Terrain failure in a suburban area of Almada - Portugal

P. C. LAMAS [1] & J. A. RODRIGUES-CARVALHO [2]

[1] Centro de Estudos Geológicos (University Nova de Lisboa, Portugal). (email: pcl@fct unl.pt)
[2] Centro de Estudos Geológicos (University Nova de Lisboa, Portugal). (email: rc@fct.unl.pt)

Abstract: The rapid urbanization of the areas around the big cities, and even in some areas inside them, very often takes place in locations with poor geological and geotechnical conditions. Mass movement affecting slopes is a common example of such problems, with very adverse social and economical consequences. This is due mainly to the lack of adequate planning. In fact, the geological and geotechnical site conditions do not receive much attention either from the politicians or from the planners who prepare the land use plans.

The northern end of Almada County, near Lisbon, on the left bank of the Tagus River, is limited by dip slopes, which have been surrounded by construction during the last few decades. Those slopes are composed of hard soil/soft rock Miocene layers partially covered by colluvium. Slope evolution essentially takes place in the form of mass movements of different types, mostly rock falls and shallow slides.

In this paper, the authors present some case studies of landslides affecting a small part of Almada's slopes, with many houses in the neighbouring area. The physical and mechanical properties of the slope materials are presented and the failure mechanisms of two landslides are discussed.

Résumé: La pression croissante de construction autour des grandes villes, est faite très souvent dans des lieux ou les conditions géologiques et géotechniques sont très faibles. Les mouvements de terrain dans les versants sont un exemple typique de ces problèmes, lesquels sont accompagnés par des conséquences sociales et économiques adverses. La raison principale pour cela se doit à l'absence d'une juste planification du territoire. En effet, les conditions géologiques et géotechniques du site n'attirent toujours pas l'attention ni des politiciens ni des planificateurs, qui sont les entités qui doivent préparer et approuver la documentation nécessaire pour les décisions sur l'us du sol.

Le bord septentrional de la commune d'Almada, prés de Lisbonne, dans le rivage sud du Tage, est limité par des versants aux grandes pentes, cernées par des constructions établies pendant les dernières décades. Ces versants sont constitués par des couches miocènes composées par sol dur/roche tendre, recouvertes partiellement par des dépôts de versant. Leur évolution se fait par de mouvements de terrain distinctifs, la majorité du type chute de blocs et du type glissement peu profond.

Dans ce travail, les auteurs présentent quelques occurrences de mouvements de terrain affectant une petite partie des versants d'Almada, qui sont entourées par beaucoup de maisons et d'autres constructions. Quelques propriétés physiques et mécaniques des matériaux des versants sont présentées et les mécanismes de rupture sont décrits pour deux de ces événements.

Keywords: Slope stability, mass movement, failure, landslide, planning

INTRODUCTION

The slopes of the Tagus River south bank, in front of Lisbon, dominate, with its 80-100 m of height, the final stretch of this river and correspond to the steep face of a 7 km long *cuesta* which is, nowadays, under an increasing urban pressure. The city of Almada, restricted until recent years to its historical centre, next to the eastern end of the *cuesta*, is now expanding towards the west, covering the plateaus next to the crest and penetrating in the valleys that descend to the Tagus River.

The location of the above mentioned slopes, in an area of great socio-economic importance, with good accessibility from Lisbon, essentially since the sixties, encouraged its development. Some of the companies located on the river banks, at the toe of the slopes, have expanded and small population centers have grown inside the adjacent valleys that drain towards the river. This has induced and accelerated destabilization phenomena in the soft material slopes as well as in some rocky scarps or brought people and construction dangerously close to places where such phenomena take place.

The geomorphologic evolution of the slopes is carried out, mainly, by landslides affecting *in situ* clayey silts or colluvium deposits which constitute, in the most part, the slopes facing the Tagus River or the slopes of the adjacent valleys perpendicular to the river. At the steepest stretches of the slopes, composed by sandstones, silty marls and sandy limestones, the main destabilization mechanism corresponds to the failure and fall of rocky blocks and "panels", sometimes with several tens of meters in length.

The westward flank of Almada *cuesta* constitutes the Costa de Caparica Fossil Cliff, which dominates a narrow coastal plain and that extends to SE for about 20 km (Figure 1). This fossil cliff restrained for a long time the access to the western beaches of Almada County until the forties, when a road coming from that city was built. Since then, the cliff has suffered an increasing influence of human occupation. Along the first 2 km from the north, the natural stability conditions of the cliff have been modified by excavations at the slope toe for construction of houses and buildings, a park of fuel reservoirs and some agricultural activity. With these excavations, the general declivity increased, impairing the stability of the more weathered *in situ* terrain or the slope debris which cover the lower part of the slope. Also, houses and roads have been built too close to the cliff crest, interfering with its natural stability conditions.

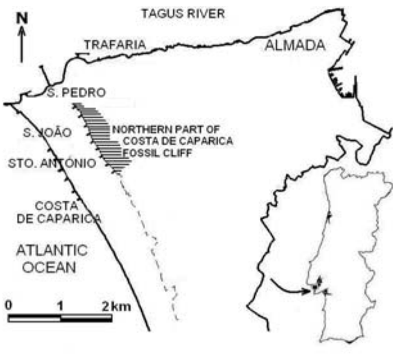

Figure 1. Location of the northern stretch of the Costa de Caparica Fossil Cliff

GEOLOGIY AND GEOMORPHOLOGY

The northern edge of Costa de Caparica Fossil Cliff extends for almost 2 km and is surrounded by urban areas. It constitutes a scarp practically without any interruption at the crest level, which stands 70 - 80 m above the coastal plain.

The stretch of scarps in reference is constituted by Miocene soft rock/hard soil layers. Its profile (Figure 2) was due not only to the lithology (soft sandy limestones and marly sandstones overlying silts and clayey silts and, closer to the toe, marls and sandy limestones alternating with some silts) and to the structure (direction of the slope almost perpendicular to the layers, which incline very gently towards SSE) but also to the sea erosion acting in recent geological times.

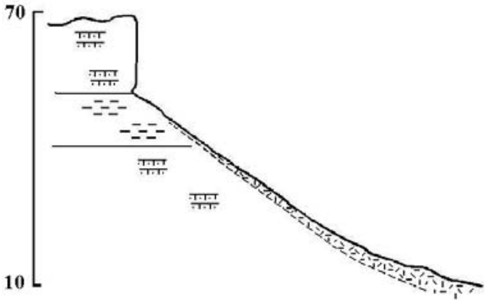

Figure 2. Main profile of the fossil cliff.

The frequent collapses at the higher layers of the slope and the consequent accumulation of the displaced materials at the cliff toe are responsible for a gradual widening of the slope profile, although in the upper part, where those phenomena are originated, vertical walls persist.

All this stretch of the fossil cliff is in a relatively dynamic stage of its evolution, its slopes suffering modifications at a rate perceivable at the human life scale. A first evaluation of the evolution of the crest was carried out by analysis of air photographs taken at different dates and by field measurement. It gave an average rate of withdrawal of 1.9 cm.year^{-1}, for a 51 year period, between 1947 and 1998 (Lamas, 1998). Field measurements carried out later on, in May 2003, gave larger rates of withdrawal, about 4.5 to 6 cm.year^{-1}. However, these last rates concern only some stretches of the cliff with just a few tens of meters of length and are referred to a single five year period (1998-2003).

The general withdrawal at the slope crest, materialized to a great extent by mass movement events, seems to show a strong increase in the last 50 years. This was due, in part, to the increasing interference of the human activities near the scarp. The geological and morphological conditions of the slopes are responsible for different types of failure mechanisms, two of which are described here. The first one, at S. Pedro, in the northern edge of the cliff, affected a 20 m high slope essentially of silty and silty-clayey nature, with thin marly sandstone intercalations. In the winter of 1995/96, that slope was affected by a relatively deep slide that reached a house built close to the slope toe and, at the same time, the fast retreat of the rear scarp put in danger other houses placed a few meters from the crest. Very recently, in January 2004 and a few meters distant, a small subsurface slide slipped below the crest of the slope, partially undermining the foundations of some constructions built on the top of the slope. This stretch of the fossil cliff does present, therefore, all the conditions to evolve by slides starting on the crest.

A second type of mechanism happens in other parts of the cliff, where a slope of rocky crest occurs, formed by sandstone and sandy limestone layers that evolve by sporadical falls of blocks or “panels” detached from the rock mass after the opening of tension cracks. In these cases, the morphological evolution of the cliff is currently controlled by mass movements originated in the steep upper zone. As that zone retreats, the underlying silty-clayey and less abrupt part of the slope widens and, in consequence, its declivity decreases. Different occurrences of this kind have been detected in the cliff stretch overlooking Sto. António, the most recent being dated 1988, 1989, 1997 (two events), 1998 (called Sto. António rock fall, described later in this paper) and 2004. Closer to the slope toe, covered by colluvium, some evidences of superficial debris slides and mud flows are also present.

S. PEDRO SLIDE

The fossil cliff starts, in its northern limit, as a 20 m high 30º-32º inclination silty-clayey slope. The surrounding zone is densely covered by roads and houses. Initially, due to the lack of a sewage network, the domestic waters were canalized to septic tanks, then percolating into the ground. This was one of the main reasons for the first slope failure, in February 1964. That occurrence affected two houses that were still under construction in front of the slope toe and caused the destruction of a small house at the slope crest.

In consequence of that, some slope stabilization works were accomplished, which involved, at that time, the construction of two retaining structures, one of them at the slope toe, protecting the backyards of the houses under construction and another one at the crest, in the place where a 3 m high scarp was formed. During the heavy rains in the 1995/96 winter, that second wall, built in non-reinforced concrete, partially yielded following a slide affecting the slope of about 1000 m^2, driving the displaced terrain towards one of the houses, which was located a few meters from the slope toe (Figure 3). The slope toe retaining wall didn't suffer any damage apart its partial burial by the slipped material. A third retaining wall, built more recently, shortly above the slope toe wall, was partially destroyed by the advance of the slide front.

The rear scarp of the slide was initially 4 m high and, due to the percolating forces imposed by groundwater towards the slope, a fast backwards progression of that scarp was verified, threatening two small houses implanted a few meters back from the slope crest. Later, the excavation of the soil debris that filled the backyard of the house in front of the slope toe reactivated the movement, increasing the height of the rear scarp to 5.5 m.

These elements, in conjunction with the knowledge of the lower zone of the slope affected by the movement, allowed the definition of the position of the slip surface. For the interpretative model, the slipped mass was considered to have a maximum thickness of about 6.5 m in the zone of the slope crest, gradually decreasing towards the toe.

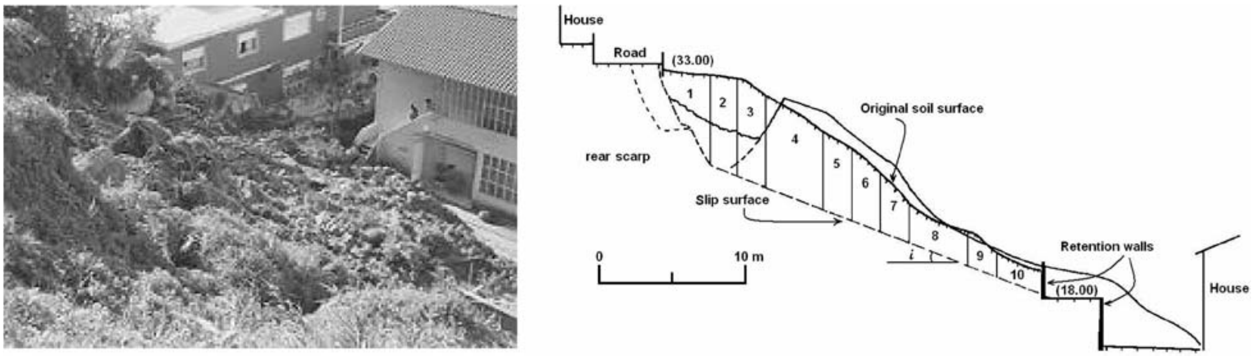

Figure 3. Sight of S. Pedro slide taken downwards; Interpretative profile.

Two boreholes drilled behind the crest of the slope a few days after the slide event, revealed the existence of groundwater at a depth of 3 m, a fact confirmed by the points on the scarp wall where groundwater was spouting.

The shear surface crossed grayish clayey silts with some marly intercalations. Collected samples less than 48 hours after the occurrence supplied the physical and mechanical data in Table 1:

Table 1. Summary of geotechnical parameters

Liquid limit (W_L)	45 %
Plasticity limit (W_P)	24 %
Dry unit weight (γ_d)	17.3 kN.m^{-3}
Moisture content (ω)	27 %
Peak strength parameters (c' ; ϕ')	24.5 kPa ; 33º
Residual strength parameters (c'_r ; ϕ'_r)	0 ; 28º

The "graben" like sinking of a stretch of the slope crest during the movement and the maintenance of the verticality of the low vegetation that covered the slope, led us to classify this movement as a planar slide. Because it was a second occurrence in the same slope and large shear displacement had occurred on the slip surface we believe that the shear strength on the slip surface would have reached the residual shear strength.

With regard to groundwater, the slope affected by the slide is located at the end of a hanging valley, short in length but deeply excavated. We believe the strong urbanization of that valley hindered surface runoff. The rain waters are lead to the drainage network, starting on the street gutters and, from there we believe they infiltrate into the soil through cracks in the drainage network.

The groundwater level stabilized more or less 3 m below the crest of the rear scarp, but we believe it might have been higher at the time of failure. The upper retaining wall, which leaned against the slope crest, would have functioned as a barrier to the percolating waters. Such conditions allowed the development of strong hydrostatic pressures over the wall and contiguous terrain and an inwards forced percolation. In the days before failure, in the light concrete pavement of a narrow street behind the crest of the slope, cracks occurred (or existing cracks were widened) parallel to the direction of the slope crest. We believe these tension cracks may have become totally filled by water immediately before failure. At the same time, a great amount of water and mud appeared in several points of the slope, mainly on the back of the recently built retaining wall, few meters above the slope toe wall.

For the back-analysis of the event, the 1:1000 scale municipal map of Almada, edited in 1995, was used as a topographic basis to draw its geometry. The potentially unstable block was divided in several slices in order to facilitate the graphical evaluation of its volume and, therefore, the calculation of the displaced mass weight, assuming it to be homogeneous from the lithological point of view. This last hypothesis is a simplification, since colluvium deposits or fill deposits were at surface, mainly in the crest area. However, the small thickness of those deposits in the overall displaced mass allowed us to ignore their effect which, at most, would lead to a light decrease in the calculated total weight for the slipped block, not really influencing the back analysis results.

On the basis of the geometry of the movement as it is shown in Figure 3, and assuming, at the moment of failure, a groundwater level 3 m below the level of the slope crest, the following value of ϕ' is given by limit equilibrium analysis for FS equal to unity and assuming c' equal to zero. (for FS=1: $\phi' = 24.3^o$ if $c' = 0$). The value of ϕ' calculated will be sensitive to the water pressures assumed. A calculation assuming a higher piezometric line within the slope, or assuming a water-filled tension crack at the crest, will give $\phi' > 24.3^o$.

Repeating the limit equilibrium analysis taking into account the existence of hydrostatic pressure corresponding to a column of water acting on a 6 m deep vertical crack at the crest gave $\phi' = 29.6^o$. (for FS=1: $\phi' = 29.6^o$ if $c' = 0$).

This shear strength is close to the residual values obtained in the laboratory on samples collected *in situ:* $\phi'_r = 28^o$ and $c'_r = 0$.

STO. ANTÓNIO ROCK FALL

About 1400 m to the south of S. Pedro slide, the fossil cliff reaches a much bigger height and its constitution is more heterogeneous presenting, at the top, an 8 m high vertical scarp (see Figure 2), formed by lime sandstones and marls. The fall of a rock "panel" with a length of approximately 10 meters occurred in February 1998, causing damages in some houses built too close to the slope toe. This event deserved a detailed study (Lamas, 1998), with the determination of its geometric characteristics and the collection of representative samples for laboratory tests in order to allow a back analysis.

The block detachment occurred from a complex surface, formed in cross-section by three planes: two of them, both vertical, seemed to correspond to two different tension cracks; the third plane, with an inclination of about 62º, linked the two others (Figure 4).

The unstable block was not in balance over the underlying clayey silts, as it could be observed at the adjacent stretches of the scarp. The reason of this was that the stretch of scarp had been already affected by a previous movement, in 1988, with the detachment and fall of a lime sandstone panel, which partially buried a small building (Lamas and Rodrigues-Carvalho, 1994). The rock fall of February 1998 could result from shear in the marly sandstone exposed between the two tension cracks. The operating forces must have been the weight of the block, possibly helped by the hydrostatic force in tension cracks.

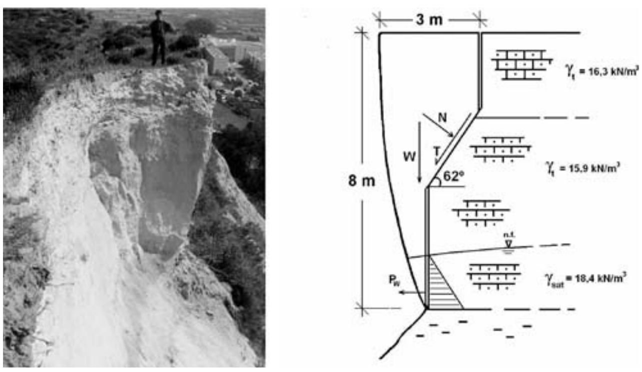

Figure 4. View of the scarp taken upwards, immediately after the rock fall of February/1998; interpretative profile of the detached block.

After the movement, the recent exposed surface revealed some moisture 1 m high from the base. Assuming that this could be the height of the groundwater level, perched on the impermeable clayey silt layers, the preexisting tension crack would enclose an equivalent height of water and the lowest 1m layer of sandstone might be saturated.

The upper tension crack was cutting a 2.5 m thick calcareous sandstone layer, characterized by a dry unit weight of 15.8 $kN.m^{-3}$. The remaining rock mass affected by the detachment is a softer and more homogeneous material, with of dry unit weight of 15.5 $kN.m^{-3}$. The inclined surface exposed between those two tension cracks, cut this last material. Several samples were obtained from that lower zone of the scarp for laboratory tests and they give, under drained conditions, the following peak and residual strength parameters: c' = 50.0 kPa; $\phi' = 33^o$; $c'_r = 0$; $\phi'_r = 33^o$.

The marly sandstone layers which seat over the clayey silts are, mainly, rock materials with very low uniaxial compressive strength. Five test specimens were dried in the oven at about 60º C, and gave values of uniaxial compressive strength between 1.9 and 4.6 MPa. Other test specimens from the same samples were submerged in distilled water ("saturated" moisture content: 20-23 %), and the measured uniaxial compressive strength decreased to values between 0.2 and 0.5 MPa.

Limit equilibrium calculations were carried out. Assuming that, at the moment of failure, there was no water pressure effect on the failure surface and in the tension cracks, and that no rotation of the block occurred (due to toppling), the Factor of Safety may be expressed as:

$$FS = \frac{c'A + (W.\cos i).\tan\phi'}{W.\sin i}$$

where:

- c' and ϕ' are strength parameters of the material in shear;
- i: dip of the failure surface;
- A: length of the failure surface.
- W: weight of the potential unstable block; assuming a detached block with unitary thickness and 3 m wide at the top, as shown in Figure 4, its weight would be 228.2 kN. For this calculation, a water content of 5.0 % was assumed for the upper 7 m of the block while for the lower 1 m, the material was considered saturated.

Limit equilibrium analysis gave a value of FS of about unity when the peak shear strength values measured in the laboratory were assumed in the calculations: i.e. c' = 50.7 kPa; ϕ' = 33º. This appears to offer a satisfactory theoretical explanation of the failure.

CONCLUSION

In the northern edge of the Costa de Caparica fossil cliff, the slope evolution takes place through mass movements which sometimes represent a threat for houses and other constructions. There are distinct failure mechanisms according to the type of material which constitutes the slope crest: layers of calcareous sandstones or clayey silt formations. Along the biggest part of its extent, the cliff has a calcareous and marly vertical scarp in its top. In this case there are frequent falls of rock blocs and "panels" of several dimensions. The rate of withdrawal of the slope crest was estimated to be about 2 cm year^{-1} in the last half century.

Stability analysis by the limit equilibrium method gave insights into the mechanisms that might have been operating during the occurrence of two failures which are characteristic of the evolution of this cliff. Both failures endangered houses built too close to slope toe or crest: one, a planar slide in clayey silts; the other, a rock fall initiated by the shear of a section of the rock mass which constitutes the upper sandy calcareous front of the fossil cliff.

Corresponding author: Dr P. C. Lamas, Centro de Estudos Geológicos (UNL), FCT/UNL, Campus da Caparica, Monte de Caparica, Almada, 2829-516, Portugal. Tel: 351212948573. e-mail: pcl@fct.unl.pt.

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