Assessment of slope stability in Maputo City, Mozambique

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Abstract: Maputo City, in the south of Mozambique, is bordered by an extensive slope which separates the upper part of the town (up to 60 m height) from the downtown area (almost at sea level). Throughout the city problems are reported on roads, buildings and other infrastructures, in which slope instability plays a significant role. Related to this are a number of corrective measures, often taken without real assessment of the degree of slope stability.

This paper describes some of the geotechnical properties of the subsurface, assesses the slope stability Factor of Safety for the main geological formations using SLIDE 5 (a slope stability software) and presents risk maps of the city. Finally, the relationship between the factors of safety, the morphology of the area, the geology and the geotechnical parameters is discussed.

Résumé: La ville de Maputo, située au sud du Mozambique, est limitée à l'Est et au Sud par un talus qui sépare la partie haute (jusqu'à 60 m d'altitude) de la partie basse (qui se trouve à peu près au niveau de la mer). Dans toute la ville sont rapportés des problèmes liés aux routes, aux édifices et autres infrastructures pour lesquelles la stabilité des talus joue un rôle significatif. En outre, les mesures correctives sont souvent appliquées sans qu'il y ait une évaluation préalable des talus et des sols nécessaire en raison de la surcharge des ouvrages.

Cet article décrit certaines propriétés géotechniques de la sub-surface, évalue le facteur de sécurité de la stabilité des talus en utilisant SLIDE 5 (un logiciel de stabilité des talus) et présente des cartes de risque de la ville. Finalement y est discutée la relation entre le facteur de sécurité, la morphologie, la géologie et les paramètres géotechniques.

Keywords: slope stability, engineering properties, finite element, safety, soil erosion, urban geosciences.

INTRODUCTION

Maputo is the capital city of Mozambique and the most important city of the country. It was built on elevated Tertiary and Quaternary deposits. Most of these deposits look stable for engineering purposes, however time after time problems such as tilting of buildings, instability of roads due to moving ground, soil erosion and slope instability are reported.

The assessment of the stability of slopes within the city can be included in urban geological studies whose importance has been stressed by Legget & Karrow (1983) and De Mulder & Cordani (1999). In this case the information produced is required to support urban planning and civil engineering practice, as from the definition, the slope instability hazard had an adverse socio-economic impact on the population. Slope failures caused severe damage to roads, private homes, drainage and sewage systems, water supply sources, collapse of the waste collecting and disposal systems, deposition of red sediments on basic infrastructures (football ground, schools), and in the beach area, displacement of hundreds of families mainly affecting the impoverished.

Since these failures presented a hazard to the public, considerable attention was given to the stabilisation and corrective measures. The use of these measures should be preceded by a prior identification of failure mechanisms in order to recommend the adequate preventative techniques, but are often taken without real assessment of the degree of slope stability. This study is one of the first orientated to assess the slope stability in Maputo City and the results show that most of the slopes are unstable and occur in the Ponta Vermelha geological formation.

GEOLOGIC SETTING

The geology of Maputo has been described in detail by Momade, Ferrara & Oliveira (1996) in their explanatory note to the geological map 1:50000, sheet 2532D3 (Figure 1).

The built up area lies on top of a sedimentary sequence of varying thickness and mineralogical composition, mostly of marine, fluvial and aeolian origin (Afonso, Marques & Ferrara 1998). These sequences are grouped into Tertiary formations (Inharrime, Santiago and Ponta Vermelha) and Quaternary formations (Matola, Machava, Malhazine, Congolote, Costa do Sol, Xefina, Inland dunes, Alluvial deposits and Tidal and Shoreline deposits).

The Inharrime Formation contains silty sandstone rich in clays and organic matter. This seems to be the deepest geological unit reached by drilling. The Inharrime Formation is overlain by yellowish brown fine to medium grain size sandstone and clayey sands of Santiago Formation. This formation is 10 to 35 meters thick and locally occurs 20 meters below the surface. The last Tertiary formation is the Ponta Vermelha Formation. This unit believed to represent the transition from Upper Pliocene to Lower Pleistocene and comprises ferruginous sandstones and silty sands of remarkable red colour varying to yellowish and whitish. Locally there is a red ferruginous crust, possibly of lateritic origin, which grades downwards into carbonaceous, white sand, which are horizontally stratified. This formation is remarkably uniform in its composition, with no visible variation in lithology or structure (Momade *et al.* 1996).

The Quaternary deposits include four Pleistocene Formations and Five Holocene deposits. The Matola Formations is the oldest Quaternary unit (Lower Pleistocene) and includes basal conglomerates and clayey sands. This is followed by alternating layers of clayey sands with levels rich in limestone, salt and ferruginous concretions belonging to the Machava Formation (Middle Pleistocene). Some pebbles are reported on the base of this formation. The Machava Formation is followed by loose sands of the Congolote and Malhazine Formations. These two formations are considered to be laterally equivalent and form, together with the above-described Ponta Vermelha Formation, extensive exposures within the built up area.

The Holocene is mostly represented by the Costa do Sol Formation (calcarenite), Xefina Formation (coastal dunes), Inland Dunes, Alluvial Deposits and Tidal and Shoreline Deposits.

The geological structure is relatively simple, being dominated by two normal faults of NNE/SSW trending, the Polana and Infulene faults. The Infulene Fault led to the formation of the low-lying valley of the Infulene River while the Polana Fault caused the formation of the escarpment analyzed in this study. This fault runs parallel to the coast being the boundary between Ponta Vermelha Formation to the West and the Xefina Formation to the coast. To the South of the city the coastal slope curves inland along the Maputo Estuary leaving a 100 to 1000 m wide strip of Alluvial Deposits between its foot and the estuary. The height of this natural slope formed by these tectonic events varies from 10 to 50 m. The characteristic angles of the problematic areas are typically 20 degrees observed at the long abandoned estuarine slope at Nações Unidas Avenue and also of the North of the city and about 40 degrees observed at the coastal slope facing and close to the sea. Locally a slope angle of 60 degrees is observed.

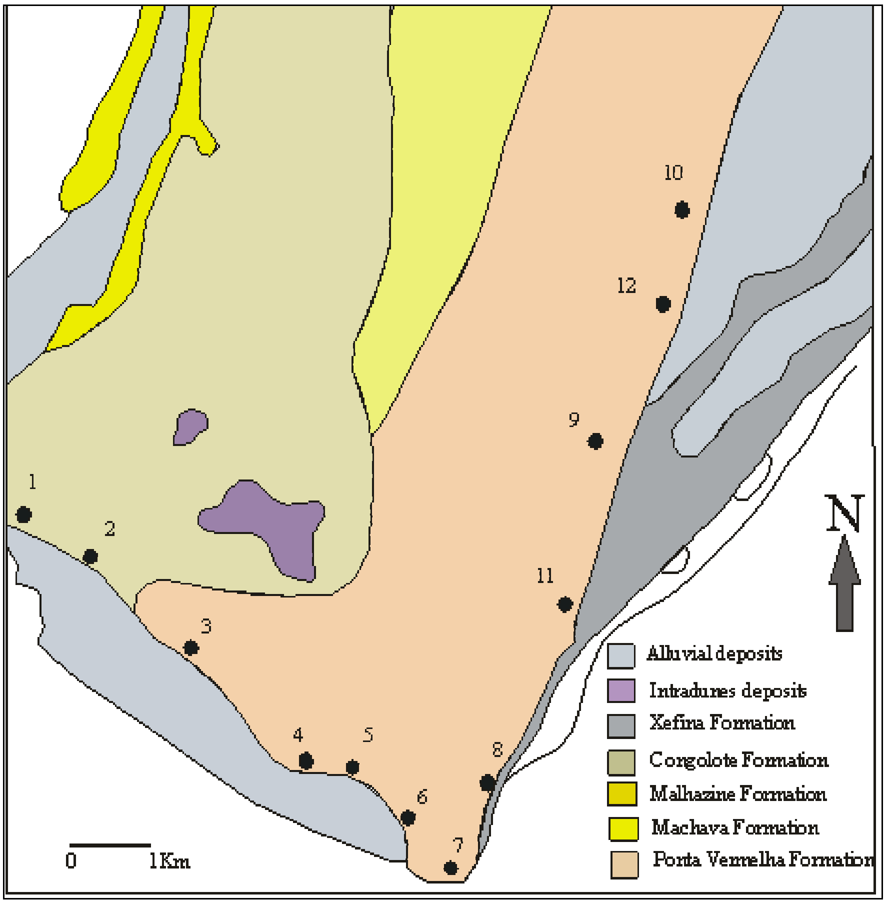

Figure 1. Geological Map of Maputo City and the sampling points.

MATERIAL AND METHODS

A total of 12 disturbed and undisturbed (block) samples were collected in test pits excavated by hand along the slope in the study area. Sampling containers were driven into the soil and immediately sealed with melted wax to keep the moisture content. It was not possible to collect undisturbed samples in two of the sites (sites 6 and 7) due to the high content of gravelly material and the loose nature of the soils. The Factor of Safety was not determined for these sites.

Specialized analytical tests were developed on these samples to determine the geotechnical properties of the soils. All tests were carried out according to British Standard, the most important being BS 1377:1975 (Methods of test for soils for civil engineering purposes) except the standard shear box which was carried out using the American Society for Testing and Material standard (ASTM 3080).

Moisture content by oven drying method, Atterberg Limits (Liquid Limit by cone penetrometer method and Plastic Limit), particles density by density bottles method and particle size distribution by sieving and laser particle sizing were determined for soil identification and classification according to the Unified Soil Classification System (USCS). Samples were sifted through a 15-mesh series (8–0.063 mm) for determination of particle size distribution. Finer grain size content (silt and clay) was obtained using a laser diffraction grain-size analyser (Malvern Mastersizer, Model APA2000).

Shear box tests were carried out to determine the shear strength parameters, cohesion (c) and internal friction angles (φ) in terms of effective stresses. These two parameters are necessary for the calculations of the stability of slopes. The applied normal stress varied from 56 to 250 kPa at low shearing velocity. This test also provides the most direct means of relating to the void ratio, *e*, and of determining the critical void ratio (or critical density) of dry sands or of saturated sands which do not contain fine material in sufficient quantity to impair the drainage characteristics.

Compressibility characteristics of the soils were obtained by the consolidation test. The collapse potential of the soils was determined by the double oedometer test which is the classical approach used for quantification of potential collapse settlement (Jennings & Knight 1975, Jennings & Knight 1957, Denisov 1951). Twin undisturbed samples were tested in oedometers, one saturated and the other at natural moisture content. Vertical stresses were doubled for each stage beginning with 6 kPa up to 400 kPa and then decreased in stage by half to 50 kPa. Each stage was maintained for 24 h. After the interpretation of the double oedometer test curve, then prediction of consolidation at natural moisture content and collapse settlement was carried out using normal consolidation theory (Lambe & Whitman 1979). Bonding between soil particles affects the collapse property of the soils and special attention was taken to their possible relation.

GEOTECHNICAL PROPERTIES OF SOILS

Table 1 summarizes the geotechnical characteristics of soils. The clay content in the soils is very low ranging from 0.08 - 1.52 %; the silt content ranges from 1.81 to 27.09% and the sand content from 71.39 to 93.66%. A large percentage of soil is in the range of medium and very fine sand as shown by the grain distribution curve A in the Figure 2. This curve represents the common grain size distribution of the soils of Maputo City. Curve B represents the only two samples that show noticeable percentage of gravel, 11.99 and 12.87 %, respectively for samples 6 and 7. These samples are located close to the section of Ponta Vermelha Formation with outcrops of ferruginous sandstone. Undisturbed samples were not collected on these sites due to the loose nature of the soils.

Table 1. Geotechnical Characteristics of soils of the study area.

Sample Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Gravel (%)	0	0	0	0	0.31	11.99	12.87	0	0	0	0	0
Sand (%)	71.39	92.7	84.56	90.46	93.66	86.1	79.10	84.18	86.22	86.46	93.28	90.43
Silt (%)	27.09	6.96	15.44	9.01	5.74	1.81	7.71	15.15	13.12	12.88	6.39	9.11
Clay (%)	1.52	0.36	0	0.53	0.28	0.08	0.32	0.67	0.66	0.66	0.33	0.46
Liquid limit (%)	21	23	22	24	25	-	25	20	28	27	-	26
Unified Classification	SM	SM	SM	SM	SM	SM	SM	SM	SM	SM	SM	SM
Moisture (%)	7.83	8.58	4.82	2.27	5.34	-	-	3.13	6.76	4.48	13.88	8.20
Mass Density (Mg/m^3)	1.52	1.97	1.38	1.66	1.6	-	-	1.45	1.75	1.58	1.55	1.63
Dry Density (Mg/m^3)	1.41	1.82	1.32	1.63	1.52	-	-	1.41	1.64	1.51	1.36	1.51
Specific gravity	2.94	2.68	2.78	2.96	2.69	2.89	2.75	2.89	2.91	3.04	2.92	2.86
Unit weight (kN/m^3)	14.91	19.33	13.54	16.28	15.7	-	-	14.22	17.17	15.5	15.21	15.99
Voids Ratio, e	1.08	0.47	1.11	0.82	0.77	-	-	1.05	0.77	1.01	1.14	0.89
Coesion (kN/m^2)	1.38	9.86	11.14	5.93	9.42	-	-	5.33	2.14	3.47	5.71	8.57
Internal Friction (°)	32.5	32.0	28.5	31.0	31.5	-	-	32.0	31.5	33.5	31.0	31.5

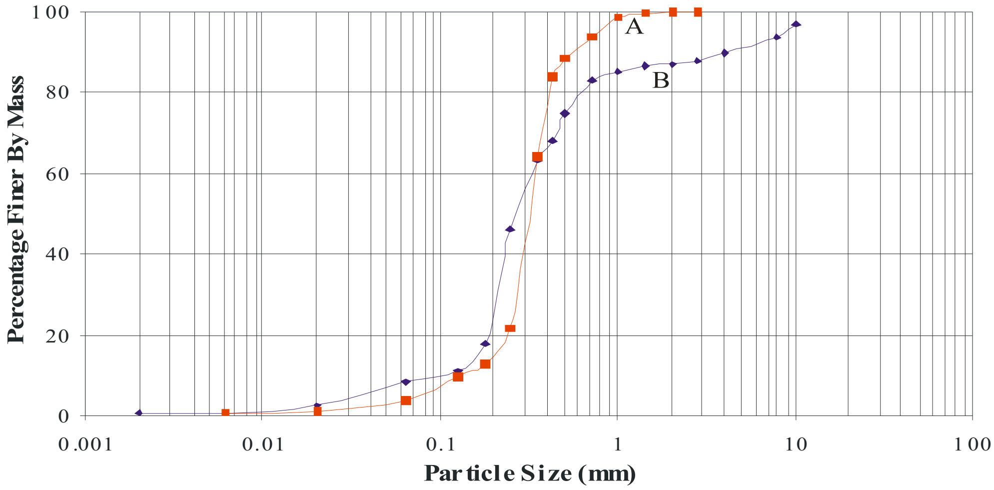

Figure 2. Typical grain distribution curves of the soils of Maputo City.

Unit weight ranges from 13.54 to 19.33 KN/m^3 for a specific gravity of 2.68 to 3.04. The natural water content varies considerably, ranging from 2.27 to 13.88%; the dry density ranges from 1.32 to 1.82 Mg/m^3 while the mass density varies from 1.38 to 1.97 Mg/m^3.

The Atterberg limits showed that all soils are sands of very low plasticity to non-plastic. The liquid limits values have small variations, from 21 to 28%. In most cases it was not possible to perform the plastic limit test due to the non-plastic character of the soils. These results are consistent with previous sieve and Atterberg limit laboratory test results (Vaz, 1990; Abel, 1996) made on soil samples of the same geological formation, except for the plasticity index that is slightly higher (~ 4).

Based on the grain size analysis and field observations three general soil types are identified: (a) medium dense-to-loose granular deposits, made up of silty very fine to medium sand; (b) dense granular deposits of silty fine to medium sands; and (c) loose to very loose, silty medium to coarse sand, slightly gravelly. All these soils are from SM group of the Unified Soil Classification System (USCS).

Shear strength parameters based on direct shear box test are: cohesion (1.38 – 11.14 kPa) with the angle of internal friction from 28.5 – 33.5°. It is evident from shear stress–shear strain plots in Figure 3 that shear strength did not drop from peak to residual level, even as the shear strain increased considerably. The stress-strain curves show an asymptotic shape, the absence of a peak and a high level of residual strength. This type of plastic failure indicates that the soils of the study area are normally consolidated and loose.

From the consolidation test it is observed that the primary settlement occurs almost immediately in all tests and lasts only at very short time. This feature can be explained by the relatively higher porosity of these soils, which allow water to drain quickly. The volume change varies from 1.86 to 18.03% and the void ratio ranges from 0.47 to 1.14. Figure 4 shows typical *e*/log curves from the double oedometer test. The straight line of the test on saturated samples gives an indication of collapse of the soil structure in the presence of water.

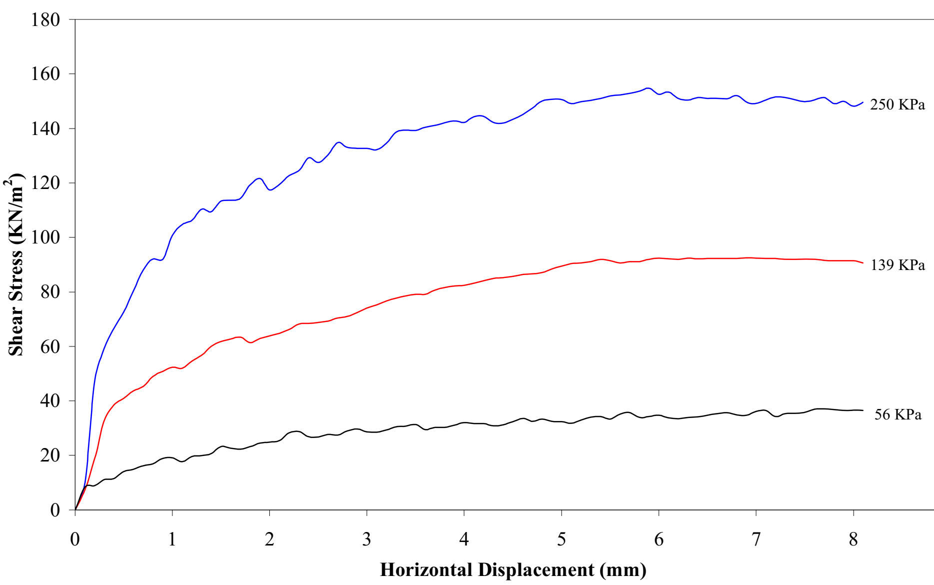

Figure 3. Typical stress–strain diagram of direct shear tests of the soils of Maputo City.

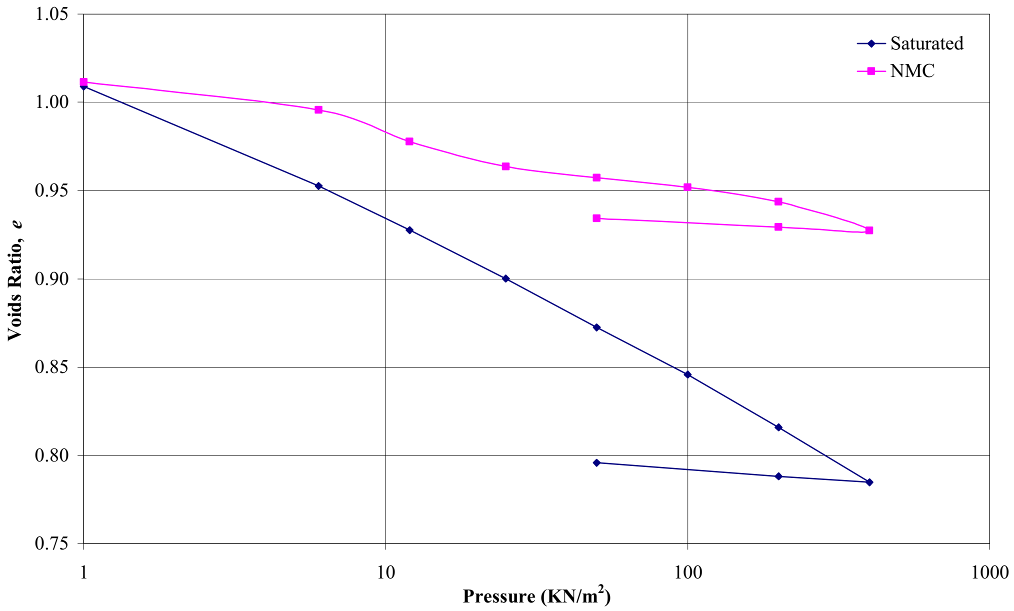

Figure 4. Typical vertical stresses-void ratio curves for different loadings of the soils of Maputo City.

SLOPE STABILITY ANALYSIS

Historical notes and causes

Slope instability problems started to be a cause of concern in the last decade when the first cases were registered. The first cases coincided with the increasing population density and development of informal and formal construction projects in the immediate coastal zone. Much of the development was above the neutral line of slides. In the late 1990s gullies were opened in the slopes in Polana-Caniço residential area near the entrance of Main Campus of the Eduardo Mondlane University and small landslides were registered in the Friedrich Engels Avenue. In February 2000 an extremely heavy, unusual and short-lived rainstorm hit Maputo with 400 mm recorded in 4 days (30% of the mean annual precipitation) and the problems of slope stability were exacerbated. Water flow into the top of the slopes saturated the soil and reduced its strength, triggering slope instability as well as causing deep gully failures. In addition, several isolated cases of damage to infrastructures occurred throughout the city:

- Located along Vladimir Lenine Av., close to the Supreme Court building, it seems that unstable ground has led to folding of the asphalt and systematic problems of road bumps (200 m West of Site 4);
- Vladimir Lenine Av., in the same area as above, the construction of a multi-story building called “Millennium Hotel” was abandoned, apparently due to unstable ground problems;
- Patrice Lumumba Av., behind Girassol Hotel, grows concern over continuous soil erosion problem (Site 5);
- Julius Nyerere Av., five buildings are subject to subsidence and slope instability, causing panic among residents;
- Friedrich Engels Av., a retaining wall and road integrity are subject to continuing erosion and slope instability (Site 8);
- Marginal Av.(Costa do Sol area), the construction of Quatro Estações Hotel was abandoned long ago, apparently due to subsidence and slope instability (Along the coastal line);
- Marginal Av.(Costa do Sol area), retention wall and coastal erosion protection trees have been destroyed by sea waves and the road is in danger (Figure 5) (along the coastal line);

Figure 5. Coastal erosion destroying the Marginal Avenue in Maputo City.

Factor of safety

The Factor of Safety is defined as the factor by which the shear strength of the slope soil has to be reduced in order to bring the slope to the state of failure. With the main purpose being to investigate the failure phenomenon of the slope a study was undertaken using both the conventional limit-equilibrium method of analysis and numerical modelling.

To assess the slope's Factor of Safety a number of steps were followed using SLIDE 5 (a finite element package). First the geometry of the slope is drawn using slope height and slope angle data collected in the field (Table 2). Next, the material properties (cohesion, internal friction and unit weight) are assigned. Then, the method of analysis, failure surface and failure criteria assumed are chosen. Limit-equilibrium analyses were performed using the Bishop simplified method (Bishop 1955) and Mohr-Coulomb failure criteria and circular failure surfaces were assumed. Finally, the computer program computes and classifies the Factor of Safety for a large number of failure surfaces and then presents the results as shown in Figure 6 with the lowest value chosen as the Factor of Safety of the slope.

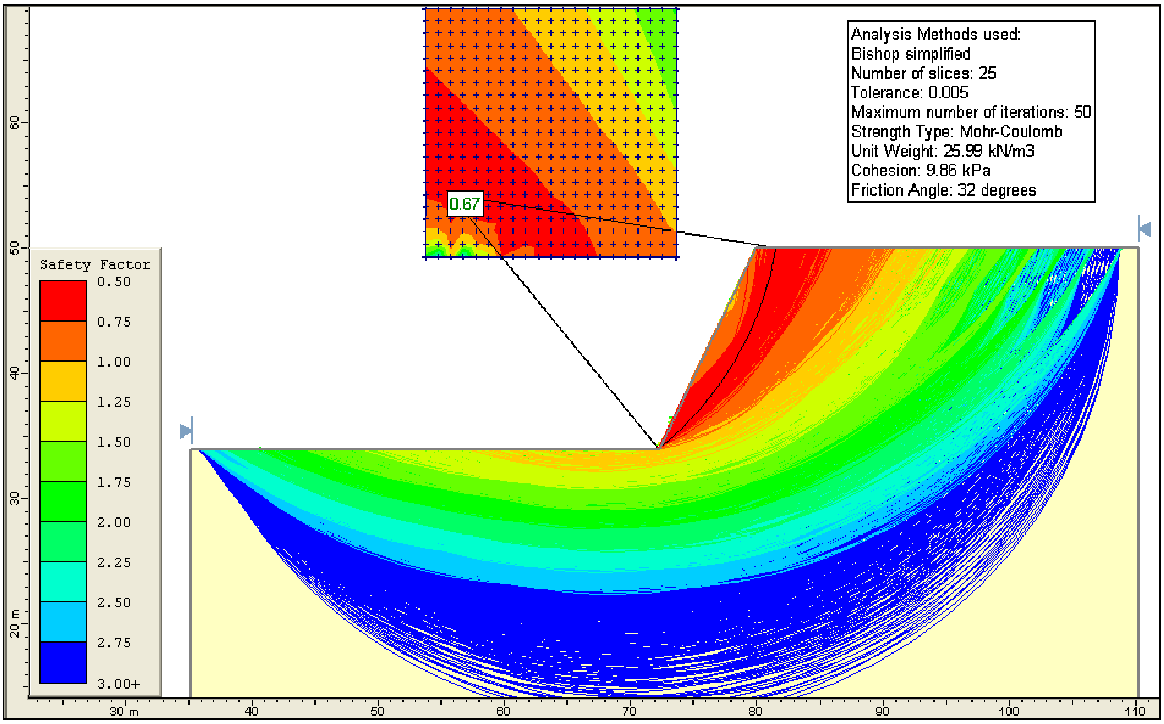

Figure 6. Model for the determination of the factor of safety.

The Factors of Safety values obtained are presented on Table 2. They vary from 0.68 to 1.76. Analysing the Factor of Safety results it is seen that sites 1, 3, 4 and 11, show stable slopes (Factor of Safety higher than 1). The Factor of Safety in the area is controlled mainly by the slope angle, i.e., there is a disproportionate relationship between the slope angle and the Factor of Safety. What is not possible to see is the relationship to friction angle, cohesion and unit weight because they are almost similar in all slopes. The influence of each parameter in the Factor of Safety is determined through the sensitivity analysis.

Table 2. Factor of safety of the slopes of Maputo City. Slopes are located in the sampling points listed in the table.

Sample Nº	Cohesion (KN/m^2)	Friction Angle (°)	Dry Unit Weight (KN/m^3)	Slope Angle (º)	Slope Height (m)	Factor of Safety
1	1.38	32.50	14.91	25	46.67	1.48
2	9.86	32.00	19.33	66	16.17	0.71
3	11.14	28.50	13.54	27.5	26.03	1.56
4	5.93	31.00	16.28	25	23.31	1.63
5	9.42	31.50	15.70	45	38	0.93
8	5.33	32.00	14.22	60	24.64	0.68
9	2.14	31.50	17.17	50	7.97	0.82
10	3.47	33.50	15.50	62	10	0.72
11	5.71	31.00	15.21	22	37	1.77
12	8.57	31.50	15.99	70	8	0.89

RELATIONSHIP BETWEEN THE FACTOR OF SAFETY AND THE MORPHOLOGY

The laboratory results of the samples collected in the 12 sites show very small differences in terms of cohesion and friction. This gives an indication that differences in the Factor of Safety will be influenced by the morphological characteristics of the slopes. This assumption is proven by the sensitivity analysis of the Factor of Safety in relation to the slope height.

The main purpose of the present investigation is to provide required information to civil engineering practitioners in Maputo, so that they can use it to accommodate project design or apply the necessary corrective measures for slope stabilization to *in situ* ground conditions. Therefore, sensitivity analysis was carried out to widen the range of option to use while solving slope stability related problems.

Sensitivity analysis is an interactive process adopted to more realistically simulate slope instability and determine the influence of the different parameters in the Factor of Safety. It indicates which input parameters may be critical to the assessment of slope stability, and which input parameters are less important. Computations were performed using the *Slide* 5 program and were based on changing the slope height on the determination of the Factor of Safety in order to identify the critical situations on the slope stability. Slope height and slope angle were manipulated individually. In the sensitivity analysis of the slope height, the Factor of Safety was calculated for the heights of 10, 20, 30, 40 and 50 m and the results are presented on Table 3 and Figure 7. The results show that there is a disproportionate relationship between the slope angle and the Factor of Safety, i.e., the bigger the slope height, the lower the Factor of Safety. Figure 7, also illustrates that slopes 2, 8, 9, 10 and 12 can not yield stable factors of safety by simply reducing the slope height.

The Factor of Safety was also determined for slope angles ranging between 10 and 80º at 10º intervals. The intervals are close to the slope angles measured in the field. The results of the sensitivity analysis in relation to slope angle are presented on Table 3 and Figure 8. It is seen that the steeper the slope, the lower the Factor of Safety of the slopes. The tendency of materials to move downward will also be greater and therefore lowering the Factor of Safety. It can also be read in Figure 8 that for most slopes 30º is the angle for which the slope becomes stable. The combination of corrective measures can also help to reduce costs resulting from removing soil material.

Actually, topography is one of the main factors controlling mass movement and in Maputo City it played an important role in slope instability. The topographic difference between the upper and down town and the respective slope angle have contributed to landslide and slope instability hazard in Maputo City.

Table 3. Results of the Factor of Safety in the sensitivity analysis in relation to slope height and slope height.

Sample	Slope Height (m)					Slope Angle (degrees)							
	10	**20**	**30**	**40**	**50**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
1	1.65	1.54	1.50	1.49	1.47	3.79	1.88	1.20	0.86	0.64	0.48	0.37	0.29
2	0.87	0.67	0.6	0.57	0.55	4.31	2.34	1.63	1.24	0.99	0.81	0.66	0.53
3	2.16	1.67	1.52	1.43	1.38	3.81	2.07	1.45	1.12	0.90	0.73	0.61	0.49
4	2.03	1.67	1.58	1.53	1.50	3.93	2.03	1.36	1.02	0.79	0.64	0.51	0.42
5	1.43	1.07	0.97	0.91	0.88	4.0	2.06	1.39	1.03	0.82	0.66	0.54	0.45
8	0.87	0.68	0.63	0.59	0.58	4.06	2.09	1.40	1.04	0.81	0.65	0.52	0.43
9	0.78	0.68	0.65	0.64	0.63	3.99	2.11	1.39	1.03	0.81	0.65	0.53	0.44
10	0.72	0.60	0.57	0.55	0.53	4.42	2.39	1.65	1.22	0.95	0.75	0.61	0.49
11	2.31	1.96	1.84	1.79	1.75	3.82	1.95	1.28	0.95	0.73	0.59	0.48	0.39
12	0.81	0.62	0.54	0.52	0.50	4.76	2.87	2.09	1.59	1.29	1.07	0.89	0.76

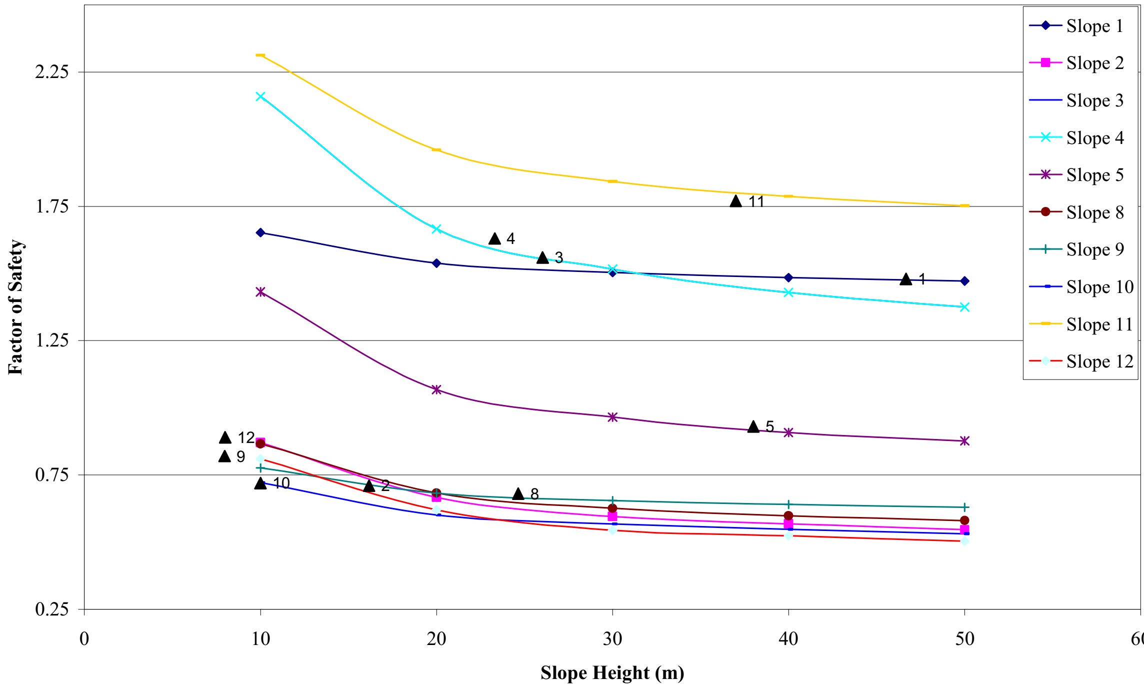

Figure 7. Graphical representation of the sensitivity analysis of the Factor of Safety in relation to slope height. The scatter plot (black triangular dots) indicates the position of the slopes analysed.

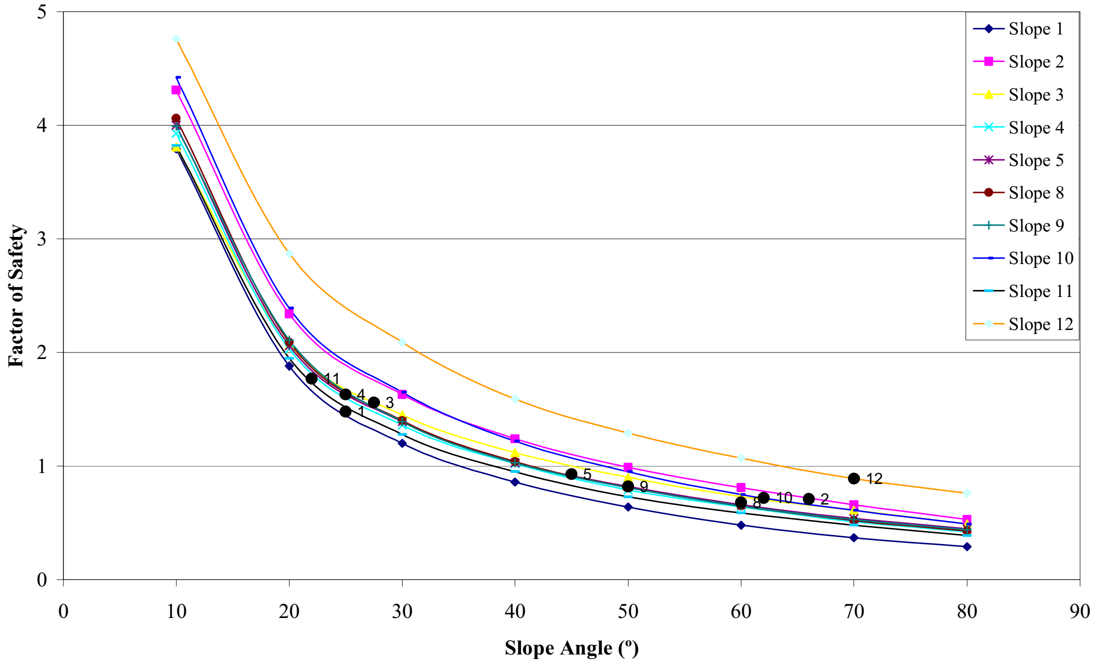

Figure 8. Graphical representation of the sensitivity analysis of the Factor of Safety in relation to slope angle. The scatter plot (black circular dots) indicates the position of the slopes analysed.

RELATIONSHIP BETWEEN THE FACTORS OF SAFETY AND THE GEOLOGY AND GEOTECHNICAL PROPERTIES

The slopes covered in this study occur on two geologic formations, the Congolote (site 1 and 2) and Ponta Vermelha Formations (remaining sites). The geological characteristics of these formations are similar and the laboratory results confirm that there are no clear typical geotechnical characteristics differentiating them. Nevertheless, a sensitivity analysis was performed in relation to cohesion, friction angle and unit weight, and geotechnical parameters used in the calculation of the Factor of Safety.

Sensitivity analysis in relation to soil relevant shear strength parameters can be particularly important for the cases of instability in Maputo, namely, in places where the best corrective measures have to be the application of soil stabilization techniques. In figure 9, the effect of individual shear strength parameters on the factor of safety is determined by varying uniformly between minimum and maximum values.

The results show that the factor of safety is sensitive to the value of cohesion in 70% of the sites and to the value of friction angle on the other 30% of sites. The Factor of Safety is not sensitive to the value of unit weight.

In addition it can be concluded that, the steepest cohesion curve indicates the greatest effect on safety factor. Unit weight has a nearly flat curve, indicating very little effect on safety factor, while the friction angle curve is an intermediate curve.

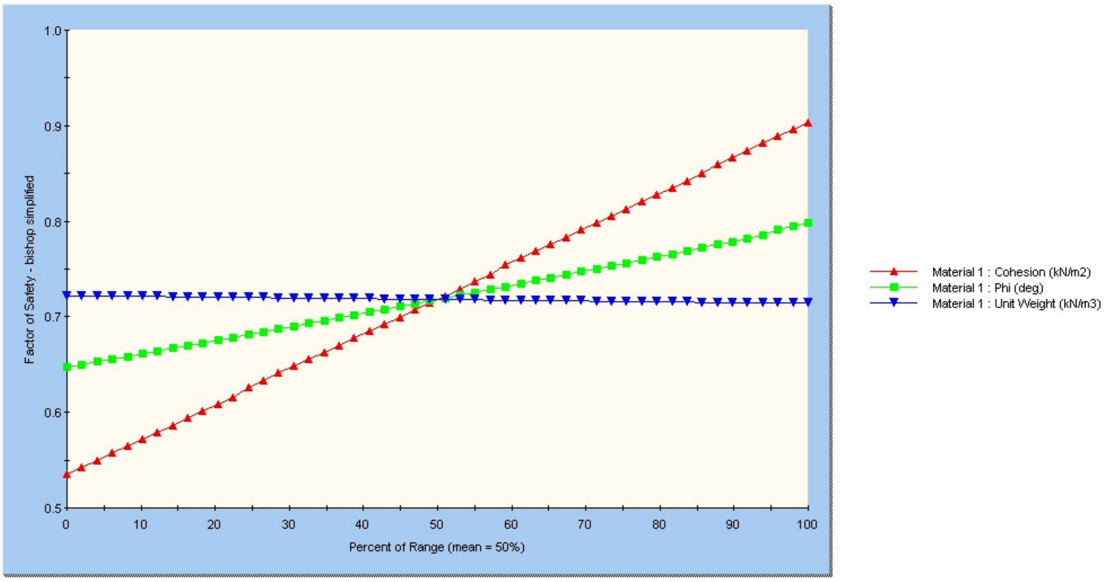

Figure 9. Typical graph of sensitivity analysis of in relation to cohesion, friction angle and unit weight in the slopes of Maputo City.

CONCLUSIONS

The stability of slopes in Maputo City has been analysed and soil engineering properties tested. From this study it can be concluded that the soils of the study area are generally medium dense to loose up to very loose silty very fine to medium sands. All these soils are from SM group of the USCS. These soils are normally consolidated and their structure becomes unstable in the presence of water.

Most of the slopes studied are unstable, because even though groundwater data were not available, the results already show very low values of Factor of Safety. A sensitivity analysis was carried out to generate alternative measures that support decision making by technicians aiming to solve slope stability and soil instability problems in Maputo. It showed that morphology is one of the main factors controlling mass movement, and it played an important role in slope instability. The topographic difference between the upper and down town and the respective slope angle have contributed to landslide and slope instability hazard in Maputo City. The Factor of Safety of the slopes in Maputo City is also sensitive to the value of cohesion.

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