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Sea Cliff Retreat Mechanisms in Northeastern Brazil

O.F. Santos Jr.†, A.C. Scudelari†, Y.D. Costa† and C.M. Costa‡

†Dept. of Civil Engineering
Federal University of Rio Grande do Norte, Natal
59072-970, Brazil
olavo@ct.ufrn.br, ada@ct.ufrn.br,
ydjcosta@ct.ufrn.br

‡ Dept. of Civil Construction
Federal Institute of Rio Grande do Norte, Natal
59015-000, Brazil
cmlins@gmail.com

ABSTRACT

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The coast of the State of Rio Grande do Norte at the Northeast Region of Brazil is undergoing an accelerated process of urbanization. The coast of Rio Grande do Norte State is formed by cliffs and extensive dune fields. The cliffs are formed by steep slopes with heights up to 50 m and inclinations to the horizontal ranging from 20º to 90º. During the last few decades, facilities for tourist activities have been built at the top of the cliffs and nearby region, ignoring the risks of landslides. This paper presents and discusses the retreat mechanisms of sea cliffs monitored along 16 km of the coastline of the City of Tibau do Sul, Brazil. The modes of failure of vertical sea cliffs include fall, topple, and slide from the upper part of the slopes. Surficial erosion and slides have been identified in slopes with inclination between 45º and 60º. The stability of the cliffs becomes more critical when seawater reaches its base. Under this situation, an incision at the toe of the cliff is formed by wave action, triggering the instability of the upper layers. The action of the sea occasionally results in instabilities of major proportions.

ADDITIONAL INDEX WORDS: *Coastal erosion, landslide, slope failure, soil shear strength*

INTRODUCTION

Sea cliffs are landforms basically originated by coastal erosion, located at the boundary between land and ocean. According to Emery and Kuhn (1982), sea cliffs are present in about 80% of the ocean coasts of the Earth. A sea cliff is classified as an alive cliff if it is in direct contact with the ocean. Alive cliffs are often continuously eroded by marine action. On the other hand, a dead or indented cliff is situated at the inner regions of the continent, far from the influence of the ocean.

In many regions of the world, population growth has forced the urbanization of sea cliff areas. However, occupation of those areas may lead to hazardous conditions due to landslides and erosion processes. The risks associated with sea cliffs occupation tend to worsen with the perspective of sea level rising due to global warming.

Assessment of sea cliff retreat processes and stability mechanisms is very important in order to establish guidelines for management of urbanization of those zones, as well as to minimize potentially hazardous scenarios. This may be achieved by proper monitoring of coastal areas.

The rate of sea cliff retreat has been addressed by several studies mostly based on historical photographic and cartographic records (Gulyaev and Buckeridge, 2004; Collins and Sitar, 2008; Cruz de Oliveira et al., 2008; Quinn et al., 2010). Research on the mechanisms of sea cliffs retreat have shown that slopes may fail by different types of movement, which may happen simultaneously in the same area (Pierre, 2006; Greenwood and Orford, 2007; Bernatchez and Dubois, 2008). Sea cliff stability depends on structural, mechanical and hydraulic properties of the soil or rock mass and their response to external agents (Hutchinson et al., 1981; Budetta et al., 2000; Duperret et al., 2002; Fiorillo, 2003; Collins and Sitar, 2009; Taibi et al., 2009). External agents may be of continental origin (ex.: weather conditions, change in stresses within the soil mass and loading on the cliff crest) or marine origin (ex.: action of waves and tides, presence of gravel or boulders, and morphology of the shore platform).

This paper presents and discusses the retreat mechanisms of sea cliffs monitored along 16 km of the coastline of the touristic City of Tibau do Sul, located in the Northeast region of Brazil. A systematic observation of types and processes of mass movements occurring in the surveyed area was carried out. Aspects that influence cliff retreat were assessed in order to provide data for management of land occupation.

Geology of the Region

Geologic and geomorphic aspects of the coast of Rio Grande do Norte State were studied by Amaral (2000). Previous studies on this topic indicate that this region is under a retreat process due to coastal erosion (Diniz, 2002; Silva, 2003; Braga, 2005; Severo 2005 and Santos Jr. et al. 2008). Figure 1 shows the location of the area investigated in the present study. Ground profile at the region is composed of Tertiary sediments of the Barreiras Formation, arranged in intercalated layers of sandstone and claystone with conglomerates. Ferruginous cemented layers are also present in the soil. In some locations, the sediments of the Barreiras Formation are superimposed by eolic dunes. The shore is composed by marine sand. The geologic profile of the region is illustrated in Figure 2.

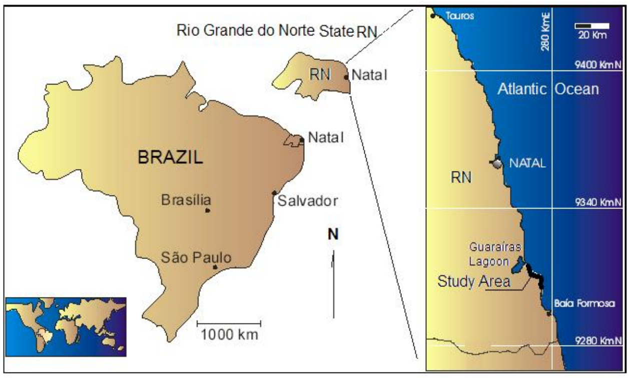


Figure 1. Map of Brazil showing the location of the State of Rio Grande do Norte, at the Northeast Region of the country.

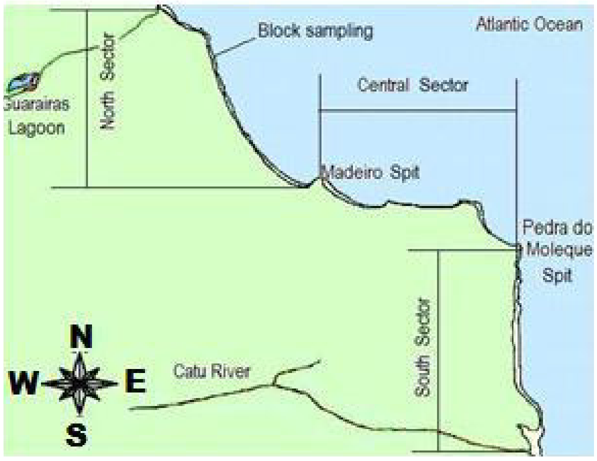


Figure 3. Map of the studied area.

METHODS AND DATA

Field Survey

The studied area was divided into three distinct sectors (Figure 3): North Sector, Central Sector and South Stretch Sector. North Sector is oriented SE-NW, and is about 6 km long. It starts at the mouth of the Guaraíras Lagoon and ends at Madeiro Spit. Central Sector is oriented E-W and has a length of approximately 4 km. It is situated between Madeiro Spit and Pedra do Moleque Spit. The South Sector is oriented N-S and is 6 km long. It begins at the Pedra do Moleque Spit and ends at Catu River estuary.

A systematic survey was carried out at the three sectors in order to identify the morphological characteristics of the sea cliffs and retreat processes. Specifically, analyses on the morphological characteristics of the sea cliffs involved measurements of height and slope of the cliffs, as well as the identification of natural or artificial protections at the cliff toe. Assessment of the retreat processes at the region included detection of pluvial erosion and mass movements.

In an attempt to assess the influence of soil water content in the sea cliff retreat processes, fieldwork was carried out in periods of the year with different pluviometric characteristics (rain and dry seasons). Landslides at the sea cliffs were photographically and cartographically recorded based on the identification of debris at the toe of the cliffs. Zones where erosion at the cliff toe prevailed due to the action of waves and currents were identified by the presence of typical incisions at the toe of the cliffs (Figure 4a).

Pluvial erosion was classified as ravines or gullies (Figure 4b). Ravines were considered as openings at the terrain with maximum width and depth of 0.5 m. Ravines larger than that were the defined as gullies.

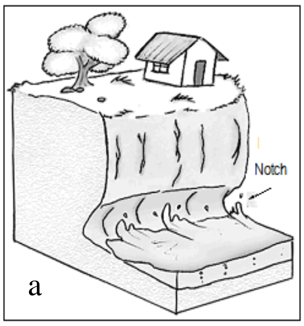
Landslides were classified as slides, topples and falls. Slides are m[...] well-defined failure surface, and th[...]id block. Topples consist of the de[...]f a mass of any size about some pi[...]d from the cliff, and descends thr[...]

S[...]tory Testing

[...]cted at the surface of a sea cliff in [...]om thr Guarairas Lagoon (see

1 Sand Dune
2 Sanstone / Claystone
3 Cemented Ferruginous Sandstone
4 Sandy Beach

Figure 2. Geologic profile of the studied area.



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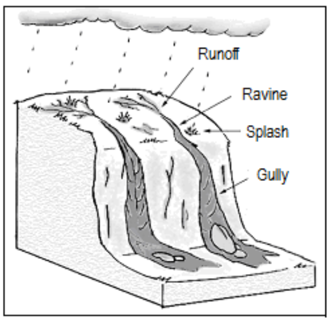

Figure 4. Types of erosion in sea cliffs: (a) pluvial erosion, (b) erosion at the cliff toe.

Figure 5. Erosion at the top of a sea cliff in North Sector, caused by rainwater discharge.

Figure 6. Landslide in North Sector after intense rain.

Figure 3). The samples were used for obtaining the geotechnical parameters of the soil of the sea cliff. One sample was collected at the crest and the other at the toe of the cliff. Sampling at the middle of the cliff was not possible due access issues and because of the high level of cementation of the soil in that location.

The collected samples were used to perform direct shear tests on undisturbed specimens in order to assess the strength characteristics of the material. Grain size analysis, Atterberg limits, crumble tests, and partial immersion tests were also carried out with the collected materials.

Two distinct series of direct shear tests were performed in order to address the effect of the degree of saturation on the mechanical behavior of the materials. The first series was conducted on specimens with natural water content, whereas the second series was performed on inundated specimens (i.e., with degree of saturation of 100%).

Crumble tests and partial immersion of undisturbed blocks were also conducted with the material (Head, 1985). The tests included molding approximately spherical specimens with 50 mm in diameter. The specimens were then immersed in a becker containing 600 ml of distilled water. The tests consisted of monitoring soil disintegration and particle dispersion under a solution of sodium hydroxide..

Partial immersion tests (capillary rise) were also performed with 50-mm diameter specimens as described above. The specimens were inserted in a becker with 200 ml of distilled water, enough to cover one third of the specimen height. During the test, the capillary rise though the soil was monitored by recording the time the water takes to reach previously selected heights.

Atterberg limits revealed that the soil classifies as a low plasticity clay (CL) according to the Unified Soil Classification System. The results of the crumble tests and partial immersion indicated that the toe of the sea cliffs is composed by a dispersive material. On the other hand, the material of the crests of the cliffs showed a larger resistance to submergence, and is classified as non-dispersive. Direct shear test results are shows in Table 1. The second column of the table indicates if the soil was tested under field water content (dry) or inundated. In both samples, it is observed that the soil degree of saturation caused a severe reduction in effective cohesion. However, no significant change on soil internal friction angle was observed due to wetting.

Table 1: Results of direct shear tests with the samples collected at the toe and crest of a sea cliff at North Sector.

Sample	Test type	Effective Cohesion (kPa)	Internal friction angle (°)
Crest	Dry	233.0	28
	Inundated	50.6	28
Toe	Dry	384.1	28
	Inundated	45.4	27

RESULTS AND DISCUSSION

Field Survey

North Sector

Sea cliffs with heights varying from 20 to 40 m and slopes to the horizontal from 20^0 to 60^0 were observed in North Sector. Vertical slopes were also identified in a few locations in North Sector. The sea does not reach the cliffs in North sector, and the toe of the cliffs is protected by sandstone boulders (*beach rocks*). Beaches in North Sector are 5 to 15 m wide and are basically composed by sand. Wider beaches tend to protect the sea cliff toe against the action of waves and currents.

Ravines and gullies at the crest and at the slope surface of the sea cliffs are common in North Sector. Figure 5 shows a gully at the crest of a sea cliff, created by the discharge of a rainwater drainage device of a road located besides the cliff.

Although rare, some landslides in Sector North have caused serious damage to facilities near the cliffs, and to beach access stairways. The most serious case took place after a three-day rain of more than 500 mm of intensity. Figure 6 shows a landslide that happened during this period.

Central Sector

The height of the sea cliffs in Central Sector varies from 35 m to 40 m and the slopes of the sea cliffs vary from 60^0 to 90^0. Central Sector is the sector where urban occupation near the coast line is more intense. West zone of Central Section is characterized by sandy beaches with an average width of 10 m during high tide periods. The wide shoreline prevents the sea from reaching the toe

Figure 7. Erosion at the toe of the sea cliff caused by sea action in Central Section.

Figure 8. Gully at the crest of a sea cliff at South Sector.

of the cliffs. However, a different scenario is observed at the central zone of Central Section. The comparatively narrower beaches at that zone have made possible the creation of large incisions at the toe of the cliffs due to sea action (Figure 7). The incisions at the toe of the sea cliffs usually cause block falls and slides at the upper part of the cliffs.

Falls, topples and slides were also noticed at the Central Section. Most of those mass movement processes takes place during the rainy season, from February to July. Figures 12 to 14 illustrate some mass movements observed at Central Section.

South Sector

South Sector is characterized by large plateaus. Pipa Plateau and Praia das Minas Plateau are the largest plateaus in the region. Pressures for land occupation in both plateaus are very high. Sea cliffs in South Sector have maximum slope of about 40^0 and heights varying from 10 m to 25 m.

Mass movements process at South Sector consist of surficial erosion only (Figure 8). There are no records of other type of movements. The base of the sea cliffs is protected against sea action by sandstones with ferruginous cementation or sand banks along the entire length of the cliff.

Mechanisms of Sea Cliff Retreat

Sea cliffs at the investigated area can be grouped into three typical profiles (Figure 9). Profile type 1 includes cliffs with nearly vertical slopes (Figure 9a). Profile type 2 is characterized by cliffs with vertical slopes at the lower part and inclined slopes at the upper part (Figure 9d). The slope angle of the upper part ranges from 45^0 to 60^0 to the horizontal. Profile type 3 is composed by cliffs with slopes with inclinations varying from 40^0 to 50^0 to the horizontal (Figure 9g).

Profile 1 is very vulnerable to falls and tumbles of blocks, as well as sliding of material from the upper part of the cliff (Figures 9b and 9c). Mass movements at the sea cliffs may also be triggered by preexisting discontinuities in the soil mass, such as bedding and faults dipping towards the slope face. Sub-vertical tension cracks growing near the crest of the slope may also cause falls, tumbles and slides of material at the top of the cliffs, especially if the crack is filled with water (see Figure 9a). Water pressure pushes the block out of the cliff.

Falls and tumbles of material are common at the lower part of profile 2 due to its steep inclination. A sliding surface may also form at the upper part of the cliff. Profile 3 is comparatively more stable than the other two types, although slides and erosion at the slope surface are possible.

Topples of material from the lower part of the cliff due to preexisting discontinuities are common in profile 2 (Figure 9e). Toppling in profile 2 may be followed by massive slides (Figure 9f).

Profile 3 is characterized by surficial sliding, which is induced by the reduction in soil shear strength due to the increase of the soil degree of saturation. Figure 9h represents the saturation of the soil at the surface of the cliff. As shown in Table 1, the material of the sea cliff undergoes a severe decrease in effective cohesion after saturation, which leads to a decrease in shear strength. Soil matric suction responds for a large component of soil cohesion in the tested soil. When matric suction reduces to zero as the pores of the soil become fully saturated, soil cohesion also decreases, and part of the shear strength of the soil is lost. This condition may lead to slides of masses (Figure 9i). The reduction in soil shear strength explains why most of the slides take place during the rainy season of the year. As shown in Table 1, the reduction in soil cohesion after inundation was more pronounced with the material of the toe of the cliff.

The mass movements that take place in profiles 1, 2 and 3 may be emphasized by erosion at the toe of the sea cliffs due to sea action. Erosion at that region of the cliffs is rather facilitated by the dispersive nature of the soil, as shown by the results of the immersion tests. The stability of the sea cliffs becomes a very serious concern when the incision at the cliff toe assumes larger proportions.

CONCLUSIONS

Failure mechanisms of sea cliffs in the Northeastern region of Brazil were evaluated in this paper. The study included a field survey along 16 km of the coastline of the State of Rio Grande do Norte. An experimental program including conventional geotechnical laboratory tests with samples collected from the sea cliffs was also conducted as part of this investigation. The results showed that mass movements at the sea cliffs at the investigated area are in great part associated with rain intensity and the action of the sea. Direct shear tests results conducted on the material of

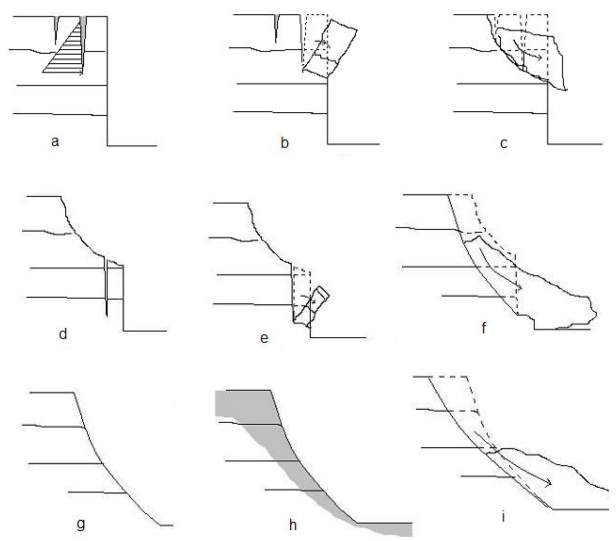

Figure 9. Typical profiles identified at the studied area and mechanisms of failure.

the sea cliffs revealed that the soil of the cliff undergo a large shear strength reduction after saturation. In addition, immersion tests results showed that the material of the slope toe is quite dispersive. Both factors, that is, the reduction in shear strength and the high dispersion potential are important factors on the reduction of the stability of the cliffs. The field survey conducted in the investigated area has shown that sea cliffs with vertical slopes are prone to mass falling, tumbling and sliding indistinctly. On the other hand, flatter sea cliffs are more likely to undergo surficial erosion processes, although slides are also possible. The action of waves and currents cause an incision at the toe of the cliffs, reducing their stability. This is particularly facilitated by the dispersive nature of the soil of the toe.

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