Urban geology of Maputo, Mocambique

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Abstract: Maputo City is the capital of Mozambique and is located in the southern part of the country on the east coast of Africa. It is situated in a coastal area with a population of approximately 1,020,000 inhabitants. The greatest population density is in the outskirts of the city, with a population density of 1693 people/km2, which is nearly five times greater than the planned density.

Morphologically the following structures may be recognized: (a) littoral accumulation zone, corresponding to beach and tidal deposits; (b) coastal zone, inclined to the sea, with a maximum height of 8 m, constituted by dunes and alluvium; (c) platform of 40 to 50 meters, gently inclined to the West with degraded interior fixed dunes and sand sheets; (d) Maputo hill, 50 to 60 m in height, which constitutes a residual relief resistant to erosion, probably related with recent faulting activity.

Natural and human factors have contributed to the occurrence of environmental and engineering geological problems in Maputo. These include landslides and slope instability, gullying, building damage, coastal erosion, informal settlements, groundwater quality, industrial pollution, and inappropriate solid waste management.

The identified geo-environmental problems in Maputo City require immediate solutions in order to make the city sustainable. The collection of detailed geological information and monitoring data, including the engineering geological characteristics of soils, hydrogeological conditions, slope instability, hydrogeological characteristics, groundwater quality etc, will serve to increase awareness of the geological impact on urban development. It is believed that an understanding of these problems will help planners devise effective urban policies and land-use planning strategies.

Résumé: La ville de Maputo, capitale du Mozambique, se trouve dans la partie sud du pays, sur la côte orientale d'Afrique. Elle se situe dans une zone côtière avec une population approximative de 1 020 000 habitants. La densité de population la plus élevée se situe dans les zones suburbaines de la ville où elle atteint 1 693 habitants/km^2, cinq fois plus que la densité planifiée.

Du point de vue morphologique, on peut reconnaître les structures suivantes : (a) zone d'accumulation littorale correspondant à des dépôts de plage et de marée ; (b) zone côtière, inclinée vers la mer, avec une hauteur maximale de 8 mètres de dunes et d'alluvions ; (c) plateforme de 40 à 50 mètres légèrement inclinée vers l'ouest, où prédominent des dunes intérieures dégradées et des couches de sable (d) collines de Maputo, de 50 a 60 mètres d'altitude, qui constituent un relief résiduel résistant à l'érosion, probablement lié à un phénomène néotectonique.

Les facteurs naturels et humains contribuent à l'apparition de certains problèmes environnementaux et de géologie d'ingénierie à Maputo. Les principaux problèmes sont le glissement de terrain et l'instabilité des talus, la création de ravines, la dégradation des édifices, l'érosion côtière, les constructions informelles, la qualité des eaux souterraines, la pollution industrielle, et la gestion des résidus solides.

Les problèmes d'environnement terrestre identifiés dans la ville de Maputo nécessitent des solutions immédiates afin que la ville soit durable. Une façon d'atteindre cette durabilité consiste à maximiser la connaissance géologique, dans la mesure où dans la ville de Maputo prédominent des problèmes liés à la géologie. La maximalisation de la connaissance géologique dans la ville de Maputo commence par la production d'informations géologiques comme les caractéristiques géotechniques des sols, les conditions hydrographiques, l'instabilité des talus, les caractéristiques hydrogéologiques, la qualité des eaux souterraines, etc. Aussitôt que cette information aura été produite, elle pourra être mise à disposition pour être utilisée dans la définition de politiques urbaines et de planification de l'utilisation de la terre et de sa couverture.

Keywords: Urban geosciences, engineering properties, slope stability, soil erosion, settlement, waste management.

INTRODUCTION

Maputo City is the Capital of Mozambique and situated in a coastal area adjacent to the Indian Ocean between the coordinates 25º 50´ and 26º 10´ S and 32º 30´and 32º 40´ E. It has an area of 602 km^2 with population density of 1693 people/km^2 (UNDP, 2001).

As the major urban centre of Mozambique, Maputo City provides an ideal case study of urban geology. Rapid population growth has resulted in housing development in sensitive areas such as slopes and flood prone areas. Informal settlement has resulted in a poor water supply network and surface water drainage systems, increased gully and coastal erosion, landslides and slope instability, and problems associated with the use of groundwater, waste management and water pollution.

The study and analysis of environmental and engineering geological problems in Maputo City are the objectives of this paper.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTINGS

Maputo City was built in a coastal area underlain by Tertiary and Quaternary deposits. According to the 1:50 000 geological sheet 2532D3 of Maputo produced by Momade, Ferrara & Oliveira (1996), 12 stratigraphic units/formations are recognised. The geological formations outcropping in Maputo City and where most development occurs (Figure 1) are described in this paper.

The upper part the Ponta Vermelha Formation comprises ferruginous sandstones and red silty sand grading down into yellow to white sand. Locally there is a red ferruginous crust, possibly of lateritic origin, which grades downwards into horizontally stratified carbonated and white sand. This formation is remarkably uniform in its composition, with no visible variation in lithology or structure (Momade *et al.*, 1996). It has a long coastal slope on its eastern and south sides.

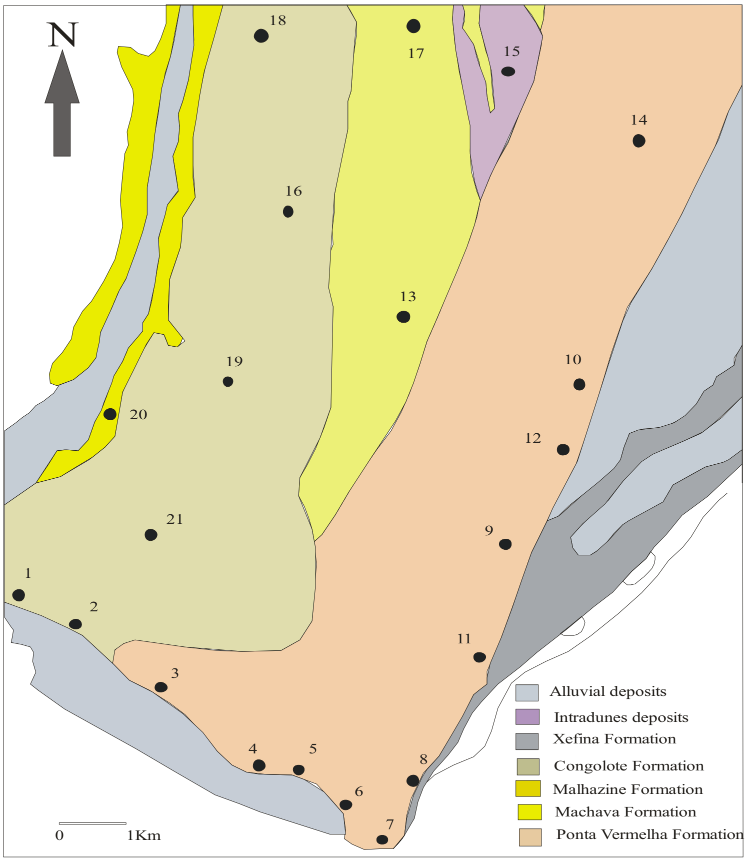

Figure 1. Geological Map of Maputo City and the distribution of the sampling points.

The Malhazine Formation is part of the interior dunes and comprises poorly consolidated whitish to reddish fine to coarse sands. The dunes are longitudinal in type and reach 30 m in height and several km in length. Ridges are fixed by vegetation and oriented NNW. The intradune depressions are filled by very fine white sands (92 to 98 % fine sand Momade *et al.*, 1996).

The Congolote formation is considered equivalent to the Malhazine Formation and comprises poorly consolidated sands with yellow, orange and whitish tonalites. The sands are fine to medium grained with only 5 % of silt-clayey fraction that is considered typical of aeolian deposition.

The Xefina Formation comprises coastal dunes of white fine to medium quartz quicksand with localised development of ilmenitic sands occupying a relatively narrow area close to the coast.

Beach and Tidal Deposits comprise slime and mud and uniformly sized white sands. These deposits are in part temporarily submerged by tides. Chemical analysis of these deposits demonstrated a high silica content.

Morphologically the following structures are recognised (Momade *et al.,* 1996): (a) littoral accumulation zone, corresponding to beach and tidal deposits; (b) coastal zone, inclined to the sea, with a maximum elevation of 8 m, comprising dunes and alluvium; (c) platform of 40 to 50 meters elevation, gently sloping to the West with degraded interior fixed dunes and sand sheets; (d) Maputo hill, 50 to 60 m maximum elevation, which comprises a residual relief resistant to erosion, probably associated with neotectonism phenomena.

Two major faults are observed. The Polana Fault being responsible for the long slope in the eastern side of Maputo City, and the Infulene Fault responsible for the Infulene River valley which is the western border of Maputo City. The Polana Fault trends NNE/SSW and runs parallel to the coast, being the boundary between Ponta Vermelha Formation to the West and the Xefina Formation and Alluvial Deposits 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 varies from 10 to 50 m. The characteristics angles of the slope are 20°, typical of the long estuarine slope at Nações Unidas Avenue and also of the North of the city and about 40° of the coastal slope facing and close to the sea. Locally a slope angle of 60° is observed.

MATERIAL AND METHODS

Disturbed and undisturbed soil samples were collected from twenty-one locations as shown on Figure 1. Samples were subjected to a range of analytical tests to determine the geotechnical properties of the soils. Tests were carried out in accordance with British Standards (BS 1377:1975 Methods of test for soils for civil engineering purposes), except the standard shear box carried out using the American Society for Testing and Material standard (ASTM 3080).

To enable detailed soil description and classification according to the Unified Soil Classification System (USCS) particle size distribution was undertaken using sieving (15-mesh series, 8–0.063mm) for the coarse fraction and a laser diffraction grain-size analysis (Malvern Mastersizer, Model APA2000) for the finer fraction. Other testing included moisture content (oven drying method), Atterberg Limits (Liquid Limit by cone penetrometer method and Plastic Limit), and particle density (density bottles method).

The strength and sensitivity of the soils was assessed by Standard Shear box test, which gives the cohesion of particles (c) and the angle of shear resistance (φ) 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 φ 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 standard 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 curves 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 summarises the geotechnical characteristics of soils. Unit weight ranges from 13.54 to 19.33 KN/m^3 for a specific gravity of 2.49 to 3.04. The natural water content varies considerably, ranging from 2.27% to 20.72%; the dry density ranges from 1.29 to1.82 Mg/m^3 while the mass density varies from 1.38 to 1.97 Mg/m^3.

Table 1. Geotechnical Characteristics of soils of Maputo City.

Sample N°.	Moisture content (%)	Liquid Limit (%)	Mass Density (Mg/m^3)	Dry Density (Mg/m^3)	Specific Gravity (Mg/cm^3)	Unit Weight (KN/m^3)	Voids Ratio, e	Cohesion (KPa)	Friction Angle (°)
1	7.83	21	1.52	1.41	2.94	14.91	1.08	1.38	32.5
2	8.58	23	1.97	1.82	2.68	19.33	0.47	9.86	32
3	4.82	22	1.38	1.32	2.78	13.54	1.11	11.14	28.5
4	2.27	24	1.66	1.63	2.96	16.28	0.82	5.93	31
5	5.34	25	1.6	1.52	2.69	15.70	0.77	9.42	31.5
6	ND	ND	ND	ND	2.89	ND	ND	ND	ND
7	ND	25	ND	ND	2.75	ND	ND	ND	ND
8	3.13	20	1.45	1.41	2.89	14.22	1.05	5.33	32
9	6.76	28	1.75	1.64	2.91	17.17	0.77	2.14	31.5
10	4.48	27	1.58	1.51	3.04	15.50	1.01	3.47	33.5
11	13.88	ND	1.55	1.36	2.92	15.21	1.14	5.71	31
12	8.20	26	1.63	1.51	2.86	15.99	0.89	8.57	31.5
13	4.11	21	1.86	1.79	2.81	18.25	0.57	5.71	30
14	ND	14	ND	ND	2.77	ND	ND	ND	ND
15	20.72	9	1.6	1.33	2.60	15.70	0.96	11.43	30
16	3.33	19	1.64	1.59	2.49	16.09	0.57	9.29	28
17	3.21	16	1.59	1.55	2.67	15.60	0.73	0.83	28.4
18	4.30	19	1.5	1.43	2.72	14.72	0.89	9.29	28
19	20.64	19	1.55	1.29	2.72	15.21	1.11	5.71	30
20	17.25	17	1.76	1.5	2.55	17.27	0.69	6.43	30.6
21	5.00	13	1.69	1.61	2.53	16.58	0.57	6.43	29

ND Not determined

The clay content in the soils is very low ranging from 0.08 to 1.52 %; the silt content ranges from 1.8 to 27.09% and the sand content from 71.36 to 96.45%. The largest percentage of soil is in the range of very fine to medium sand. Only two samples show noticeable percentages of gravel 11.99 and 12.87 % for samples 6 and 7 respectively. These samples were located from close to the boundary of the Ponta Vermelha Formation with outcrops of ferruginous sandstone. Undisturbed samples were not collected on these sites due to the loose nature of the soils.

The Atterberg limits showed that all soils are sands of very-low plasticity or are non-plastic. The liquid limit generally varies between 9 and 28% with the higher values observed in the Ponta Vermelha Formation of between 20 to 29%.

Based on the geotechnical tests of soils 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, gravelly medium to coarse sand. All these soils are from SM group of the Unified Soil Classification System (USCS).

Shear strength parameters (based on direct shear box test) indicate cohesion to be within the range 1.38 - 11.43 kPa and the angle of internal friction to be in the range 28 - 33.5°. It is evident from shear stress–shear strain plots (Figure 2) that shear strength does not drop from peak to residual level, even at high shear strain. The stress-strain curves show an asymptotic shape, an absence of a peak and a high level of residual strength typical of loose and normally consolidated soils.

Consolidation test curves demonstrate that primary settlement occurs almost immediately in all tests and lasts only at very short time. This feature can be explained by the relatively high porosity of these soils, which allow water to drain quickly. The volume change varies from 1.86 to 18.03% and the most compressible of the samples tested were from Ponta Vermelha Formation. The void ratio ranges from 0.47 to 1.14. Figure 3 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.

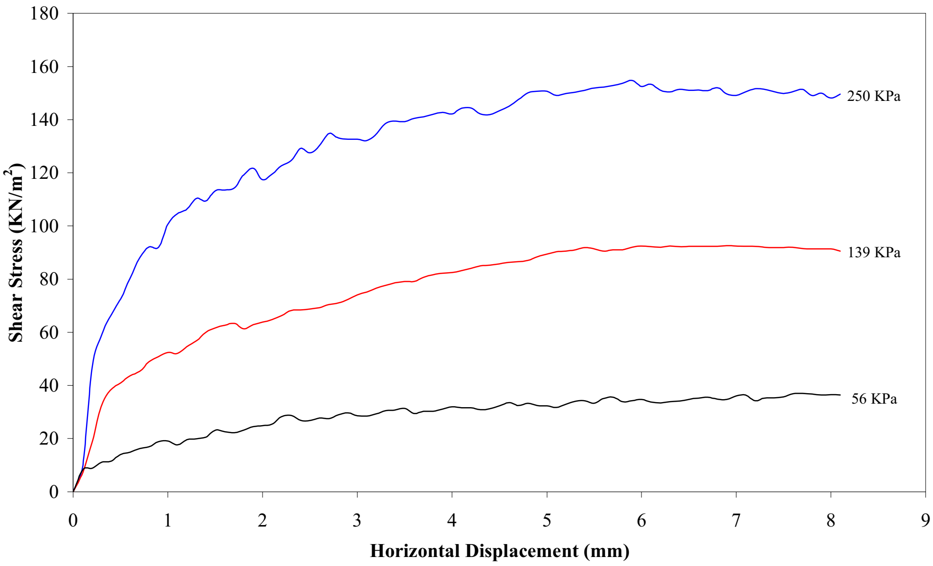

Figure 2. Typical stress–strain diagram of direct shear tests of the soils of Maputo City.

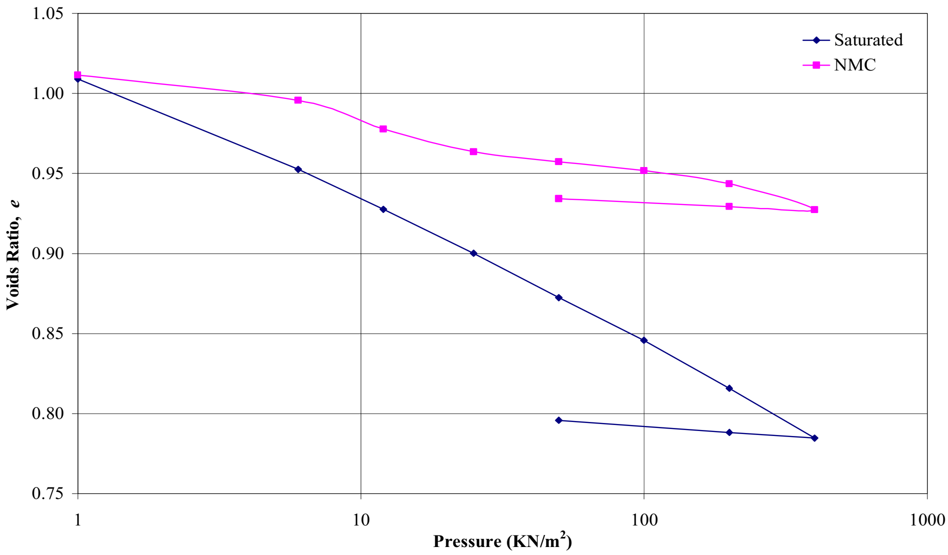

Figure 3. Typical vertical stresses-void ratio curves for different loadings of the soils of Maputo City.

ENVIRONMENTAL AND ENGINEERING GEOLOGICAL PROBLEMS IN MAPUTO CITY

Landslides and Slope Instability

Maputo City is divided in two distinct areas: down town and upper town. Most of the city its on an elevated region above a slope formed as a consequence of faulting and a small part of the city is on the lower level near the beach in the East and near the Maputo Estuary in the South (Figure 1). The slope angle is generally between 20 and 40 degrees increasing locally to 60 degrees, with a change in elevation of between 10m to 50m. Landslide events and slope instability occur on these slopes and two critical locations are described in this paper.

The first site is on an abandoned natural slope located along Nações Unidas Avenue in the South of the city where the coastal slope curves inland along the Maputo Estuary. The slope is at an angle of about 25 degrees and is, in general, straight and uniform when viewed along the slope from South to the North. It is vegetated with grass and shows a mid-slope tension crack with a vertical displacement of 30–40 cm (Figure 4). Evidence of water seepage is observed at the base of the slope. The City Council has undertaken remedial action through the construction of gabions along the base of the slope.

Figure 4. Shallow landslide along Nacoes Unidas Avenue with a vertical displacement of 30-40 cm.

The second site is at Friedrich Engels Avenue. The coastal slope at this locality faces southeast towards Maputo Bay and is approximately 40 to 50 meters high with a slope angle of 60º. The slope is thickly vegetated with shrubs and small trees. The slope is considered to be active with the most recent failure comprising a high angle slump indicated by a gap of thick vegetation in an area of about 30 m wide (Figure 5). Additional evidence of movement is observed at the top of the slope where, a 5m high masonry retaining wall has required repair, distortions of the drainage system below the retaining wall are apparent and destruction of the protection wall in the North side of the promenade has occurred (Figure 6). These observations strongly suggest that this section of the slope is in an unstable state, and will continue to suffer minor failure unless stabilised. The landslide problems in this site were first observed following heavy rainfall in February 2000. As a result of poor drainage on Friedrich Engels Avenue, surface water was able to enter a tension crack that developed in the pavement of the road. Therefore, it is assumed that water flowing into the top of the slope raised the water pressure and reduced the soil's shear strength contributing to slope instability. Additional contributory factors also include, the existence of walls and paved surfaces with a weak drainage system and head loading (construction above neutral line of slide).

The landslides and slope instability problems in Maputo City are caused by combination of various factors. The main influencing factors are described below.

Topography and Geomorphology

Topography is one of the main factors controlling mass movement. It is known that the steeper the slope, the greater is the tendency of materials to move downward. The topography determines also the water velocity in the slope, which in turn determines the size and quantity of material to be transported downward. The topographic difference between the upper town and down town and the respective slope angle have contributed to landslide and slope instability hazard in Maputo City.

Figure 5. Gap of thick vegetation (30 m wide) in the slope along Friedrich Engels Ave (Photo taken from the Marginal Ave). New vegetation starts to grow up in the area.

Figure 6. Evidence of movement at the top of the slope along Friedrich Engels Avenue. Protection wall in the North side of the promenade destroyed by the slope movement.

Geological and Geotechnical properties of soils

Landslides and slope instability occur primarily in the Ponta Vermelha Formation. This formation is composed of ferruginous sandstones and silty red sand grading down into yellow to white sand which is normally in a medium-dense to loose and locally very-loose state. These units have a very low content of fine particles, low cohesion and very-low plasticity. During heavy rainfall rapid infiltration results in saturation a decrease in the shear strength and causing instability of the soil mass.

Land use practices.

The main identified anthropogenic cause of landslides and slope instability are related to urbanization. The population density of Maputo City is nearly five times more than the planned density. The response capacity to the rapid urban population growth and increasing land use pressure was absent resulting in environmental problems such as the development of informal settlements and inappropriate construction in sensitive areas such as steep soil slopes. Poverty, weak legislation (especially in the environmental domain) and a fragile institutional framework that did not aid enforcement of the existing legislation have contributed to the problems observed.

Urbanization in the dune sands of Maputo city has resulted in a reduction in vegetation cover and an increase in the area of paved surfaces. Paving prevents infiltration, resulting in a greater volume of water run-off, shorter lag times in the hydrographs (Coch, 1995) and an increase in peak discharge. These contribute to an increase in the risk of flooding and landslides. Rapid urbanization was not supported with a good drainage system to collect the storm water. Consequently, surface water run-off is more rapid resulting in an increase in soil erosion and transport. A Combination of factors such as soil characteristics and urbanization made landslide hazard to occur. Other human factors include the constructions above the neutral line of slides and cultivation of slopes.

Hydrometeorological conditions.

The landslide and slope instability hazard in Maputo City is also related to unusual, intense and short-lived rainstorms such as occurred in February 2000 where a precipitation of 400 mm was registered in four days. This represents 30% of the mean annual precipitation. Water flow into the top of the slopes saturated the soil and resulted in movement. Water promotes movement in two ways: as an active agent, it increases the loading (weight) of soil by filling previously empty pores, and as a passive agent, it decreases the strength of the soil by reducing cohesion among particles (Coch, 1995). The high-intensity event caused flooding and soil saturation and triggered landslides and slope instability as well as forming deep, high angle gully failures. Slope failures caused severe damage to roads, private homes, drainage and sewage systems, water supply sources, the collapse of the waste collecting and disposal systems, deposition of sediments on basic infrastructures (football ground, schools) and the displacement of hundreds of families from deprived areas.

Factors of Safety and Slope Stability Analysis

Slope stability analysis was undertaken using both the conventional limit-equilibrium method of analysis and numerical modelling. Limit-equilibrium analyses were performed using the Bishop simplified method (Bishop, 1955) computed in the *Slide* 5 program. The modelled parameters for shear strength (friction angle "φ" and cohesion "c*"),* slope angle and slope height are shown in Table 2 below. The Factor of Safety obtained from modelling ranged from 0.68 to 1.76 (Table 2).

The results indicate that the factor of safety is controlled mainly by the slope angle. Input parameters for friction angle, cohesion and unit weight are relatively similar for all slopes, however a significant variation in slope angle is observed between slopes. The influence of each parameter in the Factor of Safety has been assessed by 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

Modelling of the Factor of Safety

The sensitivity analysis is an iterative process adopted to more realistically simulate slope instability and determine the influence of the different parameters in the Factor of Safety. A sensitivity analysis 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. Slope height, slope angle, cohesion, friction angle and unit weight 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. The results are presented on Figure 7. The results show that there is a disproportionate relation between the slope height and the Factor of Safety, i.e., greater the slope height, lower the Factor of Safety. Factor of Safety was also determined for slope angles ranging between 10 and 80º at 10º intervals. (Figure 8). It is seen that the steeper the slope, the lower is the Factor of Safety of the slopes.

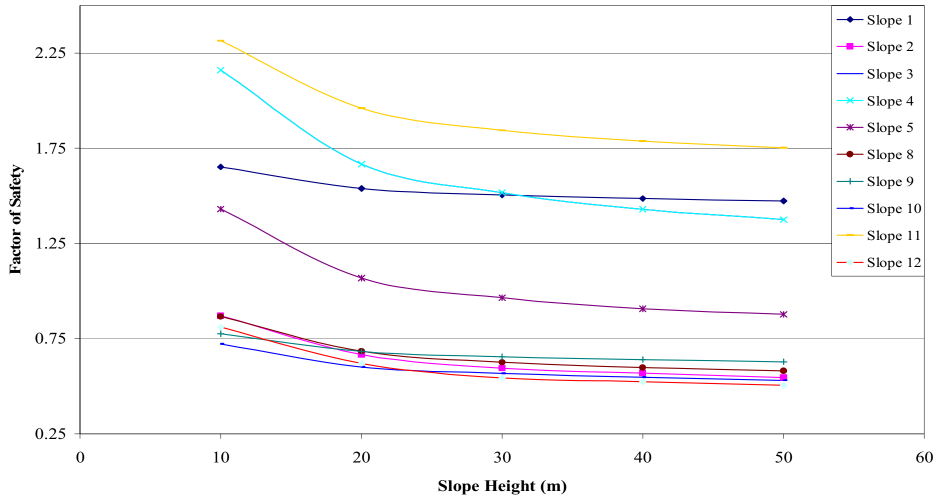

Figure 7. Graphical representation of the sensitivity analysis of the Factor of Safety in relation to slope height.

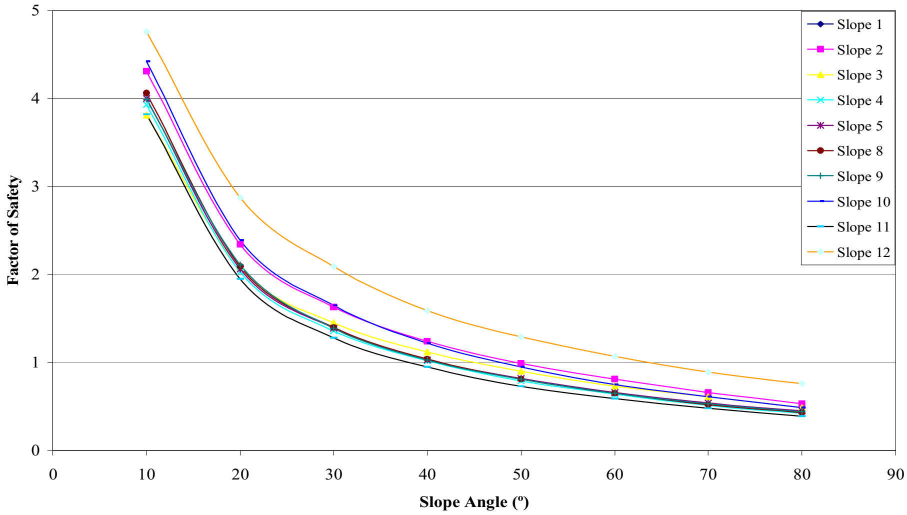

Figure 8. Graphical representation of the sensitivity analysis of the Factor of Safety in relation to slope angle.

In the sensitivity analysis for cohesion, friction angle and unit weight, minimum and maximum values were specified for each parameter. Each parameter was then varied individually in uniform increments and the Factor of Safety of the global minimum slip surface was calculated at each value. This results in a plot of Factor of Safety versus the input parameters, and allows the determination of "sensitivity" of the Factor of Safety, to changes in the input parameter (Figure 9). The results show that the Factor of Safety is sensitive to the value of cohesion in 70% of the sites and 30% to the friction. The Factor of Safety is not sensitive to the value of unit weight.

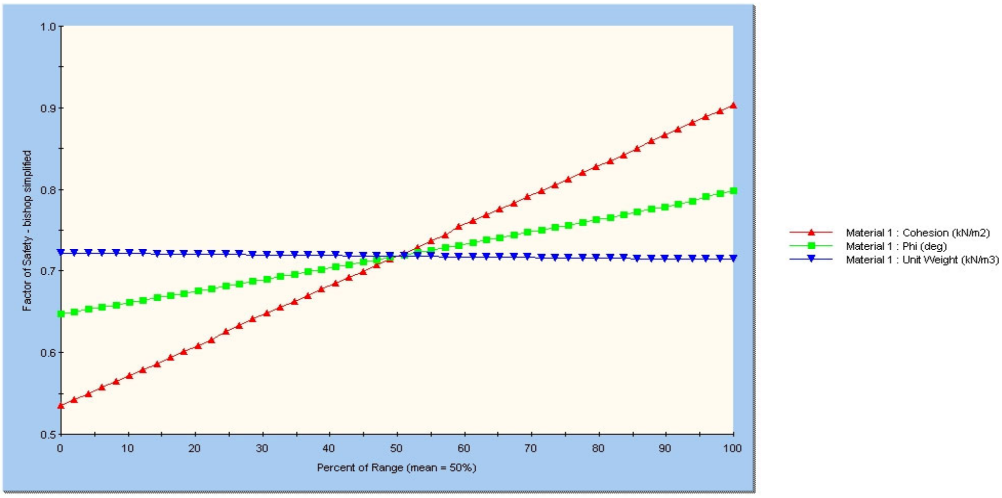

Figure 9. Typical graph of sensitivity analysis of in relation to cohesion, friction angle and unit weight in Maputo City.

Gullying and Coastal Erosion

The dune sand deposits of the Ponta Vermelha, Malhazine and Congolote Formations in Maputo are very prone to surface erosion by water. Construction on these deposits reduces the percolation area and the infiltration rate, resulting in an increase in surface water flow. On steep slopes, water drains faster over the surface increasing the risk of erosion. A combination of factors such as soil characteristics, urbanisation with lack of drainage system, topography and rainfall, make gully erosion to occur. Gully erosion affects both the steep and gentle slopes.

Gullying problems started to be a cause of concern in Maputo City after the extreme rainfall event of February 2000. Soil saturation resulted in steeply gullying failures. The critical sites are adjacent to Escola Nautica, Polana-Caniço and Ferroviario residential areas and along Nações Unidas Avenue.

At Escola Nautica the coastal slope that faces the Maputo Estuary to the South and is separated from the estuary by a coastal plain of alluvium about 250 m wide. The overall slope angle is approximately 30 degrees and is in general straight and uniform when viewed along the slope. The slope itself has a well-designed surface drainage system composed of channels parallel to the slope which are connected to watercourses that drain water down slope. However, as a result of poor maintenance these drainage channels became blocked by sand and vegetation, causing gullying when and water drained through unprotected areas.

The Polana-Caniço and Ferroviário residential areas are crossed by gullies. The gullies are extremely large, (1 to 15 m deep), with very steep side slopes (typically 60 degrees) but with locally steeper sections (Figure 10). They are W-E oriented, however some follow the orientation of the roads, mainly the Julius Nyerere Avenue. Gullying failure has occurred in a built up area causing the destruction of a number of houses. In this location, the housing development is informal, unplanned and characterized by low quality houses inhabited by the poor who have no access to tenured land. The infrastructure and services are inadequate. Remedial works are generally completed soon after gullying occurs and typically comprise gabion baskets of rhyolite used to protect the floor of the gullies, to support the base of the sides and to protect them from further erosion. The sides of the gullies are still uncovered due to their steepness and can be unstable in future heavy rainfall events. Solid waste has subsequently been observed gradually filling the channel and impeding water flow with consequent implications for the future. In addition, gullies are being used to tip solid waste.

Figure 10. Deep gully cutting through the Polana-Canico Residential Area.

The gully in the Nações Unidas Avenue (Figure 11) is on the slope with an angle of about 25 degrees and is general straight and uniform facing the Maputo Estuary to the South. The slope angle (of approximately 25º) suggests a gullying failure origin as the depth of the gully is greater than would be expected for a slump and the width of the failure is proportionately too narrow (Forster, 2001). The gully was probably caused by failure of the drainage system at the top of the slope. Water seepage is also seen at the base of the slope. Effective remedial work has been completed by supporting the slopes with gabion baskets filled with rhyolite.

Coastal Erosion

The coastline around Maputo City is dynamic due to the movement or removal of sand from a low-lying beaches by longshore currents. The coastline has moved tens of meters inland in the last two decades. Coastal erosion has resulted in the partial destruction of Marginal Avenue. Other signs of coastal erosion include uncovered roots of trees and damaged retaining walls. Basic measures to control coastal erosion, include groins, retaining walls and placement of rip-rap.

Figure 11. Gully along along the Nações Unidas Ave. Remedial work was completed by supporting the slopes with gabion baskets filled with rhyolite.

Building Settlement

Differential settlement of buildings is another common problem in Maputo City. The affected buildings are located along the Julius Nyerere Avenue adjacent to where the coastal slope in the Ponta Vermelha Formation is most prominently developed. Affected buildings are generally 8-10 storeys (approximately 25-40 m in height) and a horizontal deflection of between 150 to 400 mm has been measured at the top. A common feature for many affected buildings is water leakage from water pipes or underground storage tanks. The damage of buildings can be linked to the interaction of geological processes that may have caused tilting:

- Collapse settlement of the soils. The water leakage created different wet conditions in the affected area, and differential settlement occurs causing buildings subsidence and tilting;
- Differential settlement over a lense of weaker material as a result of long term consolidation (Forster, 2001);
- Internal erosion (piping) with removal of fine material from below one area of the foundation in the presence of water (Forster, 2001).

The hypothesis of collapse settlement is supported by the preliminary results of a research being undertaken. The soil collapse potential was assessed using the approach based on oedometer tests. It provides quantitative prediction regarding the magnitude and rate of soil collapse. The well-established methods developed on this basis are from Denisov (1951) and Jennings and Knight (1957). The Jennings and Knight (1957) method also called "double consolidation" technique evaluates the effect of both a saturation and loading at various levels. The shape of the shear stress/horizontal displacement curve given by the shear box test and logarithm of pressure/void ratio curve given by the double oedometer test form the basis for the interpretation of the collapse behaviour of these soils. Typical curves from shear box tests in Maputo City are shown in Figure 2. These indicate that the soils of this formation are normally consolidated and loose. The cohesion observed on these soils is apparent caused by negative pore water pressure. The typical curves of the double oedometer test in Figure 3 show collapse of the soil structure in the Ponta Vermelha Formation. The straight line of the test on saturated samples indicates the volume reduction under a constant level of applied stress in the presence of water. The volume change varies from 1.86 to 18.03%.

Flood Prone Areas

Areas of Maputo City are prone to flooding in heavy rainfall. The causes of flooding in these areas are mainly of geological and topographic nature but associated to land use practices. Two of these areas are the Inhagóia residential area and Bairro Indígena. The Inhagóia residential area is densely populated area and was covered by water after the 2000 floods (Figure 12). Two contributory factors can be identified. Firstly, the surficial sandy layers of the Congolote Formation are underlain by low permeability clayey layers of the Machava Formation reducing infiltration. Secondly the topographic location of the area played also an important role in water accumulation.

The Bairro Indígena was built in a swamp which is normally flooded during the rainy season. Some remedial works were been undertaken by the municipality in 1980´s which comprised the construction of a full drainage system. However, maintenance of the system is not regular, reducing its effectiveness.

Hydrogeological Characteristics and Groundwater Quality

The hydrogeological regime of Maputo City is characterized by two aquifers separated by one semi-permeable layer. An additional impermeable layer is present at the base of the system (Iwaco, 1986). The phreatic or "dunes aquifer" comprises sand of the interior dunes, which overlies a semi-permeable layer of sandy clays. This aquifer has an undefined thickness. The superficial or "gritstone" aquifer is comprises argillaceous gritstone, calcareous gritstone and limestone of the Santiago Formation, of Mio-Pliocene age and overlies on an impermeable layer of greenish-grey marga. This aquifer is semi-confined (Iwaco, 1986). The grain-size analysis of the aquifer's sediments shows a mesocurtic curve which suggests a marine depositional environment (Momade *et al,* 1996). Numerous boreholes in Maputo City extract water from the superficial aquifer, whose thickness varies from 20 to 45 m. In the coastal zone, water from this aquifer is in contact with seawater in a form of wedge, which penetrates 3 to 4 km from the limit between the sea and the continent to reach the base of the aquifer. This contact with seawater influences the groundwater quality of Maputo City.

Figure 12. Flooded area in Inhagoia Quarter after the 2000 floods.

The vulnerability of the aquifers in Maputo City is high due to their phreatic character. Groundwater pollution is a common problem and a cause of concern because the groundwater reservoirs constitute the main source of water supply through private boreholes. The network of municipal water supply covers only a small percentage of the urban population. Industrial activities, pit latrines in the informal settlements and leachate produced by the municipal waste-dumping site are the main sources of pollution. A groundwater quality study by Dimande, Vicente & Manuel (2001) in some quarters of Maputo City included the determination and assessment of major cationic and anionic species present in water. The study showed that almost all sample sites have concentrations of the main water quality parameters above the World Health Organization recommended standards for potable water. Water quality of this area is characterized by high chloride concentrations due to the geologic history of the region, which is close to the Indian Ocean. The characteristic patterns given by Stiff diagrams suggest that the water chemistry is related to the marine origin of the aquifer rocks and/or salt wedge intrusion.

Informal Settlements

The definition of a "squatter settlement" varies widely from country to country and depends on a variety of defining parameters. In general, it is considered as a residential area in an urban locality inhabited by the very poor who have no access to tenured land of their own, and hence "squat" on vacant land, either private or public. A squatter settlement therefore, is a residential area developed without legal claims to the land and/or permission from the concerned authorities to build; as a result of their illegal or semi-legal status, infrastructure and services are usually inadequate. Mozambique suffered sixteen years of civil war and many people were forced to look for security in the neighbouring countries or in the main cities of the country. In this way, people migrated from rural areas to Maputo City and established settlements in sensitive areas, such as wetlands and steep slopes, without minimum living conditions. At that time there was not enough technical capacity or political determination to address the problem of informal settlements. After the peace agreement in 1992 these people never returned to their native zones.

The informal settlements located in the outskirts of Maputo City comprise low quality houses constructed from corrugated metal, discarded packing crates, brush, plastic sheets or any other scavenged materials. These numerous but unauthorised settlements usually lack sewers, clean water supplies, electricity and roads and often the land on which they are built was not previously used because it is unsafe or unsuitable for habitation.

The informal settlements are a major source of problems. The absence of good quality houses and sanitation system lead to the opening of pit latrines by the local population. The geological conditions (permeability and phreatic level) determine the contamination level of groundwater.

Solid Waste Management

Maputo City has one main waste-dumping site located in Hulene Quarter, 10 km from the city center. This dumping site has an area of 25 hectares and was opened approximately 40 years ago. This area was formerly a fresh water natural lagoon and to solve the existing waste problems, it was decided to use it as a dumping site. At that time the lagoon was not of any social utility. The Hulene dumping site receives all kinds of waste produced in Maputo City including domestic, hospital, industrial and commercial waste. This dumping site was not designed to fulfil the minimum requirements for landfill sites and, because of that, taking into account the soil permeability, it is assumed that the leachate produced is contaminating the groundwater. The leachate flows (which contain metals) can have adverse impact in the soil for years or decades after being released. Furthermore, the leachate, if enriched with heavy metals as Cd, Cr, Pb, Cu and As, constitute a human health risk. Data from studies in the surroundings of the dump-site show high levels of groundwater contamination. The piezometric level of the aquifer is shallow (between 2.10 and 5.50 m below ground level) and easily reached by shallow wells. The surroundings of the dump-site are highly populated; there is no water supply system and the population use groundwater for their daily life.

The waste management system in the city is inefficient. It has established a network of containers around the city where the people have to dispose waste from 3 to 8 pm daily. The schedule was defined in order to avoid the waste being exposed in the containers for long time, but this is not always followed by the city dwellers. The full containers should be collected after 8 pm but it does not always happen due to deficiencies of the system (lack of material and human resources). It is normal to see accumulated garbage in the streets for days and even weeks. This system was established only for the centre of the city and the municipal markets being in the outskirts of the city and the informal settlements are not included. In these areas the people dump the domestic refuse in excavations opened in their yards therefore risking groundwater contamination.

CONCLUSIONS

The purpose of this paper is to highlight and record the environmental and engineering geological problems occurring in Maputo City. These problems range from landslides and slope instability, differential settlement of buildings, gullying and coastal erosion, groundwater pollution and solid waste management. The impacts of these problems are increasing in Maputo City and an immediate solution in order to make the city sustainable is required. It is believed that an understanding of these problems will help planners devise effective urban policies and land-use planning strategies. To date, the planning sector has not taken into account the aspects of geology described in this paper in the planning process, probably because such information is not available in a comprehensive manner. The production and availability of geological information including the engineering geological characteristics of soils, hydrogeological conditions, slope instability, groundwater quality, soil erodibility, will serve to increase awareness of the geological impact on urban development.

Acknowledgements: The work presented in this paper was carried out with funding from SIDA/SAREC in cooperation with Eduardo Mondlane University, Mozambique.

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