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Deterioration processes on archaeological sites of *Chellah* and *Oudayas* (world cultural heritage, Rabat, Morocco): restoration test and recommendations

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ABSTRACT

The *Kasbahs* of *Chellah* and *Oudayas* (world cultural heritage) are the most important archaeological Roman and Islamic sites of the imperial city Rabat (Morocco). Submitted to natural hazards and environmental aggressions, these monuments have undergone marked degradation, visible on all sides.

An interdisciplinary analysis involving different geological disciplines and environmental factors was performed to introduce an innovative restoration method intended to reduce their progressive degradation.

Gravitational instability (e.g. *Oudayas*) and erosion (e.g. *Chellah*) from fluvial-littoral geomorphological processes, regional seismicity, and certain anthropic activities are the main degradation processes to be reduced by following the proposed recommendations.

Our studies have evidenced that the ancient Phoenician building techniques, still applied for reconstruction and preservation, result in the rapid and recurring deterioration of the old walls. Materials used to construct the *Oudayas* and *Chellah* walls consist of the calcarenite (or «Salé stone» from quarries near Rabat), mainly with bad geomechanical properties used in outdoor building. Hydrated lime mixtures, and the hydrated lime:water ratio, of mortars also have bad quality. The urban water quality to be used for restoration may require the application of special cements and mortars for restoration.

A most satisfactory restoration-test was performed (*Chellah,* July 2006), taking into account our new analytical data. This method may be applicable to restoring the old *Almohade* and *Oudayas* walls (more than 10.5 km in Rabat), in order to reduce the alteration and degradation processes which systematically strike the archaeological sites of *Chellah* and *Oudayas*.

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KEY WORDS: *Archaeological sites, Rabat, Morocco, interdisciplinary analyses, alteration processes, degradation hazards, restoration test, recommendations*.

RIASSUNTO

Processi di deterioramento dei siti archeologici di *Chellah* e degli *Oudayas* (patrimonio culturale dell'umanità, Rabat, Marocco): test di restauro e suggerimenti.

La Casbah di *Chellah* e quella degli *Oudayas* (patrimonio culturale dell'umanità) sono i siti archeologici romani e islamici più importanti della città imperiale di Rabat (Marocco) e rappresentano la memoria vivente delle civiltà che hanno segnato l'evoluzione culturale della storia del nord Africa.

Questi monumenti, sottoposti a rischi naturali e a fattori ambientali negativi, hanno subito una marcata e diffusa degradazione e costituiscono l'oggetto principale di questo studio interdisciplinare.

Attraverso differenti analisi (geologiche e geomorfologiche, ambientali, tecniche costruttive, geotecniche, sismiche, archeometriche, antropiche e biologiche) lo studio mira ad identificare le cause dei principali processi d'alterazione e degradazione anche attraverso un test di restauro e a fornire più efficaci metodi di conservazione.

Le analisi geologhe e geomorfologiche hanno evidenziato due rischi principali derivanti da processi fluvio-litorali e dall'attività antropica: (*a*) instabilità gravitazionale (es. *Oudayas*), (*b*) processi erosivi (es. *Chellah*).

Le analisi geotecniche e archeometriche hanno permesso l'identificazione dei differenti materiali (calcarenite, fanghi, sabbie, mattoni grezzi e calci idrate usate come cemento) utilizzati nella costruzione di questi monumenti. La calcarenite (o pietra di «Salé»), proveniente dalle cave situate tra Salé e Medhia (a nord di Rabat) e dalle vallate dei Fiumi Akrech e Ykem, è stata spesso utilizzata nella costruzione dei siti archeologici. In realtà, essa presenta una debolissima resistenza alla compressione uniassiale, un'elevata porosità e un alto potere di assorbimento dell'acqua, caratteristiche assai sfavorevoli per un suo uso esterno. È stata inoltre evidenziata una inadeguata qualità della calce idrata e un cattivo dosaggio delle miscele soprattutto nel rapporto calce idrata/acqua.

Le originarie tecniche costruttive delle muraglie (ispirate ad antiche procedure Fenicie) utilizzavano, soprattutto, calce, frammenti di mattoni grezzi e pietre, e vengono impiegate ancora oggi per la ricostruzione e conservazione di questi monumenti ma, come questo studio ha evidenziato, non costituiscono la soluzione migliore per arginarne il rapido e periodico deterioramento.

Anche la sismicità storica dell'area di Rabat rappresenta un rischio effettivo e per ridurre la vulnerabilità di questo enorme patrimonio culturale sono ancora necessari studi specifici ed iniziative tecniche di particolare rilevanza.

Sulla base dei dati analitici raccolti è stato effettuato un test di restauro in un'area limitata del muro esterno di *Chellah* (luglio 2006) il cui risultato, dopo diversi controlli nel tempo, si può ritenere positivo. Esso consiste: (*a*) in una preliminare ripulitura e umidificazione del muro da restaurare; (*b*) nella selezione della qualità della calce idrata e nell'adeguato dosaggio delle miscele dei componenti scelti opportunamente; (*c*) nel controllo del rapporto calce idrata/acqua; (*d*) nel parziale riempimento del volume mancante con mattoni

forati sostenuti da aste di acciaio galvanizzato, allineate, regolarmente spaziate e ben ancorate al muro; (*e*) nell'applicazione accurata dell'impasto sino al riempimento completo.

Si ritiene che questo metodo possa essere efficacemente sperimentato anche per il restauro di altre muraglie (*Almohade e Chellah*) che si estendono nel tessuto cittadino per oltre 10,5 km.

Sono stati forniti, infine, alcuni suggerimenti per ridurre i processi di alterazione e di degrado più ricorrenti che colpiscono i siti archeologici studiati.

TERMINI CHIAVE: *Aiti archeologici, Rabat, Marocco, analisi interdisciplinare, processi di alterazione, rischi di degradazione, test di restauro, suggerimenti*.

INTRODUCTION

Like other imperial cities of the Morocco, the city of Rabat has Roman and Islamic monuments (proclaimed world cultural heritage) which testify to the civilisations which have marked North African history. In Rabat, the *Kasbahs* of *Chellah* and *Oudayas* (fig. 1) studied here have irreplaceable aesthetic and architectural value. However, exposed to the effects of environmental and anthropic influences, these monuments are undergoing serious degradation.

BACKGROUND

Previous investigations were performed on the alteration processes undergone by the historic monuments in Rabat by using different methodologies (BELLITIR *et alii*, 1997; BELLITIR, 1998; ZAOUIA *et alii*, 2005; ZAOUIA, 2007).

Using image treatment and the path of water infiltration in stone, BELLITIR *et alii* (1997), and BELLITIR (1998) analysed the physico-chemical alteration and water-stone interaction processes of natural rocks used in the monuments. An alteration rate from 6 to 8 mm/century was calculated, depending on the environmental conditions and type of stone.

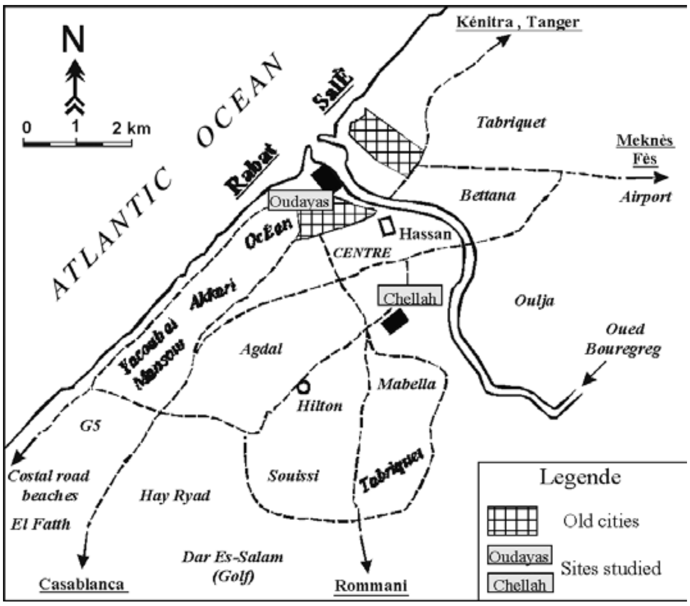

Fig. 1 - Location of the *Kasbahs* of *Chellah* and *Oudayas* in the imperial city of Rabat (Morocco).
– *Posizione della* Kasbah *di* Chellah *e degli* Oudayas *nella città imperiale di Rabat (Marocco)*.

Examining the different kinds of surface degradation on the outer side of the walls of the historic monuments from Rabat, ZAOUIA *et alii* (2005) and ZAOUIA (2007) identified salt crystals (gypsum and halite) in the calcarenite pores, revealing atmospheric pollution, mineral deposition, soil moisture, the groundwater, runoff, and irrigation return through capillary suction all being influences that contribute to degradation processes and black-crust deposits on the outer side of the walls.

No specific studies have been performed on the ancient concrete mixes used in the historic monuments of Rabat. A mixture is a composite material including a binder, aggregates, and various additives which react during setting, hardening, and ageing according to different processes still not well understood (ALESSANDRINI, 1985; CHIARI *et alii*, 1992). The literature regarding these materials offers no specific indications for individual situations that can be applied to the problem as a whole. A multidisciplinary approach, applying various methods of analyses is required to understand procedures to make the final composites, the physical-chemical nature of bonds developed among their constituents, and the origin and cause for deterioration processes (CHAROLA *et alii*, 1984; ADAMS & KNELLER, 1988; MOROPOULOU *et alii*, 1995; MOROPOULOU *et alii*, 2000).

The current interest in such complexes resides in the historical and architectural richness of their monuments, bearing the imprint of the *Almohade*s, *Andalusies*, and the *Alaouites* (ASEBRIY *et alii*, 2007).

ANCIENT AND CURRENT PROCEDURES FOR RESTORATION

The materials used to construct monuments are: (*a*) *stone*, in foundations and wall bases for durability and as a drying element in adobe mortar (*b*) *mud*, to raise walls, make bricks, and face walls; (*c*) *rough brick,* from clay without sand placed in twin moulds of different sizes and air dried.

In the techniques of *kasbah* construction (according to good practice) the general rule that a foundation is needed to transmit the structural loads to the soil is not applied for hard soils. In this case, the foundation is made according to the criterion and experience of the builder at that moment. The ancient Phoenician procedures most commonly used (BELLITIR, 1998) were:

(*a*) *Adobe wall*. The natural rock represents the main skeleton of the foundations of the walls. The walls were raised using framework moulds and compaction by tamping the adobe. The different units were distributed according to several pairing techniques, whether in the form of tight or separate vertical superposition or in an imbricate array.

(*b*) *Pillars and columns*. The pillars were made with reinforced clay bricks sometimes incorporating wood, with baked bricks, and carved stone. The pillars without footings rest directly on the soil with square or rectangular bases.

(*c*) *The whitewashing and top of the walls.* The plastering and whitewashing constitute the first aesthetic element in the vertical finish. The upper part of the walls is protected by eaves or gutters made of rushes, with slabs covered with mortar and with flat rocks that functioned both decoratively and structurally. The restoration and conservation techniques applied today are based on the

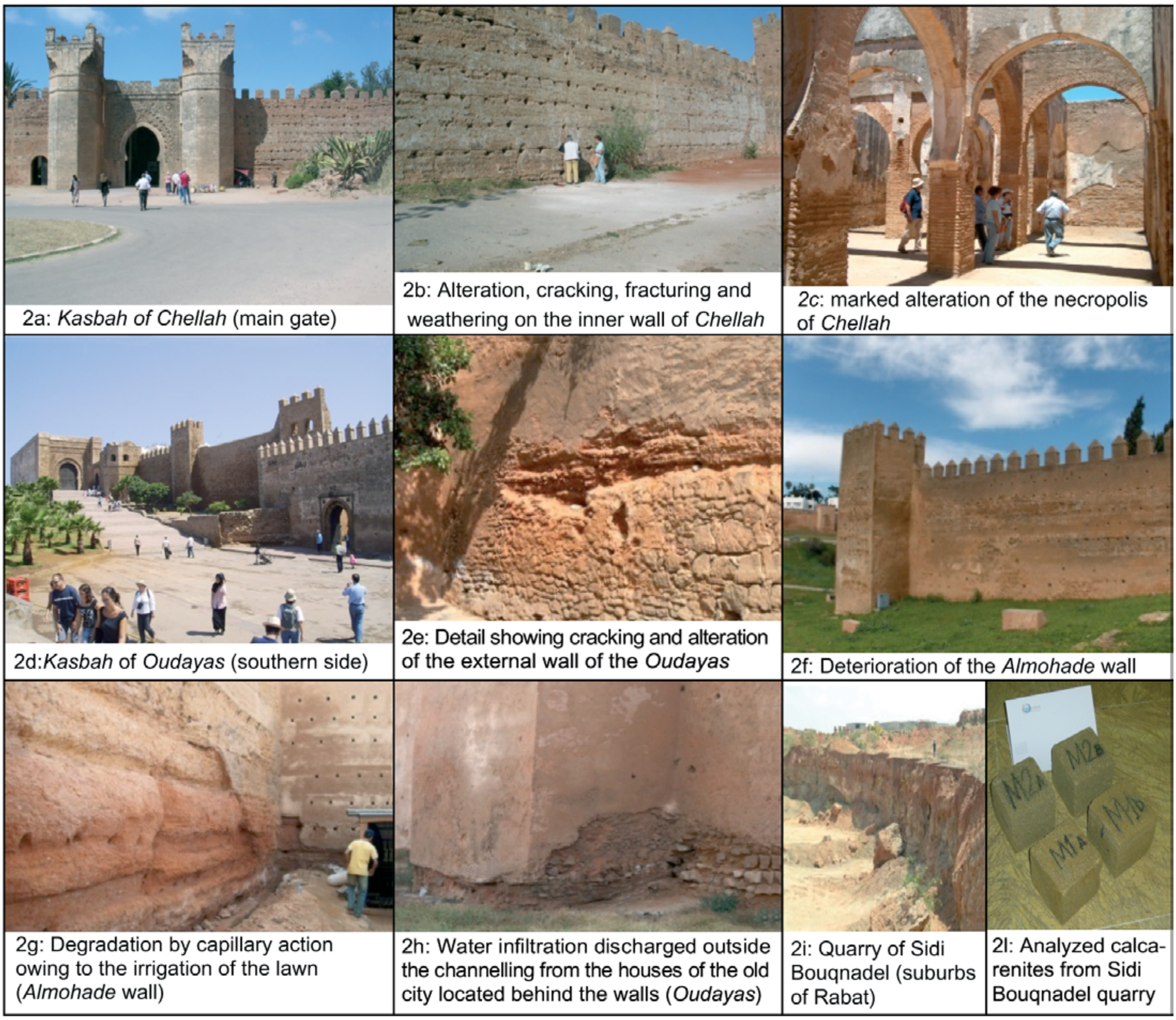

Fig. 2 - Widespread deterioration processes in the *Kasbahs* of *Chellah* and *Oudayas* and along the *Almohade* wall.
– *Diffusi processi di deterioramento nella* Kasbah *di* Chellah, *in quella degli* Oudayas *e lungo la muraglia* Almohade.

same procedures used in the original construction. Given the current deterioration of the monument, such techniques appear to be inadequate.

Aim and metodology

The alteration processes deteriorating the *Kasbahs* of *Chellah* and *Oudayas* and *Almohade* wall (fig. 2) were analysed through an integrated and multidisciplinary study outlining the main physical and chemical degradation factors. Ground-dynamic factors and temperature changes exert shearing strains on joints (about 5 m apart, usually vertical but also dipping at about 30°) of the *Chellah* and *Oudayas*, causing fissures and the collapse of certain parts of the edifices (in part responsible for the frequent destruction of the *Almohade* rampart). The highly mineralized wet air from the Atlantic Ocean coupled with local pollution, soaks the materials either by runoff infiltration or direct capillary suction from runoff or shallow groundwater and react with minerals of the used materials. Also, alveolar erosion occurs in the walls due to the wind erosion and surface degradation consisting of crumbling of the adobe components. Biological physico-chemical and mechanical alterations such as the growth of lichens mar the aesthetics (*Minaret de Chellah*); in addition, the roots of plants exert mechanical pressure, producing fractures. Bird excrement (cattle egrets and storks as biologic-factors) also cause chemical degradation. The atmospheric pollution from industrial and urban activities produces a black crust on the stone surface (*Kasbah* of the *Oudayas* and *Bab Rouah*). The watering of lawns along the ramparts and the construction of modern rooms contiguous degrade the environment (anthropic influences).

Multidisciplinary studies on the external surface wall of *Chellah* during July 2006 provided a robust preliminary «restoration test», which is still being monitored, to be extensively used throughout the walls of *Chellah* as well as in the extensive old *Almohade* and *Oudayas* walls (more than 6 km and 4.5 km, respectively).

All data were consolidated in a database but the relationships with a Geographic Information System are still in progress.

Historical and geological framework

History of the monuments

The *Kasbah* of *Chellah*, 2 km from Rabat city centre (fig. 1), represents the most characteristic vestige of the Roman Empire on the Atlantic coast after the city of Lixus (Larache). The city of *Chellah* presents two well-differentiated parts: one Roman and the other characterized by the ruins of the madrasa and the mosque of the Merenide period. The Roman city is situated in the northern part of the *Kasbah* surrounded by the *Merenide* city walls. The necropolis is protected by an imposing adobe wall, which recalls the *Almohades* and which has a majestic gate constructed with stone ashlars (Asebriy *et alii*, 2007).

In the *Kasbah* of *Oudayas* a military station was built by the *Almohades*, but transformed them (12^{th} century) into a fortress called *Mehdia*. Abandoned later, it was restored and fortified by the Moors (early 17^{th} century, Republic of *Andalusies*). Later, a contingent of the tribe of the *Oudayas* was installed by *Moulay Abderrahman* (1822-1859) in this *Kasbah*, giving the name still used.

During the *Merenide* period calcarenite was the most widely used material to construct buildings of *Chellah* and *Oudayas* (both Roman and Islamic parts), as well as to fortify edifices (Bellitir, 1998; Bellitir *et alii*, 1998).

The *kasbahs* of *Chellah* and *Oudayas* were constructed with adobe but also with brick and rubble. The product of different cultures, provide historical, sociological, and architectural information despite having undergone the constant effects of environmental factors and natural hazards. The marked degradation on all sides of these ancient monuments requires urgent measures.

Geological setting

The Rabat region corresponds to a large plateau belonging to the «meseta coast» setting in the western Mediterranean geological context (Asebriy & Tejera De Leon, 2003; Guerrera *et alii*, 2005).

The local stratigraphy comprise a Palaeozoic basement covered by an angular unconformity with a Neogene-Quaternary sedimentary succession (Naif, 1950; Cogney, 1957; Michard, 1976; El Hassani & Zahraoui, 1984; Vidal, 1989; El Hassani, 1990; Pique, 1994; Asebriy *et alii*, 2007).

The basement, intensely deformed during Caledonian and Hercynian phases, is formed by a northern sector (Sehoul Bloc), which overrides a southern bloc towards the south. The first bloc, folded and schistose during the Caledonian orogenesis (Cambrian-Ordovicien p.p), is constituted by sandstones and phyllites prevalently; the second (Ordovicien p.p.-Carbonifère p.p. in age) deformed during Hercynian phases is made by sedimentary rocks prevalently. Two hercynian tectonic systems (vertical faults: N120° and strikeslip faults: N10° and N70°) affect the palaeozoic basement.

The thin deformed sedimentary cover is characterized by (from bottom): (*a*) calcarenites and marls (Miocene p.p., marine); (*b*) sandy, conglomeratic lumachellas (Pliocene p.p., marine); (*c*) sands, calcarenites and thin conglomeratic beds (Pliocene, fluvial-marine); (*d*) aeolian sands (NE-SW dune bar systems) extending parallel to coastline (Pliocene, continental); (*e*) marine littoral deposits along the Moroccan Atlantic coast (Bouhaouli, 1974; Texier *et alii*, 1994) made up by calcarenites prevalently, deposited during different Quaternary transgressions.

The geological nature of the region has therefore imposed these types of construction materials. There are numerous quarries for these materials between Mehdia (immediately north of Rabat) and Salé, as well as in the Oued Akrech and Oued Ykem valleys. Preliminary geological observations of the stone quarry located north-west of Rabat-Salé, along the Atlantic coastline, enabled the identification of the original rocks normally used to build the monuments, doors and arches. This discovery will be useful in future restoration.

The Devonian marble from Oued Ykem and the carved stone from the Silurian of Oued Akrech were also used. The different types of sands used come from present-day beaches, living dunes, and the Bou Regreg River, where the terraces rendered the mixture of adobe and sand and pebbles used in the walls of *Chellah* and *Oudayas*.

DEGRADATION FACTORS AND RESULTS

Climatological, atmospheric and hydrogeological framework

Climatological characterization

The Rabat-Salé Airport meteorological station (34º03'N, 6º46'W, 75 m a.s.l.) with available daily record from 1961 to 2005 was used to typify a semi-arid to sub-humid Mediterranean climate in Rabat city by using the Thornthwaite's (1948) climate classification. The station averages 2,918 hours of sunshine per year (fig. 3).

The average yearly temperature is 17.2ºC, with extreme seasonal values of 13ºC in winter and 27ºC in summer (Ben Kabbour *et alii*, 2006) (fig. 3). The average precipitation is 530 mm/year with 30% of variation among years. The rainiest periods are in winter (up to 100 mm in December) and sea breezes in summer occur by the entering wet air masses from Atlantic Ocean. A hot, dry continental wind locally know as chergui causes droughts in summer with rainfall less than 5 mm (fig. 3) and deposits red silty-sandy particles. Relative air humidity decreases from 80% in the coastal fringe to around 10% inland. Potential evapotranspiration is 880 mm/year and an average evapotranspiration of 450 mm/year (around 80% of rainfall) was estimated through the Thornthwaite's (1948) approach (Zouhri *et alii*, 2008). Complementary data on weather and soil parameters (e.g. thermal efficiency, relative humidity and aridity indexes, soil moisture, etc.) to detail water balances may be found in Ghanem (1981).

Atmospheric aerosols and air pollutants

Atmospheric mineral bulk deposition in coastal areas is mainly from incoming marine aerosol (Alcalá & Custodio, 2008) through rainfall plus wind-blown dust. A bulk deposition sample accumulated during 6 successive mouths in 2004 in Temara (vicinity of Rabat) provided contents in Cl, SO_4, Na and K of 11, 4, 9 and 0.7 mg/L, respectively, with pH ~6.8. SO_4:Cl and Na:K molar ratios of 0.3 and 22, respectively, showing the influence of inland saline influxes. Extreme evaporation conditions favour the precipitation of stable minerals (e.g. halite starts to precipitate up to ~6.2 mol·L^{-1} of NaCl in water) accelerating the stone corrosion.

Two sourced-trends contribute gaseous pollutants and heavy metals in Rabat: a short-scale from industry, agriculture, and traffic, as well as a long-scale from oceans, mining facilities, and thermal power plants. Pollutants such as CO_2, SO_2, NO_X, etc., contributed as particulate matter (PM), are classified by their aerodynamic diameter (in µm) to show their rather strong ability to attack the stone. PM averages 246 µg/cm^3, with PM_{10} up to 123 µg/cm^3. Both SO_2 and NO_X reach 15 µg/cm^3 (Bounakhla *et alii*, 2003). Heavy metals as Fe, Zn, Ba and Mn from industrial sources register 0.9, 0.09, and 0.07 mg per gram of substrate sampled, respectively. Cl, Br and I ions, as typical marine constituents, reach 2, 0.05, and 0.03 mg/g, respectively. Significant amounts of K and Ca reveal inland saline influxes through wind-blown dust, mainly in summer.

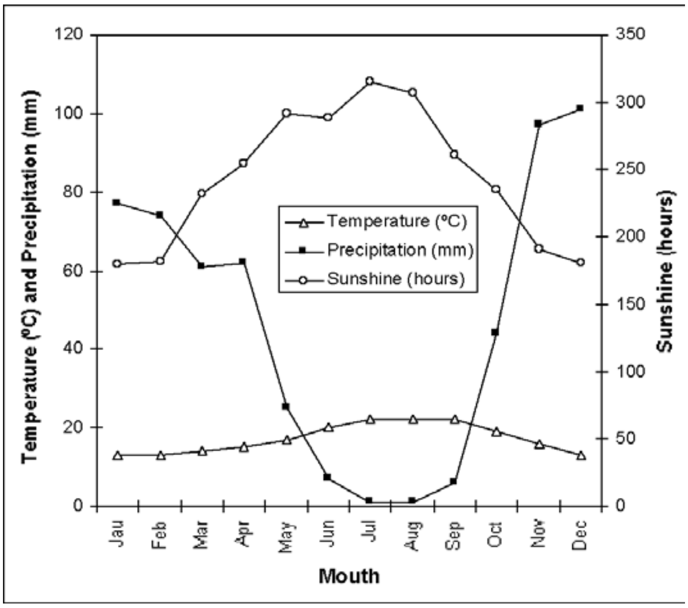

Fig. 3 - Average monthly temperature (ºC), precipitation (mm) and sunshine (hours) for 45 years of records in the Rabat-Salé Airport meteorological station.
– *Media mensile della temperature (C°), delle precipitazioni (mm) e dell'insolazione (ore) registrate per 45 anni nella stazione meteorologica dell'Aeroporto Rabat-Salé.*

Hydrogeological setting

The Rabat urban area occupies the south-western part of the *Maâmora* Basin coastal aquifer. This unconfined aquifer covering 390 km^2 is formed of Plio-Quaternary permeable sandstones, limestones, and conglomerates underlain by less permeable Mio-Pliocene blue marls and covered by permeable sands. Groundwater flows towards the north and the west (Atlantic Ocean), with piezometric levels from 100 to 1 m a.s.l. The saturated zone is 10-to-20 m in thickness, hydraulic conductivity is about 5×10^{-3} m/s, and the storage coefficient is 3.6×10^{-2} (coinciding with the drainable porosity values found in geotechnical surveys for these materials), both characterizing a moderately to highly permeable system. Diffuse recharge by rainfall and losses in streams are the main water input to the aquifer, adding up to 35.8 Mm^3/year (25% of rainfall contribution). The pumping outflow is about 38 Mm^3/year supplying industrial and agricultural activities (Ben Kabbour *et alii*, 2006). Thus, the aquifer is overexploited with localized seawater intrusion (Zouhri *et alii*, 2008).

In Rabat city, some quantity and quality factors control the interaction between groundwater and underground structures, such as foundations of ancient monuments. Groundwater pumping for supply causing depletion of piezometric levels can endanger ancient monuments grounded on adobe-based walls, when the structure initially located in the saturated zone is exposed to air-producing dewatering. Urban and poorly treated industrial effluents contribute pollutants such as nitrogen, PO_4- and SO_4-based compound to the rivers and aquifers. Pollutants flow through the aquifer while seawater intrusion induced by depleted piezometric levels also deteriorates groundwater quality for urban supply. Groundwater with Cl content up to 1000 mg/L, SO_4 content up to 450 mg/L and electrical conductivity up to 3000 µS/cm (Zouhri *et alii*, 2008) can make contact with concrete and metal foundations as well as buried structures accelerating corrosion rates. The urban runoff infiltration which mobilizes atmospheric pollutants from the pavement in rains also introduces the leaching of septic tanks, buried solid residuals and garbage, brines, etc., affecting adobe-based foundations and walls bases by direct capillary suction. SO_4:Cl molar ratios vary from the seawater value (0.1) in western areas most affected by marine intrusion to 1.4 in inland areas with anthropic contribution of SO_4. Meanwhile, Mg:Ca molar ratios up to 1 show contributions of Ca from lithology and urban activities. The chemistry of the groundwater used for the urban supply is corrosive; requiring the application of special cement and mortar to restore the foundation.

Applied geomorphology

In the *Kasbahs* of *Oudayas* and *Chellah* area a geomorphological analysis, including an inventory of the zones with unstable points, were analysed for risks affecting these monuments, as well as to propose solutions. This involved drawing a geomorphological map showing slopes and geological risk points.

The geomorphological map was made over a topographic map at a scale of 1:5000, using a photo of the area at a scale of 1:10000 covering an area from the *Kasbahs* of *Chellah* and *Oudayas* to Salé (fig 4). Areas with changes and breaks in slope (concave and convex) were identified in this cartography. The main orographic elements were documented (fig. 5).

The zone mapped presents scant relief of between 0 and 75 m a.s.l. In all cases, there was a strong lithological control of the relief, in the absence of major structures, since the general array of the materials was subhorizontal. As the area lies at the mouth of the Bou Regreg River on the Atlantic Ocean, the main elements are derived from wind, coastal and fluvial processes, and anthropic

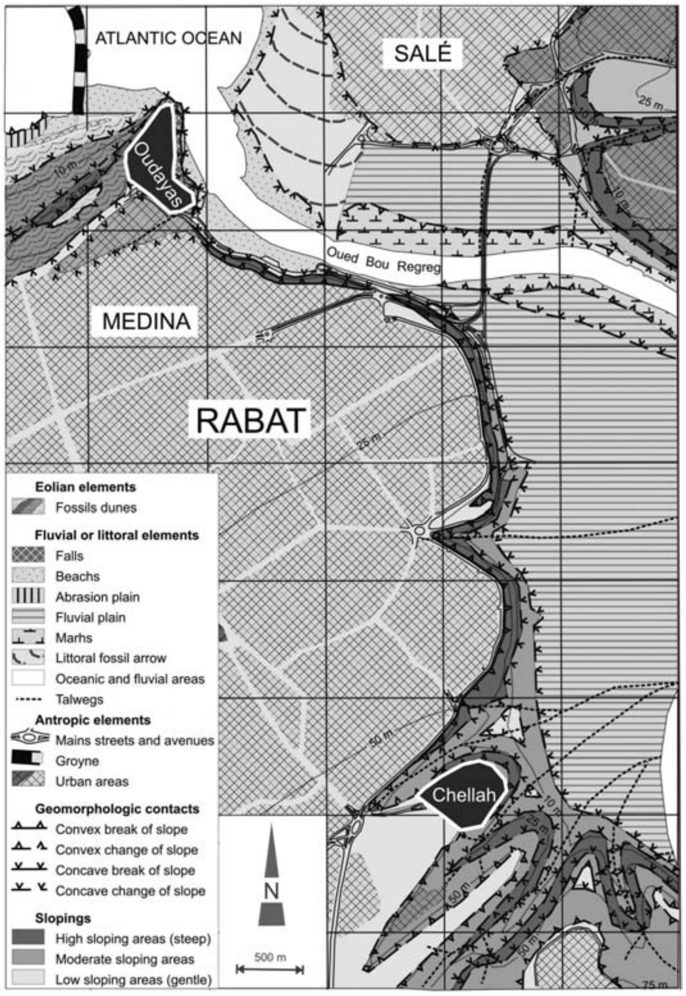

Fig. 4 - Geomorphologic and slope map of the *Chellah* and *Oudayas* sites and the Salé area (after ASEBRIY *et alii*, 2007; modified).
– *Carta geomorfologica e della pendenza dei siti di* Chellah, Oudayas *e dell'area di Salé (da* ASEBRIY et alii, *2007; modificata).*

effects. The geomorphological elements were grouped as follows (fig. 5): fluvial (*Bou Regreg* River, the marshes on both banks of the river under the bridge of Hassan II Avenue, flood plains, gullies), littoral (beaches of Rabat, the cliff of *Oudayas*, the surface abrasion to the east of Rabat beach, and the coastal fossil arrow at Salé, wind-shape (longitudinal fossil dunes), anthropic (roads, streets, bridges, urbanized zones, breakwaters to consolidate beaches and delimit semi-port zones).

Four zones examined after the site analysis were striking for their geological risk (figs. 6, 7). Two appeared in the sector of *Oudayas* (I/EP-1, I/EP-2) and two others in *Chellah* (I/EP-3, I/EP-4). In agreement with the prior geomorphological study, the main specific risks that could affect the historical sites were: flooding/erosion in the zones near the rivers, gullies, and crags; erosion by sloughing off in the areas near the coast, landslides of the taluses, and falling rocks at the foot of rocky formations; disturbance caused by vegetation activity (roots and moisture), which in turn usually add to the risk of the aforementioned situations. In detail, each point has the following characteristics:

(*a*) *I/EP-1*: This site involves gravitational instability linked with sloughing that can involve the falling of boulders. The falls can affect the calcarenites of the fossil dunes NW-ward displacements in a zone of some 25,000 m^2. This phenomenon, which occurs in a uniform talus, is favoured by the appearance of a strong diaclase and by littoral, fluvial, and climatic action.

(*b*) *I/EP-2*: This site is gravitational instability related to sloughing that can involve the fall of boulders and crumbling. The falling can affect the calcarenites of fossil dunes with westward displacements in a zone of some 20,000 m^2. This phenomenon that occurs in a non-uniform talus is encouraged by a strong diaclase and by littoral, fluvial, and climatic action.

(*c*) *I/EP-3*: This site is affected by erosional risk due to a gullies, the direction of flow being N245E. The surface area of this is some 125,000 m^2 over marly and conglomerate lithologies. This phenomenon can be encouraged by diaclases in the conglomerates, and the causes are climatic.

(*d*) *I/EP-4*: This site is affected by erosional risk due to gully erosion, the flow direction being towards N245E. The surface area is some 100,000 m^2 over lithologies of marls and conglomerates. The phenomenon may be encouraged by diaclases in the conglomerates and vegetation activity.

GEOTECHNICS

(*a*) *Geomechanical stations*. GS-1 to 4 stations were installed in the previous I/EP-1 and I/EP-2 sites to determine the stability of the rocky massif. The methodology of BIENIAWSKI (1989) was used to analyse results. Scores values between 33 and 43, classify the massif as Class IV (bad quality). Cohesion was calculated between 1.0 and 3.0 kp/cm^2, and its inner contact angle between 15 and 35°.

(*b*) *Calcarenite physical properties*. Two samples of calcarenites used for wall construction were tested on laboratory to measure their geotechnical properties (tab. 1). Sample S1 (from a wall section under reparation in Rabat) and sample S2 (from the quarry Sidi Bouqnadel) were cut off with a cubic shape and 10 cm per side (fig. 2). According to the Stapledon's classification, the rock has very low resistance; its higher water-absorption limits outdoor uses for its vulnerability to weathering by salt crystallization, and pollution sheltering, by freeze-thaw cycles, and by carbonatation processes most currently affecting the coastal zones.

TABLE 1

Results from physical and mechanical tests on two samples (S-1: wall from Rabat city; and S-2: from Sidi Bouqnadel quarry) of calcarenite (data from ASEBRIY *et alii*, 2007).
– *Risultati ottenuti dalle prove fisiche e meccaniche realizzate su due campioni (S-1: muraglia di Rabat; S-2: cava di Sidi Bouqnadel) di calcarenite (dati da* ASEBRIY et alii, *2007).*

TEST	RESULTS	
	S-1	S-2
Uniaxial compression resistance (Kp/cm^2)	62.2	42.3
Specific density (T/m^3)	1,715	1,540
Real density (T/m^3)	2,725	2,725
Water absorption (%)	17.5	23.6
Total porosity (%) (mercury measurement)	28.7	34.5
Half-radius porosity (µm)	81.2	87.6
(%) hollow total volume (pores from 10 to 200 µm)	77.3	84.5

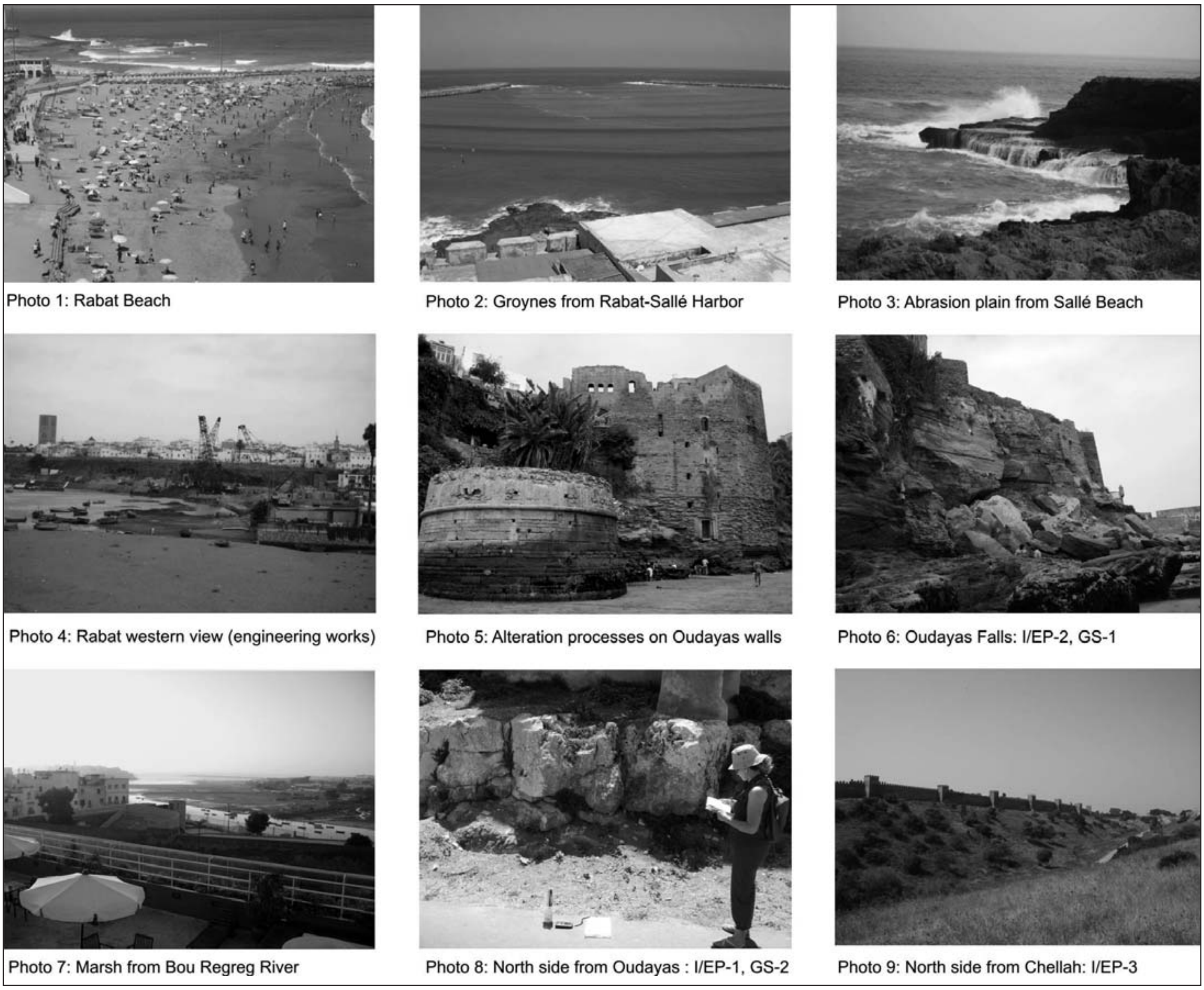

Fig. 5 - Photographic documentation of the main geomorphologic elements and geologic risk zones.
– *Documentazione fotografica dei principali elementi geomorfologici e delle zone di rischio geologico*.

(*c*) *Tests on the adobe.* The adobe provided by local suppliers, its components, and different mixtures of adobe mortar were tested in the laboratory (tab. 2). The lime (sample S3) was analysed for carbonate content (UNE 103200/93), moisture by warm drying (UNE 103300/93), and minimum density (NLT 204/72). The clay (sample S4) was submitted to granulometric analysis (UNE 103101/95), Atterberg limits (UNE 103103/94 & UNE 103104/93), moisture by warm drying (UNE 103300/93) and minimum density (NLT 204/72). For the sand (sample S5), moisture was analysed by warm drying (UNE 103300/93) and minimum density (NLT 204/72). Puzolane (sample S6) was assessed for moisture by warm drying (UNE 103300/93) and minimum density (NLT 204/72). The galvanized steel (sample S7) was analysed for mechanical resistance (UNE 36068/96). Finally, for the determination of the mechanical resistance of the adobe (sample S8), the UNE EN 196-1: 1996 guideline for determining the mechanical resistance of cements was applied. For this last material, 8 mixtures were performed (S-8.1 to S-8.8). All samples were compacted for 30 sec on a vibrating table at a frequency of 3000 cycles per min before being tested following the norms listed in tab. 2. The physical properties from geotechnical tests and the results from X-Ray diffractometry for different proportions of wall mortars are described in tabs. 3 and 4, respectively.

Seismic activity and monument stability

The city of Rabat is located in south-western part of the Rif furrow. This domain overall is regarded as quite deformed and tectonically stable. Seismic activity is relatively weak in Rabat; but historical seismicity is reported from powerful Atlantic earthquakes in the Gulf of Cadiz and SW of the Cape St. Vincent (fig. 8).

Historical seismicity

Historical documents on seismicity in Morocco (Rodriguez, 1940; El Mrabet, 2005; Levret, 1991) indicate that Rabat has been shaken several times by violent

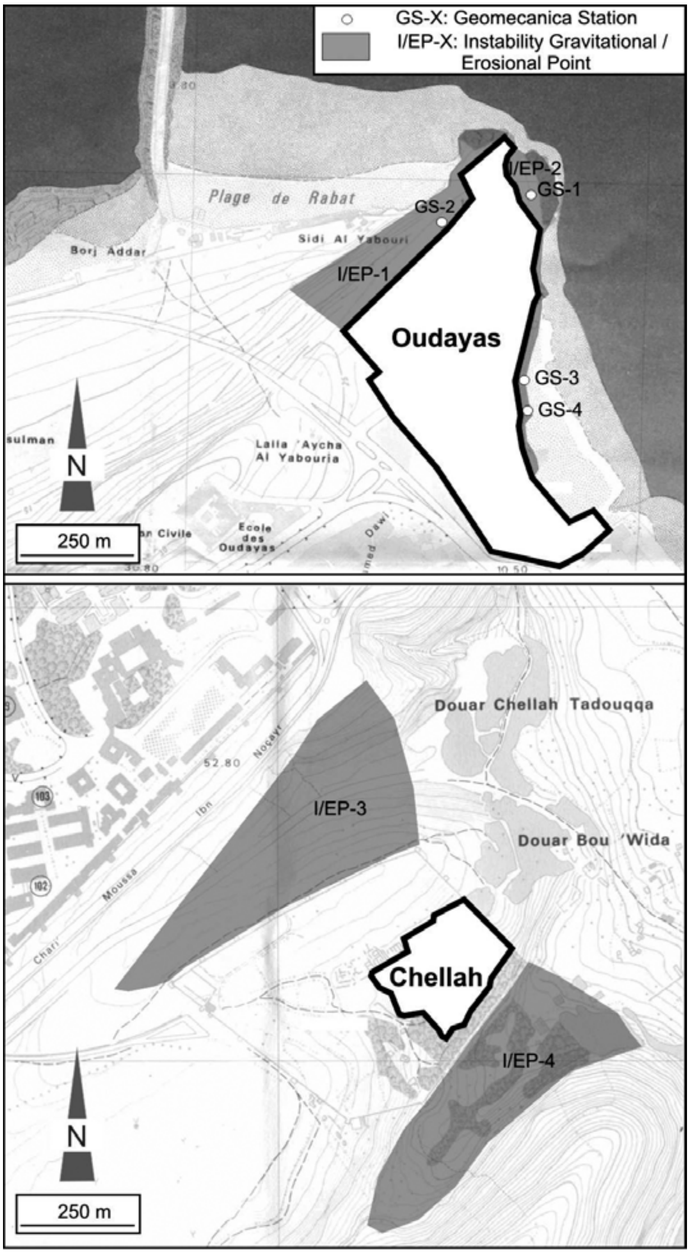

Fig. 6 - Map of geologic risk areas
– *Carta delle aree di rischio geologico.*

TABLE 2

Geotechnical analyses on materials for experimental restoration test (*Chellah*).
– *Analisi geotecniche dei materiali utilizzati per il test sperimentale di restauro* (Chellah).

MATERIALS (sample)	**ANALYSES (norm applied)**
lime (S-3)	Carbonate content (UNE 103200/93)
clay (S-4)	Granulometry (UNE 103.101/95)
	Atterberg limits (UNE 103.103/94 & (UNE 103.104/93)
lime (S-3) sand (S-5) puzolane (S-6) clay (S-4)	Moisture (UNE 103.300/93)
	Minimum density (NLT 204/72)
galvanized steel (S-7)	Steel Mechanical resistance (UNE 36.068/96)
wall mortars (S-8.1 to S-8.8)	Mechanical resistance (UNE EN 196-1: 1996)

TABLE 3

Physical characteristics and proportions of the mortar wall.
– *Caratteristiche fisiche e dosaggio della malta muraria.*

CHARACTERISTICS		**WALL-MORTAR MIXTURE** (samples 8: S-8.1 to S-8.8)							
		S-8.1	S-8.2	S-8.3	S-8.4	S-8.5	S-8.6	S-8.7	S-8.8
Dosage	lime (S-3)	43.4	24.0	23.9	16.1	19.3	12.0	8.1	20.7
	sand (S-5)	21.9	28.2	28.1	31.7	26.4	35.6	40.1	23.2
	puzolane (S-6)	0.0	25.9	0.0	30.8	29.5	30.6	31.0	20.5
	arlite	0.0	0.0	27.6	0.0	0.0	0.0	0.0	0.0
	clay (S-4)	7.1	0.8	0.8	0.8	0.8	0.8	0.8	0.8
	water	27.7	21.2	19.6	20.6	24.1	21.0	20.0	24.9
	water/lime ratio	0.64	0.89	0.82	1.28	1.25	1.75	2.46	1.21
Mechanical resistance (MPa)	compression (28 days)	0.64	1.26	0.84	0.75	0.81	0.44	0.36	0.84
	compression (91 days)	1.32	2.45	1.80	1.39	1.51	0.77	0.60	1.66
Density (g/cm^3)	8 days	1.62	1.68	1.28	1.66	1.67	1.70	1.69	1.73
	28 days	1.40	1.63	1.24	1.62	1.61	1.64	1.65	1.61
	91 days	1.42	1.66	1.27	1.62	1.62	1.66	1.67	1.66
Volumentric retraction (%)	8 days	1.71	0.94	0.29	0.45	1.02	0.47	0.08	1.99
	28 days	1.77	1.19	0.21	0.55	1.15	0.45	0.20	1.90
	91 days	1.64	1.28	0.25	0.52	0.91	0.53	0.19	2.17

earthquakes mainly from Atlantic origin (e.g. 881, 1356, 1531; 1755; 1757). The earthquake of 1st November 1755, known as the Lisbon earthquake (GUTSCHER, 2004), is used as a reference for seismic hazard gradation in Morocco to be one of the most serious earthquakes recorded. Its maximum intensity reaching X degree (Mercalli Modified, 1956) in Faro (MOREIRA, 1984), and its estimated magnitude around 8.5-9.0 (MOREIRA, 1979; CAMPOS ROMERO, 1992; MARTINEZ SOLARES & MEZCUA RODRIGUEZ, 2002), was cause of serious damages in Rabat and Salé and other Atlantic coastal cities of Morocco from Tangier to Agadir and even in the interior of the country to Fez and Meknes.

Recent marine geophysical data highlights a zone of active subduction beneath the Gulf of Cadiz, which appears to have caused the 1755 earthquake and the ensuing tsunami (GUTSCHER, 2004). The cities Rabat and Salé underwent extensive damage, several houses collapsed, water levels rose (LEVRET, 1991), and the unfinished mosque of Hassan was damaged: columns were thrown to the ground in detached sections and generally laid out in the same direction, apparently indicating the effect of an abrupt horizontal movement. According to these descriptions, intensity from VII to VIII (MSK) was sustained in Rabat (LEVRET, 1991).

Instrumental Seismicity

The current seismic activity affecting Rabat city is negligible. The seismic data recorded in Morocco since

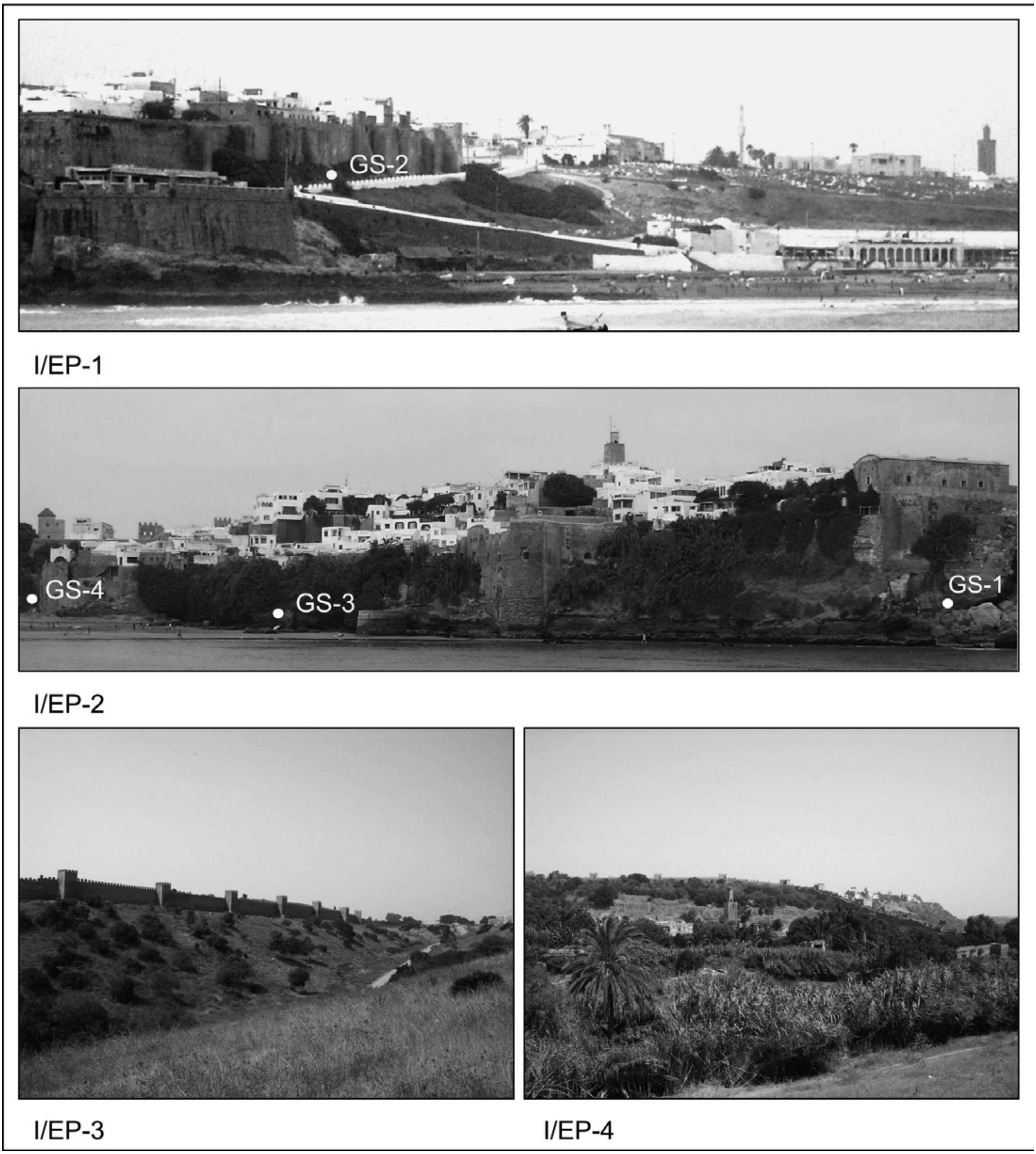

Fig. 7 - Photographic documentation of the main geologic risk areas and location of the geomechanical stations.
– *Documentazione fotografica delle principali aree di rischio geologico e ubicazione delle stazioni geomeccaniche.*

1901 reflect great stability (fig. 8), although Rabat city was shaken several times (e.g. 1915, 1956, 1964, 1969, 1979 and 2001). The most violent ones, recorded in March 15, 1964 and February 28, 1969, with magnitude of 6.2 and 7.3, respectively, were felt most strongly along the Atlantic coast (intensity VI MSK) and northern Morocco (CHERKAOUI, 1988). The event of 1969 even caused six deaths and 200 injured during the collapse of the old houses in the medina of Rabat, Salé and Safi (CHERKAOUI, 1991). On June 28, 2001, a violent quake shook the plain of Gharb (northern Rabat), causing damages in Kenitra and panic in Rabat (fig. 8).

TABLE 4

Mineralogy (by using X-ray diffractometry) from different wall mortar mixtures.
– *Composizione mineralogica (per mezzo di analisi diffrattometriche a raggi X) dei differenti impasti della malta muraria.*

Sample 8	Qtz	Cal	Ca-Hyd	Px	Sol
mixture (S-8.1)	x	xxxx	tr		
mixture (S-8.2)	x	xxx	tr	±	tr
mixture (S-8.3)	x	xxx	±		
mixture (S-8.4)	x	xxx		±	tr
mixture (S-8.5)	x	xxx		±	tr
mixture (S-8.6)	x	xxx		±	
mixture (S-8.7)	xx	xx		±	
mixture (S-8.8)	x	xxx	tr	±	

Abbreviations and symbols. Qtz=Quartz; Cal=Calcite; Ca-Hyd=Calcium Hydroxide; Px=Pyroxenes; Sol=Sulphate. xxxx=very abundant; xxx=abundant; xx=less abundant; x=scarce; ±=very scarce; tr=trace.

Seismic hazard and recommendations

Actions to prevent seismic damage in buildings, and installations known to be at normal risk are based on the division of Moroccan territory into five zones of increasing seismicity. The RPS (2008) code application for building is not extended for all construction categories, including historical monuments.

The NAKAMURA's (1989) method was used to find a map of the distribution of predominant periods in order to improve a zonation of seismic application in Rabat (BADRANE, 2008). This method, based on the recording and processing of seismic ambient noise, is a well-know technique to characterize the dynamic response of unconsolidated shallow geological materials during earthquakes in urban areas (seismic site effect) (GARCIA-JEREZ *et alli,* 2007).

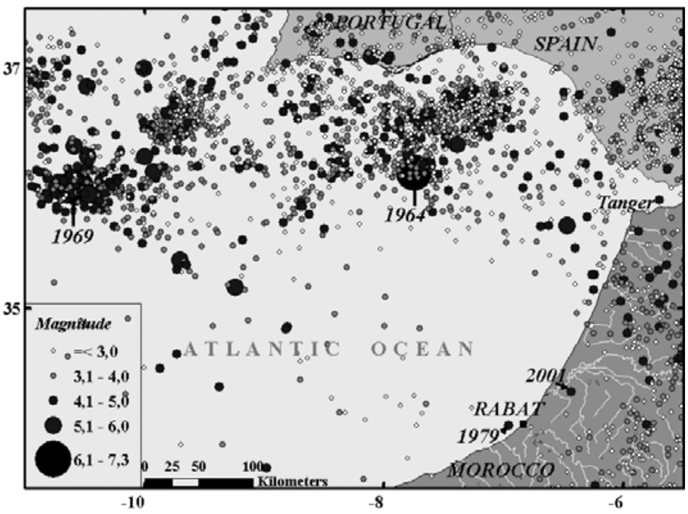

Fig. 8 - Seismic activity for SW of the Cape of St. Vincent, the Gulf of Cadiz and adjacent margins from 1901 to 2007 (data from CHERKAOUI, 1988 and National Geographic Institute of Spain, Madrid).
– *Attività sismica a SW del Capo San Vincente, del Golfo di Cadice e margini adiacenti dal 1901 al 2004 (dati da CHERKAOUI, 1988 e dall'Istituto Geografico Nazionale di Spagna, Madrid).*

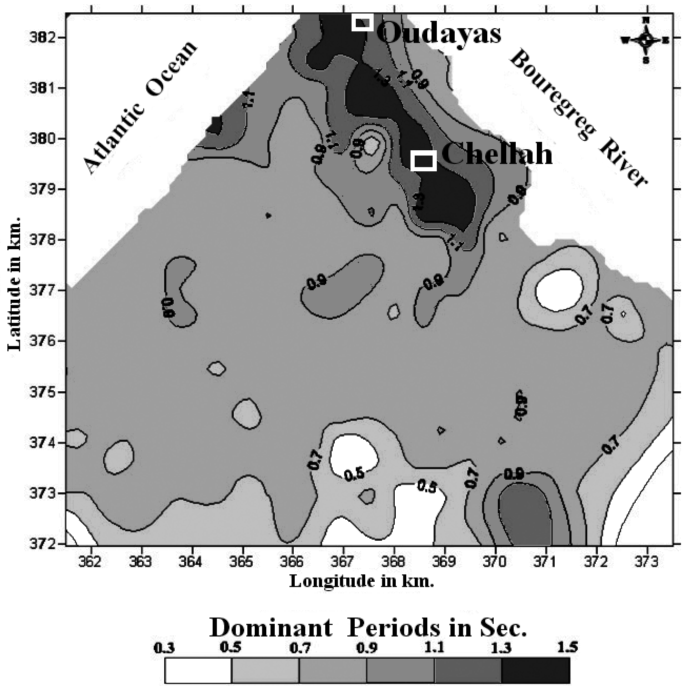

Fig. 9 - Seismic microzonation map of the city of Rabat (BADRANE, 2008).
– *Carta della microzonazione sismica della città di Rabat (BADRANE, 2008).*

The highest predominant periods were concentrated in the northern part of the study area, parallel to the Bou Regreg River. This upslope area is characterized by very thick sediments probably including cohesionless urban fillings from successive historical constructions. Predominant periods decrease towards the south (fig. 9) in agreement with the thinning of the upper soil layer (called red soil of Rabat), as described in the geological and geomorphological setting of Rabat (LAOUINA *et alii*, 1994). The predominant periods in *Oudayas* and *Chellah* increase up to 1.1 and 1.5 sec., respectively.

Specific studies on site seismic zonation are necessary to quantify seismic vulnerability of the cultural inheritance. It would be irresponsible to avoid taking measurements under the pretext that the historic monuments have persisted for centuries.

MINERALOGY AND PETROGRAPHY

Several samples, belonging to (i) natural stones, mortars, and binders from the wall bases of *Chellah*, (ii) natural materials cropping out in the surroundings, and (iii) some materials currently used for restoration were studied with mineralogical and petrographic methodologies (S-9 to S-29; tab. 5).

All the samples show very similar mineralogical composition, excluding one sample with small amounts of halite, probably precipitated from evaporated marine aerosol. Optical microscopy reveals remarkable textural differences among samples. In terms of details, mortars are composed mainly of scarce heterogeneous binders (not well carbonated) and an aggregate containing fragments of mono- and polycrystalline quartz, quartz arenites (generally in the coarse-grained fraction), biocalcarenites, sparites, metamorphic rocks, feldspars, and rare pyroxenes, epidotes and tourmalines. Rare volcanic glass was found in several sam-

TABLE 5

Bulk mineralogy (by using X-ray diffraction) of mortars, stones, plasters and alteration products (see description) of the walls of *Chellah* (from ASEBRIY *et alii*, 2007, modified with integration of new data).
– *Composizione mineralogica principale (per mezzo di analisi diffrattometriche a raggi X) di malte, pietre, intonaci e prodotti di alterazione (vedi descrizione) della muraglia di* Chellah *(da* ASEBRIY et alii*, 2007, modificata con integrazione di nuovi dati).*

Description	Sample	Qtz	Cal	Fs	Mic	Chl	Kao	Hal	Tlc	Fe-Ti Ox	Hm	Sol	S
mortar	S-9	xxx	xx		tr					tr			
mortar	S-10	xxx	xx		tr	tr	tr			tr			
stone	S-11	x	xxxx										
stone	S-12	x	xxxx	tr	tr								
alteration products	S-13	x	xxx	tr				x		tr		tr	
stone	S-14	xx	xxxx	tr	tr								
mortar	S-15	xxx	xx	tr	tr								
mortar	S-16	xxx	xx	tr	tr					tr		tr	
mortar	S-17	xxx	xx	tr									
mortar	S-18	xxxx	xx										tr
mortar	S-19	xx	xx	±	tr					tr			
mortar	S-20	xxx	xx	tr	tr					tr			
mortar	S-21	xx	xx	x									
stone	S-22	xxx	xx										
mortar	S-23	xxx	xx		tr					tr			
stone	S-24	xxx	xxx	tr						tr			
plaster	S-25	xx	xxxx						±		±		
plaster	S-26	xxxx	xxx		±								
plaster	S-27	x	xxx										
plaster	S-28	x	xxx						±				
plaster	S-29	xxx	xx	±	tr								

Abbreviations and symbols. Qtz=Quartz; Cal=Calcite; Fs=Feldspars; Mic=Mica Group; Chl=Chlorite; Kao=Kaolinite; Hal=Halite; Tlc=Talc; Fe-Ti Ox=Iron and/or Titanium Oxides; Hm=Hematite; Sol=Sulphate; S=Sulphite; xxxx=very abundant; xxx=abundant; xx=less abundant; x=scarce; ±=very scarce; tr=trace.

ples. Opaque minerals, probably involving Fe-oxides and sulphides, are very rare. The aggregates contain a clast population ranging in size from fine-grained sands to fine-grained conglomerates. Clasts are heterogeneous, varying from well-rounded with medium sphericity to angular with elongated shapes. Porosity is abundant and variable in shape and size. Plasters (often one superimposed over another) were examined and sampled in some portions of the walls (tab. 5). The main difference in the mineralogical composition between the outer plasters (samples S-27 and S-28; tab. 5), more recent, and the more ancient inner one (sample S-25; tab. 5) is the quartz content. Sample S-29, a mortar fragment (located below S-26) used to rectify the masonry surface, has a mineralogical composition similar to that of mortar S-26 but it is texturally very different, showing a coarser grain size and notable heterogeneity.

Many natural materials, from the surroundings of Rabat, together with some materials currently used for restoration (tab. 6) had been investigated in detail (samples S-30 to S-45). Particularly, sample S-41 is residual clay composed mainly of quartz with minor amounts of hematite and clay-group phyllosilicates (tab. 6) employed to colour the plaster used for restoration. Sample S-42, defined by the local workers as «lime», is composed of a sandy-size fraction of carbonate fragments and scarce quartz, plus a fine-grained fraction of calcite and Ca-hydroxide. The sample S-43 represents a mixture of natural materials currently used for restoring the walls that partially surround the city of Rabat. It seems that Ca-hydroxide, which should be the most abundant phase of the sample in order to help the carbonatation process and to give solidity, is in fact too scarce (tab. 6). Sample S-44 is the lime currently sold in Rabat, and its composition is comparable with that of sample S-42 (tab. 6). Sample S-45 is a mixed material composed of lime (sample S-44) and pozzolana, and it has been used in a restricted restoration test.

MAIN RESULTS ON DEGRADATION PROCESSES AND DISCUSSION

(*a*) *Geomorphological considerations.* Two types of risk areas were identified: (i) taluses and cliffs facing the river and the ocean in *Oudayas;* (ii) areas near the gullies in *Chellah*. In zones submitted to gravitational instability by sloughing that might involve the fall and tipping over of boulders, the river-flow regulation of building walls is recommended to avoid the effect of the sloughing. In addition, it is recommended that the anchorage of the blocks in danger of being dislodged be reinforced. In zones affected by erosional risk of incised gullies, the recommendation is to channel the gully streams by concrete-lined spillways in order to avoid the creeping erosion undermining walls and causing instability on slopes. These hydraulic measures will reduce concentrated recharge in the urban area where piezometric levels are depleted, thereby limiting the interaction of foundations and walls with polluted groundwater.

(*b*) *Geotechnical considerations*. Mechanical resistance, density and contraction are the most relevant parameters controlling the durability of the monuments. These parameters were tested in cement mixtures, comparing the proportion of each component by each physical property (tab. 7 and fig. 10). Three groups were estab-

TABLE 6

Bulk mineralogy (by using X-ray diffraction) of samples from stone quarries located north-west of Rabat-Salé, along the Atlantic coastline, and from materials currently used for restoration actions.
– *Composizione mineralogica principale (per mezzo di analisi diffrattometriche a raggi-X) di campioni provenienti da cave ubicate a NW di Rabat-Salé, lungo la costa atlantica e di materiali comunemente utilizzati nelle attività di restauro.*

Sample	Qtz	Cal	Dol	Ank	Fs	Mic	Chl	Kao	Px	Sm	Hal	Hm	Tlc	Ca-Hyd
samples from stone quarries														
S-30	xxx				xx	x	±	±						
S-31	xxxx				x	tr	tr	tr	±					
S-32					±	±				xxxx				
S-33	xxxx	±			±		±	±				±		
S-34	xxxx				±									
S-35	xxxx						±	±						
S-36	xxxx	x			±		±	±				±		
S-37	xxxx	±			±							±		
S-38	xxxx	xx	±		±		±	±			±	±		
S-39	xxxx	±	±		±									
S-40	x	xxx		xx		tr								
materials currently used for restoration actions														
S-41	xxx					±	±	±				±		
S-42	±	xx												x
S-43	xx	xx	x					tr			x			
S-44	x	xx											tr	x
S-45	xx	xx												±

Abbreviations and symbols. Qtz=Quartz; Cal=Calcite; Dol=Dolomite; Ank=Ankerite; Fs=Feldspars; Mic=Mica Group; Chl=Chlorite; Kao=Kaolinite; Px=Pyroxenes; Sm=Smectite Group; Hal=Halite; Hm=Hematite; Tl=Talc; Ca-Hyd=Calcium Hydroxide; xxxx=very abundant; xxx=abundant; xx=less abundant; x=scarce; ±=very scarce; tr=trace.

TABLE 7

Influence of the components in the characteristics of the buildings.
– *Influenza dei componenti nelle caratteristiche delle costruzioni.*

IMPROVE	HARM
MECHANICAL RESISTANCE	
seriously: * Lime (K = +0.80)	seriously: * Sand (K = -0.87) * *w/l ratio* (K = -0.85)
slightly: * Clay (K = +0.51) * Water (K = +0.59)	slightly: * Puzolane (K = -0.54)
DENSITY	
seriously: * Puzolane (K =+0.93)	seriously: * Arlite (K = -0.97)
slightly: * *w/l ratio* (K = +0.59) * Sand (K = +0.41)	slightly: * Lime (K = -0.59)
RETRACTION	
seriously: * Water (K = +0.89) * Clay (K = +0.88)	seriously: * Sand (K = -0.85)
slightly: * Cal (K = +0.64)	slightly: * *w/l ratio* (K = -0.53) * Arlite (K = -0.43)

lished to compare the different mixtures of wall mortar (tab. 3). The first was performed to find the optimal lime content and the water:lime (W:*L*) ratio in relation to the mechanical resistance and contraction of the mixtures S-8.2, S-8.4, S-8.5, S-8.6, and S-8.7 (fig. 10): (i) density was less influenced by lime content and W:L ratio; (ii) a high mechanical resistance required a minimum lime content of 20% and maximum W:*L*=1.1; (iii) the contraction values in the above cases were high (> 1%), and therefore these mixtures should not be used to plaster walls. The second group compared, S-8.2 mixture made with puzolane and S-8.3 mixture with arlite replacing puzolane. The use of and thus could be used to lighten repairs at considerable heights, as well as to reduce contraction. Also, there was less resistance at 28 days, although over the long term, the increase was notable due to the silica puzolane in the arlite. In the third group, mixtures S-8.1, S-8.2, and S.8.8, were selected to compare the proportions of the components (tab. 3): (i) S-8.1 nowadays used in wall reparations; (ii) S-8.8 used in experimental reparation; (iii) S-8, prepared on the laboratory to experiments mixture S-8.8 reducing the clay colorant. Some conclusions were drawn: (1) puzolane influences mechanical resistance, doubling the resistance to compression with nearly half the conglomerate (mixtures S-8.1 and S-8.2); (2) the lime and clay proportions were most influential on contraction, with values exceeding 2%; (3) density and durability of the mortar was influenced by puzolane according to comparisons of mixtures S-8.1 with S-8.2 and S-8.8.

(*c*) *Minero-petrographic properties*. Analyses show that the aggregates of ancient mortars of *Chellah* are texturally

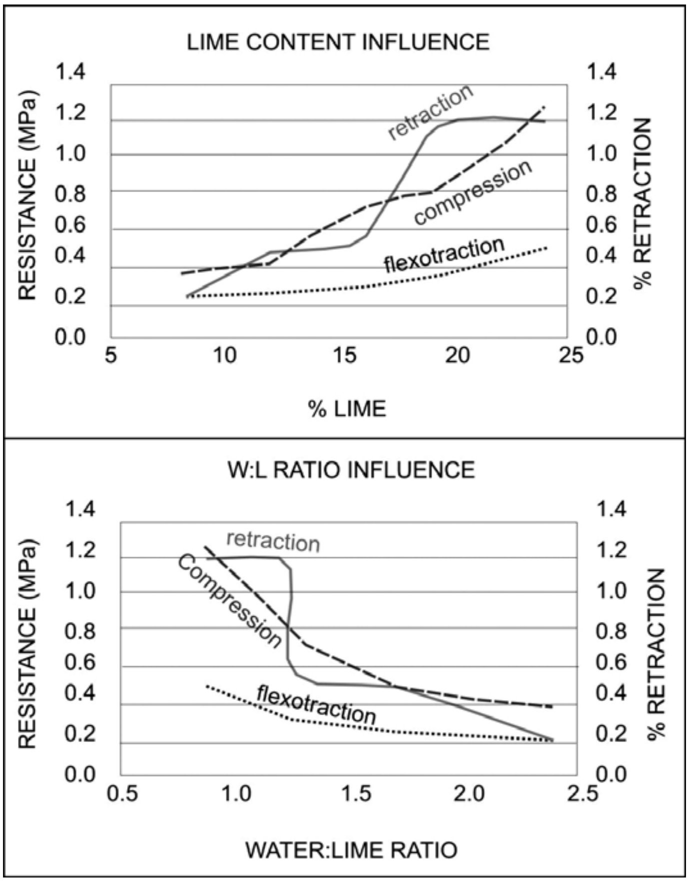

Fig. 10 - Lime content and water/lime ratio influence according to the % resistance and % retraction after 28 days.
– *Influenza del contenuto in calce e del rapporto acqua/calce secondo la resistenza e la ritrazione percentuale dopo 28 giorni.*

very heterogeneous. They are made up of rock fragments belonging to the geo-materials cropping out in the surroundings. Binders used in the past included high amounts of calcite that result from the Ca-hydroxide carbonation process currently sold in Rabat and widely employed in modern restoration. These are made up mainly of a very low amounts of hydroxides, offering low binding capacity. The binding effects are further lowered by the addition of sand, compositionally and texturally not homogeneous and, above all, not refined, as indicated by the presence of clay minerals, Fe oxides, and halite. Wind-blow halite is common in dry coastal areas where rapid evaporation of salty light rains enriches the soil in this mineral, which should be removed when these materials are employed for building. However, hydrogeological evidence indicates that halite may also precipitate by the use of local saline groundwater supplied for restoration or by the rise of soil moisture.

The finding of two layers of plaster in several portions of the walls, superimposed over the mortars, leads us to believe that all the masonry was plastered and subjected to ordinary upkeep. Moreover, plasters, rightly considered easily replaceable in case of deterioration, protected the softer masonry from weathering (seepage and runoff from heavy rains, marine aerosol contributions, sudden temperature changes, etc.). This study shows that the greyish colours of the original surfaces of the masonry markedly differed from those visible today: this has implications for the new restoration methods and materials,

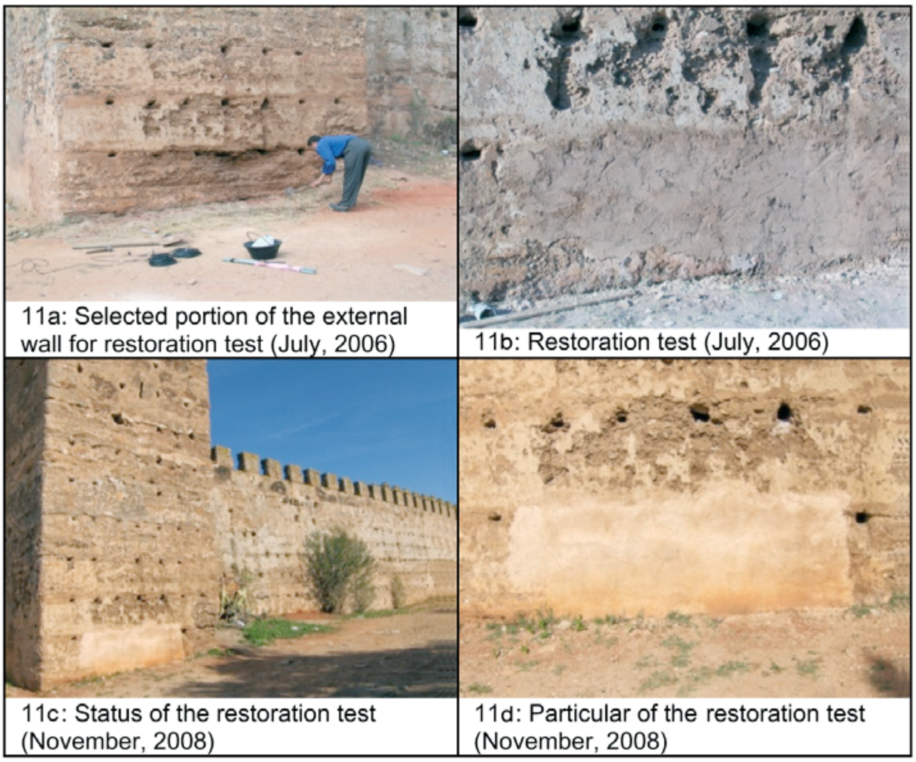

Fig. 11 - Documentation of the restoration test made on the external wall of the *Chellah*.
– *Documentazione del test di restauro realizzato sul muro esterno di* Chellah.

which should respect the ancient mixtures. Moreover, the surfaces of masonry where plastered with white lime, contrasting sharply with the current reddish colour.

Restoration test of *Chellah*

From analytical results and criteria explained above, an experimental repair was programmed in one designated portion of the outer wall of *Chellah*.

The adobe was made with traditional components at different proportions, experimentally using puzolanes and varying the amount of water (and monitoring its quality) in the mixture. The repair technique used consisted of setting lines of galvanized-steel supports of 10 mm in diameter and 50 cm long anchored in the wall by epoxy resin and spaced 20-40 cm apart vertically, and 9 cm horizontally. On these anchoring, ceramic bricks cut to fit were set in the form of horizontal shelves over which mortar was laid, the load being lightened with ceramic fragments. The repair was made leaving 3 cm from the face of the wall to later apply a layer of plaster made of the same mixture as the mortar, and a layer of plaster made of a lime and fine sand rich mixture.

The steps for the repair were as follows. Holes were drilled with a bit 20 mm to 25 cm and cleaned; galvanized rods were driven into the holes and anchored with epoxy resin. The section to be repaired was cleaned and moistened, and the lower area the repair section was stepped. The bricks were cut and placed on the metal supports and finally the mortar was applied, lightened by ceramic fragments (the mortar mixture being 20.7% lime, 23.2% sand, 20.5% puzolane, 10.7% clay, and 20.9% water (tab. 8).

In relation to the components used in the region, lime manufactured in the Rabat area is not meticulous, has a light-grey colour, and contains remains of ash and inert grains; the sand in the region is made by crushing yellowish calcarenites with bad quality; the puzolane comes from greenish volcanic lava up to 4 mm in size; the clay in reality is a reddish clayey marl abundant in Rabat area, used as a colorant.

The application technique: requires fixing the water in the mixture by the criteria of mortar workability. The same quality during the test must be maintained by adding the minimum quantity for proper handling. The water:conglomerant (W:C) ratio was 1.21, somewhat less than that usually used. The plaster (2 to 2.5 cm thick) and mortar applied had the same composition in order to even out the surface (this layer was allowed to dry two weeks before

Table 8

Suggested proportions for building components.
– *Dosaggi raccomandati per i componenti costruttivi.*

USE	W/L	COMPONENT	PROPORTION	
			WEIGHT	
inner part of the wall	< 1.1	Lime	31%	1.0
		Sand	36%	0.6
		Puzolane	33%	0.6
plastered layer	< 1.0	Lime	31%	1.0
		Sand (D_{max} < 5 mm)	36%	0.6
		Puzolane (D_{max} < 5 mm)	33%	0.6
finished plaster layer	< 0.9	Lime	60%	1.00
		Sand (D_{max} < 3 mm)	30%	0.25
		Puzolane (D_{max} < 3 mm)	10%	0.10

applying the second layer). The last layer (0.5 to 1.0 cm thick) was applied over the rough plaster previously scarified and wetted for better adherence. A same mortar without clay was used in order to reduce contraction. A chemical colorant was applied to produce the brick red colour.

The monitoring over time of restoration test carried out on the external wall of the *Chellah* demonstrates its resistance to weathering (fig. 11) testifying to its efficacy and durability. The brick red colour of the test area continues unchanged in relation to the normal colour of the wall of *Chellah* (fig. 11).

CONCLUSIONS

This report offers a new interdisciplinary and integrated methodology focused on the causes of degradation and alteration of monuments of Rabat (Morocco) for their restoration and maintenance.

The interaction of environmental, anthropic, and geotechnical factors causes degradation that diminish the durability of the monuments. While the site is subjected to intense weathering by chemical and physical processes (Peltier, 1950), the geotechnical properties of stone (relatively low density, and high drainable porosity) and adobe used for construction, makes the monuments especially vulnerable to the high relative air humidity, and the persistent salty moisture. Moisture in wall bases from inadequate or even non-existent pluvial and wastewater evacuation systems around the monument, plus emissions of exhaust gases (particularly hydrocarbons) and particulate matter are additional anthropic factors attacking the stone and the adobe walls. These factors are impossible to eliminate, but can be mitigated.

In the wall section of *Oudayas*, situated on the bank of the Bou Regreg River, geotechnical, climatic, and anthropic factors act jointly, causing gravitational instability due to sloughing of the talus on which the wall stands. Salty particles from breakwaters with rough sea, such as the abundant plant cover are factors accelerating degradation.

Seismic activity and vibrations from surroundings constructions and traffic are ground-dynamic factors causing damage. Earthquakes, although exceptional, have inflicted serious damage on the monuments, as can be appreciated by cracks in the calcarenite ashlar of the facade and in the arches of the main gate of *Oudayas*, *Bab El Kébir*. The anthropic influence on the stone is less intense but more continuous in time. Both natural and anthropic factors can lead to weaken the stability of the monuments, when added to the effects of the rest of the degradation factors mentioned.

Some recommendations for maintaining and restoring the historical monuments of Rabat and Salé are:

(1) To avoid the deterioration at *Oudayas*, retention walls against sloughing need to be installed along the Bou Regreg River. Unstable blocks on the slope should be anchored for stability. Water seepage and runoff should be channelled to prevent weathering and erosion at *Chellah*, and construction connected to the structures of the complexes should be avoided. Plants and organisms should be removed periodically from walls. Heavy transport should be avoided nearby to avoid vibrations and pollution. Finally, as far as possible, different structures should be reinforced following regional seismic regulations.

(2) For restoration of the walls, archaic techniques should be abandoned to adopt the technique discussed above. In the proportions of restoration materials, it is recommended to avoid lime that is not at least of minimum quality (at least 12% calcium carbonate and free of foreign bodies). The maximum separation between rows of bricks in the reparation system should be 50 cm to avoid the breakage of the adobe that serves as the bedding. Rather than clay used for coloration in the adobe, chemical colorants should be used in the outer layers (plastering and finishing). The mixes should be made by machine (portable cement mixers), carefully following the proportions listed in table 8 and applying the appropriate amount of water, as ionic exchange and puzolanic reactions begin with hydration maintaining water quality. If there is a delay in using the mixture, later mixing breaks down the structures formed up to then. Surface contraction by evaporation should be reduced in the last plaster layer by a lime-rich mixture using the lowest *W:L ratio* possible or else by maintaining moisture on the finished surface for the first 36 h by frequent wetting or by protection from drying (plastic sheeting, wet burlap sacks). Finally, galvanized steel netting (chicken wire) should be used to absorb the forces of traction resulting from the loss of surface water (the netting can be shaped to the surface being plastered and later finished. In any case, the use of local water will require sulphate-resistant cements and mortars for foundation and wall restorations to minimize long-term precipitation by halite and sulphate-type minerals.

These recommendations are the result of exhaustive analyses and experimentation and are applicable to other sectors of the monuments under study as well as to other Islamic monuments in general.

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