Characterization of problematic soils for slope and foundation stability: case study from Dakar

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Abstract: For a better understanding of the role of the problematic soils in the instability phenomena observed in Dakar, extensive investigations and laboratory tests have been performed. These soil investigations included: (i) testing of characteristics of these soils regarding their clay mineral compositions using X-ray diffraction; (ii) study of their physical properties; (iii) study of their mechanical behaviour by triaxial compression and circular ring shear tests. (iv) study of their swelling characteristics. Thus, the studies have allowed valuable results to be gained regarding slope instability mechanisms, foundations failure mechanisms, the causes of cracks on buildings, and accordingly, to propose suitable and economical recommendations for design of foundation and slope stability measures, and to avoid the damage resulted from these instabilities. The results obtained, revealed that there is a strong relationship between the observed instability phenomena and the geotechnical properties of these problematic soils. The nature and content of clay minerals in these soils strongly influence their geotechnical properties and their susceptibility to swelling or shrinking, and their resistance to slide. The physical and mechanical tests performed revealed that the mechanical behaviour of these residual soils changes greatly with their montmorillonite content.

Résumé: Pour une meilleure compréhension du rôle des sols résiduels dans les phénomènes d'instabilité observés à Dakar, un programme intensif d'études et d'essais de laboratories a été effectué. Ces études et essais comprennaient: (i) détermination des caractéristiques des sols en ce qui concerne leur composition en minéraux d'argile en utilisant la méthode de diffraction à rayon X; (ii) étude des propriétés physiques des sols; (iii) étude des propriétés mécaniques des sols par des essais de compression triaxiale et de cisaillement circulaire; (iv) étude des caractéristiques de gonflement des sols. Ainsi, ces études ont permis de récolter d'importantes informations sur les mécanismes de rupture des pentes et des fondations, les causes de la fissuration des bâtiments, et aussi de proposer des solutions adéquates et économiques pour un meilleur design des foundations et la stabilisation des pentes, et aussi de prévenir les dommages causés par ces instabilités. Les résultats obtenus ont révélé qu'il y a une relation étroite entre les phénomènes d'instabilité observés et les propriétés géotechniques de ces sols problématiques. La nature et la teneur en minéraux d'argile influence fortement les propriétés géotechniques de ces sols et leur susceptibilité à gonfler ou rétrécir, et aussi leur résistance au glissement. Les tests physiques et mécaniques effectués ont montré que les propriétés physiques et mécaniques de ces sols changent fortement avec leur teneur en montmorillonite.

Keywords: geotechnical properties, slope stability, foundation conditions

INTRODUCTION

Rapid urbanisation in Dakar (Senegal) is giving rise to an increase in housing developments and reduction of the most favourable construction ground available for new buildings. As the most favourable areas are occupied, marginal lands are being developed. However, these marginal areas are largely covered with swelling soils and/or are located adjacent to coastal slopes. These areas show evidences of different slope and foundation instabilities causing several types of building damage. The instability phenomena represent a challenge to a safe urban planning for Dakar city, and reflect different triggering mechanisms including soil conditions. However, the influence of the soil behaviour on the instability phenomena is not yet fully understood. Hence, a great interest has been triggered to solve such geotechnical problems e.g. by finding out appropriate and efficient geotechnical and economical techniques. A better understanding of the geotechnical properties and behaviour of this type of soils is of fundamental importance regarding e.g. engineering analysis of foundation and slope stability not only in Dakar city, but consequently also in urban development (Sarr 2002).

Hence, the main objectives of this research are:

- To experimentally study the geotechnical properties or behaviour of the soils of Dakar;
- To analyse the relationship between the observed instabilities phenomena and the properties of these soils;
- To develop a better understanding of the behaviour of these soils regarding slope and foundation stability.

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Following this introduction, the main geographical and geological features of the study region are first presented. The methodology approach used and the experimental tests carried out for this research are then described. Then the results of the performed tests are discussed. Finally, an analysis of the soils properties regarding slope and foundation instabilities, proposed recommendations, and main conclusions are given.

BACKGROUND ON THE STUDY REGION

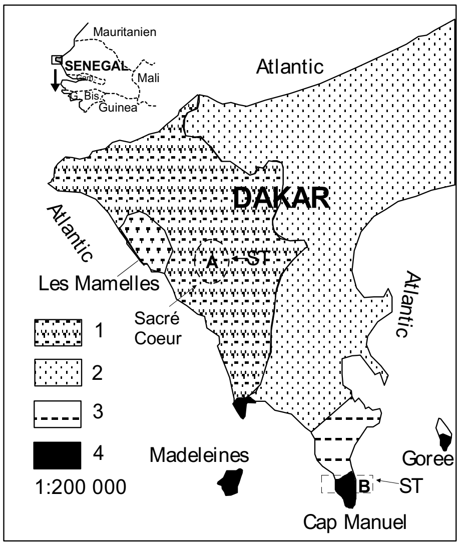
Geographical conditions

The investigated region is located on the western coast of Dakar (Senegal, Figure 1). This region belongs to the Sudanese-Sahel climatic zone. It is characterized by seasonal moisture variations. Indeed, this climatic zone is marked by two main seasons: dry season (October to May) with an average monthly temperature of 18°C to 25°C, and rainy season (June to September) with average temperatures between 30°C and 35°C. The rainfall is often stormy and consequently leads to soil erosion. The annual rainfall over the period 1960–1970 was in the range of 500 to 900 mm while over the period 1970–1994, the mean annual rainfall was only in the range of 300 to 600 mm (Fall, 2000).

Geological conditions and studied soils

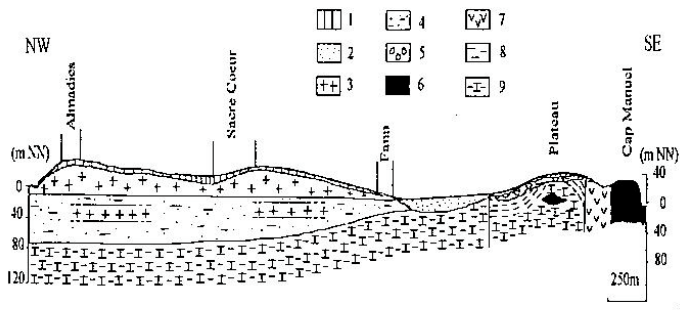
Geological conditions

The geology of this region is characterized by a long period of volcanic activity from Tertiary to Quaternary and by cycles of transgression/regression of the Atlantic Ocean (Figures 1-2). Therefore, the construction ground and the slopes of western Dakar are predominantly compounded of volcanic materials and sediment rocks or soils. Hence, globally four rock categories can be identified in the region regarding their age and type. These are volcanic Quaternary, sedimentary Quaternary, sedimentary Tertiary, volcanic Tertiary. The volcanic Ternary is mainly characterized by two rock types: the basalt of Cap Manuel and the volcanic tuffs. The outcrops of the volcanic tuffs generally build slopes in the south western coast of Dakar. These slopes are generally affected by landslides. Hence, these soils are studied in this paper. The volcanic Quaternary is predominantly characterized by basalt rocks. These basalts have been exposed over a long period of geological time, and so they are altered at their upper part. This weathering led to the building of residual soils whose thickness can reach about fifteen meters in some parts of the region. These residuals soils cause several foundation problems. Therefore, a detailed study of the properties of these residual soils is also carried out in this paper. Details about the geology of the study area are given in Bellion (1980), Dia (1980), Elouard (1980), Fall *et al.* (1996), Fall (2000), Lô *et al.* (2002).



1 Volcanic Quaternary; 2 Sedimentary Quaternary; 3 Sedimentary Tertiary; 4 Volcanic Tertiary.

Figure 1. Location and geology of the study area (ST: zones A and B)



1 – Residual soils; 2- Dune sand; 3-Hawaiit; 4-Prebasaltic sand. Ternary; 5-Laterite; 6- Basanit; 7-Tuffs; 8 Clay; 9; marl; fault

Figure 2. Geological profile of Dakar (Dieng, 2000)

Residual soils

The studied residual soils are located in zone A of the study area (Figure 1). This zone consists mainly of Quaternary deposits characterized by the imbrications of volcanic and sedimentary deposits. Quaternary volcanic deposits are distinguished stratigraphically from the Miocene volcanism. The geology of the zone A is very simple and can be described as follows. First, hard volcanic rocks (basalt) built the basis. The basalt rocks are represented by pure Hawaiite or dolerited Hawaiite. These rocks are rich in andesin-augit and olivin. The alteration of the basalts led to the formation of a gravelly layer on their surface. The residual soils, whose investigation is one object of this study, lie on this gravelly layer. Their thickness is lower than 15 m. These residuals soils, called by many authors as postbasaltic silts, according to Lappartient (1971) result from the association of the alteration products of the volcanic rocks (basalt) to dune sands to form the clayey sands and suprabasaltic sandy clays. The latter outcrops in zone A and built mostly the foundation ground. However they form no slopes in this area. The results of engineering geological field investigations carried out by the above authors revealed that three main types of materials cover this site from zero to three meters in depth: (i) a gray sandy clay of a high plasticity, (ii) a clay sand of slight to medium plasticity, (iii) mixed, in some areas with increasing percentage in-depth of altered basalt blocks and lateritic gravels. Anterior X-ray diffraction study by Lappartient (1971) revealed the presence of kaolinite and montmorillonite clay types in these soils. The residual soils are in partially saturated state as the ground water level is deep.

The volcanic tuffs

The volcanic Tuffs, whose colours extend from yellow-green to brown-green, are generally fine-grained, heterogeneous, very soft and less coherent material, which can locally include basalt, lime marl, and quartz blocks. Their outcrops are in the zone B of the study area.

Over wide areas, in detail, a mainly clay-sandy facies (fine-grained volcanic tuffs) could be differentiated from a silt-sandy facies (coarse-grained volcanic tuffs) inside the outcrops of the volcanic tuffs. Both types of facies can also interleave together. According to the results of drillings performed in the study area, the different facies of volcanic tuffs can be described as follows:

- The fine-grained volcanic tuffs show a mainly yellow-green and greenish color and are composed of weakly sandy, clay-silty materials. They almost form the whole outcrops and slopes of the volcanic tuffs in the study area.
- The coarse-grained volcanic tuffs appear at the basis of the tuffs slopes. They are composed of dark-green, cohesive, silt-sandy materials. Small blocks of basalt, lime, marl and quartz are present in the coarse-grained volcanic tuffs.
- The coarser-grained and gray-black volcanic tuffs don't outcrop in the study area. They lie approximately 10 m under the sea level, i.e., at the basis of the coarse volcanic tuffs.

The volcanic tuffs form slopes with flat to moderate angle, whose height varies between 20 m and 25 m and are mainly overlain by a laterite crust. They present several signs of old and active landslides processes as described in the next section.

Slope instabilities and building damages in the study region

Slope instabilities

The landslide mapping performed by Fall (2000) and presented in Figure 3 has shown that different landslide types have occurred in the volcanic tuffs. The most common landslide types are represented by flows and slides. From Figure 3, it can be also seen that, the hard laterite crust (on the volcanic tuffs) is affected by falls. This is due to faster erosion of the underlying tuff layers. Indeed, this partial erosion often creates overhanging laterite crust, whose fall leads to the accumulation of laterite blocks at the foot of tuff cliffs as shown in Figure 3. Unlike the falls, the slides particularly affect the volcanic tuffs (Figure 3). Figure 3 clearly shows slides with head scars on the upper part of the slopes. The slide toe is characterized by the building of an accumulation zone composed of loosened tuff material (due to the slide). Due to its low cohesion, this material is subjected to wave erosion. The slide area is also marked by active erosion channels (Figure 3). The field landslide mapping has also shown that the flows develop in the volcanic tuffs and involve tuff materials that were already loosened by old slides (Figure 3). This reactivation of old landslide areas by flows occurred in the rainy season. The flows were characterized by curved crown scarps, a large length-to-width ratio, and a presence of shrubs as well as plants around the accumulation zone (Figure 3). However, the accumulation zone is exposed to the sea erosion.

Building damage

In zone A of the study area, i.e. the area of the residuals soils, it was noticed that cracks have been damaging many civil engineering structures because the characteristics of the swelling and shrinkage of the soils were not properly accounted for in the design of buildings.

The observed cracks generally take a characteristic form (Figure 4), whos essential features are as follows:

- Vertical cracks, slightly inclined, in the central part of the walls or on the level of the joints. This phenomenon is observed, according to the inhabitants, at the end of the rainy season, when the maximum potential of swelling is developed. It appears that a horizontal extension strain, causes a partial rupture of the wall. The evolution of the damage in masonry shows evidence of the active cracking phenomenon.
- Material stiffness heterogeneity-related cracks appearing at the interface between brick and mortar, masonry wall and concrete column, concrete walls and beams. These cracks are caused by high vertical shear stresses transmitted along the interfaces, as the most rigid material moves relatively to the less rigid part.

- A deflection of the pavements surrounding the housings. The pavements are subjected to vertical differential movements, which led to their cracking and their vertical dissociation from the housing walls. The infiltration of water to the right of the foundations and walls is then allowed.
- Horizontal and diagonal cracks in walls are also noticed. They are due to horizontal shearing stresses between the upper and the lower parts of walls after differential settlements had occurred. Swelling is minimum at the corners and maximum in the center of the buildings. In general, the cracks go up to approximately 45 degrees starting from corners of window or door frames, and radiating through the building.

The damage reported herein are related to periodic movements of the soil foundation and are destructive. These movements have produced an extension of the network of cracks, and destruction of the construction. These problems have triggered an interest to carry out an investigation in order to determine the causes of this damage and to find out efficient and low-cost construction methods.

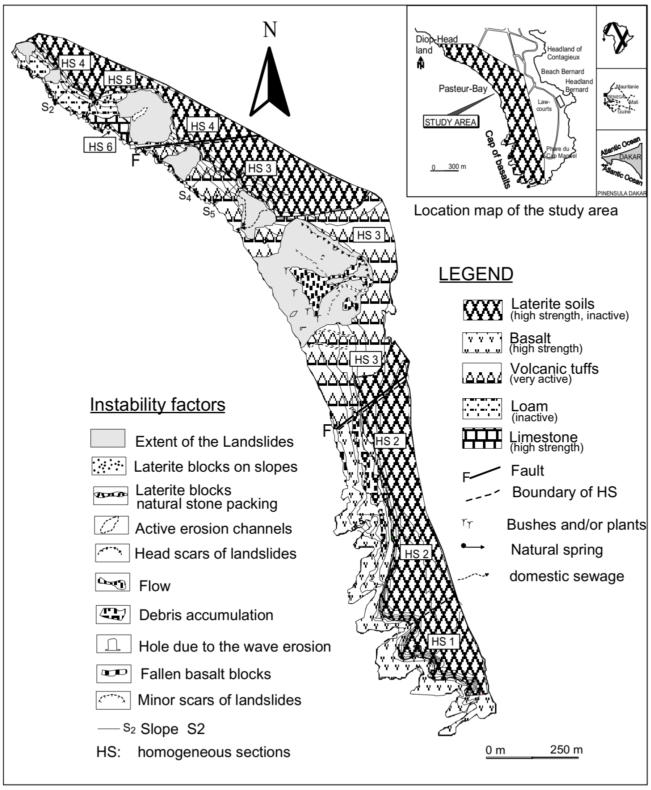


Figure 3. Landslide map of Cap Manuel showing the types and the extent of the landslides in the volcanic tuffs (Fall, 2000)

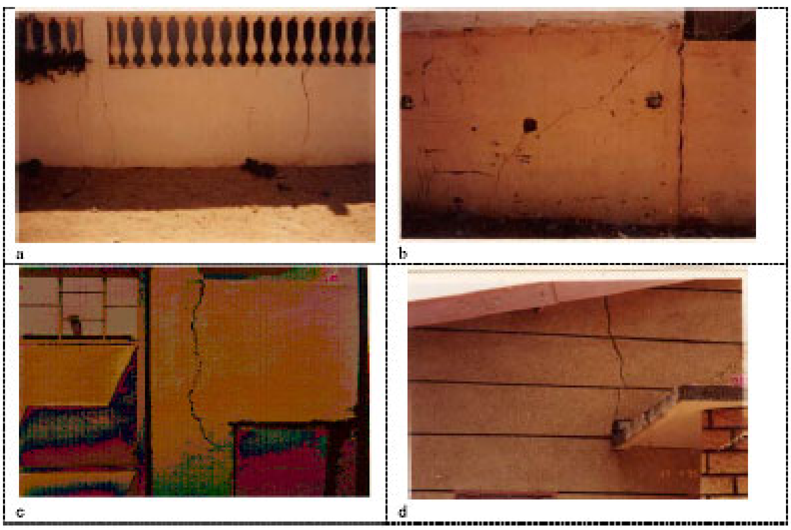


Figure 4. Structural distresses are manifested by (a) vertical, (b) diagonal cracks in walls and windows, (c) jamming of doors, (d) rupture and dislocation of columns.

METHODOLOGY APPROACH AND EXPERIMENTAL PROGRAM

Figure 5 shows the methodological approach used for the investigation and analysis of the geotechnical properties of the problematic soils regarding slope and foundation instability. It also indicates the relationship between the different work steps of the investigations and the experimental tests carried out, which are mainly to German standard (DIN). The methodological approach presented includes five main parts.

- The first part concerns the study of the clay mineralogical composition of the soils. The main objective of this stage is to determine the type and the quantity of clay minerals present in the studied soils, since previous studies (e.g. Lappartient, 1971) have suspected the presence of swelling clay mineral in the above soils. This provides a better understanding of the physical and mechanical behaviour or properties of these soils. Hence, for this purpose, XRD tests were performed on several soils (residual soils and tuffs) samples.
- In the second part of this study, the physical properties of the soils were investigated. The performed physical tests are shown in Figure 5. These tests have allowed information about density, water content, plasticity and consistency, activity, water absorption ability of the soils to be obtained. This information is useful to understand the behaviour of the soils.
- The third phase of the study was focussed on the investigation of the shear characteristics of the soils. To clarify the shear characteristics of the soils, that form the slopes (volcanic tuffs) in the study area, and their causes, several shear tests were performed. The performed tests were suitable to obtain detailed information about the fall of the peak strength to residual strength and about the influence of water on the shear strength and behaviour of the soils. The study of the shear behaviour of the soils in study area was performed by carrying out triaxial and ring shear tests. The ring shear test provides the advantage of large shear displacement and analogy of the shearing mechanism to landslide movement along slip surface. The ring shear tests allowed us to determine the residual shear parameters of these soils. Indeed, it is well known (e.g. Azzam (1984, 1988), Müller-Vonmoos et al. (1985), Skempton (1985), Mitchell (1993), Stark & Eid, 1994) that the difference between the peak and the residual shear strength of soils containing swelling clays mineral can be considerable.
- The fourth stage was then concentrated on the study of the compressible and swelling properties of the soils. Oedometer tests were performed on undisturbed samples from the residuals soils. The results of these tests have allowed valuable information about the compressible and swelling behaviour of the studied soils to be gained.
- Finally, in the last stage of the study, all data and results derived from different types of geotechnical tests (clay mineralogical composition, physical properties, shear test, compressible tests) were integrated and analyzed together regarding the observed slope and foundation instability phenomena. Then, suitable and economical recommendations for design of foundation and slope stability measures are proposed.

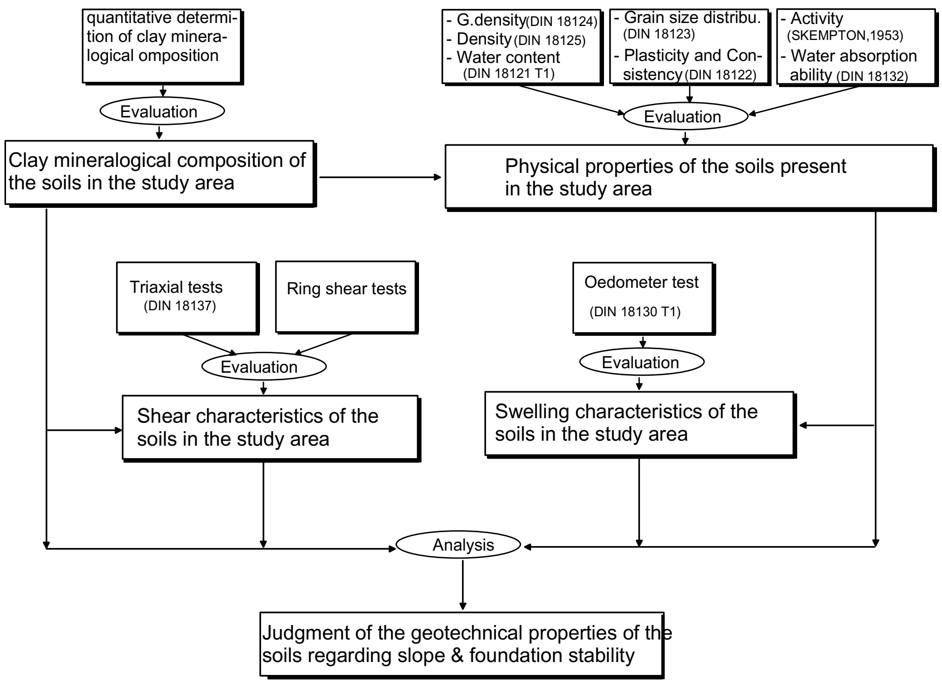


Figure 5. Methodological approach used for the investigation and analysis of the geotechnical properties of the problematic soils regarding slope and foundation instabilities.

RESULTS AND DISCUSSIONS

Clay mineralogical composition of the soils

The main results of the investigations of the clay mineralogical composition of the studied soils, summarized in Figures 6-7, have shown that all soils contain swelling clay minerals (e.g. montmorrillonite). From these figures it can be seen that, while the clay minerals are almost exclusively composed of montmorrillonite (97-98%) in the volcanic tuffs, they are comprised of kaolonite (40-80%), montmorrillonite (10-50%), and illite (0-20%), mainly in the residual soils. Figure 6 shows the clay mineral profile of one hole in the residuals soils. It indicates that at 3m depth, the montmorrillonite contents increases drastically. The weathering could explain the observed presence of clay minerals as well as the high proportions of swelling clay minerals observed in both soils, i.e. volcanic tuffs and residuals soils. Indeed, the kaolinite might come from the destabilizing of plagioclases, while the ferro-magnesium minerals (olivine, pyroxene, and amphibole) might give birth to montmorillonite. This presence of swelling clay mineral in the studied soils could have significant influence on the geotechnical properties and/or behaviour of the volcanic tuffs and residuals soils. This assumption is investigated and discussed in the following sections.

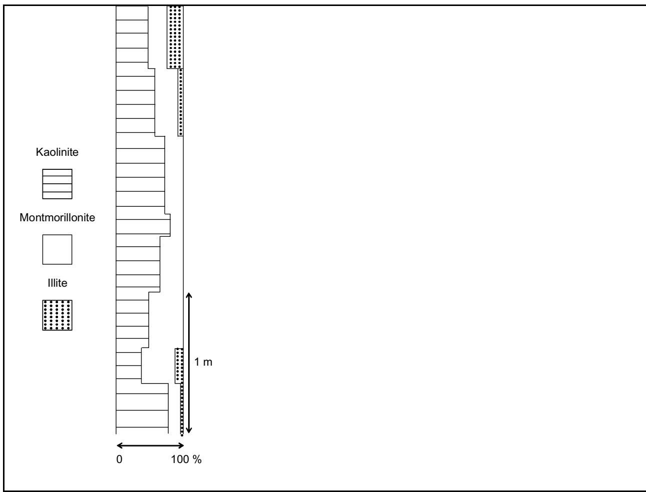


Figure 6. Clay mineral distribution profile by depth

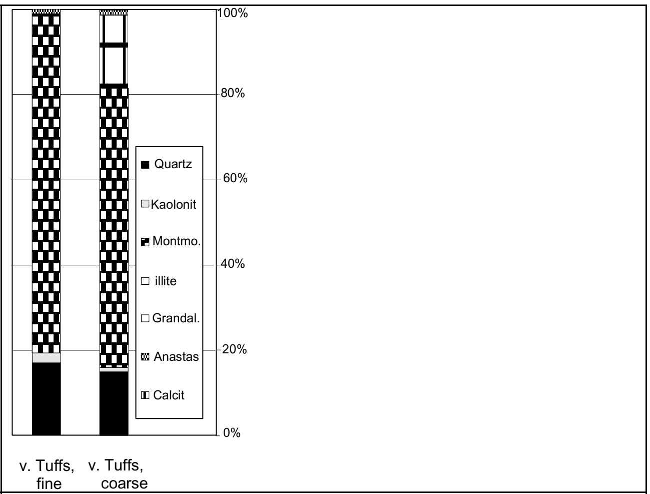
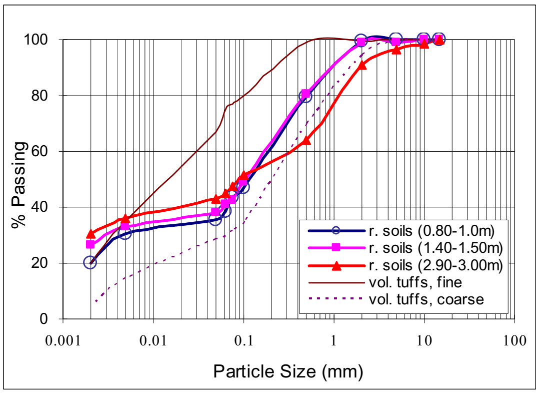


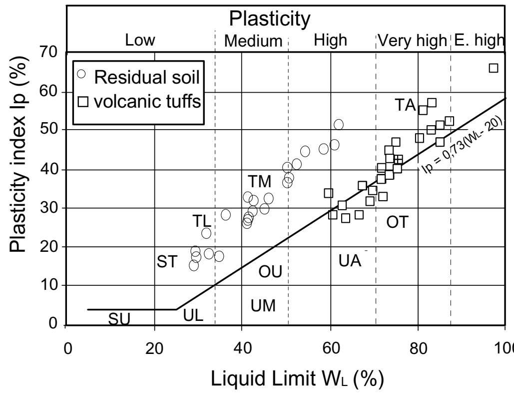
Figure 7. Mineralogical composition of the clay-silt fraction of the volcanic tuffs.

Physical properties of the soils

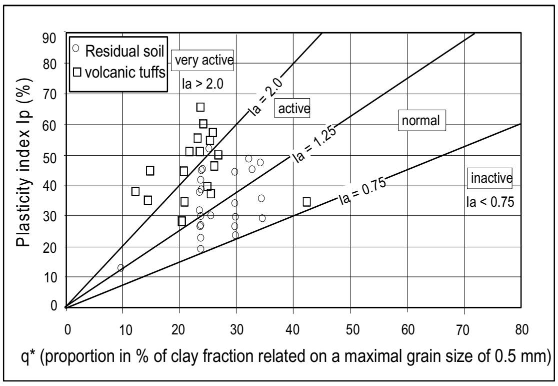
In order to assess the physical properties of the studied soils, the following soil mechanical tests were performed on several soil samples: determination of (i) soil density (according to DIN 18125), (ii) water content (DIN 18 121 T1), (iii) soil grain size (DIN 12 123), (iv) plasticity parameters (DIN 12 122), (v) water absorption capacity (DIN 18 132), (vi) activity index (according to Skempton, 1953). The main results of this study are summarized in Figures 8 and presented in detail in Fall (2000), Fall & Azzam (2000*a*), Fall & Azzam (2000*b*). The results indicate that the natural water contents of the soils are low. The analyzed samples are mostly partially saturated. The degrees of saturation range from 13 to 95%. This is explained, on the one hand, by the strong surface desiccation and the intensification of surface evaporation that are characteristic to dry tropical countries. On the other hand, this can be partially explained by the increase of the soil water content with the depth. The values of dry density vary between 1.7 and 2.2 g/cm^3 for the residuals soils, and between 1.8 and 2.1 g/cm^3 for the volcanic tuffs. Figure 8a, which shows the average grain size distribution of the residual soils and volcanic tuffs, indicates that the residual soils can globally be classified as sandy clay. However, the grain size distribution varies with the depth. On the surface, the residuals soils are composed of sands slightly clayed to clayed. In-depth, they become increasingly clayed and associated with more and more ferruginous and basaltic gravels, precursory signs of the subjacent bedrock. From figure 8a, it can be also noted, that the volcanic tuffs are globally represented by sandy and clayey silt material. Figure 8b gives a clear overview over the plasticity properties of the studied soils. While the liquid limit (W_L) of the volcanic tuffs is high (60-90%), the residual soils generally show medium to high W_L (30-60%). Therefore, the volcanic tuffs are to be regarded as a high to very high plasticity soil according to the plasticity diagram of CASAGRANDE. However, in general, the residuals soils are to be considered as a soil with medium to high plasticity. The high to very high plasticity of the volcanic tuffs, and the low to high plasticity of the residual soils are in concordance with the results of the clay mineralogical investigations. The results of the water absorption ability tests have shown that the volcanic tuffs display a high to very ability to absorb water (Figure 8c) because of their high montmorillonite clay mineral content. Indeed, their Enslin-values vary between 112% and 137%. In contrast, the residual soils show medium to high Enslin-values (Dieng, 2000). These high Enslin-values give significant indications about the presence of active clay minerals in the clay and silt fractions of the studied soils, particularly in the volcanic tuffs. Then, the results of water absorption ability tests agree well with those of clay mineralogical composition analysis. These results are also in perfect concordance with the determined activity index of the soils. Figure 8d shows the activity diagram of the soils in the study area. It can be observed, that the volcanic tuffs with an activity index of about 1.5-3.0 are to be considered as active to very active. The residual soils are to be regarded as normal to active soils since their activity index mostly varies between 0.75 and 2.0. The values of activity index confirm the presence of relatively significant amount of swelling clay minerals in the soils of the studied areas.



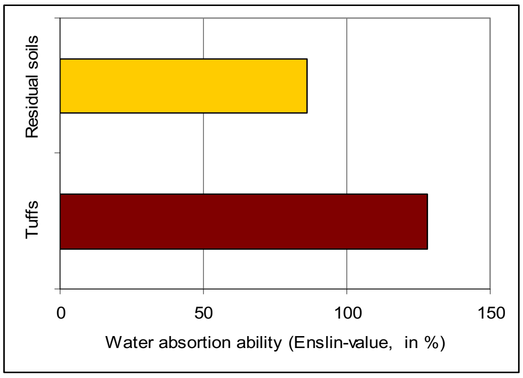
a. Grain size distribution of the soils in the study area; r.: residual



b. Diagram of plasticity of the studied soils; E. extremely



c. Activity diagram of the soils present at the study area



d. Average water absorption ability of the studied soils

Figures 8. Main physical properties the residual soils and volcanic tuffs;

Shear characteristics of the soils

In this investigation, triaxial shear and ring shear tests were conducted to investigate the shear characteristics of the soils in the study areas. Triaxial tests were used to obtain data for peak shear parameters and the influence of water content on the shear strength of the studied soils. However, since the triaxial shear test doesn't allow displacement, ring shear tests were carried out to acquire data for residual shear parameters. Only the results of shear tests performed on volcanic tuffs are presented in this paper, since the slopes are exlusively built from tuffs.

Triaxial tests were performed on several soils samples according to DIN 18137 (Part 2). Consolidated, undrained (CU) and consolidated drained (CD) triaxial tests were carried out on cylindrical soils samples. The main results of the triaxial shear tests on volcanic tuffs are summarized in Tables 1-2 and in Figure 9. Figure 9 presents the shear stress-displacement relationships obtained from consolidated and undrained triaxial tests on the volcanic tuffs. It can be seen that the fine-grained volcanic tuffs yielded a peak friction angle of approximatelly 21°, while the coarse-grained volcanic tuffs show a peak friction angle of about 28° (Table 1, Figure 9). This difference in peak friction angle between the two facies of volcanic tuffs migth be attributed to their difference in proportion of swelling clay minerals; this means that the peak strength and the friction angle of the tuffs decrease with the increased amount of swelling clay mineral. Indeed, the fine-grained tuffs contain more montmorillonite than the coarse volcanic tuffs. The results obtained from the study of the influence of water content on the shear parameters of the volcanic tuffs have shown that increasing the water content has significant impact on the shear strength of the tuffs. Thus an increase of the water content of 20% to 35% led to a reduction of about 62% of the peak strength of the fine-grained volcanic tuffs. While the coars grained volcanic tuffs, because of their lower swelling clay content, show a fall of about 35% of their peak strength as their water content increases by 20% to 28%.

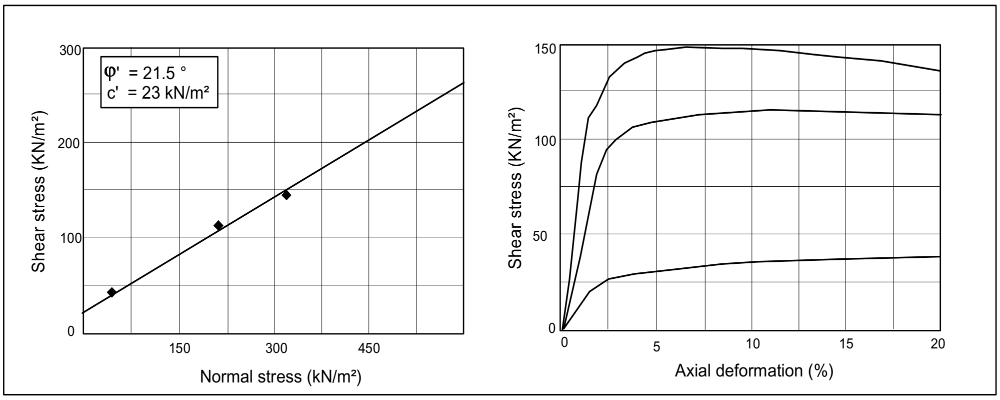


Figure 9. Typical results of CU-triaxial tests performed on a sample of fine-grained volcanic tuffs

Table 1. Peak shear parameters of the volcanic tuffs

Soils types	Effective friction angle φ'(°)	Effective cohesion c'
Fine-grained volcanic tuffs	21.5	23
Coarse-grained volcanic tuffs	28.5	28

Table 2. Influence of water content on the shear strength of the volcanic tuffs

Soils types	Initial water content (%)	Shear strength (kN/m²)	Fall of the shear strength
Fine-grained volcanic tuffs	20	224	62%
	35	85	
Coarse-grained volcanic tuffs	20	264	35%
	28	170	

The ring shear tests were performed on disturbed soils samples, whose water contents were close to the liquid limit (W_L). After consolidation, the specimens were sheared at constant rate of 0.03mm/min until residual strength was attained. It was assumed that no considerable pore water pressures appear with this speed during the shear process. This means that, the shear process practically occured under pore-water-pressure-free conditions and the measured total stress corresponds to the effective normal stress. The results of the performed ring shear tests indicate that both test procedures (triaxial and ring shear tests) produce similar peak shear parameters for the volcanics tuffs. Their average effective shear friction angles are between 19 and 22°. However, the results of the ring shear tests have shown that the volcanic tuffs show low residual shear parameters; a major reduction of the peak shear stress to a very low residual shear value is observed. For example, Figures 10a and 10b present the shear stress-displacement relationships obtained from ring shear tests on fine-grained and coarse-grained volcanic tuffs, respectively. It can be seen that the tuffs reach the residual strength only after a great strength loss (brittlness index, I_B = 40%) and long shear displacement (about 20 to 28 cm). In detail, the fine-grained volcanic tuffs show a higher strength loss (I_B = 50-70%) and longer shear displacement (about 25 cm) than the coarse grained volcanic tuffs. The fall of shear strength is about 50% in the latter, while the average shear displacement is about 23cm. The reason for these low values of residual shear parameters and this high strength loss is the presence of swelling clay mineral (montmorillonite) in the volcanic tuffs. Additionnally, the higher proportion of montmorillonite in the fine-grained volcanic tuffs is responsible for the higher degragadation of the shear parameters after peak strength and longer shear displacement observed in the fine-grained volcanic tuffs. Thus, the nature and content of clay minerals in volcanic tuffs strongly influence their mechanical behaviour. This assumption is supported by the results of XRD tests and by the results (Figure 11) of shear tests performed by Olson (1974) and Müller-Vonmoos *et al.* (1985) on pure clay minerals (kaolonite, montmonrollinite, illite). From Figure 11, it can be noted the shear curve of the volcanic tuffs is relatively similar to this of montmonrollinite. The above authors have demonstrated that the shear strength loss of montmonrollinite is caused by the slide process between the elementary layers (inner-crystalline grain sliding). According to the authors, montmonrollinite has the lowest residual strength among the clays minerals (kaolonite, illite, montmorollinite) and they also need the longest shear displacement up to the residual strength. Hence, the soils containing high proportion of montmonrollinite (volcanic tuffs) show low residual shear values and long shear displacement. Azzam (1984) shows that overconsolidation of Montmorillonite leads to higher brittleness index, lower residual shear strength at shorter displacement.

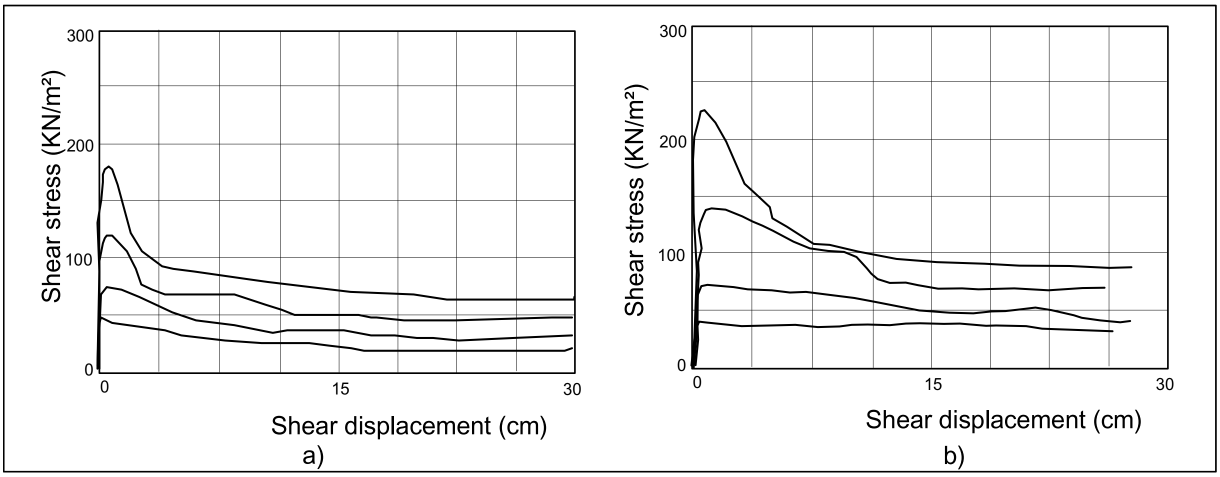


Figure 10. Typical stress-strain behaviour of the (a) fine-grained and (b) coarse-grained volcanic tuffs

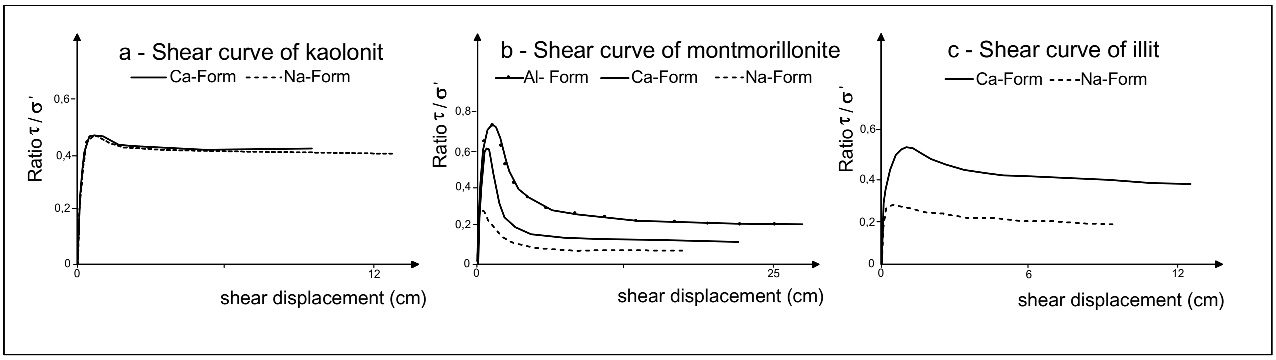


Figure 11. Stress-strain behaviour of the clay minerals: kaolonite, montmorollinite, Illite (after Olson 1974, Müller-Vonmoos *et al.* 1985)

Swelling characterisitcs of the soils

Since the results of the investigations of the clay mineralogical composition and of the physical properties of the studied soils have shown that these soils contain swelling clay minerals, the swelling potentials and pressure of these soils were studied. As it is well-understood that climatically-driven soil moisture changes can lead to swelling and shrinkage of clays, affecting shallow foundations. Such moisture changes are increased dramatically when trees are planted or removed close to existing buildings. Since the construction ground in the study area (zone A) are exclusively composed of the residual soils, only the results of the study of swelling pressure and potentials of the residual soil are presented in this paper. To study the swelling pressure of the residual soils, two kinds of swelling pressure tests were carried out on disturbed and undisturbed soil samples: (i) direct method (Measurement of swelling pressure with oedometer test) and (ii) constant volume method.

The obtained results have shown that the determined swelling pressures of the so-called constant volume method and those of the direct method are almost identical. Figures 12 shows two examples of typical *e* vs. log σ' curves of the residual soils obtained from swelling pressure tests on soils samples. Residuals soils undergo volume change by swelling when the soil is wetted. If volume changees are not allowed, swelling pressures develop in the tested samples (Figure 12). The average swelling pressure is about 160 kPa for the intact soils and about 167 kPa for the remolded soils. This difference in swelling pressures between undisturbed and disturbed soils samples can be attributed to the fact that expansive soils are more prone to volume change when remolded and compacted, largely because of the breakup of the cementation and possible production of high negative pore water pressure that may later be relieved. Thus, the same clay may vary in its expansive characteristic, depending on whether the soil is in its natural state or compacted at the start of construction. Furthermore, the swelling pressure depends on the initial water content, clay content and soil density. The average swelling index of the residual soil calculated according Casagrande's method amounts to 0.03. Hence, the results of swelling pressures tests confirm the potential for the residual soils to swell when exposed to water as demonstrated by the results of water absorption and XRD tests.

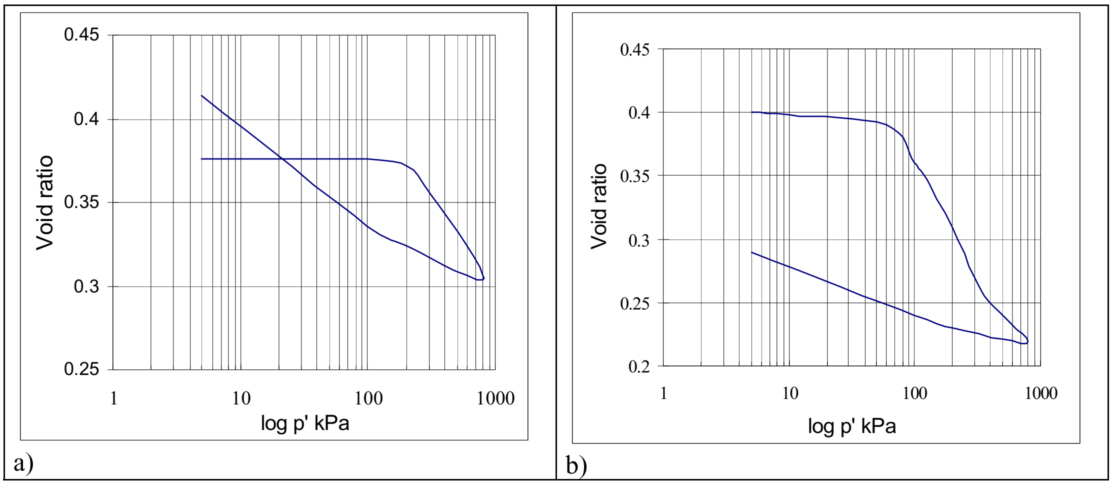


Figure 12. Typical swelling and compressibility curves of the residual soils

In addition to swelling pressure, plasticity and water absorption ability tests, the swelling potentials of the the residual soils were estimated by plotting the activity versus clay fraction on the swelling potential classification chart developed by Seed *et al.* (1962) (Figure 13). From Figure 13, it can be noted that the swelling potential of the residuals soils falls mostly in the high category. As shown, plotted values for samples of tuffs and residuals soils indicate swelling potentials of approximately 5 to 25% and 2 to 15% respectively. This confirms the results of swelling pressures tests. These results are also in full concordance with those of water absorption ability tests and with the determined activity and plasticity values of the residual soils.

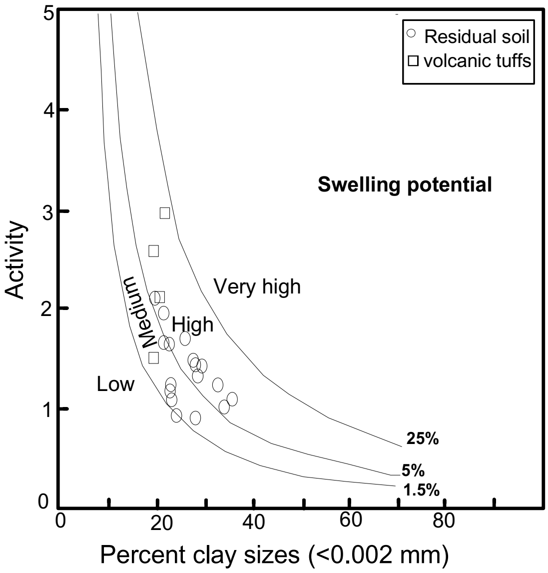


Figure 13. Average position of the studied soils in the classification chart for swelling potential proposed by Seed *et al*. (1962).

Analysis of the soils properties regarding slope and foundation stability

The results of the quantitative determination of clay mineralogical composition conducted on the volcanic tuffs have revealed that these tuffs contain a relatively high proportion of swelling clay mineral (montmorollinite). Because of these swelling clay minerals, the tuffs show unfavourable geotechnical properties regarding slope stability or landslide resistance. Indeed, the tuffs display high plasticity, activity and ability to absorb water. Their shear strength is low and not favourable for slope stability. Their high plasticity, activity and water absorption ability indicate the sensivity of the tuffs to an increase of soil water content. An increase of the water content in the tuffs in the rainy season by 15% leads to a significant reduction of their shear strength by 62%. Water infiltration into the tuff slopes causes a humidification, plasticity and swelling of the volcanic tuffs. This means, that the shear strength of the tuffs will be reduced. Therefore, it should be expected a destabilizing effect of the water on the stability of the tuff slopes.

Additionnaly, the volcanic tuffs are characterized by very low residual friction angles. A large shear displacement (20 to 28 cm) is necessary in order to reach the residual shear strength of the volcanic tuffs (Figure 5). This is accompanied with a major fall in the peak shear strength to the residual strength (brittleness index $I_B \sim 50$ to 70%; I_B calculated according to Bishop (1967). This is caused by the strong reorientation of the montmorillonite particles by large shear displacement. This reorientation means that the sliding tuff slopes would become ever more unstable. Thus, it can be assumed that the landslide mechanism in the volcanic tuffs is progressive. Finally, the very low residual friction angles of the tuffs favor an easy reactivation of old landslides areas in the tuffs. Considering the facts mentioned above, it can be affirmed that the presence of montmorillonite in the volcanic tuffs increases the susceptibility for slope instabilities.

For the remediation of the landslide processes as well as the improvement of the stability of the slopes in the study area, several measures were recommended. Among them, one can mention: drainage measures, coastal protection measures, engineering biological measures. Details of these measures are given and explained in Fall (2000).

The geotechnical tests performed on the residual soils have shown that these soils have medium to high plasticity, normal to high activity, and medium to high water absorption value. Also, these soils show generally high swelling potential and develop swelling pressure of about 170 kPa. These relative poor geotechnical properties of the residual soils are mainly caused by the presence of swelling clay minerals. Because of the swelling clays the residuals soils present unfavourable properties for foundation stability, particularly in this region. Indeed, the climate of the study area is characterized by a long dried period (nine months) followed by a wet period. The balance between evaporation and rainfall controls the moisture conditions in the residual soils. During rainy season, water infiltration beneath the foundation results in expansion of the clays contained in the residual soils. Thus, ground movements exert non-uniform stresses under the structures. Most of housings in Dakar are constructed using a reinforced concrete slab foundation with high rigidity. Therefore, those induced movements damage the rigid structures, particularly at the end of the rainy season, during which the soils are mostly saturated. The problem to be resolved with the swelling soils is not only the volume increase occurring during rainy seasons but also the volume decrease occurring during the long dry season. These periodic movements of swelling and shrinkage involve cracks within the buildings. In our study area, the lightest houses exerted pressures on soils smaller than 100 kPa; in such a case, when the maximum potential of swelling is developed, the stiff buildings are lifted. The differential and periodic movements in the buildings create cracks that destroy the structures in time. Additionaly, when trees are growing close to buildings in the study area, the evaporative and transpirative needs of the tree roots can reduce soil water content. The shrinkage of the residual soil because of the presence of montmorillonite eventually leads to subsidence of the ground surface, causing structural damage. On the other hand, when trees are removed, the water content of these soils will increase, clay swelling pressures develop, and this can cause heave of the ground surface.

Suitable methods of foundation construction such as lattice foundation is proposed to prevent them from expansion and collapse movements of the clays : (i) paving the area around the structure and installing adequate drainage prevents rainfall water infiltration; (ii) protect the foundations from soil contact by providing a space between the floor and the ground surface; (iii) design a shallow foundation capable of withstanding differential movements and mitigate theirs effects in the superstructure (iv) excavate partially the active soil and replace it with an inert material, such as crushed stones, gravels, and coarse-grain material. So, when the soil expands, it squeezes into the gravel voids and it swelling pressure is reduced.

CONCLUSIONS

For a better understanding of the role of the problematic soils in the instability phenomena observed in Dakar, a methodological approach was used to study the geotechnical properties of these soils regarding slopes and foundation stability or instability in this project. For this purpose, extensive investigations and laboratory tests have been performed. These soil investigations include: (i) testing of characteristics of these soils regarding their clay mineral compositions using X-ray diffraction; (ii) study of their physical properties; (iii) study of their shear characteristics by triaxial compression and circular ring shear tests; (iv) study of their swelling characteristics. The results obtained revealed that there is a strong relationship between the observed instability phenomena and the geotechnical properties of these problematic soils (residuals). The geotechnical properties of these soils are not favourable for foundation and slope stability. These soils are mainly characterized by unfavourable plasticity, activity, water absorption ability, swelling and shear characteristics regarding slope and foundation stability. The nature and content of clay minerals in these soils strongly influence their geotechnical properties and their susceptibility to swelling or shrinking, and their resistance to slide. Consolidation tests and ring shear tests revealed that the mechanical behaviour of these residual soils changes greatly with their montmorillonite content. The analysis of the obtained results has also allowed an appropriate and adequate consideration of the geotechnical factors affecting the slope and foundation stability in this region and the elaboration of stabilization and prevention measures according to the instability factors.

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