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Geotechnical characterisation and back analysis of a landslide in marl deposit: A case study of Algiers Sahel (coast), Algeria

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The purpose of this study is to present the results of geotechnical investigations and landslide analysis in a marl deposit at the Sahel (coast) of Algiers in northern Algeria, where many landslides take place in the Plaisancian marls, particularly following rainfall periods each year, causing severe damage to infrastructures and buildings. The physico-mechanical characteristics of the soils obtained from three different sites (El-Achour, Daly-Brahim and Ouled-Fayet) were analysed to identify the mechanism of these landslides. In the study, the laboratory test results providing grain-size distribution, Atterberg limits, water content, shear strength, and compressibility were analysed. The findings showed that, although the soils were characterised by slightly higher plasticity at Ouled-Fayet, they were generally homogeneous in the studied sites. The upper soils, generally weathered, exhibited low shear strength parameters, which are lower than the undisturbed formation beneath. The stability analysis based on limit equilibrium methods (LEM) showed the significant influence of pore water pressures on slope stability, suggesting that the weathered soils are prone to instability processes due to the effect of long rainy periods.

INTRODUCTION

Landslides are considered one of the most destructive natural hazards in the world, accounting for approximately 9% of the natural disasters that occurred worldwide during the 1990s (Yilmaz 2009), causing large numbers of casualties and huge economic losses in the mountainous areas of the world (Dai *et al* 2002). Landslides are very common in northern Algeria, where they are triggered by a combination of several factors linked to the site geology, land morphology, hydrology and climate, as well as antropic activities (Bahar & Djerbal 2016). Studies have revealed that several landslides occurred in many regions, such as Constantine (Benaissa *et al* 1989; Lafifi *et al* 2009; Bougdal *et al* 2013), Medea (Medjnoun 2014), and Kabylie (Machane *et al* 2009; Bouaziz & Melbouci 2015; Meziani *et al*

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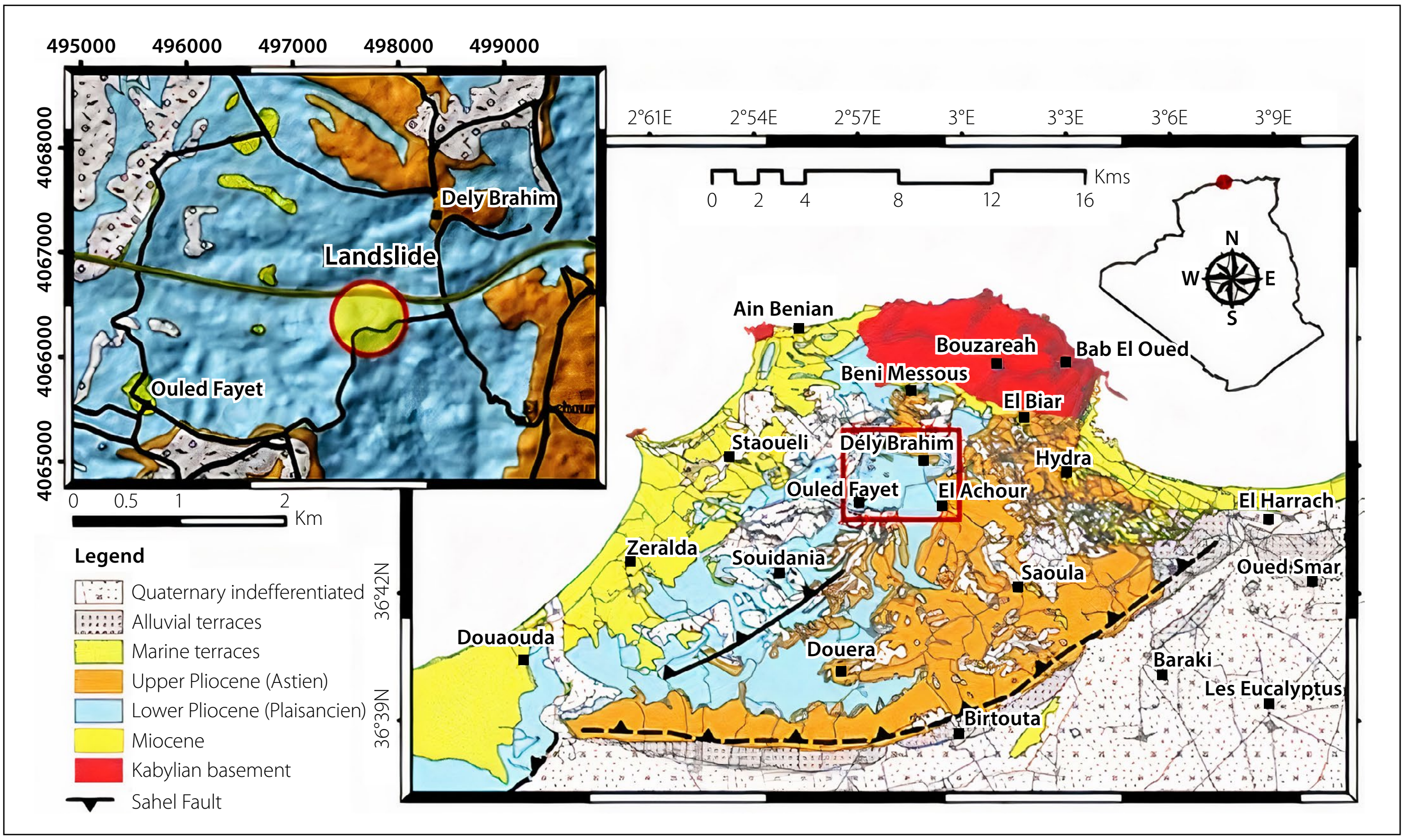

Figure 1 Geological map of study sites (Royer *et al* 1961)

2018). Algiers is one of the cities affected by this geological hazard which causes severe damage to structures and infrastructure. After the independence of Algeria (in 1962), rapid urbanisation took place, which extended to marginal lands southwest of the Sahel (coast) of Algiers once the areas became more favourable for construction. El-Achour, Daly-Brahim, Ouled-Fayet and Sidi-Abdellah are among the new urbanisation areas which are affected by landslides.

The superficial or deep instability processes (rotational or complex) were mainly observed in the Plaisancian marls and sandy clays providing the transition between the Plaisancian and molassic Astien facies (Aymé 1965). Some studies showed that the landslide triggers in most cases were linked to rainfall or to antropic actions which cause modification of the soil stress state (Bahar & Djerbal 2016). The study of Bièvre *et al* (2016), on the other hand, purported that the variations in the soil strength parameters due to weathering may also be one of the important causes of instability.

This study focused on the Plaisancian marls that outcrop in a large area of urban expansion in the southwest Algiers Sahel (coast) where an important deterioration of the mechanical properties of the marls is one of the main causes of the slope instability processes. This study analysed the results of laboratory tests (grain-size distribution, index properties, direct shear, and compressibility tests) obtained from inspections of an existing database of soil laboratories and companies. In order to conduct a deep investigation, the study examined several samples from the subsoil of El-Achour (site A), Daly-Brahim (site B) and Ouled-Fayet (site C). Other tests were also carried out to evaluate both the residual strength parameters and the susceptibility to progressive failure. Finally, a back-analysis based on limit equilibrium methods (LEM) was performed to examine the role of soil mechanical deterioration due to weathering, and the role of pore water pressures on the slope stability of the study area.

Study area

The study area is located on thick deposits of Plaisancian marls in the southwest of the Algiers Sahel (coast) (Figure 1). The geological formation of the Plaisancian marls outcropping in the Algiers Sahel, with a thickness of more than 200 m, is a homogeneous massive deposit of sedimentary rocks resulting from organic and mineral sediments in a shallow marine environment (Bouteldja *et al* 1997). The marls are covered by an Astien series of sandy clay and sandstone, which form the plateaus (a high plain or tableland) of El-Achour and Ouled-Fayet to the northeast that have been subjected to intense erosion (Meghraoui 1988). The Sahel is a succession of hills formed by Plaisancian marls with a slope inclination varying from 5% to 30% (Derriche & Cheikh-Lounis 2004). The topography resulted from the post-Astien tectonics, which caused the uplift of the Atlas Mountains and the formation of the Sahel anticline and the depression of Mitidja (Royer *et al* 1961; Aymé 1956). It should be noted that the landslides, characterised by wavy morphology (Bougdal 2007), occur in the weathered marl horizons of which the thickness varies with the degree of weathering, reaching about 8 m in depth, even at a slope inclination greater than 10%. The degree of weathering affects the strength parameters and therefore the slope stability of the Plaisancian marls.

METHODOLOGY

The methodological approach adopted by the study included the different phases as summarised below.

In the first phase, several technical reports were collected from different public administrations, soil laboratories and companies. These reports were analysed to obtain physical and mechanical data on the soil of El-Achour (site A), Daly-Brahim (site B), and Ouled-Fayet (site C) (Figure 2).

In the second phase, the landslide area was selected in Daly Brahim (site B) to

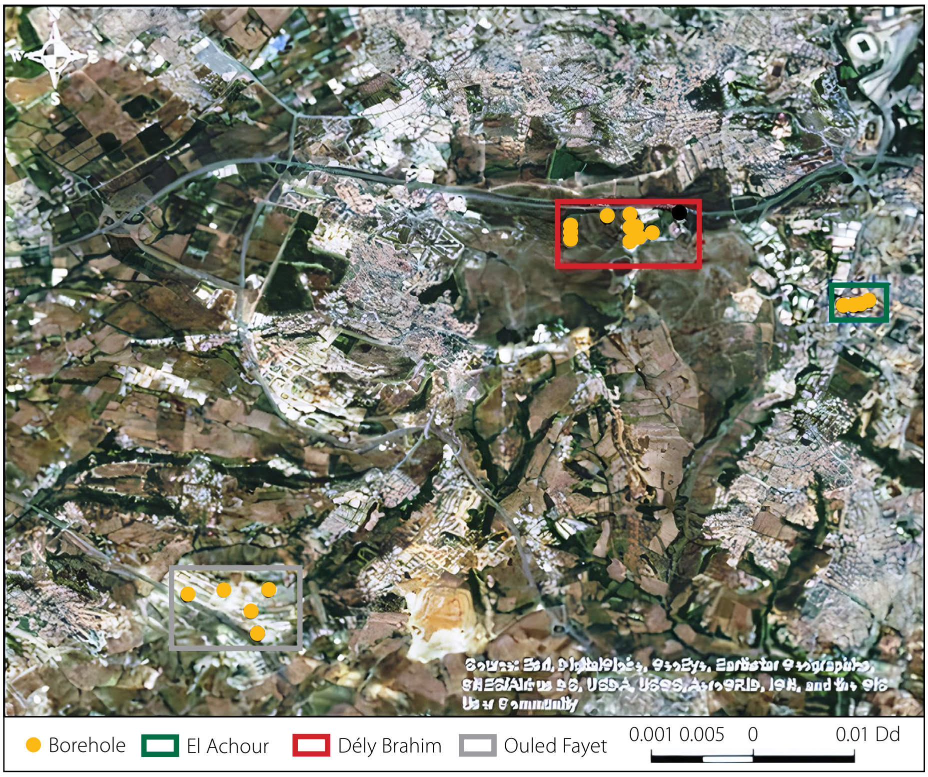

Figure 2 The geographical layout of the study area indicating the boreholes from where the examined soils were extracted

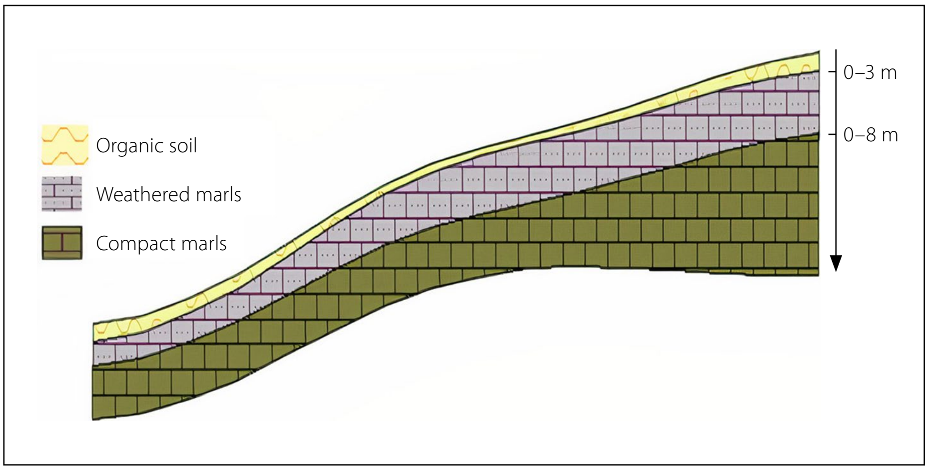

Figure 3 Typical soil stratigraphy

support the collected data. In this area, some samples were extracted for further laboratory investigation conducted essentially to evaluate the grain-size distribution, the Atterberg limits, compressibility, and the residual strength parameters.

In the final stage, slope stability analyses were performed for site B to evaluate the effect of both strength parameters and pore water pressure on the slope safety factor.

Data collection method

Data for the study was collected from the technical reports obtained from the archives of local authorities, soil laboratories and companies. Thus, 80 reports and additional field data were analysed. This data provided 156 laboratory test results including grain-size distribution, index proprieties, shear-strength parameters, compressibility and swelling properties.

During this study, some samples from Daly Brahim were extracted and nine laboratory tests were performed to support collected data, by providing additional information on grain-size distribution, Atterberg limits, compressibility, and shear-strength parameters.

Laboratory tests

Laboratory tests were performed on 11 soil samples from site B. Eight disturbed samples were taken on the scarp of shallow landslides between 0.5 m and 1 m depths and three undisturbed soil samples were taken at depths of about 5, 12 and 27 m. Laboratory tests were performed according to the AFNOR standards (French Standardization Association). Grain-size distribution was evaluated by mixed sieve-sedimentation analysis, as described in NFP 94-056 and NFP 94-057, and the Atterberg limits were measured using the procedure described in NFP 94-051.

The volume-change behaviour was evaluated by oedometer tests on the material taken from different depths according to XP P94-090-1. The shear test results collected from reports were carried out according to NF P-071-1, at a shear rate of 0.016 mm/min, which is lower than the maximum shear rate suggested by the standard ($v_{max} = 125/t_{100}$ mm/min, with t_{100} = end of consolidation time) for all the considered samples. All tests were performed on the samples at three different levels of normal stress.

Slope stability analysis

The slope stability analyses were performed for site B to examine the effect of both strength parameters and pore water pressures on the slope safety factor. The analyses were performed using the computer programme SLOPE/W (by Geoslope International Ltd) based on LEM. Moreover, the Morgenstern-Price method (1965) was used and a slip surface reaching the base of the weathered soil was analysed. Pore-water pressure distribution at the basis of stability analysis was evaluated by the SEEP/W programme (by Geoslope International Ltd) and different hydraulic boundary conditions were considered.

RESULTS AND DISCUSSION

The stratigraphy of the three investigated sites was reconstructed on the basis of the material extracted from 22 boreholes (locations indicated in Figure 2). The analysis shows that the weathered marls close to the ground surface are greenish-yellow mottled. The weathered horizon thickness reaches to about 8 m; beneath this depth, the undisturbed marls are generally very consistent and hard. Figure 3 shows a scheme of the typical soil stratigraphy.

Physical characteristics and index properties

The grain-size distribution curves (Figure 4) show that the considered soils are fine-grained in all three sites, with more than 70% dry weight composed of

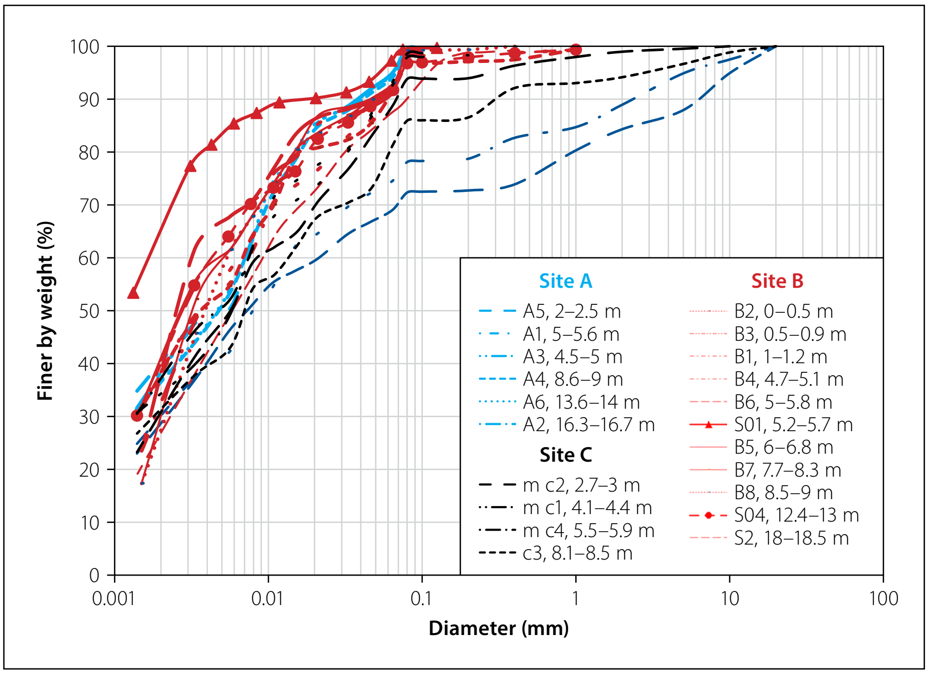

Figure 4 Typical grain-size distribution of the soils of the three study sites

particles smaller than 80 µm. The clay fraction is important and can reach about 59%. Derriche and Cheikh-Lounis (2004) observed that the shallow weathered marls can contain a grain-size component coarser than those of the deep marls. They claim that such coarser components fill the deep shrinkage cracks formed through the weathered marls. The curves in Figure 4 show that particles coarser than 0.8 – 1 mm were found also in the deeper unweathered soil. The origin of such particles was not investigated in this work.

Figure 5 depicts the results of the variation in dry unit weight (γ_d), water content (w), saturation degree (Sr), liquid limit (LL), plasticity index (PI), and calcium carbonate content ($CaCO_3$) with depth. As Figure 5 depicts, the dry unit weight of the weathered layer of sites A and B increases from about 14 kN/m^3 close to the ground surface to about 19 kN/m^3 at a depth of about 8 m, below which, in the underlying undisturbed formation, it is almost constant. It is worth noting that some samples were extracted in May, and others between October and March of the following year. Irrespective of the month of sampling, the weathered marls were saturated (Sr = 100%) or almost saturated at the investigated depths. This result has important consequences for the response of pore water to rain, as shown in the section of slope stability analysis. The water content decreases from about 30% close the ground surface to an average of about 15% in the undisturbed formation. Site C, in contrast, has a dry unit weight and water content almost constant along the verticals, and close to the minimum and maximum values, respectively, of the corresponding parameters of the other two sites. The higher water content and lower dry unit weight of site C are probably due to the presence of more expansive clay minerals. In fact, the Atterberg liquid limits of site C are generally higher than the other two sites (Figures 5 and 6), whereas the clay fractions are similar. This site is actually known for its high swelling potential (Medjnoun 2014), associated with the predominance of illite-montmorillonite minerals (Bougdal 2007).

The experimental results indicate that a high clay fraction is dominant in all three sites. The clay soils, weathered from the parent rock mass, contribute to landslide occurrence due to their chemical and physical properties (Yalcin 2007). The intense rainfall in the region probably causes osmotic phenomena of water adsorption which leads to the mechanical deterioration of the shallow layers of weathered marls (Picarelli & Di Maio 2010), with important implications for the stability of the considered slopes (Di Maio *et al* 2015; Di Maio *et al* 2017).

Compressibility

Figure 7 shows the *e-logσ'$_n$* curves obtained for undisturbed samples, which

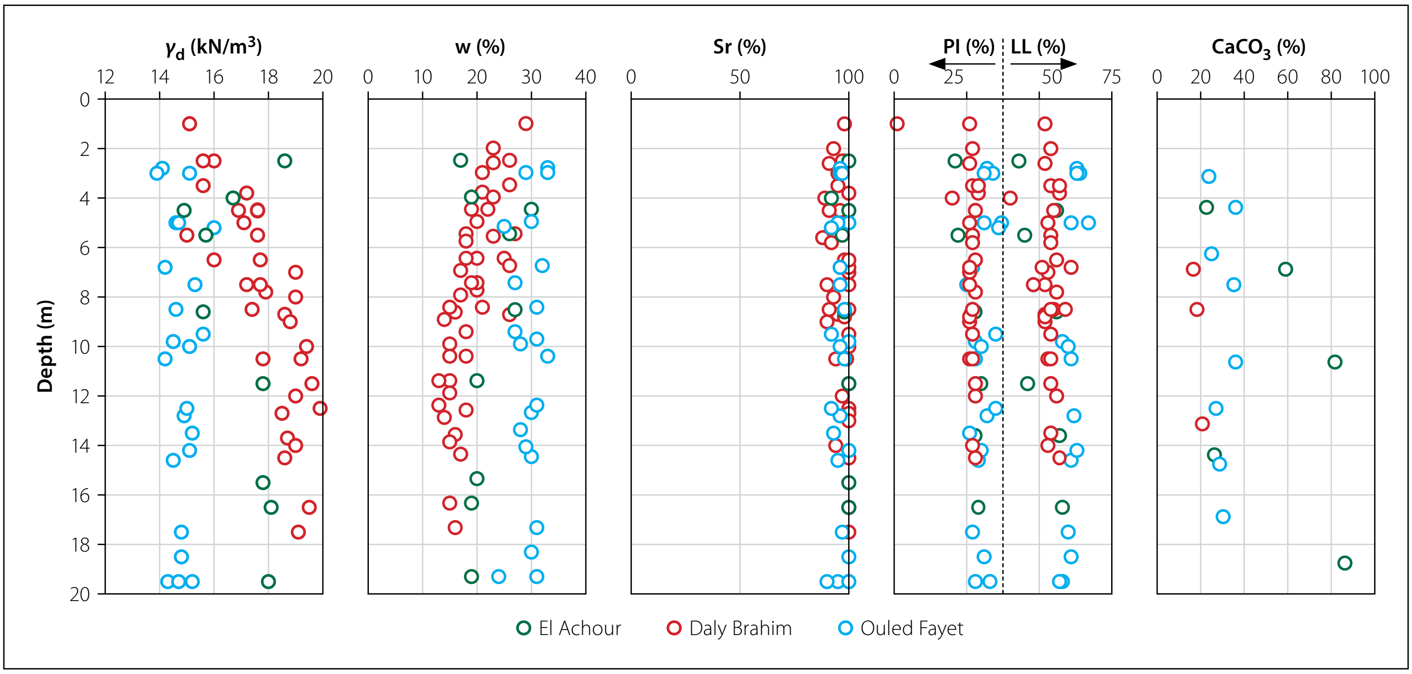

Figure 5 Profiles of γ_d, w, Sr, LL, PI and $CaCO_3$ content for El Achour (Site A), Daly Brahim (Site B) and Ouled Fayet (Site C)

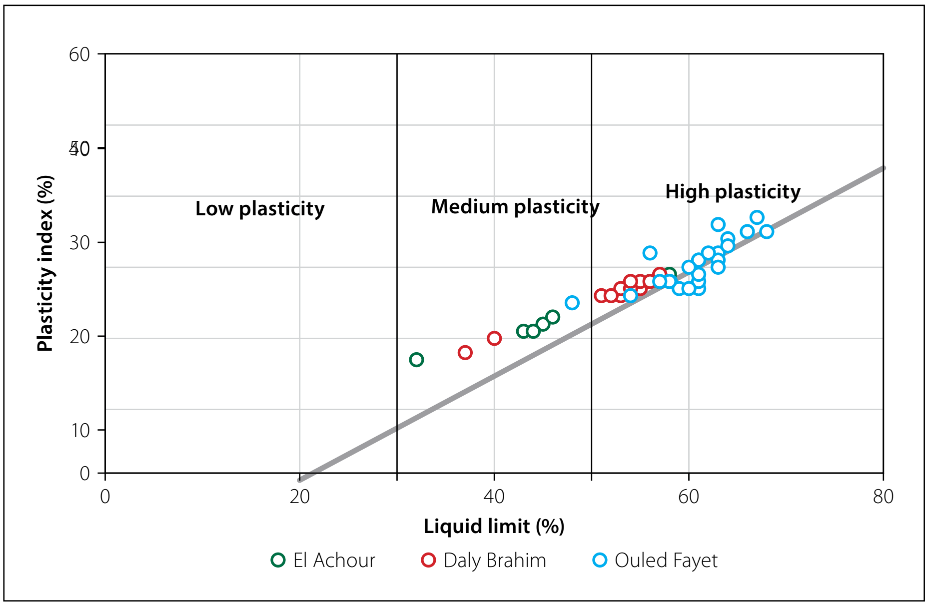

Figure 6 Plasticity chart of the studied soils

were extracted from both the weathered and unweathered formations of site A (Figure 7a), site B (Figure 7b) and Figure 7d), and site C (Figure 7c). It should be noted that the volume change behaviour was evaluated by oedometer tests on the material sampled from several different depths. The profiles of compression index (C_c), swelling index (C_s), and over-consolidation stress (σ'_c) are reported in Figure 8. The comparison between σ'_c and the effective vertical field stress (σ'_v) of the corresponding sample showed that the considered soils are over-consolidated. The over-consolidation is mainly due to the erosion of an overburden constituted by more than 100 m thick deposit of sandstones and Astien sands (Bougdal 2007). Most of the considered

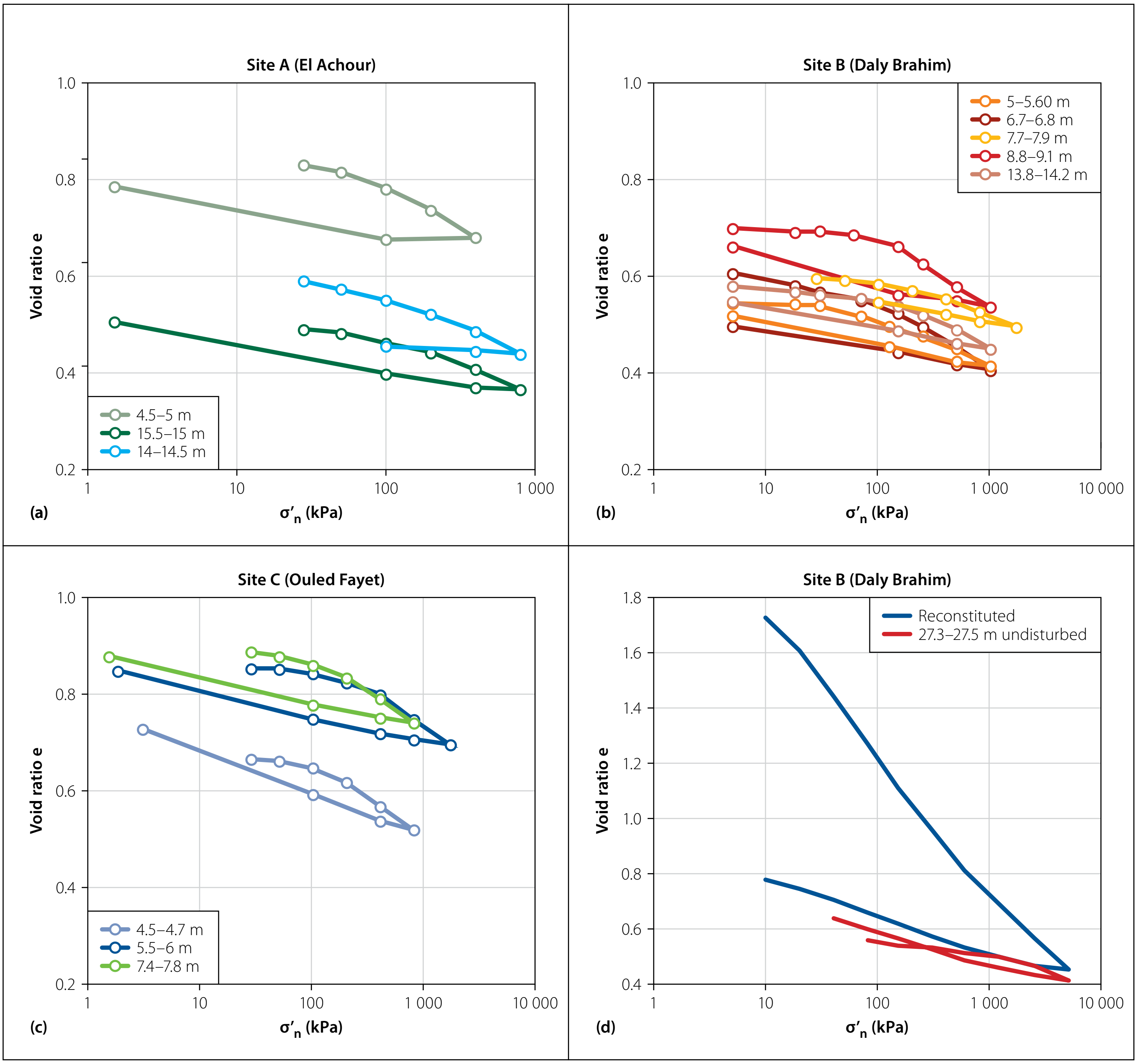

Figure 7 Compressibility curves obtained for undisturbed samples extracted from the three investigated sites A, B and C [(a), (b) and (c)] respectively, and oedometer curves of the material extracted from site B undisturbed and reconstituted at the liquid limit (d)

samples show a loss of the over-consolidation effects, whereas the deeper samples (e.g. those in Figure 7(d)) still maintain it. Figure 7(d) compares both the oedometer loading and unloading curves of the undisturbed soils (sampled from a depth of about 27 m at site B) and the curves of the same soils reconstituted at the LL.

Figure 7 indicates that the undisturbed soil is strongly over-consolidated, and its curves have an average slope very close to that of the unloading curve of the reconstituted soil. The C_c values ranging from 0.08 to 0.2 indicate that the soils have low to medium compressibility known to be a characteristic of marls and weathered marls, respectively (Carter & Bentley 2016).

Shear strength parameters

Figure 9 illustrates the results for Daly-Brahim subsoil. The shear tests were carried out on samples of weathered marls, constituted by 60% – 70% silt and 40% – 30% clay, i.e. on the fine-grained samples of Figure 4. The tests provided average values of cohesion c' and friction angle ϕ' of about 20 kPa and 14°, respectively. However, beyond this depth (more than 8 m), both the average c' and ϕ' increase up to about 45 kPa and 16°, respectively. Figure 9 refers to undisturbed materials, thus the shear behaviour depends not only on the grain-size distribution and plasticity but also on the soil fabric and on the soil stress-strain history. The obtained failure curves, with low friction angles and relatively high cohesion intercepts, are typical of over-consolidated materials. The mechanical deterioration of the shear parameters in weathered marls is probably due to the phenomenon of weathering. On the one hand, the weathering of the marls involves physical and chemical processes which lead to strength degradation (Eberhardt *et al* 2005; Picarelli & Di Maio 2010), the effects of which can be evaluated by laboratory tests on intact soil samples. In the field, however, other weathering effects can occur. Shunchao and Vanapalli (2015) reported that drying and wetting cycles can induce the development of fissures and cracks, which modify the original structure of the clay, thereby decreasing the stress level and increasing both water inflow and porosity.

Besides the collected results, other experimental results were obtained from the laboratory tests conducted within the scope of this study. The shear behaviour from peak to residual shear strength was evaluated on two samples (S01 and S04) extracted from a depth of 5 m in weathered marls (S01) and

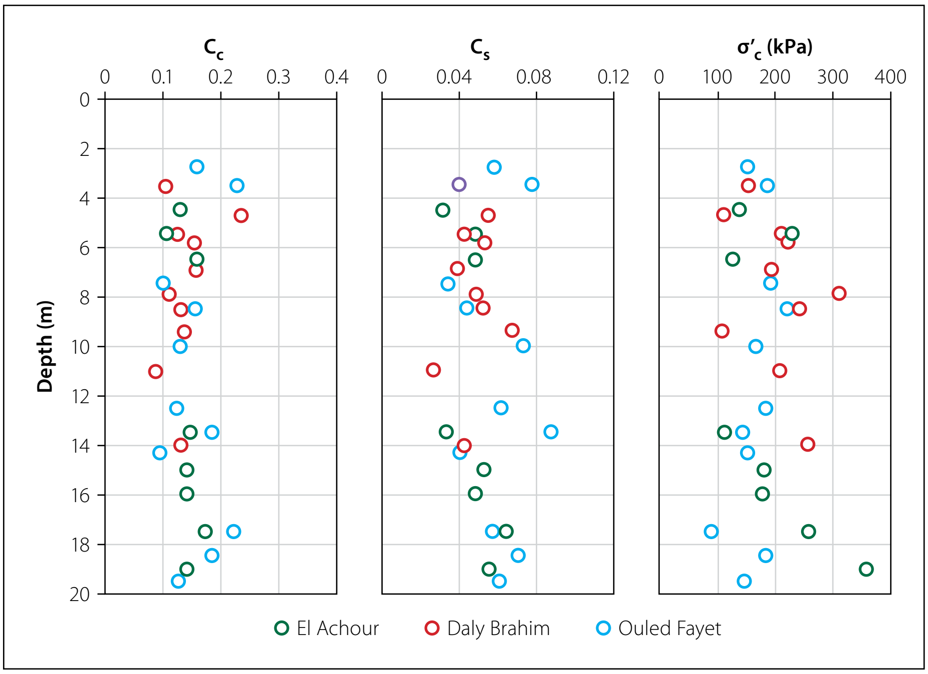

Figure 8 Profiles of the Cc and Cs indices and over-consolidation pressure σ'c

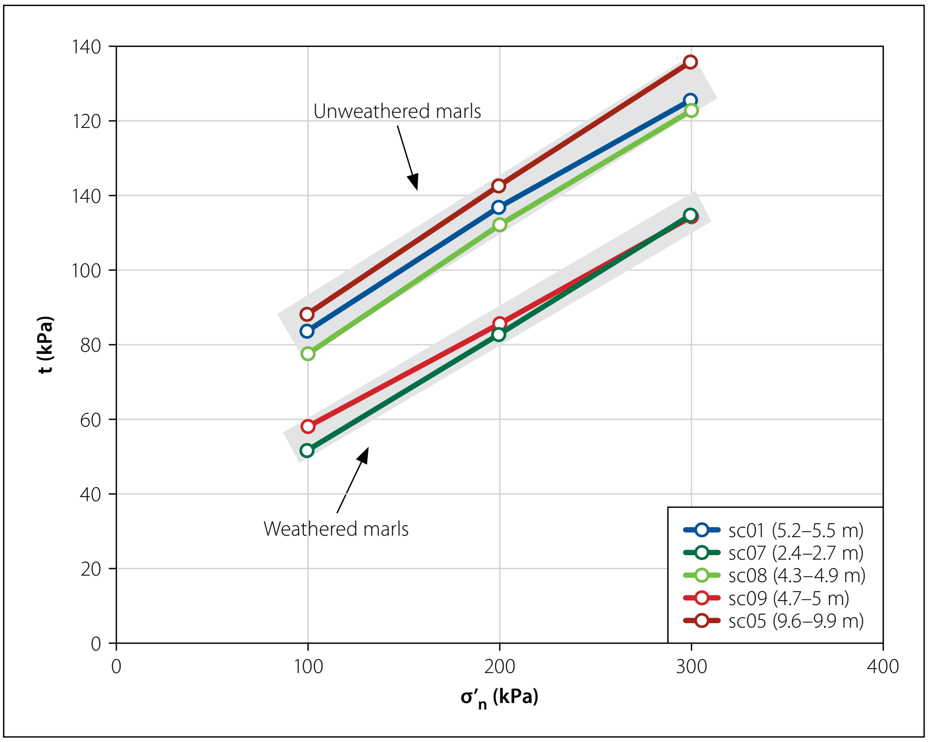

Figure 9 The results of the direct shear test performed on marls samples extracted from various depths

from about 12 m (S04) in unweathered marls, respectively. Sample S01 was consolidated under a normal stress of 197 kPa, and was then sheared (Figure 10). The first two cycles were performed at low displacement rates (v = 5 μm/min). The following cycles were performed faster in order to obtain a complete alignment of the clay particles within a few days. At a displacement of about 40 mm, the rate was lowered to 5 μm/min again, after which additional cycles were performed to obtain the drained residual shear strength parameters, residual friction angle ϕ'_r and residual cohesion c'_r (Figure 12). The same specimen was subsequently consolidated under a higher normal stress at 297 kPa and sheared again to the residual conditions. Figure 11 presents the results obtained for a specimen of sample S04 extracted from the unweathered formation. The specimen was consolidated and then sheared to the residual conditions at a rate of 5 μm/min. Figure 12 shows that the residual friction angle of weathered marls is ϕ'_r =11°. Under the reasonable hypothesis that c'_r is null, ϕ'_r of the sample of unweathered marls is 13°, a little bit higher, probably because of the difference in grain size distribution and c.f. (Figure 4).

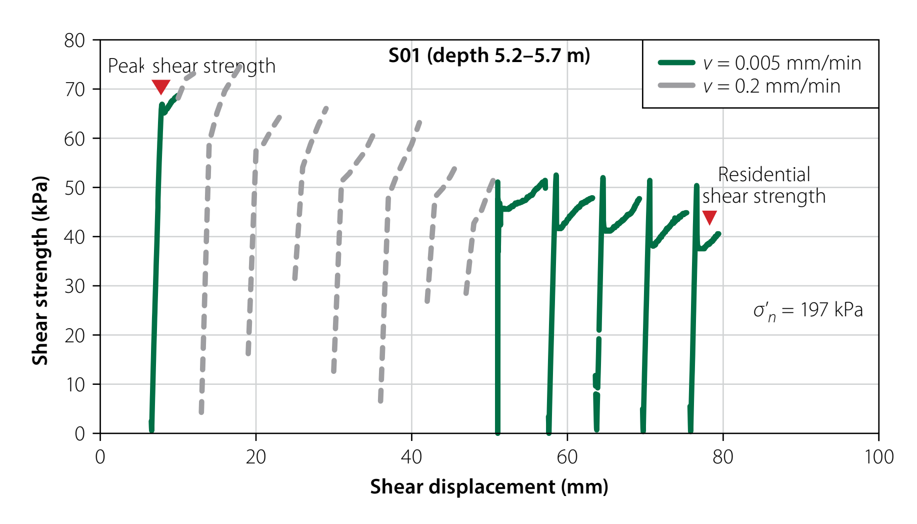

Figure 10 Shear strength versus shear displacements for a specimen of weathered marls (S01)

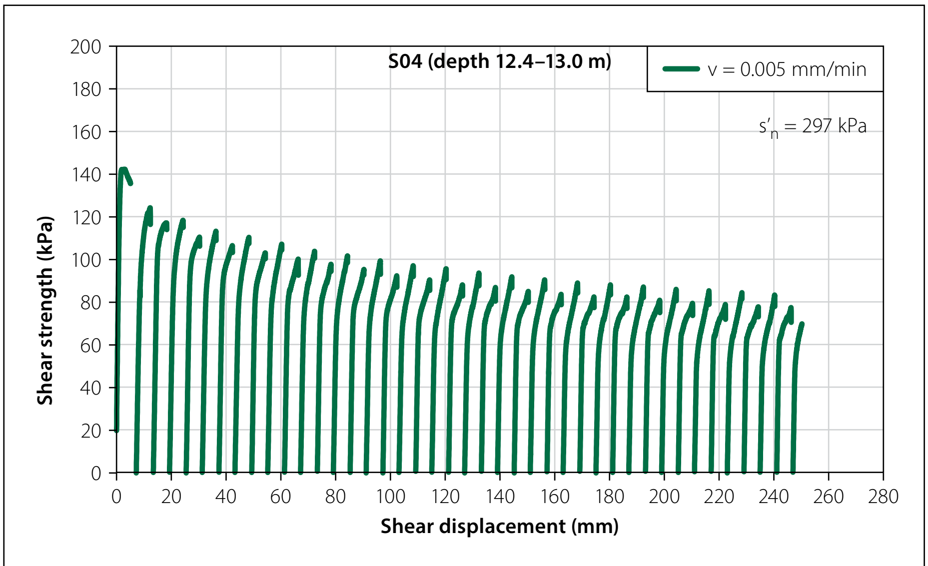

Figure 11 Shear strength versus shear displacements for the undisturbed material taken from unweathered marls (S04)

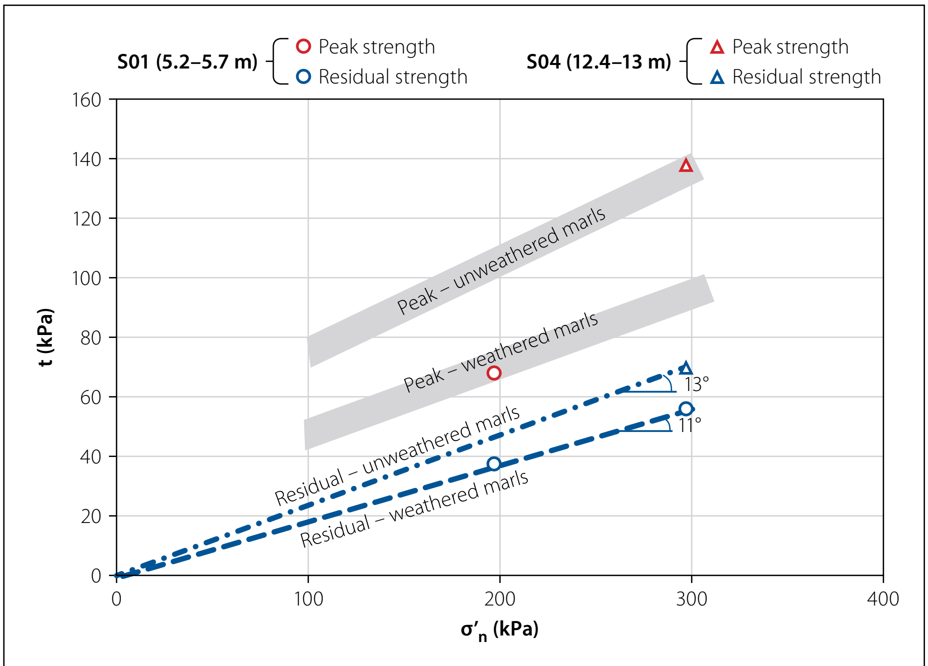

Figure 12 Peak and residual shear strengths versus shear displacements for specimens of weathered (S01) and unweathered marls (S04)

Both values are consistent with the presence of important percentages of clay minerals (Lupini *et al* 1981). The comparison between the peak strength lines and the residual ones shows the dramatic drop in strength from peak to residual, indicating the susceptibility of the soil to progressive failure.

Slope stability analysis

The stability analyses were performed for a slope from Daly Brahim (site B), where the instability problems mainly occur in the upper weathered marl horizons (Figure 13).

The calculations were performed with reference to the section A-A' (Figure 14a). The pore-water pressure distributions for the analyses in 2D and drained conditions were evaluated by the code SEEP/W for the domain represented in Figure 14b. Since the soils have high values of the degree of saturation and the water level recorded in some piezometers ranges from 0.3 m to 10 m depths, the soil was always studied saturated so that three different hydraulic boundary conditions were considered:

1. hydraulic head equal to the elevation of the ground points on the two vertical boundaries AB and CD, and water pressure u = 0 on the ground surface
2. hydraulic head 5 m lower than in the first case on the two vertical boundaries and null unit flux (q = 0) on the ground
3. hydraulic head 10 m lower than in the first case on the two vertical boundaries and null unit flux on the ground.

The first condition on the ground (u = 0) corresponds to continuous rain with intensity higher than the soil hydraulic conductivity, while the second condition (q = 0) corresponds to dry weather. The results of the stability analyses performed using SLOPE/W for the worst slip surface are illustrated in Figure 15a, and for the three water pressure distributions are shown in Figure 15b in terms of c' – ϕ' couples which provide a safety factor SF = 1. The figure shows that the strength parameters characterising the peak strength of the undisturbed, not weathered, formation are much higher than those corresponding to failure along the considered slip surface, even in the case of u = 0. In contrast, the parameters of the weathered formation are closer to those corresponding to failure, for the case of u = 0 on the ground surface (condition 1) corresponding to continuous rain with intensity higher than the vertical permeability. The values of residual friction angle ϕ'_r (11°–13°) are equal to or even lower than the parameter that brings the slope to

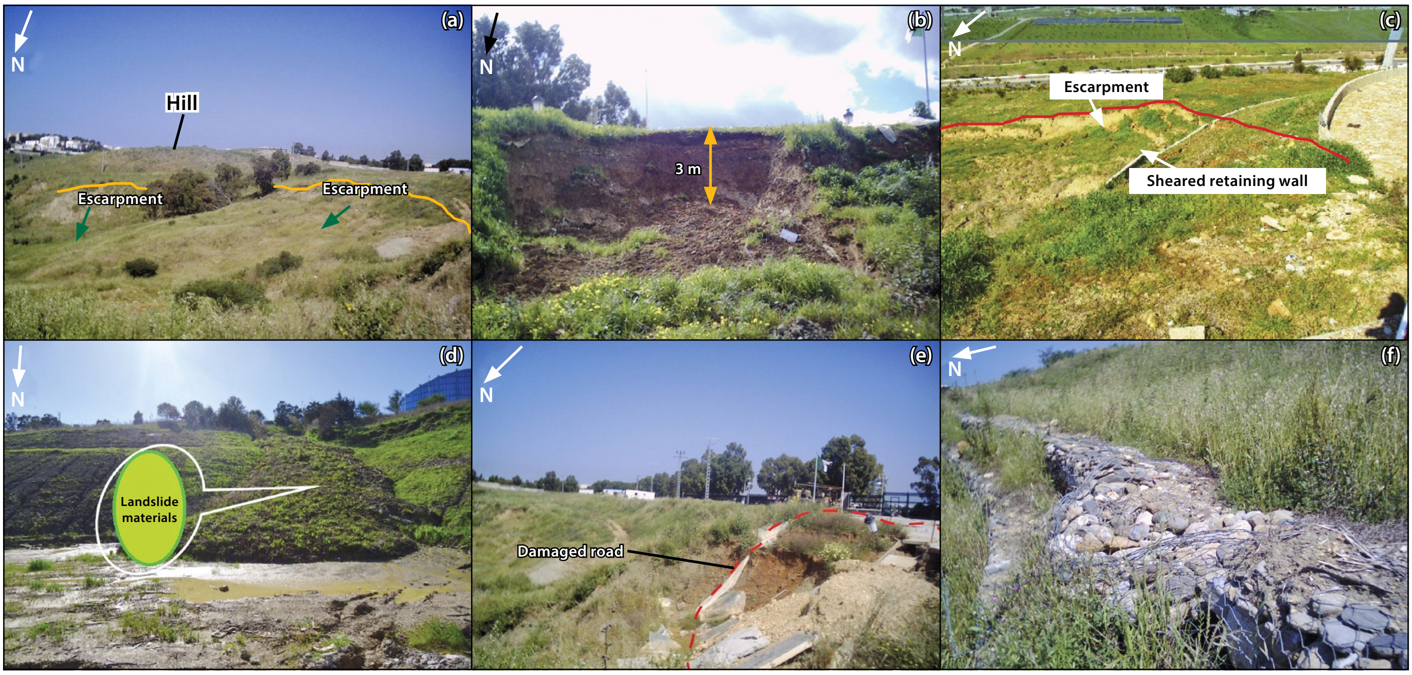

Figure 13 Landslide area at Daly Brahim (Site B)

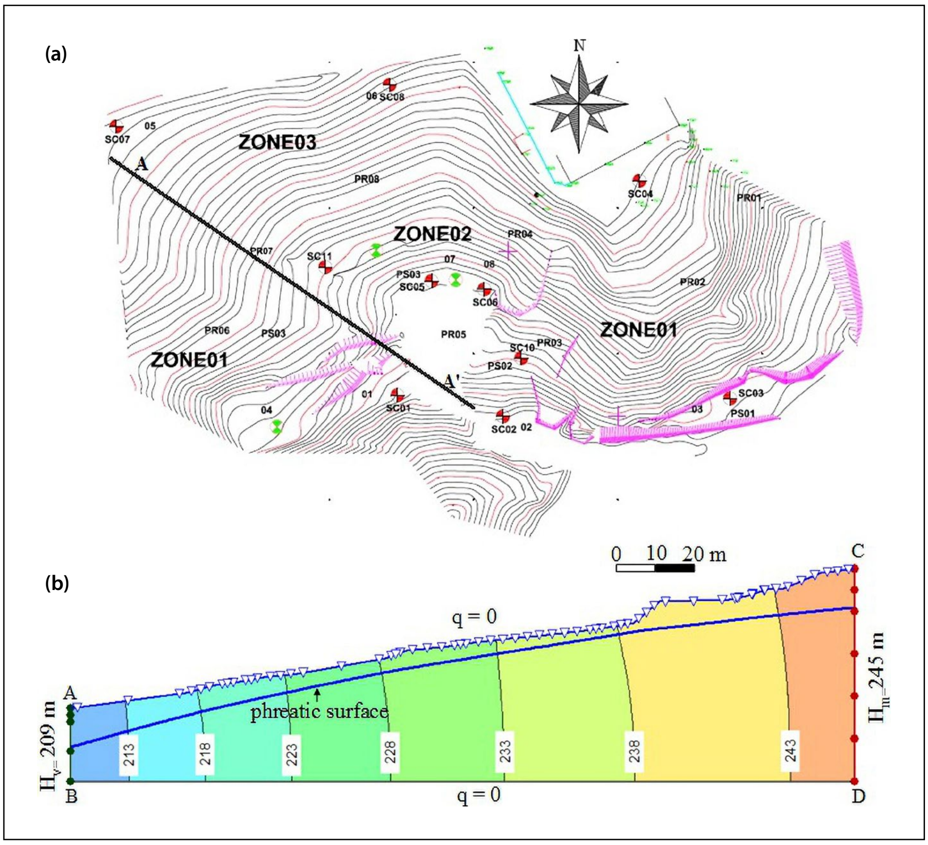

Figure 14 (a) Map of Dounia Park at Daly Brahim and a trace of the section AA′ considered for the stability analysis; (b) section AA′: hydraulic head distribution relative to the third condition (Hm=245 m, Hv=209 m, and unit flux q = 0 on the ground surface

failure under the third hydraulic condition. It is thus reasonable to hypothesise that the real available strength parameters are intermediate between the peak and the residual ones.

As a matter of fact, the considered landslide located in site B occurred after considerable rainfall in 2011. In most cases, the infiltration of precipitation into the slide surface triggers a landslide (Eberhardt *et al* 2005). The investigated part of the shallow marls shows a decrease in mechanical interlock parameters. The weathering and additional water infiltration can further reduce the shear-strength parameters. The increase in pore water pressures decreases the shear strength, thus reducing the factor of safety (Bahar & Djerbal 2016; Liu & Li 2015).

CONCLUSIONS

The purpose of this study was to report the results of geotechnical investigation and landslide analyses in marl deposits. The Plaisancian marls that outcrop in the urban expansion areas in the southwest of the Algiers Sahel (coast) are often affected by slope instability processes. In order to evaluate the impact of weathering and climate on the safety factor of the slopes, back-analyses of a landslide that occurred at one of the sites were also performed. The results of the study reveal that the soils of the unstable slopes considered at EL Achour, Daly Brahim, and Ouled Fayet are fine-grained and exhibit medium to high plasticity; and the Atterberg liquid limits of Ouled Fayet soil are generally higher than those of the other two sites. The upper greenish-yellow mottled soils are weathered and generally present significantly higher water content than the undisturbed sample below. The latter is generally very consistent and hard. The thickness of the weathered horizon reaches about 8 m and the instability processes generally occur in the weathered marls. A comparison of strength parameters obtained by the laboratory tests and strength parameters obtained by back analyses shows that the most critical conditions are reached in the weathered marls during long rain periods, and the available strength parameters are intermediate between the peak and the residual ones. It is worth noting that the considered pore water pressure distributions were obtained considering steady-state hydraulic conditions. The time required to reach these conditions can

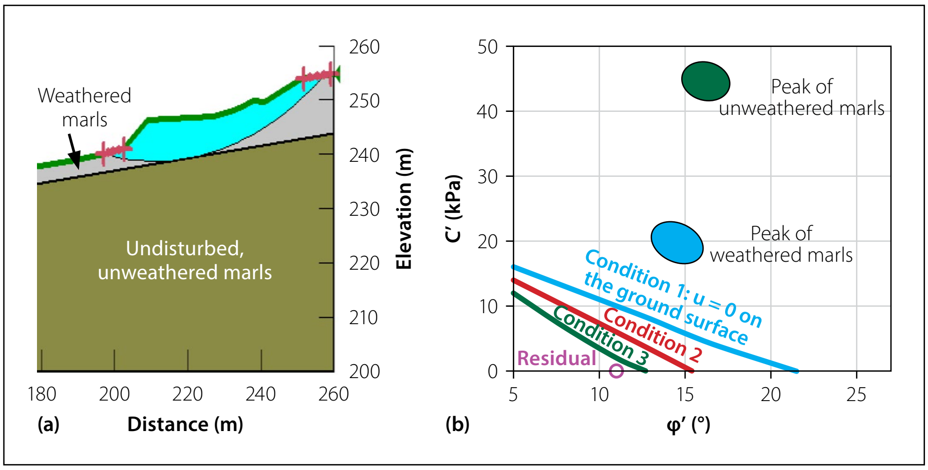

Figure 15 (a) Model for the LEM stability analysis and critical slip surface; (b) limit curves of the couples of c′ and φ′ values providing SF = 1 for the three different hydraulic boundary conditions, areas of c′ and φ′ couples and point of φ'_r obtained experimentally for the considered soils

be strongly influenced by the presence of cracks and fissures which act as paths of fast water flow or pressure propagation.

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