes with vegetation. The parabolic dunes with vegetation can show the past climatic variation and the lower level of the sea water, which in its turn gave the necessary space for the wind to carry the sediments. Following this, the oldest dunes were dispersed and their sediments filled up part of the present recessions on the mesas surfaces, thus making them plain.

The geological aspect of the area is made up of materials from sedimentary origin. At the mesas the sediments of the Formação Barreiras (barren sand-table), which consist of intermixed layers of argillaceous sandstone, clay, pudding-stones and ferruginous sandstone are found. The sediments of Formação Barreiras appear on the surface of the coastal cliffs. The dunes are made up of fine quartz sand brought about by the wind. On the coastal plain sandy beaches can be found. Another body of beach rock which shows a linear geometry can also be found there. They are cemented by carbonates and are seen at some sections along the area under study, in line approximately parallel to the coastline (beach rocks).

METHODS

The whole area was visited with the objective to mapping the features which are related to the retreat of the coastal cliffs. Observations were made at each section identified in the morphological mapping of the coastal area of the Tibau do Sul municipality, carried out by AMARAL (2001) according to Figure 2. These observations took into account the protection offered by the cliff base against the basal erosion; the materials which form the slopes; the shelving geometry and the occurrence of instability at the escarpments.

Protection from the erosion caused either by beach rocks or sand bank carried by the waves to the cliff base was surveyed. The cliff faces were observed in order to identify the geo-technical properties of the materials that form the slope walls, the presence of vegetation, the geometry of the form and failures that could be characterized as weak points for the occurrence of mass retreat.

Field works were carried out during the rainy season and the dry season, with view to identify the influence of rainfall on the failures suffered by the cliffs. Slope instability caused by debris from sliding materials from the upper part of the escarpment was registered by photography and mapping of the region from June 2000. The sections in which basal erosions are predominant were identified based on ruptures at the cliff base.

Samples were collected to be used for the study of the geotechnical properties of the materials collected from the three sections in the area under study. At previously selected places undisturbed block samples were collected to be used in tests of strength and compressibility.

For the geotechnical characterization experiments were carried out on the following parameters: particle size, Atterberg limits (liquid and plastic limits), and specific solid weight. The undisturbed samples were submitted to unconfined compression tests and direct shear tests. With the objective to study the effects of rain water infiltration into the material that form the cliffs, the experiments were carried out using samples in their natural state (showing a very low water content) and also saturated.

RESULTS AND DISCUSSION

Laboratory Experiments

The experimental results showed that the sediments that form the coastal cliffs are predominantly sandy clay and low compressibility clay. Based on the clay color it was possible to clearly identify two main types of materials. The upper part of the cliffs is composed of red sand clay with a slight strengthened with iron oxide. At the lower part white clay was noted with more rigid red nodules. A third type of material can be found at some sections of the studied area. These are layers of

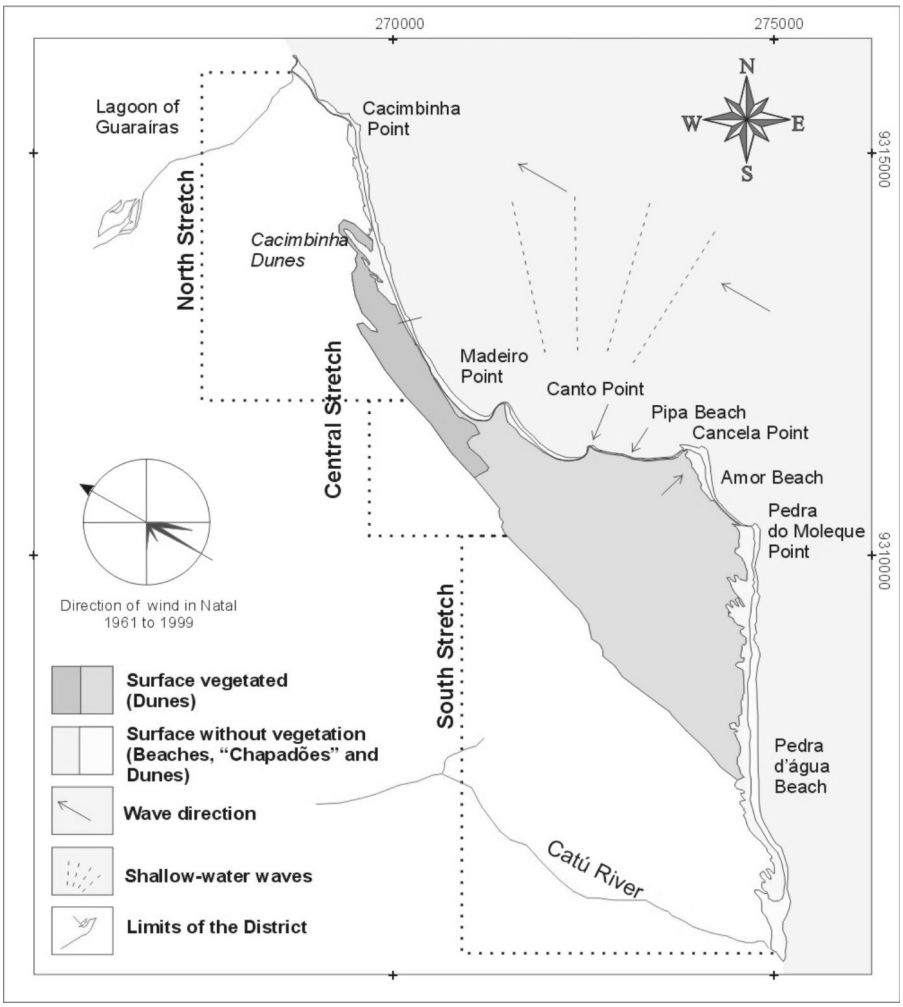

Figure 2. Morphological mapping of Tibau do Sul (AMARAL, 2001).

ferruginous sandstones at the middle of the cliffs or blocks of this material at the slope base.

Confined compression tests carried out using samples in their natural state and saturated showed that the soil is not of the collapsible type. On the other hand, crumble tests showed that the material at the lower part of the slope could be considered as dispersive, that is, in the presence of water it tends to melt.

The results of the simple compression tests showed a high rate of dispersion. The material at the upper part the strength to compression ranged from 340 to 610 kPa in twelve samples tested. The base material showed variations in the range of 380 to 617 kPa. This variation could be the result of small natural discontinuities in the samples of the upper part and to the heterogeneity of the material at the lower part.

The direct shear tests were carried out using naturally humid samples as well as those saturated. The results are shown in Table 1. The analyses of these results show that there is a loss in the strength of the material, either at the upper or at the base of the cliff, when it is saturated.

Field Observations

The field work developed during the study of the coastal area initially consisted of the identification of the types of natural processes of the cliffs superficial dynamics. The data obtained from this allow a preliminary analysis of the processes to which the cliffs are submitted.

Table 1. *Results of direct shear tests.*

Localization	Conditions of water content	Cohesion (kPa)	Angle of friction
Upper part	Natural	193	45
	Soaked	50	28
Lower part	Natural	318	52

In general, instability processes in the cliffs were observed, associated to heavy rainfall (pluvial erosion and/or mass gravitational movement) and to the action of the waves on the shoreline and directly on the base of the cliffs. The first case exerts a greater influence on the northern and southern sections. The central section is influenced by both situations, being the wave influence very clear. The types and processes of retreats observed in this area are shown in Figure 3.

The combination of the mass movements is a result of the complex structures of the slope. Mass movements classified as complex ones were also observed, because there are more than one type of movement, such as fall of blocks of sediments, toppling and sliding. The most commonly observed situation was the fall of blocks of sediments which gave rise to the formation of talus deposits at the base of the cliff, as it can be seen by the significant amount of debris from this origin at the base of the cliffs along the whole extension visited.

Generally, these blocks were detached from regions situated at the upper part of the cliffs and at the middle of the slope. They probably result from the penetration of water in vertical discontinuity (together), formed by tension relief which exert a pressure on the detachment of the block from the massif. This same mechanism seems to be responsible for the occurrence of movements classified as toppling.

The most important movements in terms of number consisted of sliding and erosion at the upper part of the slope, followed by the fall of unstable material. These movements damaged the buildings at the margin of the cliff, especially because of the destruction of the access routes to the beach. These types of

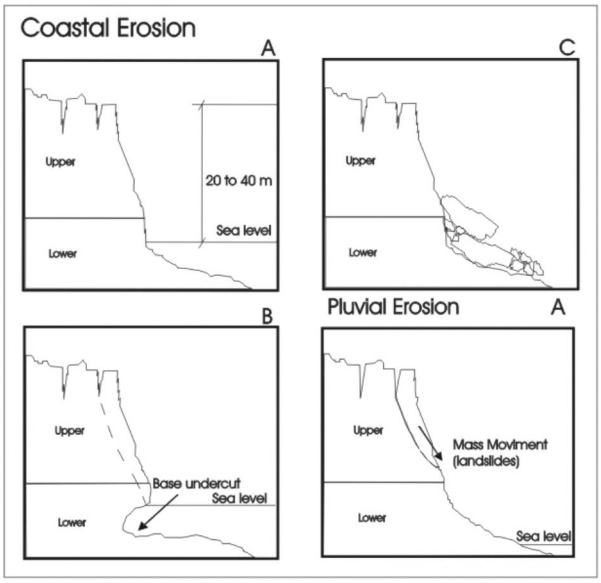

Figure 3. Retreat mechanism of the cliffs.

movements are mainly found at the central section.

Erosion was also observed at the upper part of the slope at the superficial sandy layer. Below this level, the declivity is practically vertical, thus favoring the fall of materials either due to different strength degrees (some layers are cemented with iron oxide) or, especially, the erosion action that reaches the base of the slope thus undermining the slope base.

All these mechanisms together cause the retreat of the slope as time goes by. The evolution of the retreating process is clearly evident when the amount of debris from past instability at the base of the slope is observed. Besides, proximity to the slope is a hazard to some adjacent buildings as well as to the access road to other beaches further to the south.

CONCLUSIONS

The direct influence of the waves and the removal of the sediments from the base of the slope stimulate the retreat process. Block falls and stumbling can also contribute to this process.

Sand movement caused by the waves at beaches with sea cliffs and the decrease of the unstable volume of sediment rise the erosion power of the waves in these regions. This aspect is exacerbated by the existence of dispersive clay at the base of the sea cliffs.

Besides the natural retreat caused by the ocean natural movements, the retreat of the cliffs are also caused by pluvial erosion. In the northern and southern of the area under study continental pluvial erosion and the mass movements are considered as the most important natural occurrences. At the central section a higher intensity of the ocean influences, through the direct action of the waves on the slope base, were observed.

The result of the sea cliff retreat/failure mechanisms is an increase in the risk of destruction of the buildings located near the slope borders. The incidence of these risks is lower in the cliff areas protected by ferruginous sandstones.

LITERATURE CITED

AMARAL, R. F., 2001. A Dinâmica Ambiental e o Problema da Erosão na Zona Costeira do Município de Tibau do Sul. IDEMA. Internal Report. 45 p.

BRAY, M. F. and HOOKE, J. M., 1997. Prediction of Soft-cliff Retreat with Accelerating Sea-level Rise. *Journal of Coastal Research*, 13(2), 453-467.

BUDETTA, P.; GALIETTA, G. and SANTO, A., 2000. A methodology for of the relation between coastal cliff erosion and the mechanical strength of soils and rock masses. *Engineering Geology*, 56, 243-256.

DUPERRET, A.; GENTER, A.; MORTIMORE, R. N.; DELACOURT, B. and DE POMERAI, M. R., 2002. Coastal Rock Cliff Erosion by Collapse at Puys, France: The Role of Impervious Marl Seams within Chalk of NW Europe. *Journal of Coastal Research*, 18(1), 52-61.

HAPKE, C.; RICHMOND, B., 2002. The impact of climatic and seismic events on the short-term evolution of seacliffs base don 3-D mapping: northern Monterey Bay, California. *Marine Geology*, 3135, p. 1-20,.

HUTCHINSON, J. N.; CHANDLER, M. P. and BROMHEAD, E. N., 1981. Cliff recession on the Isle of Wight, SW coast. *Proceedings of the 10th International Conference of the Soil Mechanics and Foundation Engineering* (Stockholm), pp. 429-434.

KIRK, R. M.; KOMAR, P. D.; ALLAN, J. C. and STEPHENSON, W. J., 2000. Shoreline Erosion on Lake Hawea, New Zealand, Caused by High Lake Levels and Storm-Wave Runup. *Journal of Coastal Research*, 16(2), 346-356.

LIZARRAGAARCINIEGA R. and FISCHER, D. W., 1998. Coastal Erosion Along the Todos Santos Bay, Ensenada, Baja California, Mexico: An Overview. *Journal of Coastal Research*, 14(4), 1231-1241.

MANSON, G. K., 2000. Subannual Erosion and Retreat of Cohesive till Bluffs, McNab's Island, Nova Scotia. *Journal of Coastal Research*, 18(3), 421-432.

PERATH, I. and ALMAGOR, G.. The Sharon Escarpment (Mediterranean Coast, Israel): Stability, Dynamics, Risks and Environmental Management. *Journal of Coastal Research*, 16(1), 225-228.

SANTOS JR., O. F., AMARAL, R. F. and SCUDELARI, A. C. 2001. Mecanismos de ruptura de taludes em sedimentos terciários da Formação Barreiras no litoral do Rio Grande do Norte. *Proceedings of the 3rd Brazilian Conference on Slope Stability* (Rio de Janeiro, Brazil, ABMS Brazilian Society of Soil Mechanics and Geotechnical Engineering), pp. 125-131.

SETUR. 2002. Secretaria de Turismo do Rio Grande do Note. Os impactos sócios, econômicos, culturais e ambientais provocados pela atividade turística no município de Tibau do Sul/RN. Access in april / 2003. http://www.sebraern.com.br/estudos_e_pesquisas_tibau.htm.

WILCOCK, P. R.; MILLER, D. S.; SHEA, R. H. and KERKIN, R. T., 1998. Frequency of Effective Wave Activity and the Recession of Coastal Bluffs: Calvert Cliffs, Maryland. *Journal of Coastal Research*, 14(1), 256-268.