Natural and man made causes for the “Elísio de Moura” earth flow in Coimbra, Portugal.

Causes naturelles et anthropiques pour le fluxe de sol de “Elísio de Moura” a Coimbra, Portugal.

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Abstract

The paper reports the 27 December 2000 landslide which occurred in the city of Coimbra, central Portugal, affecting loose fill soils and slope debris derived from the red sandstone of Triassic age. With urban spread, the base of the hill slope on which farming had taken place over many centuries was terraced to provide residential properties and the excavated material end-tipped at the top of the slope, modifying the slope gradient from the original 18° to 38°. The loose fill was placed without engineering precautions, directly on to the debris slope material. Following a small slip in 1998, remedial works were undertaken involving large diameter piles anchored into the bedrock. This engineering construction formed the backslope and restricted the extent of the December 2000 landslide which occurred during a period of unusually heavy rainfall.

Keywords: natural risks; precipitation; landslide; earth flow; Coimbra.

Résumé

Le travail rapporte le glissement de sol de 27 Décembre 2000, qui s'est produit dans la ville de Coimbra, Portugal centrale, affectant des sols lâches et des débris de pente dérivés des grès rouges du Triasique. Avec l`expansion urbaine, le talus a la base de la colline, sur laquelle l´agriculture avait eu lieu pendant beaucoup de siècles, a été terrassée pour construire des édifications résidentielles. Les matériaux excavés ont été déposés au sommet de la colline, modifiant le gradient de pente du 18° original à 38°. Un terrassement lâche a été construit sans précautions de génie civil, directement au dessus des débris de pente. Après un petit glissement de sol en 1998, les travaux de réparation ont été exécutés utilisant des piliers à grand diamètre ancrés dans la roche en place. Cette construction a limité l'ampleur du glissement de sols de Décembre 2000 qui se et produit pendant un période de précipitation exceptionnellement intense.

Mots-clés : risques naturels; précipitation; éboulements; fluxe de sols; Coimbra

Introduction

On 27 December 2000, a large mass movement occurred in the city of Coimbra, Central Portugal, known as the "Elísio de Moura". With the expansion of the town in the 1970s, a new development took place where an east facing slope in the Triassic sandstones, is overlain by a veneer of Quaternary debris. In order to construct apartments at the base of the slope, extensive excavations were undertaken to form a series of cut terraces which extended into the underlying bedrock. The arisings from these excavations were end-tipped at the top of the 18° slope and accumulated at their angle of repose, some 38°.

As presented in Table 1, two periods of dumping were undertaken in 1975 and 1980, which provided a relatively level platform at the top of the hill on which villas were constructed in the early 1980s while apartment blocks were built at the base of the hill.

The paper discusses the evolution of the slope from its initial agricultural use to the placement of the fill and the subsequent hill slope disturbance which took place in 1998 and 2000. The remedial works carried out following the 1998 instability are described and the influence of these on the mass movement on 27 December 2000 discussed.

Geology

The bedrock of the area is the Triassic red sandstones of the Grés de Silves Formation, which outcrop along a north-south zone, a few kilometres wide. Unconformably underlying the Triassic sandstones are Pre-Cambrian schists while overlying the sandstone are the Jurassic dolomitic limestones known as the Coimbra Beds.

Within the red, red-brownish or even yellowish sandstones of the Grés de Silves Formation are some layers of silt and others of gravel to small cobble sized conglomerate. The layers are commonly in the order of a half a metre thick and show a typical upward fining sequence. Generally the sandstone bedrock is covered by slope debris, which increases in thickness to several metres towards the base of the hill.

The strike of the beds is generally N20ºW while the dip is some 12º to the south west, such that with the main hillside facing east, the rocks dip into the slope. At the base of the slope two small faults were observed with disturbed zones some 100 mm wide. These are oriented approximately N70ºW with a dip of some 45º to the south.

Evolution of the slope

Prior to the development of the Elísio de Moura slope with the construction of apartment buildings, the natural equilibrium of the hillside was controlled by the weathering, run-off and erosion of the red Triassic sandstone of the Grés de Silves Formation. This natural evolution created a slope angle of some 18º. A small and shallow valley developed on the hillside, related to the two secondary faults observed at the bottom of the hill. This valley was filled with hillwash, typically red in colour, probably being derived from the sandstone. These Quaternary deposits reach a thickness of more than 4m at the bottom of the slope.

For many centuries, agriculture was carried out on the slope using ancient techniques to create flat terraces and manually excavated galleries to obtain water for irrigation. The galleries draining the sandstone formation were generally some 0.7 m wide and 1.8 m high. These old agricultural activities, developed over many centuries, appear to have created a different equilibrium, which was broken a few decades ago when farming was abandoned due to the increase in land values with the expansion of the urban area of Coimbra (Table 1).

Table 1

The urban expansion that occurred in the 1970s started with the construction of the "Elísio de Moura" avenue, named after a philanthropist doctor. By the end of the 1970s several platforms had been excavated on the west side of the avenue, stepped into the base of the hill (Fig. 1). These platforms, created in order to construct residential buildings, parking areas and garages, were excavated into both the slope debris and the underlying sandstone. The materials excavated from the north west of the "Elísio de Moura" avenue were transported to the top of the hill and dumped there, creating a wide platform. As a consequence, the angle of the hill slope was increased from the original 18º to 38º in the fills. Subsequently the platform formed by the fill at the top of the hill was used for the construction of several villas, seen in the upper part of Fig. 1.

Figure 1

Based on field observations, the distribution of the fills, information from residents and photographs dated from the spring of 1983, it is concluded that the dumping of the fill was done in two phases. The first filled area was completed in the middle of the 1970s. With a thickness of less than 7 m, the material was dumped essentially north of the failure area (Fig. 1). The second fill was completed at the beginning of the 1980s and had a thickness of up to 14 m. As seen in Fig. 1, small eucalyptus trees grew on this slope and erosion gullies had developed in the loose materials.

The first small problems recorded occurred in 1995 and consisted of excessive deformations on top of the second fill, requiring the construction of a small stone wall to allow access to the garages at the back of the villas. More serious problems were detected in the spring of 1998, when a slip scar up to 0.5 m high appeared at the top of the fill, some 5 m from the edge of the slope, impeding access to the villas parking areas.

The residents consulted a geotechnical expert and an investigation was undertaken comprising three 18 m deep percussive boreholes at the back of the villas (Lidónio, 1998). A total of 25 standard penetration tests (SPT) were undertaken as the holes advanced. All the borings encountered fill material to a depth of more than 10 m, with SPT 'N' values between 4 and 11. Beneath this recently placed fill, the SPT 'N' values were between 20 and 33 in the slope debris and weathered superficial materials while in the underlying sandstone, 60 blows would often only produce 100 mm penetration.

Following this site investigation, a programme of remedial works was prepared which included the placement of 33 piles. As these were required to penetrate into the sandstone bedrock, they had lengths of some 20 m. In order to provide sufficient lateral restraint, the piles were 0.8 m in diameter and placed at 1.5 m intervals. They were linked by a crest beam anchored into the bedrock beneath the villas, using sixteen 600 kN anchors at 3 m spacings, inclined at 45º (Macedo, 1998). These remedial works began on 3 August 1998 and have been described by

Lemos, Lourenço & Gonçalves (2001), Lourenço & Lemos (2001) and Lemos, (2002).

The 27th December 2000 failure

The following description of the sequence of the 27 December 2000 failure is mainly based on the oral report of one of the residents of the villas who was on the concrete slab above the failed soils at the time of the occurrence (Miraldo, 2000).

In the afternoon of 27 December 2000, a 0.4 m wide by 0.7 m deep crack opened under the concrete slabs at the outer limit of the back yard of the villas. As some rainwater was seen accumulating in the crack and in the upper surface of the fill, the residents of the villas requested a contractor to be at the site at the end of the working day, to plan the opening of a trench to drain the water from this critical area. While standing on the concrete slab discussing this intervention, at around 1900 hrs they observed that a 10 m length of the stone wall, at the boundary of the concrete slab, had fallen. At around 2040 hrs, the remainder of the wall fell as a single unit. The sound of tree roots breaking was heard at progressively shorter intervals until it became continuous. This was followed by a softer sound over several minutes, related to the general movement of the destabilized soil mass.

At the same time, alarmed screams and the sounding of car horns came from the Elísio de Moura avenue at the bottom of the slope. When everything became quiet, the noise of a torrent was heard for several minutes, associated with the flow of the saturated soil. In the darkness of a night of rain, it was impossible to see clearly what was happening but with the use of a flashlight, it was possible to observe the total loss of soils beyond the cast-in-place concrete piles (constructed in 1998) and below the concrete slab where the residents remained during the failure.

The following morning, it was possible to observe that a large volume of soils had moved downhill from below the line of piles (Figure 2). Before the failure, the concrete slab was less than 3 m above the fill while after the mass movement of material downslope, the slab was as much as 13 m above the ground in the hollow. The soils which accumulated at the toe of the slope destroyed and buried two blocks of garages belonging to the building of the Elísio de Moura avenue and destroyed the three upslope pillars of a building at the first and second floor levels, leaving the remaining twelve floors suspended (Fig. 3). In addition, Lemos, et al. (2001) record the destruction of 27 garages and 31 cars. Fortunately no lives were lost.

Figure 2

Figure 3

Failure Mechanism

The interpretation of the failure is based on the following:

a) the meteorological data;
b) the description of the failure given by one resident of the villas who was on site at the moment of failure (Miraldo, 2000);
c) field observations;
d) the drillings executed in 1998 (Lidónio, 1998) and
d) the geotechnical study of the site (Quinta Ferreira, Lemos & Dias, 2002).

The fieldwork allowed the local conditions to be determined, in particular the geomorphology, the geology and the characteristics of the disturbed area. The movement of the ground ranged from large "flow" movements in the central area to limited displacements at the sides (Fig. 4). Within the affected area, approximately 75m wide by 100m long (7,500m^2), the main hollow seen in Fig. 2 had an area of some 1,400m^2.

Figure 4

It is considered that the rupture would probably have started by a deep "circular" failure, passing through the loose fills and slope debris. During this process, the top of the hill moved downwards while the toe of the area remained relatively stable. The movement in the loose materials resulted in a re-arrangement of the particles, thus reducing the volume and transferring stress to the pore water. This induced the liquefaction of about 10,000m^3 of saturated soils where the fill was thickest. The liquefied “mud like” material ran downhill through a bottle-neck shape (Figs. 4 and 5), hitting the garages and apartment block at the base of the hill.

Figure 5

The anchored piles constructed in 1998 significantly reduced the mass movement (Fig. 2), limiting the volume that failed and thus the damage, both at the top (close to the villas) and at the bottom of the slope. The volume of soil that remained unaffected above the anchored piles was some 15,000m^3 (Fig. 6).

Figure 6

Causes of the 27 December 2000 failure

Rainfall

To evaluate the influence of the rain in the development of the Elísio de Moura earth flow the records of the Geophysical Institute of the University of Coimbra (GIUC), only 1 km from the site, were collected and analysed. The precipitation records began in 1864 and have been continued since.

Based on the precipitation data from 1864 to 2003, the daily average rainfall distribution in Coimbra is shown in Fig. 7. From Fig. 7 and Table 2, the annual rainfall pattern can be seen to involve seven months (October to April) with average daily rainfalls above 2.65mm and five months (May to September) with lower rainfall values. The lowest values for daily average rainfall are found between the middle of July and the middle of August, with minimum values of less than 0.1mm.

Figure 7
Table 2

Analysis of the rainfall between 1864 and 2003 indicates that the wettest year was in 1935/36 with 1716 mm and the driest year 1952/53 with only 468mm. Table 2 gives the precipitation characteristics of the area on a monthly basis, indicating the maximum and minimum monthly rainfall and highlighting the year in which the maximum rainfall occurred. It also provides the maximum, minimum and average daily rainfall for each month and when the maximum rainfall in a single day occurred, giving the day, month and year. Figure 8 shows the accumulated rainfall in each of the years from 1982/83 to 2002/03. It can be seen that the year 2000/01 was unusually wet, with 1612mm of rainfall compared with the average of 968mm. In the 139 years of records, there are only four years with precipitation above 1600mm, indicating a mathematical re-occurrence interval of 30 years.

Figure 8

Figure 9 shows the accumulated rainfall for the year 2000/01, starting at 1 August. The Elísio de Moura earth flow on 27 December 2000 and the problems of April and June 1998 are highlighted. As discussed above, the total rainfall in 2000/01 was significantly in excess of that recorded in other years and in November and December when there were only 11 days without rain. As a consequence, at the time of the Elísio de Moura earth flow (27 December 2000) the fill and slope debris were saturated. In November 2000, the accumulated rainfall was 231mm, compared with the average of 120mm (an increase of 193%) while in December (until the date of the failure), the accumulated rainfall was 272 mm, 217% above the average for the whole month of December. Thus, the total rainfall during November and December was 503mm, which corresponds to more than half of the annual average rainfall (968 mm).

Figure 9

Geotechnical characterization

The soils were studied to determine their geological and geotechnical characteristics. The tests included grain size analyses, Atterberg limits, water content, organic matter content, methylene blue, nuclear gauge (Troxler 3440), modified Proctor and direct shear. The direct shear test was undertaken on two samples, one from the fill and one from the slope debris. Figure 5 indicates the sampling locations and a summary of the test results is given in Table 3.

Table 3

The sampling was undertaken in April 2001, some 4 months after the earth flow when the monthly precipitation was only 50% of the average. The water content was always above the optimum water content obtained using the Proctor test, while the dry unit weight was in general below the maximum value of the Proctor test. Compared with the loose, tipped nature of the fill, the compactness of the disturbed soils had clearly been increased due to re-arrangement during the mass movement.

Particle size distribution curves indicate that in the fill material the percentage of fines (<0.074 mm) was between 20% and 48% while for the slope debris it reached 58%. The results of the direct shear test on a sample of slope debris gave an angle of friction of 24º, significantly less than the 37° obtained for the coarser fill material.

As discussed above, the main earth flow had a valley-type profile with the material to the sides of the hollow experiencing little movement. From the information obtained during the investigation, the likely rupture surface is indicated in Fig. 6. This shows the failure is likely to have taken place through the debris veneer present before the fill was placed which had a lower shear strength.

Discussion

As noted above, the development of two cracks in 1998 resulted in the residents of the villas reinforcing the fill material by the placement of a number of piles. This decision proved to be extremely important. It not only saved the lives of the residents who were on the concrete slab at the moment of failure but also prevented the destruction of the villas at the top of the hill. Further, by limiting the amount of soil which suddenly moved, it prevented the total destruction of the apartment buildings at the toe of the slope and the possible loss of life.

Based on the data obtained and the observations of the failure it is clear that the soils were dumped over the slope without following proper engineering procedures:

a) there was no attempt to remove the approximately 1 m thick topsoil, plants and roots which covered the hill prior to the tipping;

b) the low strength slope debris covering the sandstone was also left "in situ";

c) no excavation was undertaken in order to mobilize the higher strength of the sandstone;

d) no drainage of either the bedrock or the fill was carried out;

e) the fill was end-tipped without using suitable compaction techniques (i.e. no layers were placed and individually compacted during the formation of the embankment);

f) the fill was dumped over a small water line filling the open valley which formerly existed, thus modifying the geomorphology and drainage of the hill slope;

g) the slope angle was increased from the original 18º to a maximum of 38º, corresponding approximately to the dry angle of rest of the dumped soils;

h) the outlet the galleries constructed for irrigation was blocked by the overlying fill.

If the soils had been placed using proper engineering practices, preparing the embankment foundation, draining the slope, compacting the soil in layers to a suitably dense state, etc, the influence of the precipitation which saturated the loose soils could have been minimised and the consequent failure of the fill could have been avoided, or at least greatly reduced.

Conclusions

The Elísio de Moura earth flow occurred at a time when the precipitation was considerably above the average. The percolating water saturated the loose fill and the natural slope debris, reducing the factor of safety of the slope. Once the mass movement began, re-arrangement of the soil particles resulted in a reduction in the volume of the mass, such that the stresses were transferred from block point contact to the contained pore water.

The failure occurred almost entirely in the loose tipped soils which had been dumped over the slope debris in the 1970s and 1980s. There is no evidence that any drainage was undertaken prior to the tipping and/or that the material was placed as an engineered fill.

The combination of unfavourable meteorological conditions and inadequate fill construction procedures created the conditions for the largest mass movement in the urban area of Coimbra.

The damage caused by the earth flow was significantly reduced by the reinforcement works executed two years before the failure, after some evidence of instability was seen in the upper part of the fill. The reinforcement avoided the destruction of the villas on the top of the fill and saved the lives of the people in that area and in the apartments at the toe of the slope. It is salutory to note that while the reinforcement works executed in 1998 cost around €200,000, the remediation works after the 27 December 2000 movement cost some €5,000,000.

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LEGENDS

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Table 2 – Precipitation characteristics at the GIUC, between 1864 and 2003.

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Figure 1 –Slope geology superimposed on a 1983 photograph indicating the fills placed at the top of the hill and the platforms excavated in the sandstone of the Grés de Silves (Photo of F. Gomes da Silva).

Figure 2 - General view of the earth flow, taken from the building at the bottom of the slope, showing the limit of the original fill. The maximum height of the piles exposed during the earth flow is 13m.

Figure 3 - Accumulation of soils against the building at the foot of the earth flow, which destroyed two floors, leaving the remaining twelve floors suspended. a) After the failure; b) One year later, after repairing the affected concrete structure.

Figure 4 – Zoning of the earth flow superimposed on a 1983 photograph.

Figure 5 – Geological map and limits of the earth flow (modified from Lemos & Quinta-Ferreira, 2004).

Figure 6 – Cross section along the earth flow (line AB of Fig. 5); modified from Lemos & Quinta-Ferreira, 2004.

Figure 7 – Distribution of daily average rainfall, and average between 1864 and 2003.

Figure 8 – Accumulated rainfall for the years 1982/83 to 2002/03 and accumulated average from 1864 to 2003. A few relevant years are identified.

Figure 9 – Accumulated rainfall for the years 1997/98 to 2000/01, accumulated average from 1864 to 2003 and dates of occurrence of landslides in the area of Coimbra.

TABLES

Table 1 - Chronology of the main events related with the “Elísio de Moura” earth flow.

Date	Event	Remarks
Sixties	Progressive abandon of farming activities.	Urbanization of the area.
1975	Dumping of the first fill.	At north of the slip zone (thickness up to 7m).
1980	Dumping of the second fill.	On the slip zone (thickness up to 14m).
1982-1983	Construction of the Villas.	Backyards on top of the second fill.
1983-1984	Construction of the apartment buildings.	At the base of the hill, bellow the second fill.
1995	Excessive deformations on top of the second fill required the construction of a small stonewall.	First recorded small problems, not related at the time with the instability of the fill.
1998 (April, 18)	Small fissures were noticed on the pavement of the backyards of the Villas.	Start of first severe problems after intense rain. P-3 = 20mm; P-15 = 132mm
1998 (June, 6)	Development of two scarps on top of the fill: - 40m long, 0,4m wide and 0,5m high; - 35m long, less than 0,1m wide and 0,05m high.	Forced the execution of a geotechnical study (see below). P-3 = 0mm; P-15 = 108mm.
1998 (July-August)	Geotechnical prospecting. Design and execution of the reinforcement structure on top of the second fill, by cast in place piles and an anchored crest beam, supporting a concrete slab.	Prospecting: 3 boreholes and 25 SPT. Reinforcement structure: 33 piles with ϕ=0,8m, L=20m, spaced 1,5m; crest beam with 16 anchors of 600kN spaced 3m; 9 small piles with ϕ=0,25m. Cost: €200,000
2000 (December, 27)	Failure of the slope Affected area: 7,500m^2; Liquefied area: 1,400m^2. Liquefied volume: 10,000m^3.	P-3 = 38mm and P-15 = 81mm. Damages: 27 garages, 31 cars, cut all the three west pillars of the apartment building with 14 floors. Cost: €5,000,000

P-3 and P-15 as proposed by Chleborad (2000): P-3 – accumulated precipitation in the three days before the occurrence; P-15 – accumulated precipitation in the 15 days before the 3 days.

Table 2 – Precipitation characteristics at the GIUC, between 1864 and 2003.

Rainfall (mm)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Monthly Average	120	106	105	88	78	42	15	15	53	102	120	125
Minimum	0,6	0,0	0,0	0,6	0,0	0,0	0,0	0,0	0,0	4,3	1,6	1,1
Maximum	375	378	294	295	197	155	69	80	220	296	464	409
Year	*2001*	*1902*	*1937*	*1884*	*1931*	*1988*	*1988*	*1885*	*1868*	*1960*	*1963*	*1934*
Daily Average	3,9	3,8	3,4	2,9	2,5	1,4	0,5	0,5	1,8	3,3	4,0	4,0
Minimum	2,7	3,0	2,6	2,1	1,8	0,5	0,1	0,1	0,3	2,1	2,8	2,9
Maximum	5,6	4,7	4,7	3,9	3,6	2,6	1,1	1,1	3,9	4,4	5,2	5,0
Daily Maximum*	73,5	66,8	64,8	62,6	99,0	56,2	38,9	50,5	120,4	71,3	108,0	93,1
Day	*3*	*11*	*21*	*3*	*2*	*28*	*1*	*19*	*30*	*15*	*11*	*21*
Month	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Year	*1877*	*1900*	*1924*	*1960*	*1931*	*1974*	*1902*	*1977*	*1936*	*1979*	*1963*	*1989*

* absolute values.

Table 3 – Some geotechnical properties of the soil samples tested (modified from Quinta-Ferreira et al., 2002).

Sample Nº	Lith.	Nuclear gauge (Troxler 3440)				Grain size (% pass)			Limits			Proctor		Methylene Blue	Classification	
		Depth (cm)	γd (kN/m^3)	γ (kN/m^3)	w (%)	0.074 (mm)	2 (mm)	50.8 (mm)	w_L (%)	w_P (%)	I_P (%)	γd (kN/m^3)	w_{opt} (%)	(g/100g)	Unif.	AASHTO
1	sd	25	11.2	12.3	9.6	18.1	46.2	94.9		NP					SM	A-1-b(0)
2	sd	25	14.5	16.7	14.6											
3a	fill	20	18.0	20.3	12.7											
3b	fill	30	17.5	19.7	12.3	29.6	58.0	100	27	19	8	17.4	4.7	0.6	SC	A-2-4(0)
4a	fill	30	17.4	20.6	18.3	44.4	61.2	100	27	18	9	16.8	9	0.8	SC	A-4(3)
4b	fill	15	17.0	20.0	18.7											
5	fill	25	18.1	20.1	10.9											
6	fill	25	18.1	20.2	11.6	27.3	63.9	100						1.0		
7	fill	25	17.3	18.3	6.0											
8a	lf	15	17.1	19.0	10.8	47.8	71.3	100	33	21	12	18.6	9	1.1	SC	A-6(4)
8b	lf	30	18.1	20.0	11.0											
9	lf	30	18.2	20.0	9.5	34.0	73.2	100	26	9	17	19.1	8.2	0.9	SC	A-2-6(3)
10	sd	25	17.3	19.1	11.0											
11a	sd	30	17.3	19.5	13.0											
11b	sd	20	17.1	19.5	14.3											
12	sd	30	14.4	16.4	14.1											
13	sd	30	16.5	18.7	13.1	58.3	85.8	100	35	23	12			1.9	SC	A-6(6)
14	sd	30	16.4	18.0	9.8											
15	lf	30	17.1	19.7	15.4											
16	lf	30	17.1	19.9	16.1	19.6	43.2	100	46	19	27	19.1	7.8	0.3	GM	A-2-7(6)
17	co	10	17.4	19.8	13.9											

Lith – lithology; fill – fill; co – coluvium; lf – liquefied fill; sd – slope debris.

γd - dry unit weight; γ - "in situ" unit weight; w – water content; W_L – liquid limit; W_P – plasticity limit; I_P – plasticity index:

FIGURES

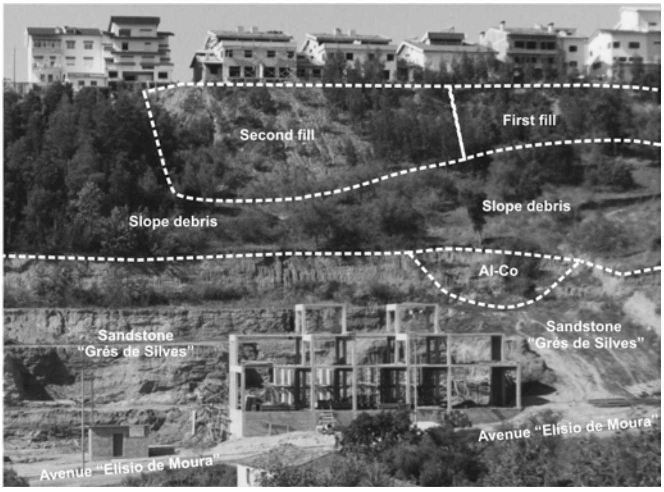

Figure 1 –Slope geology superimposed on a 1983 photograph indicating the fills placed at the top of the hill and the platforms excavated in the sandstone of the Grés de Silves (Photo of F. Gomes da Silva).

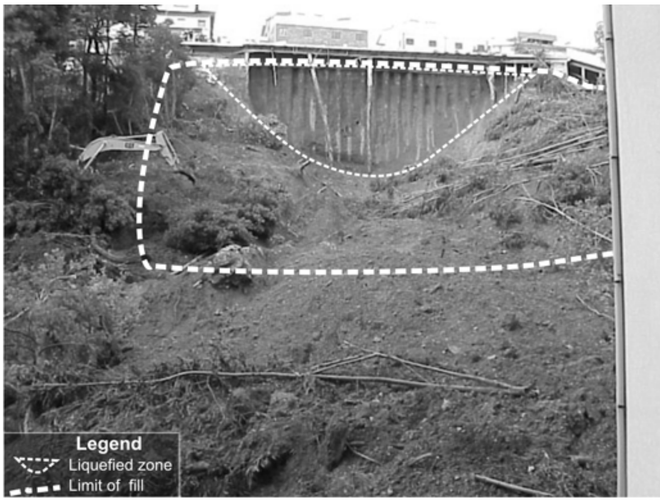

Figure 2 - General view of the earth flow, taken from the building at the bottom of the slope, showing the limit of the original fill. The maximum height of the piles exposed during the earth flow is 13m.

Figure 3 - Accumulation of soils against the building at the foot of the earth flow, which destroyed two floors, leaving the remaining twelve floors suspended. a) After the failure; b) One year later, after repairing the affected concrete structure.

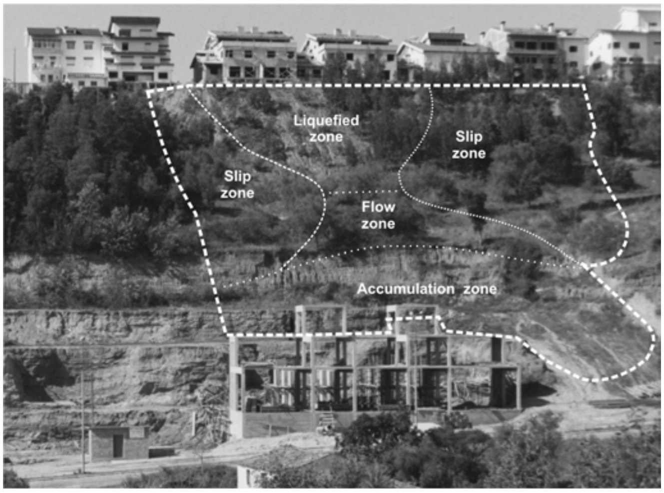

Figure 4 – Zoning of the earth flow superimposed on a 1983 photograph.

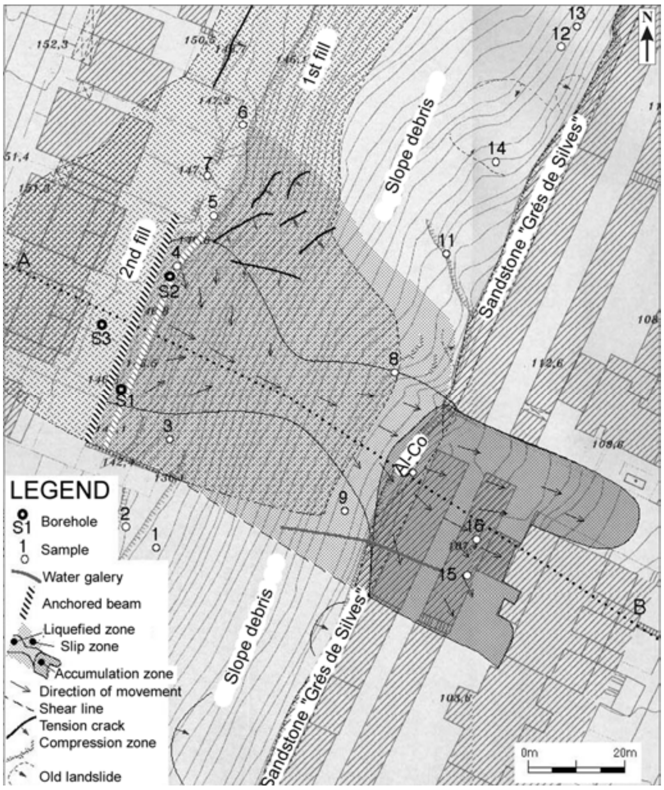

Figure 5 – Geological map and limits of the earth flow (modified from Lemos & Quinta-Ferreira, 2004).

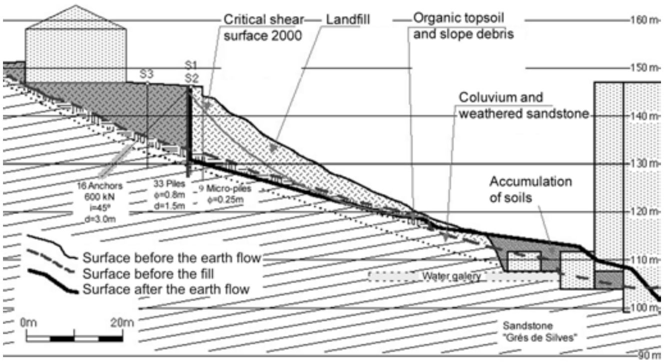

Figure 6 – Cross section along the earth flow (line AB of Fig. 5); modified from Lemos & Quinta-Ferreira, 2004.

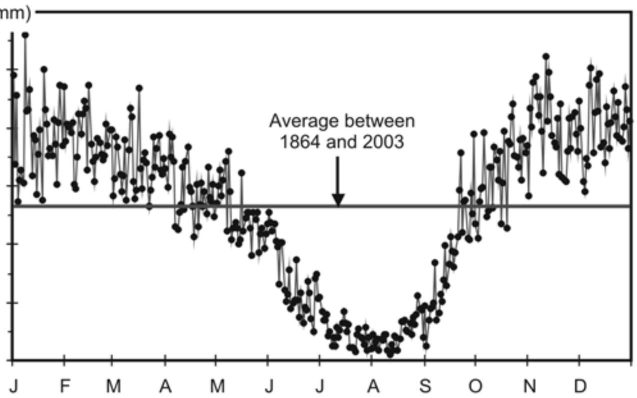

Figure 7 – Distribution of daily average rainfall, and average between 1864 and 2003.

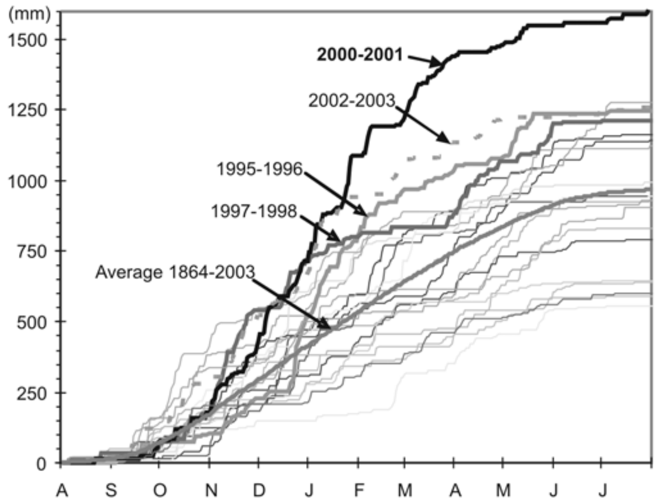

Figure 8 – Accumulated rainfall for the years 1982/83 to 2002/03 and accumulated average from 1864 to 2003. A few relevant years are identified.

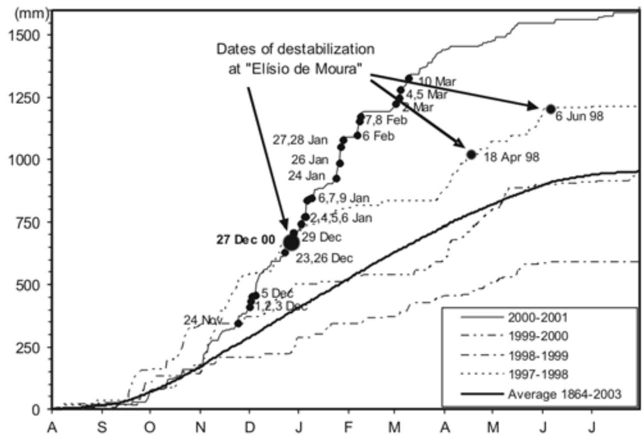

Figure 9 – Accumulated rainfall for the years 1997/98 to 2000/01, accumulated average from 1864 to 2003 and dates of occurrence of landslides in the area of Coimbra.