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Study of the geo-mechanical evolution of the Paleozoic massif of Al Hoceima's tectonic klippe, by analyzing the instability structures and the interpretation of geotechnical data (Rif, Morocco)

L'évolution géo-mécanique du massif paléozoïque de la klippe tectonique d'Al Hoceima (Rif, Maroc) par l'analyse des figures d'instabilité et l'interprétation des données géotechniques

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Abstract. The instability of a rocky slope occurs after a long period of geomechanical deformation. We also realize that the slopes undergo a number of mechanical stresses over time, having for effect the induction of an intense change in the mechanical characteristics of the materials. The study of these phenomena, which can be considered as a natural permanent danger, is significant in every prevention plans and urban planning, as well as in the scientific research field. Al Hoceima's Paleozoic klippe (northern Morocco) is more affected by these ground instabilities, where the behavior of the rock masses seems in fact governed by complex processes, resulting from the geological and tectonic evolution which conditions the transformation of the rock under the effect of shearing and granulometric reduction. Thus, and in order to better understand the process of instability, from the predisposition phase to the triggering phase ; the study and interpretation of the geomechanical structures of instability (the granulometric reduction, shearing, dilatancy, punching and fluidification phenomena), makes what is necessary for the reconnaissance of the evolved and highly unstable zones possible.

Keywords : sliding, geomechanics, dilatancy, fluidification, Northern Morocco.

Résumé. L'instabilité d'un versant rocheux intervient après une longue période de déformation géo-mécanique. On se rend compte également que les versants subissent un certain nombre de sollicitations au fil du temps, ayant pour effet d'induire une modification intense dans les caractéristiques mécaniques des matériaux. L'étude de ces phénomènes, considérés comme un danger naturel permanent, a une importance considérable dans toutes planifications d'aménagement et de prévention, aussi bien que dans le domaine de la recherche scientifique. La klippe paléozoïque d'Al Hoceima (Maroc septentrional) est plus touchée par ces instabilités de terrain, où le comportement des masses rocheuses paraît en fait régi par des processus complexes, issus de l'évolution géologique et tectonique qui conditionne la transformation de la roche sous l'effet du cisaillement et de la réduction granulométrique. Ainsi, et dans le but de mieux comprendre le processus de l'instabilité, du prédisposition jusqu'à la phase de déclanchement ; l'étude et l'interprétation des figures géo-mécaniques de l'instabilité (la réduction granulométrique, le cisaillement, la dilatance, le poinçonnement et les phénomènes de fluidification), rendent possible ce qui est nécessaire à la reconnaissance des zones évoluées et fortement instables.

Mots Clés : glissement, géo-mécanique, dilatance, fluidification, Maroc septentrional.

INTRODUCTION

Landslide inventories and geo-mechanical deformation studies of slopes are key tools for land use planning and management, civil protection plans, civil engineering works, and risk reduction programmes. Their importance lies in expanding the knowledge area in this domain, notably the geomechanical characterization of slope instabilities; as well as the determination of the current state of slope instability by the analysis of the instability structures, particularly: shear structures, dilatancy, granulometric reduction, punching structures, and fluidizing phenomena.

Studying field instability is always difficult because it is influenced by many factors such as geological structure, tectonics, hydrogeology, and the mechanical properties of the rock masses. In the region of Al Hoceima, located on the Mediterranean side north of the Rif chain (Fig. 1a), the relief aspect is very modeled (Maurer 1968), and has a morphological diversity common to the entire Rif littoral (Morel 1988, El Fellah 1996, Margaa 1994, Azzouz 2002). The morphological fragmentation is substantial around Tala Youssef and Sabadia where the margins are composed of slopes largely divided by valleys generally North and South oriented (Maurer 1968).

The tectonic evolution of Al Hoceima's klippe leads to slow deformation and readjustment by mass movements, subsidence and creep, and settlement. These phenomena are specially encountered along the coastline between Boussekoûr and Cala Bonita. Field instability is quite destructible because many landslides and rock slips occur regularly and play a major role in the morphological shaping of coastal slopes. At the microscopic scale, the rocks undergo a textural disintegration affecting the assembly of the grains, by granulation and by fracturing. The ultimate evolution of all these slow deformations is the sudden collapse of the rocky mass, which threatens infrastructure and human life.

THE GEOLOGICAL AND TECTONIC CONTEXT

The Rif, which represents itself as a stack of nappes with general vergence towards the foreland in the South (Chalouan *et al*., 2001), is the western extremity of the Mediterranean alpine chain. It is part of a Bético-Maghrebian (Rif, Tell Algerian-Tunisian, Sicilian and Calabro-Peloritano) structural ensemble and South Apennines (Fig. 1a), which shows a very similar geological evolution in the main stratigraphic recordings of the series deposited along these mountain ranges (Guerrera *et al*. 2012, Guerrera & Martin-Martín 2014). The Rifian chain is the result of complex tectonics, whose training scenario has been the subject of several studies (Durand-Delga *et al.*

1962-64, Durand-Delga 1980, Suter 1980, Frizon de Lamotte *et al*. 1991, Chalouan & Michard 2004, Guerrera & Martin-Martín 2014), it constitutes with the Betic chain a tectonic arc (Gibraltar Arc) which has developed in a convergence zone following the relative combined movements between the African and Eurasian plate. From inside to outside, the Rif chain consists of three main structural domains: the Internal Zones, or Alboran Domain, the Maghrebian Flyschs, and the External Zones (Chalouan & Michard 2004).

The study area is limited especially to the Al Hoceima Paleozoic klippe, located in the northeastern part of the Bokoya Massif (Internal Domain) (Fig. 1b), which occupies the central northern part of the Rif chain and consists of the external *Dorsale Calcaire*; the internal *Dorsale Calcaire*; and the Paleozoic tectonic klippes (Sébtides, Ghomarides). Al Hoceima's klippe is an elongated strip generally oriented ENE-WSW, occupies a topographic depression delimited by very well-adjusted abnormal contacts (Azzouz 1992), and rests on the south side on the calcareous ridge or on the tertiary base (Fig. 1c). It consists mainly of: the Beni Hozmar nappe (Ordovico-Silurian conglomerate bars, Devonian platy limestones, and a Carboniferous greso-pelitic series) ; the Quemado nappe contains the griotte limestones late Silurian (Blumenthal 1937) and the Givetian zebra limestones (Megard 1963), the Aâkaili nappe (Ordovico-Silurian structures made up of predominantly sandstone or pelitic series) ; the western part of the AL Hoceima klippe is composed of different turbiditic series, mainly marl, calcareous and pelitic.

Neotectonic activity is expressed by two families of normal faults (Chalouan 1995). The first family is parallel to the main lengthening of the Bokoya massif, with directions from N55 to N70, and sometimes N120, these subequatorial faults are relatively more frequent and low discharges; the second family is described in the Plio-Quaternary conglomerate bars of the sector of Sabadia and in the consolidated dunes which surmount them, it is constituted by transverse faults of direction N160 (Chalouan 1995, Azzouz 2002). These faults cut geological structures over all the coastal slopes of the Al Hoceima klippe (Fig. 1b) and thus create huge debris sections, enclosing minor fracturing with spacings of a few millimeters to a few centimeters. The general orientation of this fracturing determines the initial direction of landslides.

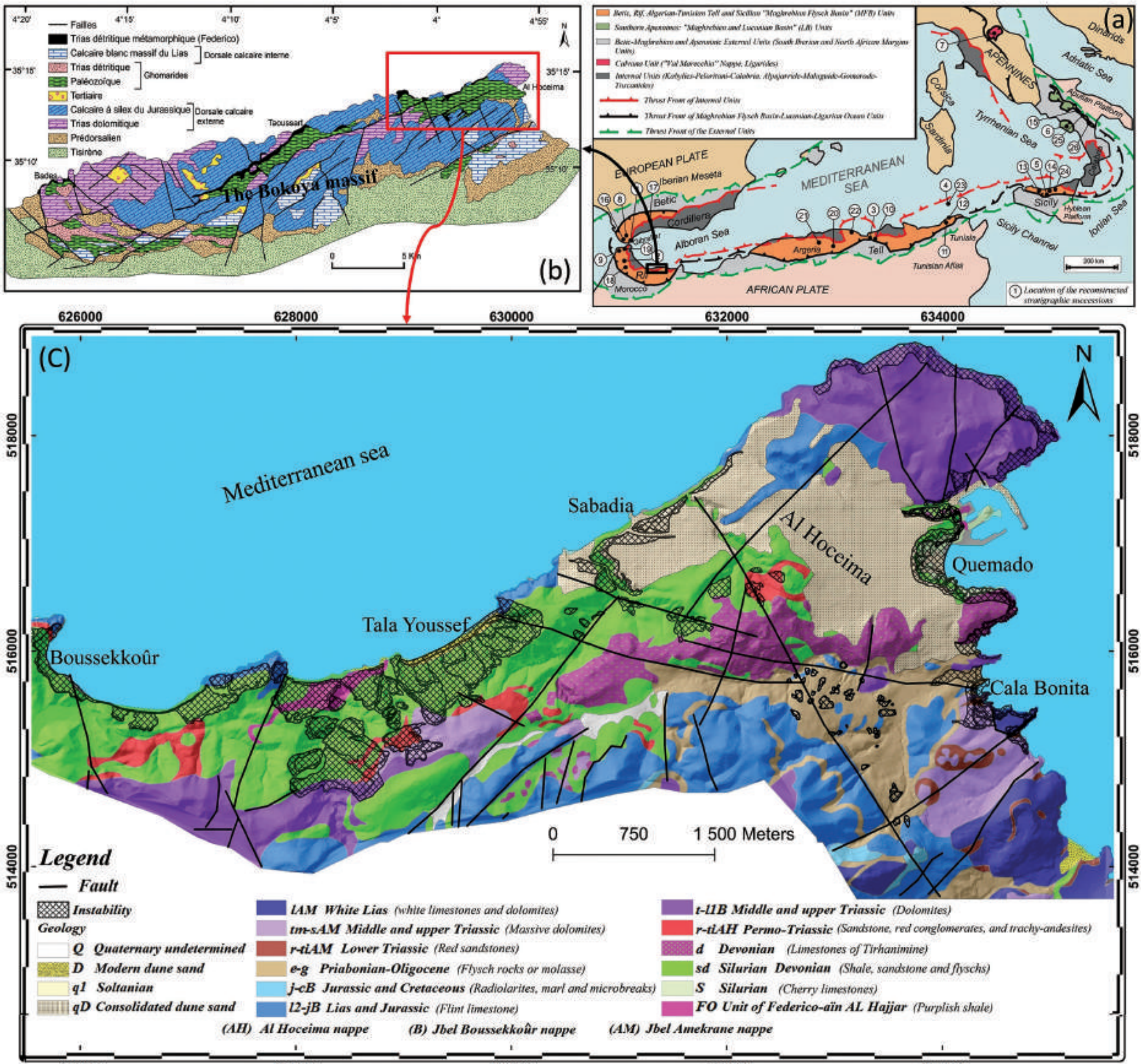


Figure 1. The geological and tectonic context of the study area : (a) Betic-Maghrebian (Rif, Algerian-Tunisian Tell, Sicily and Calabro-Peloritani arc) and South Apennine chains (Guerrera & Martin-Martín 2014) ; (b) The structural map of the Bokoya chain (Azzouz 1992) ; (c) The morpho-structural map of the Al Hoceima klippe (extracted from the Al Hoceima geological map at 1/50000).

MATERIALS AND METHODS

Many researchers have mentioned the existence of a strong relationship between the relaxation of Plio-quaternary tectonic stresses and the occurrence of landslides in the Al Hoceima region (Margaa 1994, El Fellah *et al*. 1996, Azzouz *et al*. 2002).This relaxation has given rise to several phenomena and geo-mechanical processes continue affecting the intraformational heritage of the geological structure. In this context, and in order to understand the mechanisms and processes of the mechanical evolution of the Rocky massifs, this work was designed to establish a method of analysis based on the one hand on the mapping by photo-interpretation of the images Satellites from the Google Earth database (Fig. 2) ; On the other hand, on the analysis and interpretation of field data (witnesses and instability structures at the Klippe of Al Hoceima), and the interpretation of geotechnical data (table 1) identified locally at the scale of an unstable site (Al Hoceima Port slip) (LPEE 2012).

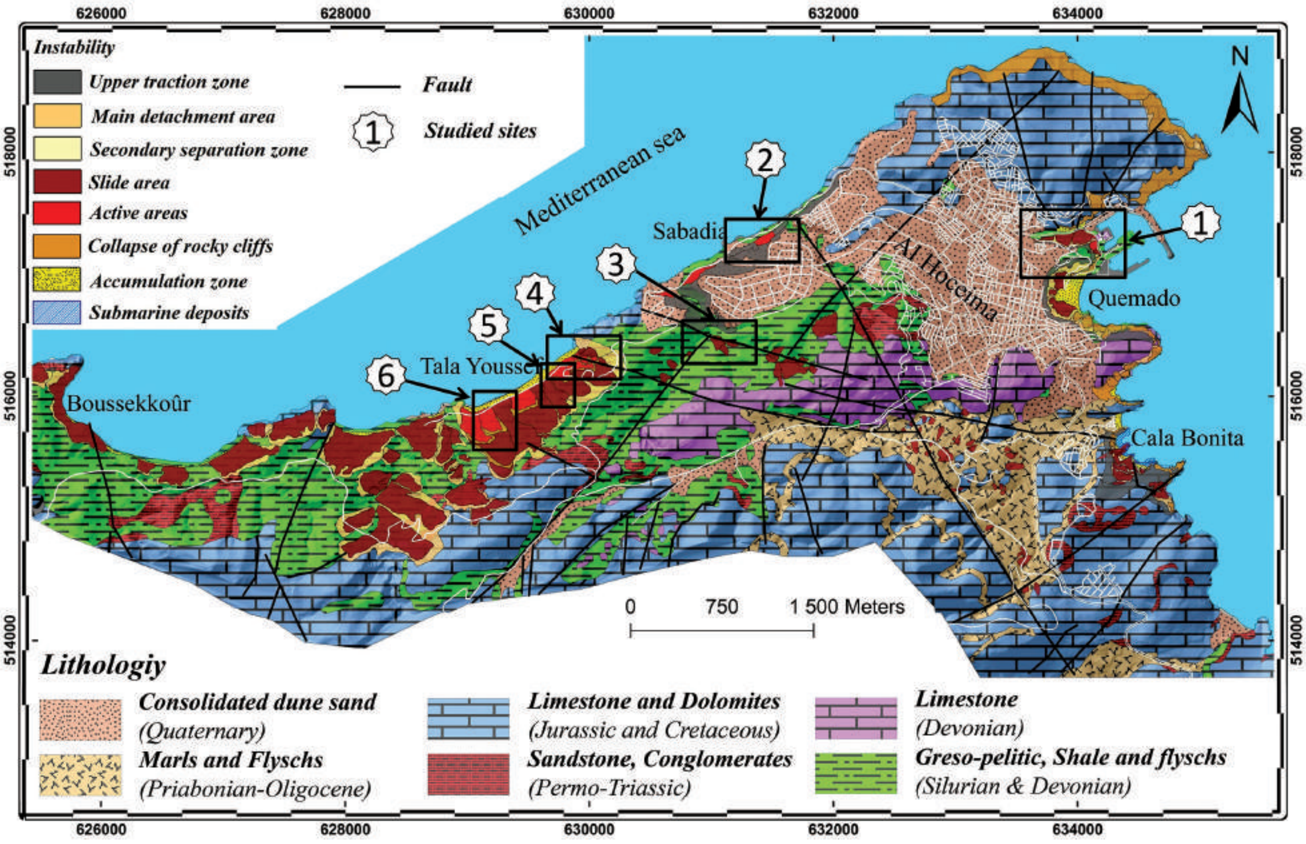


Figure 2. Morphodynamic map obtained by photo-interpretation of satellite images from the Google Earth database (2010-2018), and the geomechanical analysis of unstable zones by fieldwork.

ANALYZES THE INSTABILITY STRUCTURES IN THE KLIPPE OF AL HOCEIMA

Fragmentation and fracturing structures

In terms of rock mechanics, fatigue can be defined as a change in resistance of a material, induced by the action of external stresses such as climatic cycles, seismic activity, and gravity. Field observations and analysis of satellite images have shown that this fatigue phenomenon promotes the growth of the fracture network and the appearance of tension slits. These discontinuities are quite different from the net and old tectonic fractures, and which respect the general orientation of the main stresses ; these are the seat of water circulations in the rainy periods, with a fairly large permeability, accelerating the chemical alteration which gradually weakens the material and which eventually becomes detrimental to the stability of the entire slope.

Geo-mechanical deformations

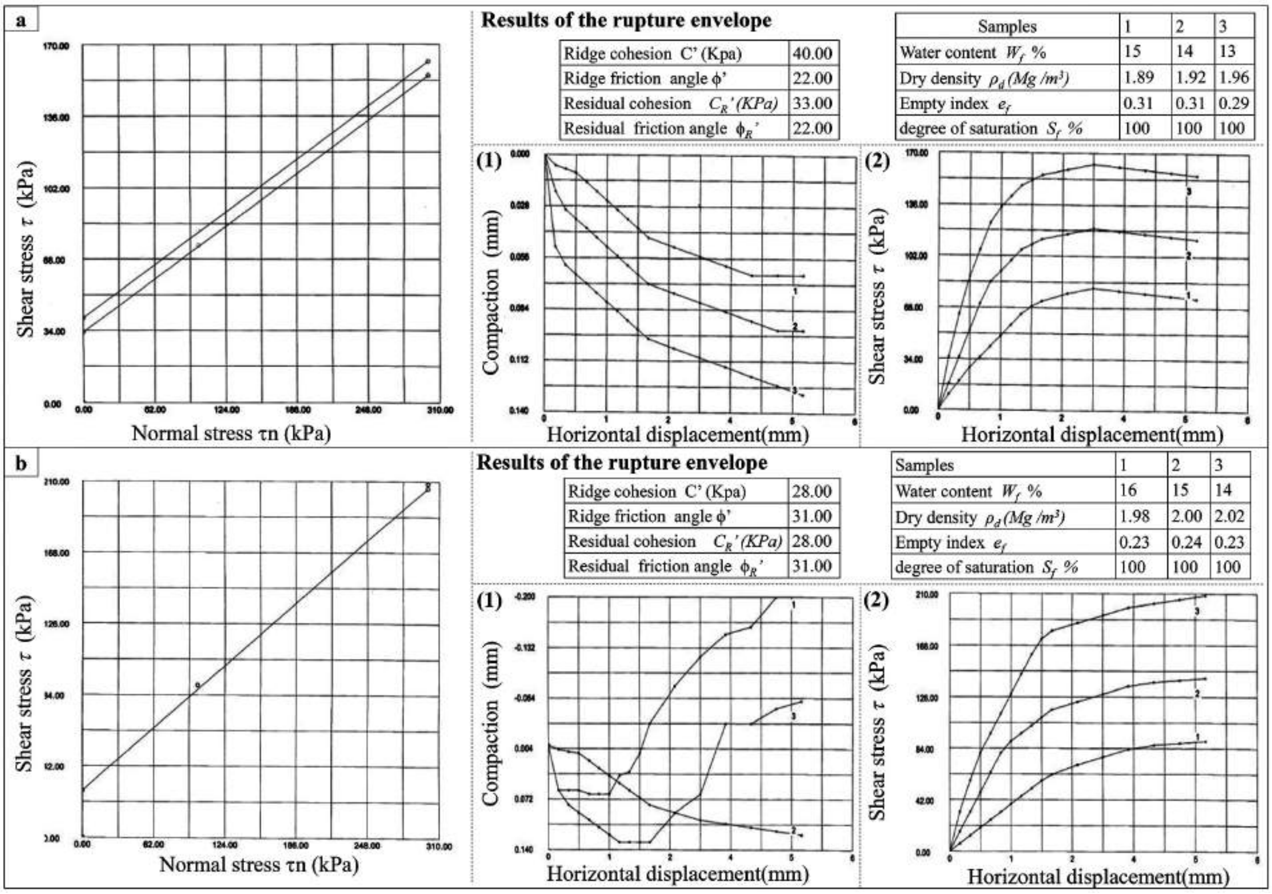
Mechanical properties of the unstable site of the port of Al Hoceima

Analysis of mechanical properties data (Pic and residual) (table 1) shows that the majority of samples (SC2-2 ; SC4-4 ; SC4-5 ; SC4-6 ; SC4-7 ; SC4-8 ; SC4-9 ; SC5-13 ; SC5-14 ; SC9-25 ; SC9-26) Having a contracting behavior during the deformation, which confirms the loose state of the materials constituting these samples, this is explained by the arrangement of the grains which is not optimum. The Curves "stress-strains" Of these samples, usually have a similar look to that of the sample «SC7-22» (Fig. 3-b), they show only the residual resistance without any figuration of peak resistance, with A fairly strong tangent at the origin (Fig. 3-b2), in this case it is found that the values of the horizontal displacement correspond to the behaviour of a loose environment (Labriki *et al*. 2017) ; On the other hand, the curves «stress-deformation» of the samples (SC6-18 ; SC6-19 ; SC7-22), are similar in appearance to the sample «SC4-4» (Fig. 3-a), with a peak resistance for weak deformations, this resistance decreases gradually with the accentuation of shear stresses and stabilizes at the Residual resistance of the material (Fig. 3-a2), it is thus observed that these variations of the resistance correspond to the behaviour of a dense environment (Labriki *et al*. 2017). These results suggest that the behaviour of the rocky masses in this area is found in the structure of an evolved and anisotropic environment.

Table 1. Geotechnical data used, from seven core drill holes (SC2, SC4, SC5, SC6, SC7, SC8, SC9) performed by the Public Laboratory for Testing and Studies (LPEE 2012)

Samples taken	**Depth in (m)**	**Coordinates in (m)**			**Granulometry**			**Cohesion and friction**			
								Pic		**Residual**	
		X	**Y**	**Z**	**> 2 mm**	**2 mm à 80 µm**	**< 80 µm**	**C’ (Kpa)**	**Φ’ (°)**	**Cr’ (Kpa)**	**Φr’ (°)**
SC2-1	(12,20-12,70)	633506	514433	173.0	32	21	47	-	-	-	-
SC2-2	(18,00-18,50)	633506	514433	173.0	80	10	10	29	26°	22	26°
SC2-3	(26,20-26,90)	633506	514433	173.0	35	26	39	-	-	-	-
SC4-4	(10,40-10,70)	634044	517281	41.3	4	7	89	39	23°	32	23°
SC4-5	(12,30-12,80)	634044	517281	41.3	5	6	89	39	22°	33	22°
SC4-6	(15,50-16,00)	634044	517281	41.3	44	25	31	40	22°	33	22°
SC4-7	(21,80-22,40)	634044	517281	41.3	33	30	37	30	26°	24	26°
SC4-8	(27,60-28,00)	634044	517281	41.3	22	39	39	32	24°	26	26°
SC4-9	(33,60-34,00)	634044	517281	41.3	20	42	38	39	22°	33	22°
SC5-10	(1,50-2,00)	633460	515417	80.0	9	27	64	-	-	-	-
SC5-11	(7,50-8,00)	633460	515417	80.0	41	39	20	-	-	-	-
SC5-12	(17,80-18,20)	633460	515417	80.0	23	27	50	-	-	-	-
SC5-13	(20,00-20,50)	633460	515417	80.0	13	37	50	26	27°	19	27°
SC5-14	(32,50-33,00)	633460	515417	80.0	23	34	43	32	27°	26	27°
SC5-15	(41,50-42,00)	633460	515417	80.0	15	30	55	-	-	-	-
SC6-16	(1,80-3,00)	634117	517209	44.13	23	27	50	-	-	-	-
SC6-17	(8,50-9,50)	634117	517209	44.13	33	38	29	-	-	-	-
SC6-18	(14,00-14,50)	634117	517209	44.13	8	31	61	13	32°	13	32°
SC6-19	(19,00-19,50)	634117	517209	44.13	35	28	37	44	34°	44	34°
SCD6-29	(34,50-35,00)	634086	517265	45.29	22	13	65	-	-	-	-
SC7-20	(1,80-2,50)	633458	515506	78.0	68	22	10	-	-	-	-
SC7-21	(7,80-8,20)	633458	515506	78.0	40	20	40	-	-	-	-
SC7-22	(11,30-11,60)	633458	515506	78.0	29	34	37	28	31°	28	31°
SC7-23	(12,50-13,00)	633458	515506	78.0	42	31	27	-	-	-	-
SC8-24	(4,20-5,10)	633427	515556	84.0	84	4	12	-	-	-	-
SC9-25	(2,80-3,50)	633863	517330	23.71	24	31	45	30	25°	24	25°
SC9-26	(4,20-4,60)	633863	517330	23.71	11	29	60	32	24°	26	24°
SC9-27	(7,20-7,50)	633863	517330	23.71	15	37	48	-	-	-	-
SC9-28	(11,70-12,40)	633863	517330	23.71	12	36	52	-	-	-	-

Parallel to the variations in the resistance, the «compacting-moving» curves highlight the phenomenon of dilatancy, which accurately describes the volume changes observed in granular materials when subjected to a shear. Indeed, a granular material is said to be dilating if its volume increases under increasing shear, and contracting if its volume decreases as the shear increases. The results obtained for the Paleozoic formations of the unstable site of the port of Al Hoceima generally show the two trends ; A dilating behavior designated by a volume increase of the sample in the initial phases of the assay (Fig. 3-a1), and a contracting behavior reported by a negative dilatancy of the sample (SC7-22) (Fig. 3-b1).



Results of the rupture envelope

Ridge cohesion C' (Kpa)	40.00
Ridge friction angle ϕ'	22.00
Residual cohesion C_R' (KPa)	33.00
Residual friction angle ϕ_R'	22.00

Samples	1	2	3
Water content W_f %	15	14	13
Dry density ρ_d (Mg/m³)	1.89	1.92	1.96
Empty index e_f	0.31	0.31	0.29
degree of saturation S_f %	100	100	100

Results of the rupture envelope

Ridge cohesion C' (Kpa)	28.00
Ridge friction angle ϕ'	31.00
Residual cohesion C_R' (KPa)	28.00
Residual friction angle ϕ_R'	31.00

Samples	1	2	3
Water content W_f %	16	15	14
Dry density ρ_d (Mg/m³)	1.98	2.00	2.02
Empty index e_f	0.23	0.24	0.23
degree of saturation S_f %	100	100	100

Figure 3. The mechanical behavior of unstable Paleozoic formation in the Al Hoceima port (Site1) (LPEE 2012) : (a) "Stress-strain" curves of the sample (SC4-4) shows the behavior of a dense material ; (b) "Stress-strain" curves of the sample (SC7-22) shows the behavior of a loose material.

Shear structures (figures de cisaillement)

Many sites observed in the field show that discontinuities, according to which the rock mass moves, prone to strong shear stresses. The friction of the elements of the rock on each other during the sliding, induces a continuous grinding of the rock, resulting from a penetrative fracturing at the level of the shear planes. The Paleozoic formations have multiple discontinuities permitting shear, resulting in a total loss of the cohesion of the rocky masses (Fig. 4). This leads to the emergence of fine-material rock slides in which deformations are located (Fig. 5 & 7). These early phenomena are frequently observed on the margins and in the deposits of the various unstable sectors studied.

The dilatancy indicators (les témoins de la dilatance)

Dilatancy is an ongoing process, particularly affecting the grains along the schistosity planes, forming a pattern of bursting into juxtaposed elongated particles, the result of general shearing and responsible for friction and collisions at the grain scale (Pollet 2004). The rock materials observed at the slip foot (unstable site of Tighanimine and Tala Youssef) show an intraformational fragmentation of the rock blades between shear levels with differential particle displacement (Fig. 4, Fig. 5-a1) ; They form a pattern of dilatancy (Ui *et al*. 1986, Pollet 2004) marked precisely by the bursting of the grain structure, accompanied by an increase in volume (Fig.4, Fig. 5-a2).These figures of dilatancy are visible, in the majority of the Paleozoic formations of the klippe of Al Hoceima, and at all scales of observation (macro and microscopic), by rocky panels cut gradually in blocks, in clasts, in platelets and Glitter. Therefore, at the microscopic level the micro-clasts reveal a dispersive displacement from the source clast (Fig. 5-a3). The quantification of the rate of dilatancy in the rock panels of the worms, showed a potential for evolution of the very important instability from upstream to downstream (Fig. 5). In fact, three levels of evolution of the dilatancy are distinguished according to the sliding zone (head, body or sliding foot) :

- Low dilatancy (Fig. 5-a1) : Visible in the summit part of the slide ; First order bursting ; the initial shape of the calcite veins is still visible and can be reconstituted by the Assembly of the external outlines of the clasts ; Small volume increase.

- Intermediate dilatancy (Fig. 5-a2) : Visible in the sliding body; Second-order bursting (fragmentation of clasts in wafers

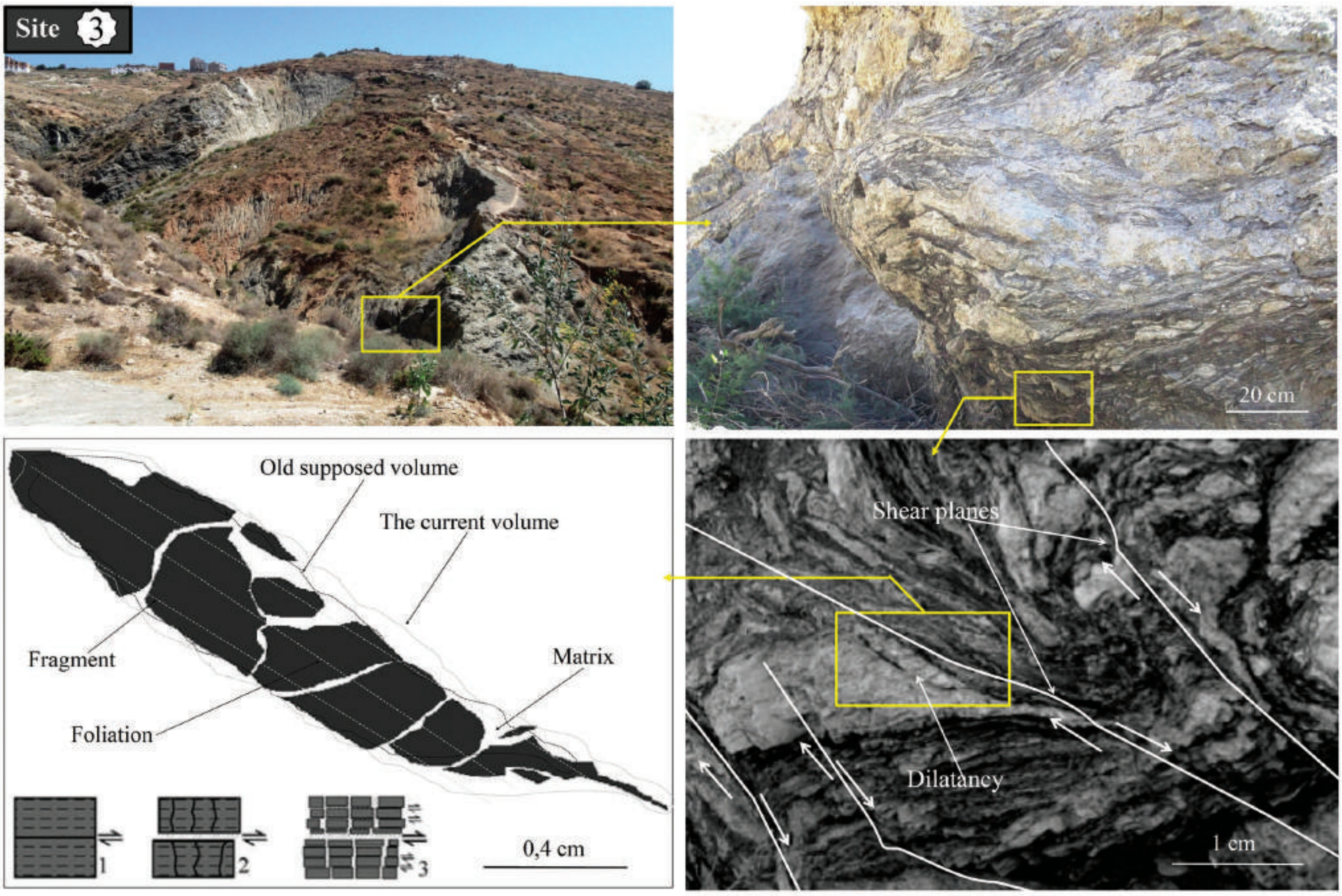


Figure 4. The shear-dilatancy relationship at the foot of rotational sliding of wadi Tirhanimine (See the location in fig.2)

and flakes) ; the initial form is rarely visible and disturbed in some places with folding and difficult reconstituted by the Assembly of the external outlines of the clasts ; A remarkable volume increase.

- Strong dilatancy (Fig. 5-a3) : Visible in the sliding foot ; Appearance of a fine matrix, contains rounded and elongated elements ; Definitive loss of the original texture of the calcite veins ; Volume decrease.

The granulometric reduction

The dynamic disintegration taking place during displacement, and the production of debris and the matrix by particle size reduction (Pollet *et al*. 2005), have the effect of transforming the rocky mass of a coherent rock into a heterogeneous breccias. These debris are packaged in a fine matrix, with a high retention capacity, whose texture changes over time and with the addition of exogenous material (Maquaire *et al*. 2003).

The granulometric analysis data obtained at the port of Al Hoceima (table 1) show granulometric heterogeneity as a function of depth. The dominance of the fine fraction that often characterizes the samples SC2, SC4, and SC6 at a depth of 10m 14.5 m, reflects a granulometric reduction probably coinciding with a shear surface (sliding surface). The redistribution of the results of the granulometric analysis according to the percentage of the fine fraction (< 80 µm) (Fig. 6), often shows that the behaviour of the formations of this site is comparable to that of their fine fraction in (76% of the samples analyzed). Leaching of the clay elements from the upper horizons and their accumulation in the lower horizons and discontinuities are well evidenced by the results of this granulometric analysis. Thus, the intensity of the granulometric reduction is a very important indicator of the evolution of the material and its ability to be unstable.

The intensity of the granulometric reduction can be identified by comparing the parameters of volumetric distributions of clasts in the starting zone and the granulometry of the deposits (Pollet 2004). Image analysis, from field photographs (Fig. 7), shows a very remarkable change in the particle size from upstream to downstream. The blocks become more and more small with progressive filling of the fractures by a fine material, result of the decay of the Rocky particles by collision and friction.

Upstream the structure of the matrix around the blocks and the fragments of the rock is not clear. The fragmentation of the large blocks is done by friction in the shear planes (Fig. 7-b1) ; In the middle zone, the schist slabs increasingly lose their initial structure, and the size of the elements becomes progressively reduced and have strongly fractured borders, demonstrating a gradual deconstruction of the material from the wall to the Center (Fig. 7-b2), and producing a fine material that feeds more and more the matrix around the fragments of the rock ; Downstream, the initial structure (nesting and stratification) is completely extinct, with the appearance of a coarsely granular chaotic facies, composed of fragments and elements of different sizes scattered in a matrix with fine materials (Fig. 7-b3).

Punching structures (figures de poinçonnement)

The observation of large blocks within a matrix, which are necessarily, induced by local pressure phenomena, particularly during the encounter with a topographic obstacle, express in

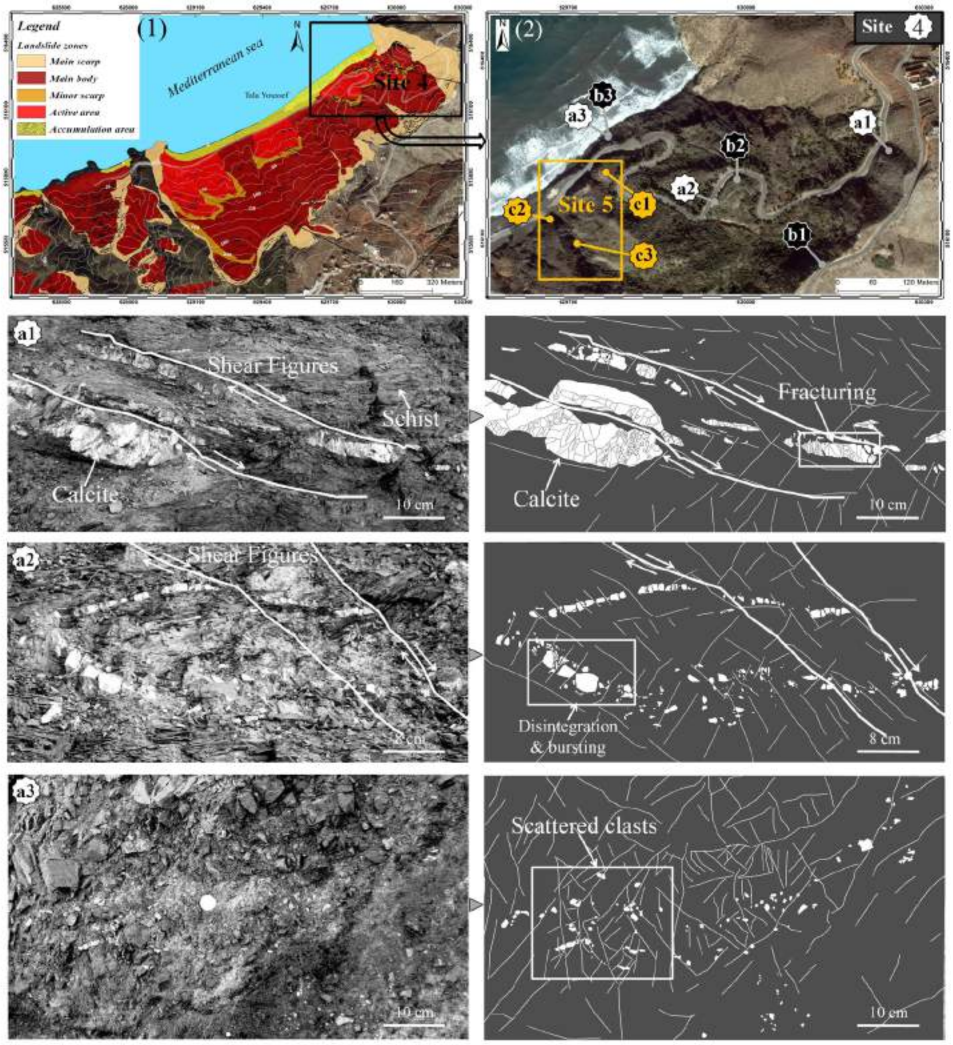


Figure 5. The dilatancy indicators in unstable site of Tala Youssef (site 4) : (a1) intraformational fragmentation of the calcite blades between shear levels ; (a2) dilatancy figure marked by a burst of grain structure accompanied by an increase in volume ; (a3) scattered clasts and dispersive displacement visible in the sliding foot.

particular punching effects (Pollet 2004). At Tala Youssef, some more resistant blocks are exposed to the surface of the sliding body, and along the valleys that cut out the unstable slope (Fig. 8). These blocks show a strong fracturing and a low dilatancy induced by direct shear of the rock mass, so they are punching blocks that still retain the initial structure of the rock, and the figures of onset of decay at the stage before the slide is triggered. The presence of these punching blocks, in the bodies of the Tala Youssef slides, testifies to the compressive periods (slowing of the speed of movement related to the hydro-climatic variation) in a fluid flow that allowed the mobility of a large rock mass.

The role of water and fluidizing phenomena

Fracturing, shearing, dilatancy, and granulometric reduction are all parameters influencing the variation of hydrogeological conditions and promoting infiltration. The analysis of many active landslides in the Al Hoceima region reveals a clear correlation between rainfall (mainly seasonal) and soil mass displacement rates (Margaa 1994, Azzouz 2002). The most important variable appears to be the pore water pressure in the porosity of the rock, related to changes in hydraulic conditions (Reid 1997). Thus the behavior of the rocky massif evolves then with the changes of the mechanical

	Number of samples	Percentage (%)
80 µm ≤ 12%	3	10.34
12 %< 80 µm ≤ 35 %	4	13.79
> 35 %	22	75.86

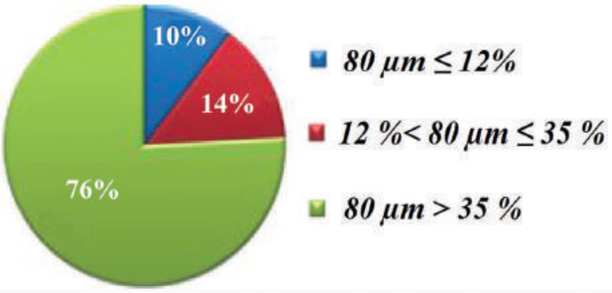


Figure 6. The particle size distribution according to the percentage of the fine fraction (G.T.R classification)

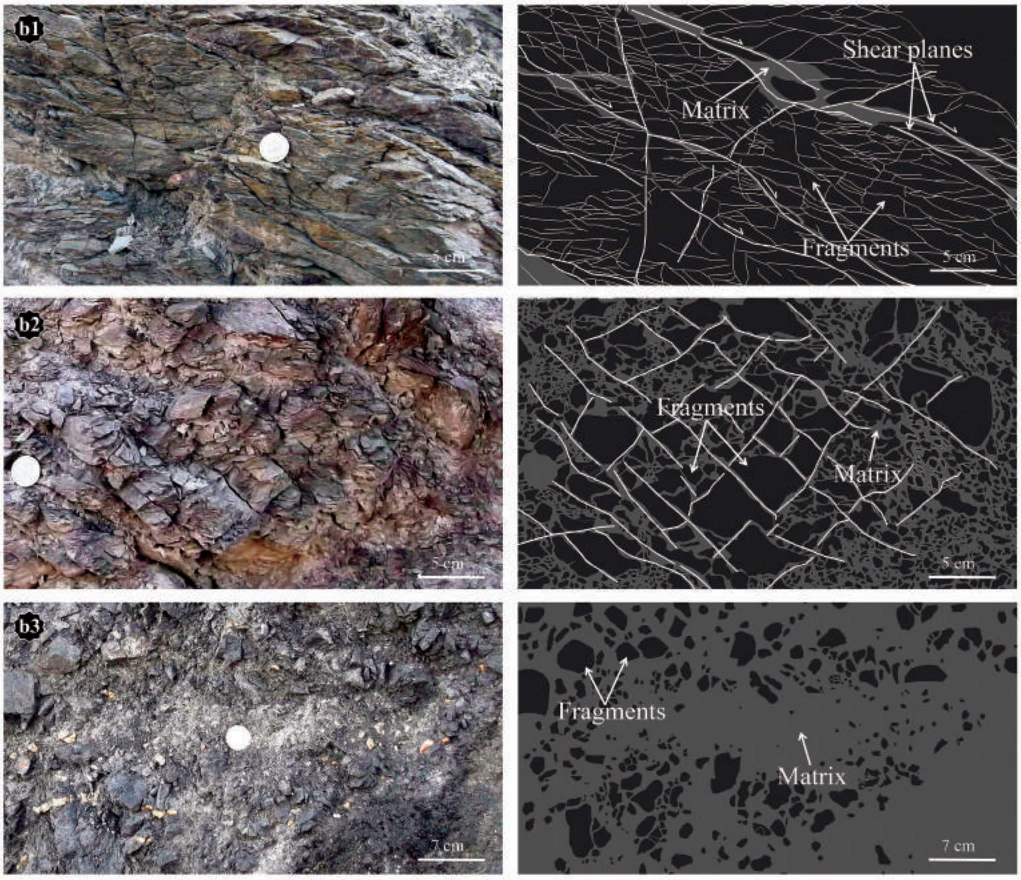


Figure 7. Image analysis of the granulometric reduction from upstream to downstream in unstable site of Tala Youssef (See the location in Fig. 5): (b1) in upstream, the fragmentation by friction in the shear planes ; (b2) in the middle zone, the size of the elements becomes progressively reduced and have strongly fractured borders ; (b3) in downstream, the initial structure is completely extinct.

properties of the material and the substantial storage of the water in the slope. The result is a destabilization of the rock mass by fluidification, or by the visco-plastic pathway, or even a brutal rupture (Fig. 9 site 1).

The fluidity of the material is evidenced by a number of structures observed in the deposits (Tala Youssef, Tighanimine, Sabadia...). These are figures, folding and translation, stretching or circumvention of obstacles (Fig. 5 site 4 and 5). The continuous production of fine particles, by the granulometric reduction, leads to the appearance of a granular material (Fig. 9 site 1), whose fine particles fill the interstices, allowing a certain fluidizing of the schist materials. The greater the quantity of the fine elements, the lower the interactions between grains. The water content in the unstable rock masses is relatively low ; otherwise it will result in a muddy casting behaviour. Alone, some rocky masses bordering the valley bottoms and along the "Sabadia corniche" contain a considerable amount of water (see figure 5 site 2), and thus develop, a particular behavior possible in case of high water intake, especially flows of low extenders.

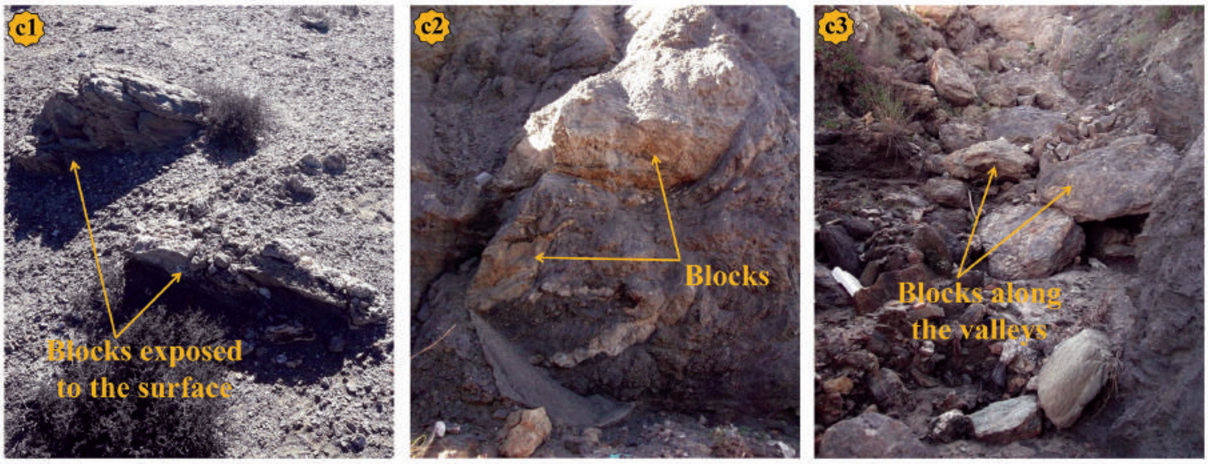


Figure 8. Punching structures in the bodies of the Tala Youssef slides (See the location in fig. 5) : (c1) more resistant punching blocks are exposed to the surface of the sliding body ; (c2) punching blocks rise to the surface ; (c3) accumulation of punching blocks along the valleys cutting the unstable slopes.

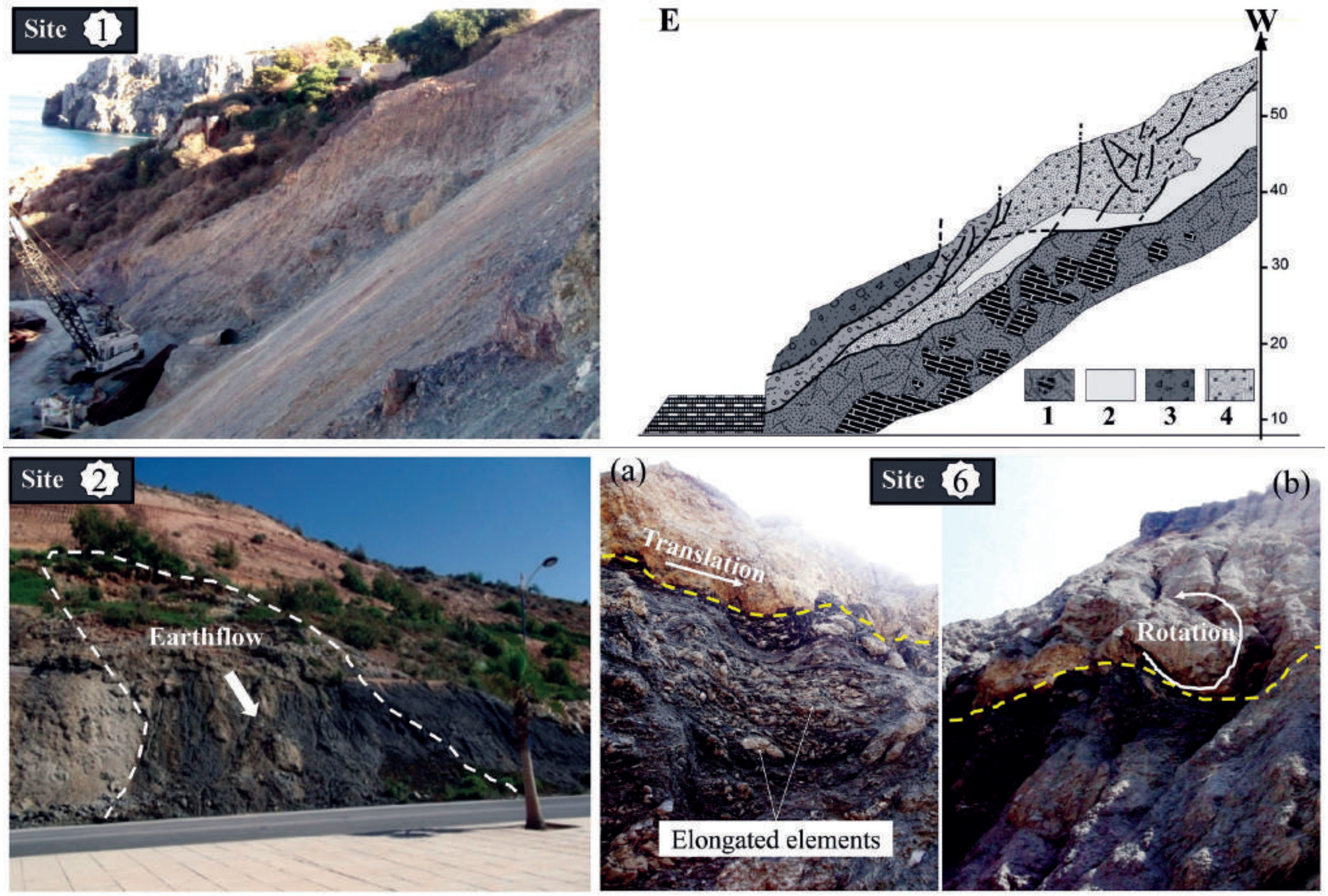


Figure 9. The role of water and fluidizing phenomena (See the location in Fig.2) : Interpretive section through the rupture zone in the complex slide of the Al Hoceima port (1- Chaotic ensemble 'schists and limestone blocks', 2- Blade of rocks with fine materials, 3- Soil and surface accumulation, 4- Upper level with chaotic materials) (Site 1) ; plastic behavior «loose materials» favored by water (sabadia cornice) (Site 2) ; fluidizing phenomena with elongated elements indicating the direction of movement (a), rotation of a block indicating the difference in speed between the lower levels and the higher levels (b) (Site 6).

DISCUSSION

The geo-mechanical evolution of the rock mass is a very complex deformation process, very slow and continuous in time. In the Bokoya chain, and particularly in the Paleozoic massif of Al Hoceima tectonic klippe, these deformations usually end with rotational or translational (Azzouz *et al.* 2002) and complex sliding. In addition, the mode of rupture in the majority of the most known sliding in the region, is generally associated on the one hand with a stack of tectonic scales, separated by low slope contacts often filled by soft materials (Andrieux 1971, Mourier 1982, Azzouz 1992), like the Triasic clay, who plays the role of the soap layer, that ensures the movement in the Cala Bonita slide (Azzouz *et al.* 2002), or the marly sole of the Predorsalien on which slide the Triassic dolomites of the external "Dorsale calcaire" in the Sikha Asfalou slide (El Fellah *et al.* 1996) ; on the other hand, this rupture has been attributed to normal faults (oriented NE-SW) (Margaa 1994), and to a network of fissures and faults that are oriented along the three directions (NE-SW, NW-SE and E-W) (Azzouz *et al.* 2002).

This model based on morphostructural analysis, remains valid to describe the movement mode and the morphological aspect in all types of pre-existing landslides. However, the best applications of this model, remain very limited in the hazard analysis and the susceptibility of slopes to landslides. Comparably with similar phenomena described in the Alps ; Prager *et al*. (2009) noted that the final and sudden collapse of the Köfels (Tyrol, Austria) landslide, only occurs after a long period in the weakening of the Rock resistance, induced by coalescence between discontinuities due to the propagation of pre-existing fractures and another fragmentation subsequently developed, according to the model of progressive failure (Einstein *et al*. 1983, Eberhardt *et al*. 2004) ; As well as, in the Flims rock slide (Swiss Alps), the motion was initiated by sliding of limestone blocks along the bedding plans, according to a transportation model (slab-on-slab) (Pollet *et al*. 2004) based on dynamic disintegration during the movement that turns the rock mass into a granular mass.

At the end of the descriptive and analytical studies of the failure modes in the Mediterranean coastal slopes of the Bokoya massif. We take note that ; the predisposition inherent in the structural and tectonic contexts guides and determines the nature and form of movement (El Fellah *et al*. 1996, Azzouz *et al*. 2002) ; and also that the results provided by the geo-mechanical analysis from the field data testify the presence of a slow deformation process, resulting from the fragmentation and bursting of the rock structure by shearing along the major discontinuities, and thus induces a reduction in the particle size by a continuous disintegration process. The dilatancy associated with shearing, the particle size reduction resulting from dynamic disintegration, and the punching phenomenon associated with the compression phases during displacement, constitute the most important instability structures to define the state of geo-mechanical evolution in a slope. In addition, the basal undercutting due to the action of the sea, seismic activity and rainfall (Margaa 1994, Fellah *et al*. 1996, Azzouz *et al*. 2002) are the main factors of acceleration and triggering for landslides.

CONCLUSION

In order to provide a simple and consistent explanation, which aims to explain the occurrence and behavior of landslides in the Al Hoceima Paleozoic klippe. We have assumed that the combination of morpho-structural analysis and the study of geo-mechanical deformation is the key to understanding these phenomena of instability as soon as we look at hazard and risk. For this reason, this interpretation model tries to evaluate the deformation phases of a slope predisposed to movement, and to establish the evolution scenario of instability from the early phase to the acceleration phase. Thus, building on the morphostructural analysis, we find that in a first phase, and following the tectonic evolution, the rock masses were subjected to continuous and irreversible deformations. It can be schistosity, faults, foliations and/or joints. In combination with lithology, these major discontinuities always control the type and shape of the movement.

In a second phase, relying this time on the geo-mechanical analysis, we note that the basal undercutting due to the action of the sea, gradually annulled the normal stress on the slopes, and promotes the disruption of balance between the forces that tend to initiate the movement and the opposing forces. This imbalance is manifested widely in the upper part of the unstable areas (Tala Youssef, Tighanimine, Sabadia...), by fairly frequent shear figures, and a first-order burst of the rock blades that also induces a low dilatancy of materials. At this stage, a rupture can occur by shearing of a large number of discontinuities from the base to the top of the rock mass. Thus, particles resulting from the granulometric reduction support less on each other (reduction of the effective stress), which annihilates the shear strength.

In the last phase, and following the geo-mechanical evolution of materials during the second phase, the triggering factors (earthquakes and rainfall) take place to initiate and/or accelerate the movement. In such a way, and on the one hand, the most obvious relationship between earthquakes and mass movements is represented by fracture of surfaces (Ait Brahim *et al*. 2004, Tahayat 2008), and the minimum magnitude of activation of these movements is in the order of (M = 4) (Guzzetti *et al*. 1999) ; on the other hand, rainfall action is often governed by very short-term climatic conditions in the case of spontaneous and superficial phenomena. But in the case of deep movements (case of Tala Youssef). The water circulation in layers with reduced granulometry increases the effect of a fluid flow by reducing the intergranular cohesion. This behavior is widely observed in the Madeleine rock slide (Savoie, France) (Pollet & Cojean 2003, Pollet 2004) by punching figures and fluidification phenomena, observed both in our study area, which translate the action of horizontal tensile and compressive stresses in unstable slopes.

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