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Slope Instability in the Valley of Temples, Agrigento (Sicily)

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ABSTRACT. The town of Agrigento and the surrounding Valley of Temples represents a place of world importance because of the historical, archaeological and artistic value of their monuments. Since ancient time the town planning expansion of Agrigento has been controlled by the particular geological set up of the area and the repeated and extensive instability phenomena The safeguard of this precious cultural heritage is seriously threatened by slope failures including falls, rock topples and rock slides involving the calcarenitic outcrops. While rotational and translational slides occur when failures develop in the clay and sandy-silt soils below the calcarenitic levels, involving wide areas. This paper explains the geological and structural set up, the geotechnical aspects and man-made factors that exert major influence on this phenomena, on the stability of the area and on the basal foundation of the temples, above all of the Juno Temple.

Key terms: Slope stability, Clay, Biocalcarenite, Cultural heritage, Agrigento, Italy

Introduction

The town of Agrigento is set in a physically fragile environment between unstable slopes and ancient structures in urgent need of conservation and restoration (Fig. 1). This delightful place raises issues that lack ready-made solutions. Over the last few years a research team has been carrying out studies specifically focused on the geomorphological evolution and the stability of the historical and archaeological site. There is no need to stress how charming this symbiosis of history, archaeology, geology and geotechnics is.

A brief description of historical features concerning the origin and development of the Agrigento urban area is given below.

The Gelon mercenaries founded the town of Akragas in 581 BC. In 446 BC, the town was defeated by Syracuse after a long war. By the late 5th century BC it was no longer a leading force. It had to withstand a siege from the Carthaginians, who power in 406 BC, compelling the inhabitants to withdraw inland. It took the local inhabitants a year to win the town back and start rebuilding it. Then Akragas was taken and pillaged by the Romans in 210 BC and renamed Agrigentum. Prosperity returned to the town under the Roman Empire. Then in 840 AD the town was occupied by the Arabs and then it was conquered by the Normans in 1086. During the Middle Ages the name of the town was Girgenti until 1937, when it was changed to the current one of Agrigento.

The Greek city and the subsequent Roman one were located in an area including both Girgenti Hill and the Rupe Atenea, where the acropolis was located, because of its inaccessibility and because it overlooked the whole terraced valley below, today known as the Valley of the Temples. A mighty boundary wall has existed to defend the city since its foundation, today considerable remains of it can be found along its course. The walls, which in some stretches were excavated in the calcarenite bank, followed the morphological trend of the area. Exaggerating cuttings and overhangs, they were reinforced by towers and other constructions. There were several gates in this wall, especially in the cuttings. The town was built up inside the walls during 5th century BC. The hill of the Temples was almost completely given over to religious life. Building work on the Temples began at the end of the 6th century. The first Temple to be built was the Temple of Heracles, then the Temple of Juno Lacinia and then the Temple of Concord, followed by the one dedicated to Olympian Zeus (which was never finished), the Temple of Castor and Pollux and the Temple of Volcano on another hill to the North West (Fig. 2). Urbanization during the Hellenistic-Roman times, which started an age of construction and of reorganization, improved the already existing urban areas. The conditions changed suddenly at the beginning of the 4th century. The built up area was mainly on the side of the valley and the sacred area became totally abandoned. In later centuries, this situation persisted, up to the current chaotic situation. For this reason, caves can be found in the middle of the built-up area, reducing the stability of the town.

Geological Characters of Agrigento and the Valley of Temples

Sicily was involved in the geodynamic process of Apenninic-Maghrebian orogenesis during Miocene-

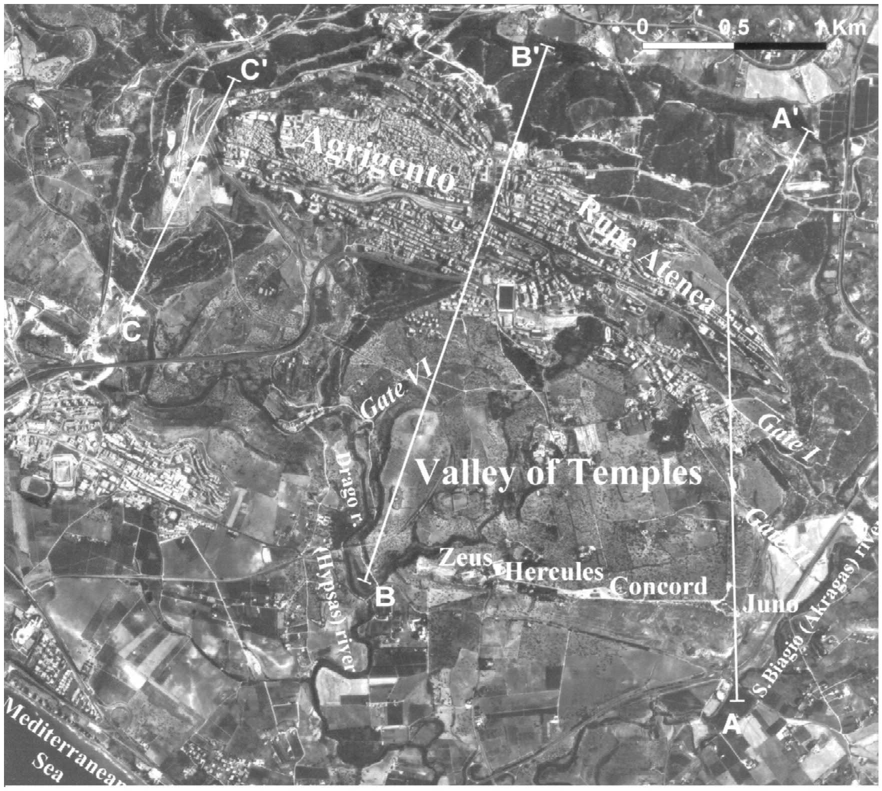

Fig. 1 - Aerial photograph view of the Valley of Temples and the Town of Agrigento. A - A': geological cross section

Fig. 2 - Aerial view of the valley bounded by the E - W oriented ridge

Pleistocene. The Agrigento area is located along the central-southern coast of Sicily, structurally belonging to the "Gela" nappe. The most ancient outcrops date to the Tortonian and are constituted by terrigenous molassic deposits, followed by Messinian rocks of the "Gessoso-solfifera series" (evaporitic limestones and gypsum), the Pliocene sediments of the "Caltanissetta basin" and the most recent Plio-Pleistocene outcrops (Catalano & D'Argenio, 1982; Ghisetti & Vezzani, 1983; Grasso & Butler, 1991).

The structural setting of the Valley of Temples area and the town of Agrigento is represented by an asymmetrical syncline with an approximately EW axis dipping to the North whose core consists of a sandy-clay sequence with various calcarenite bodies (Agrigento Formation - Lower Pleistocene) (Fig. 3). This sequence lies, probably discontinuously, on clay soils from the Middle-Upper Pliocene (Monte Narbone Formation). Along the coast these formations are overlain by discontinuous strips of terraced marine deposits, arranged in several orders, the oldest one belonging to the Sicilian Age (Motta, 1957; Ruggieri & Greco, 1967; Carta Geologica d'Italia, 1972).

The Monte Narbone Formation is represented by blue-grey silty-marly clays (up to 200 m thick) with a fairly regular stratification indicated by thin silty-sand levels. To the north, the Monte Narbone Formation crops out on the downslope of the Rupe Atenea Valley and the Girgenti hill. In addition it crops out to the South, close to the coastline, where it is not covered by terraced marine deposits, and in the deepest incisions. The sedimentological and palaeontological analyses show that this clay interval is laid down in platform-lithofacies, within bathial depths (300-400 m).

The Agrigento Formation is characterized by the presence of three main facies clayey-sandy silts (facies A); *Arctica islandica* marly sands (facies B); biocalcarenites and biocalcirudites (facies C), (Cotecchia et al., 1996).

Facies A) is constituted by yellow marly silt, with thickness up to several dozen meters, including several biocalcarenitic levels of facies B) and C). These terrains lie on the biocalcarenite level by *onlap* contact (Fiorillo, 1999b); at the top they are covered by facies B, generally by erosive and concordant contact.

Facies B) is constituted by sands characterized by bioturbation and macrofossils; the thickness is up to several meters. At the top these terrains gradually evolve to facies C).

Facies C) is made up of calcareous sandstone, characterized by a *bottomset-foreset-topset beds* systems. The bottomset beds are composed of alternating flat-parallel strata variously cemented with low imbricate clasts, often coarse and poorly sorted. The foreset beds highlight the clinostratification, by well cemented levels dipping 10° but in some cases up to 35°, made up of fine and coarse clasts; Red Algae, Bryozoans, Echinoids and Lamellibranchs are plentiful. The topset beds are composed of thin well-sorted strata, with a prevalence of weakly imbricated planar clasts with many Echinoids. The thickness of facies C varies from a few meters to about 35 meters. These facies are repeated four times inside the Agrigento Formation.

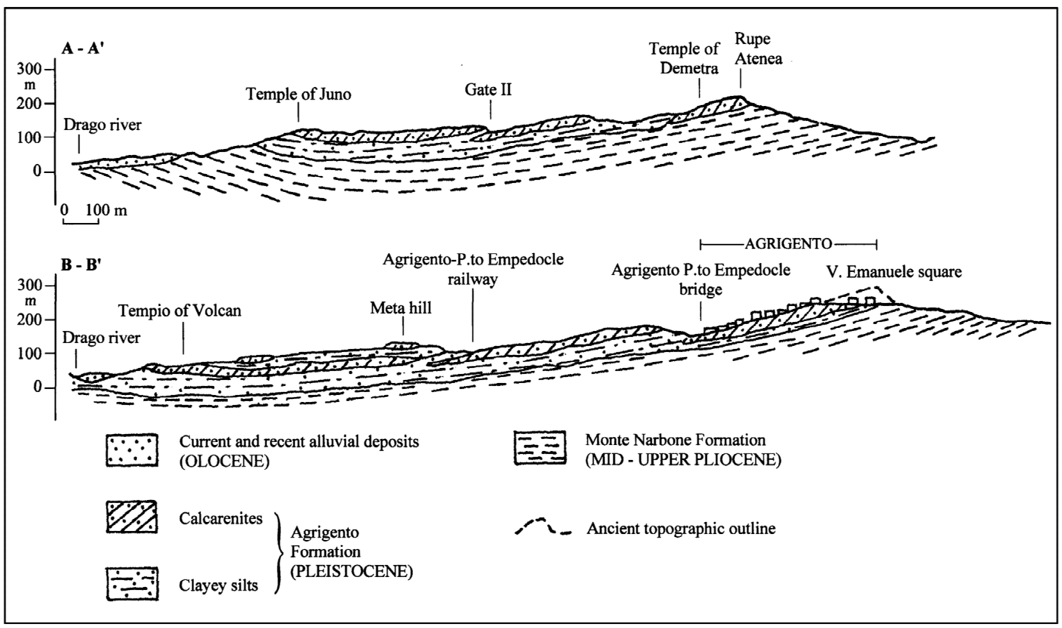

Fig. 3 - Geological cross-section along the valley of Temples

Structural Setting

Facies C characterizes four tabular bodies, giving the whole Valley of Temples a special lithostratigraphical and structural setting. The town of Agrigento is located on the lower calcarenite body which extends from the Temple of Demetra in the East, to the Girgenti hill in the West. It has a maximum thickness of 30-35 m that decreases towards the SE, until it tapers off, at its most easterly extension, and passes laterally into facies A. The inclination of the whole body is approximately 20° to the South; the clinostratification confers an inclination up to 50° on the strata, (Fig. 3).

The second calcarenite body extends as far as the left slope of the incision in Gate II and continues to the west. The average thickness is approximately 15 m with an inclination of approximately 20° to the south. These first two calcarenite bodies, together with the silty deposits, constitute the edge of the asymmetrical syncline with an approximately EW axis dipping to the north. Indeed, the third calcarenite body points out this broad syncline structure and constitutes the base on which the temples lie. The thickness varies from 5 to 20 m, in general, rising from the north to the south. The last calcarenite body emerges in isolated borders with a maximum thickness of about ten meters, (Fig 4).

The tectonic events generating the syncline are referable to the Emilian age (D'Angelo et al., 1979), therefore, they are contemporaneous or slightly subsequent to the deposition of the Agrigento Formation. After the Emilian age, the area was involved in mainly vertical movements, as indicated by all the terraced deposits found in it between the coastline and the Valley of Temples.

The results of the structural analysis show that the main fracturing system has a gravitational origin; it has been favored by the slope morphologies and the overlaying of the fragile horizontal calcarenite on ductile deposits (clayey-sandy silts). This system develops in parallel with the direction of the slopes and is more evident at the margins of the calcarenite bodies where the fractures are open and persistent. Another joint system develops, basically, transversely to the slope, mostly with a direction N40W (Gates II and VI) and N40E (Gate II). This particular structural setting causes the formation of slices (Gates I and II) and block wedges (Gate VI) at the edges of the calcarenite body and afterwards, their detachment, collapse and dropping.

In some areas (the Temple of Juno and Gate VI) the outcrops indicate probable local sliding phenomena among the various levels along the stratification surfaces, during the folding of the rocks (Pagliarulo & Andriani, 2000).
The effects of compressive tectonics are present in the terrain cropping out along the ancient Gate II and Gate VI, where the second biocalcarenite insertion is partly piled and deformed under the terrain of the transgressive-regressive cycle above.

Fig. 4 - The temple of Juno at the south eastern corner of the ancient fortification and the scarp below the temple

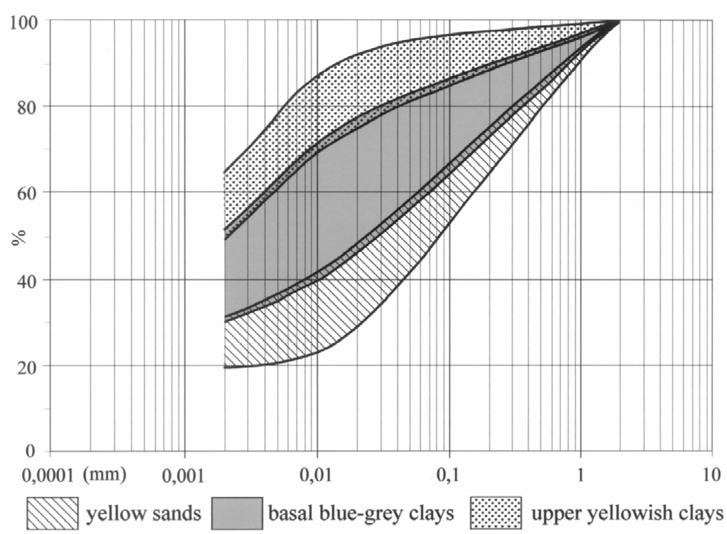

Fig. 5 – Grain size distribution of the upper and basal clays and of the sands from the Rupe of the Temple of Juno

Locally, these ancient ways were traced by removing the pelites present between the second and the third calcarenite insertion, in order to use the top of the second insertion as a practicable way.

The syncline deformation of the terrain has thus led to the consideration of the presence of flexural slip, as is suggested by Hutchinson (1988, 1995) for similar clayey terrain. It should be noted that inside the Valley of Temples, along these surfaces, the direction of any gravitational slip would be the opposite of the original tectonic one.

Geotechnical Characterristics

The first systematic studies of the terrain making up the Valley of the Temples were carried out at the end of the 1970's when, following the landslide on the eastern side of the hill, a campaign of geognostic investigations was carried out with the aim of stabilizing the area affected by landslides and the overlying calcarenite bodies. More general data regarding the terrain of the town of Agrigento and more specifically about the grey-blue clays is reported

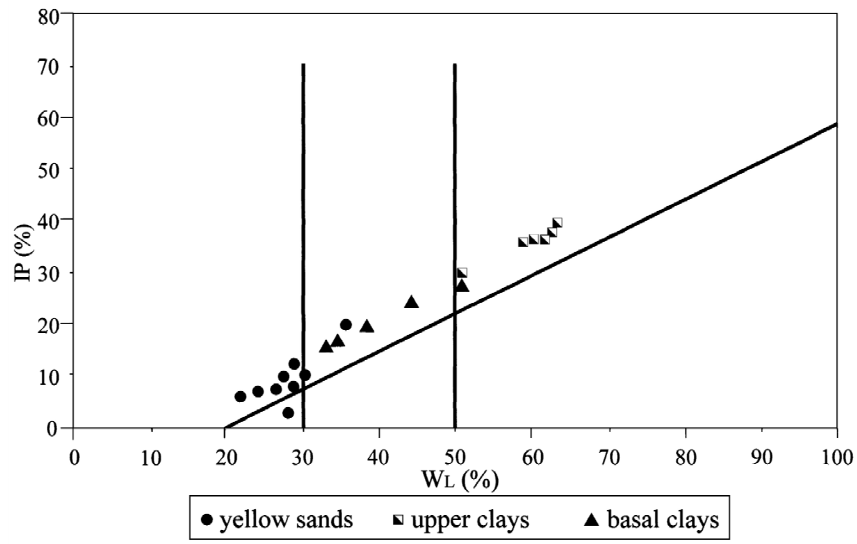

Fig. 6 – Casagrande plasticity chart

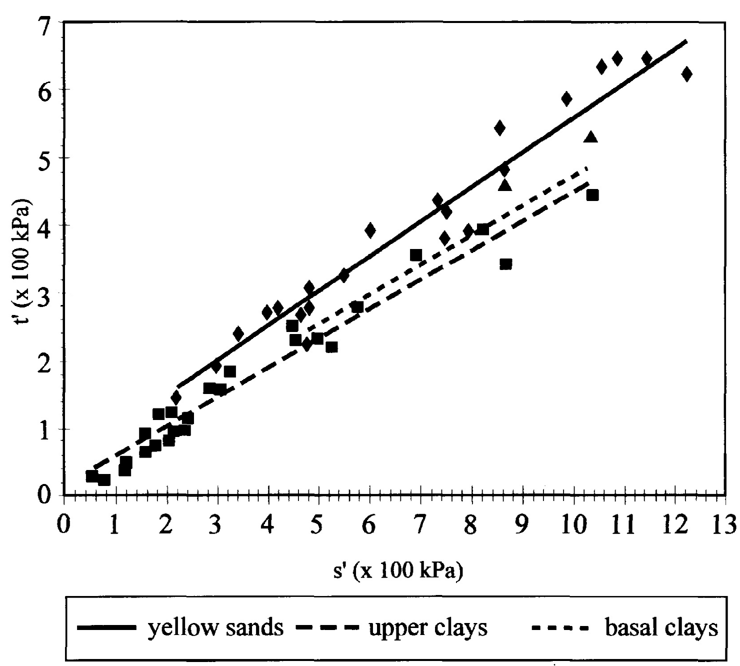

Fig. 7 – Shear strength envelope of clays and sands from the Temple of JunoTable 1: 1976 landslide. Geotechnical parameters.

in some notes (Croce et al., 1980 and 1966; Jappelli et al., 1984) presented in previous meetings and in the report of the "Commissione di Studio per la Salvaguardia della Valle dei Templi" (Study Commission for safeguarding the Valley of Temples) (Cotecchia et al., 1994). Specific geognostic investigations, aimed at consolidation interventions of the rock on which the Temple of Juno Lacinia is constructed, were carried out during the course of 1999.

Clay and sandy-silts lithotypes

The following tables, respectively for the materials of the 1976 landslide area and of the Rupe of Juno, and Figures 5-6-7 summarize the results of the geotechnical characterization tests of the clayey (*upper* clays above the calcarenite body and *basal* ones under the calcarenite body) and sandy lithotypes present in the Temples, deriving from geotechnical laboratory and/or on site tests.

Table 1: 1976 landslide. Geotechnical parameters.

Litho facies	Upper clays		Yellow clays		Clays (out of landslide)		Clays landslide body		Basal clays	
Subfacies					Sand	Clay	Sand	Clay	Sand	Clay
γ_t (kN/m^3)	21.0		21.1 (± 0.4)		21.0 (± 0.6)	20.9 (± 0.4)	20.6 (± 0.8)	20.2 (± 0.8)	20.6 (± 0.5)	20.5 (± 0.8)
γ_d (kN/m^3)	17.5		17.9 (± 0.4)		17.6 (± 0.6)	17.2 (± 0.6)	17.0 (± 1.2)	16.2 (± 1.2)	17.1 (± 0.7)	16.6 (± 1.2)
W (%)	20		17.7 (± 2)		19.6 (± 2)	21.6 (± 2)	21.5 (± 4)	25.0 (± 5)	21.0 (± 2)	24.0 (± 5)
e.	0.57		0.54 (± 0.04)		0.55 (± 0.06)	0.60 (± 0.06)	0.62 (± 0.12)	0.70 (± 0.14)	0.61 (± 0.07)	0.66 (± 0.14)
S (%)	98		91 (± 9)		96 (± 2)	97 (± 2.5)	94 (± 5)	97 (± 2)	95 (± 1.5)	98 (± 2)
> 2 μ (%)	47		75 (± 10)		62 (± 9)	42 (± 9)	67 (± 16)	42 (± 13)	64 (± 22)	43 (± 17)
WL (%)	62		-		4 (± 0.5)	61 (± 13)	41 (± 7.5)	59 (± 8)	41 (± 5)	61 (± 13.5)
PI (%)	37		-		26.4 (± 1.5)	39 (± 10.5)	21 (± 7)	34 (± 9)	19 (± 6)	37 (± 11)

Table 2: Temple of Juno. Geotechnical parameters.

Lithological facies	Upper clays	Yellow sands	Basal clays
γ_t (kN/m^3)	20.2 (+/- 0.3)	19.7 (+/- 1.1)	21.0 (+/- 0.2)
γ_d (kN/m^3)	16.3 (+/- 0.6)	16.8 (+/- 1.6)	17.5 (+/- 0.1)
W (%)	24 (+/- 3)	17.7 (+/- 6)	18.6 (+/- 4)
e.	0.69 (+/- 0.07)	0.63 (+/- 0.15)	0.57 (+/- 0.15)
S (%)	95 (+/- 3)	71 (+/- 28)	95 (+/- 4)
> 2 μ (%)	46 (+/- 20)	76 (+/- 15)	62 (+/- 20)
WL (%)	59 (+/- 6)		39 (+/- 8.7)
PI	35 (+/- 3.7)		20 (+/- 6)
Carbonates (%)	23 (+/- 7)	51 (+/- 13)	36 (+/- 11)

Calcarenites

As is well known, the mechanical properties of a rocky mass depend on the mechanical response both of the rocky matrix ("intact rock") and of the solutions of continuity made up of the layer joints, the fractures, etc. Generally the mechanical and bending behavior of the rocky mass depends on the structural link characteristic existing between the discontinuities. It should also be pointed out that the anisotropy of the calcarenite mass investigated does not allow us to acquire an unequivocal geomechanical framework, due to the existing stratigraphic and structural variability.

With reference to the table below, which summarizes the geomechanical parameters of the "intact rock", the calcarenite comes within the soft rock category with a uniaxial resistance value varying between 2 and 3 MPa. In any case there is certain dispersion around the mean value of compression strength, resulting from both the textural variability within the individual calcarenite beds and from the degree of soaking and drying in which the material is breaking. In the specific case of the basal foundation of the Temple, an increase in the compression strength from the top to the bottom of the layer has been noticed in accordance with a certain texture variation of the calcarenites. The shear behavior for all the samples was strain-softening, characterized by a shear decay of the peak strength values to the residual ones with a significant increase of flexure.

As regards the geometric parameterization of the discontinuities, we basically took the on-site geostructural surveys into consideration. The peak shear resistance parameters were estimated by applying the well-known experimental report of Barton (Barton et al., 1976). The roughness index JRC_0 was determined on the site on several joint surfaces with different degrees of weathering and exposure, while the JCS_0 index was estimated to approximately 1/10 of C_0, considering the ductility of the joint surface. In accordance with the indication of Barton and Bandis (1982), the parameters JRC_0 and JCS_0, measured on the site, were reduced to take account of the scale effect.

Table 3 - Mechanical parameters of intact rock

Volume weight	γ_t [kN/m^3]	18.1
Porosity	n [%]	25 -35
Soaking coefficient	i [%]	13 - 20
Uniaxial compression strength	Co [MPa]	2 - 3
Traction resistance	To [MPa]	0.25 - 0.85
Elastic tangent modulus	Et [GPa]	0.5 - 0.8
Intercept cohesion	c [MPa]	0.6 - 0.9
Angle of shear strength	Φ [°]	30° - 35°

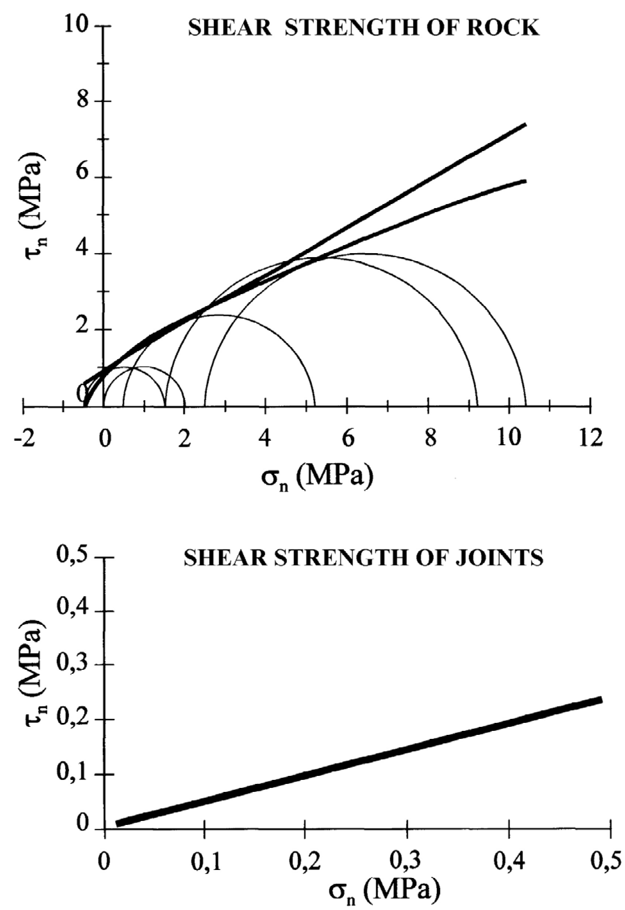

Fig. 8 – Shear strength of the calcarenites

Figure 8 reports the shear force-normal force ratios of the joints. As regards the residual strength of the joints, it was considered plausible to refer to the Jr/Ja (Joint roughness number/Joint alteration number, Barton et al., 1976) shear strength index from which a range of values of Φ_r = 7°-12° is obtained considering that it refers to open joints blocked by sandy debris coming from the walls of the joints.

As previously mentioned, the strength characters of the rocky mass are mainly affected by the discontinuity surfaces and by the mobility of the blocks.

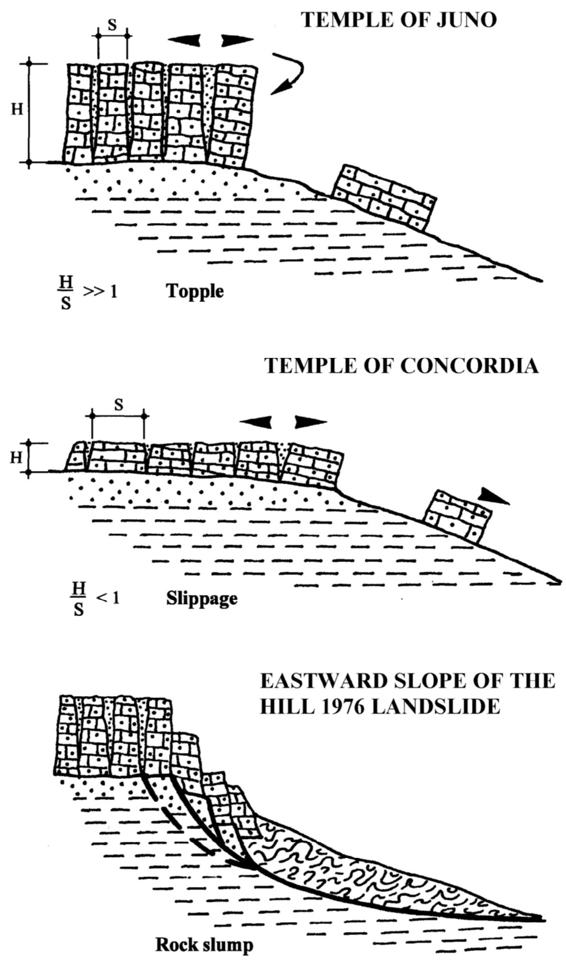

Fig. 9 – Kinematic evolution of the slopes

Slope Instability

There are widespread forms of geomorphological unbalance in the area which threaten the stability of the town of Agrigento, the temples and many other ancient structures and infrastructures (ancient roads, paleo-Christian necropolises, boundary walls, etc.).

Serious damage was caused by the landslide in February 1944 along the northern side which involved an old part of the town of Agrigento (Ministerial commission, 1968; Cotecchia et al., 1995). In July 1966 a large landslide affected the whole Arab quarter in the western sector of the town (Croce et al., 1980; Fiorillo, 1999). In December 1976 a gravitational landslide was reactivated along the eastern slope, in the sector between the Temple of Juno and Gate II, blocking access to the Valley and to the town from this side (Jappelli & Musso, 1984; Musso & Ercoli, 1988).

Generally the instability of the area derives from its characteristic structural layout: overlying rock types with a fragile behavior (calcarenites) on ductile behavior lithotypes (clayey-silts, marly clays). In this area, this simple structural layout is articulated because of the presence of different calcarenite beds which succeed one another in a pelitic complex (Agrigento formation) and because of the general syncline layout of the terrain which determines an overlapping of the two different lithotypes along inclined surfaces.

Because of the presence of a syncline structure it is possible to distinguish bedding dips out of the slope and bedding dips into the slope, along which landslide phenomena assume different kinematics. Located above all along the perimeter of the whole Valley of Temples or in internal sectors along the river cuttings, these dips are generally characterized by clayey deposits along the middle basal section and by a biocalcarenite bed at the top of variable thickness and affected by a series of joints.

The instability phenomena along these dips particularly concern the summit biocalcarenite bed, where the joints control and condition the reversal of the front, arranging the rock in prisms. The kinematics of the summit blocks seems to depend on the calcarenite thickness/space in the joints ratio. It has been observed that when this ratio is high, generally higher than one unit (calcarenite thickness > joint space) the evolution of the blocks is of the *topple* type. This type characterizes, for instance, the scarp adjacent to the Temple of Juno, where the calcarenite is divided into unbound prisms which are susceptible to toppling. When the ratio is limited, generally lower than one unit (calcarenite thickness < joint spacing), the evolution of the calcarenite blocks is firstly of the toppling type and then evolves as a *rock slide* (Fig. 9).

This evolution for instance characterizes the calcarenite rim adjacent to the Temple of Concordia, where the backward movement has involved the local paleo-Christian necropolis, now leaving just a few meters between the Temple and the scarp.

In other sectors, as a result of conditions favoring erosion at the foot of the scarps, there are landslides involving the pelitic substrate deep down. In this case the typical kinematics is the *rock slump* and the summit calcarenite blocks are arranged according to stepping characteristics. This type of evolution concerns the eastern side of the Temples hill for instance, where the 1976 landslide also occurred (Figs 10- 11).

The bedding dips into the slope are located inside the Valley of Temples; the clays of the substrate do not generally crop out along these slopes since they are covered by the biocalcarenite bed with its layout determined by the position of the clayey layers below.

Because of the limited inclination angle of the layers, only the northern sector of the valley has characteristics allowing total mobilization. As mentioned in the Introduction, a catastrophic landslide occurred in July 1966

(Croce et al., 1980), affecting an area covering over 40 hectares, (Figs 12-13). The summit of the landslide involved the "Macello" area and the Arab quarter, leading them to be transferred to Villaseta (about 2 km south); significant damage occurred along the local railway line to Porto Empedocle, and in the valley section, the structure of the road bridge over the River Drago was damaged. Recent surveys have confirmed that the type of gravitational movement occurring in 1966 was one of translational slide with a shear surface within the clay component terrain underneath the calcarenite bed.

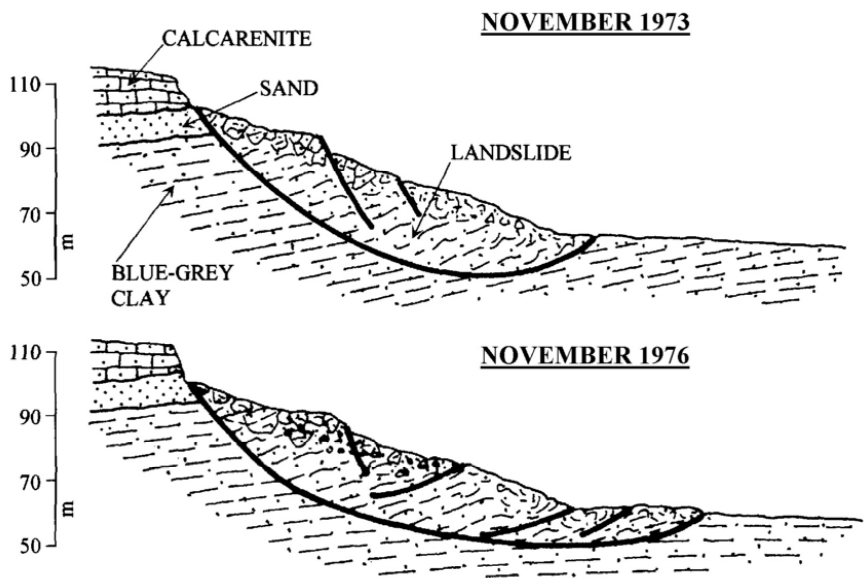

Fig. 10 – Geological sections and evolution of the landslide occurring in 1976

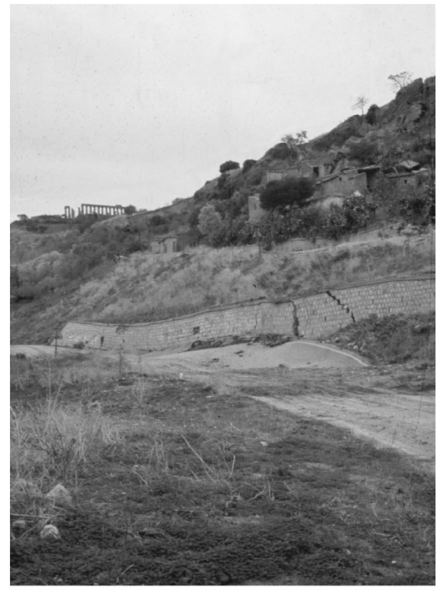

Fig. 11 - The landslide of 1976, close to the Temple of Juno

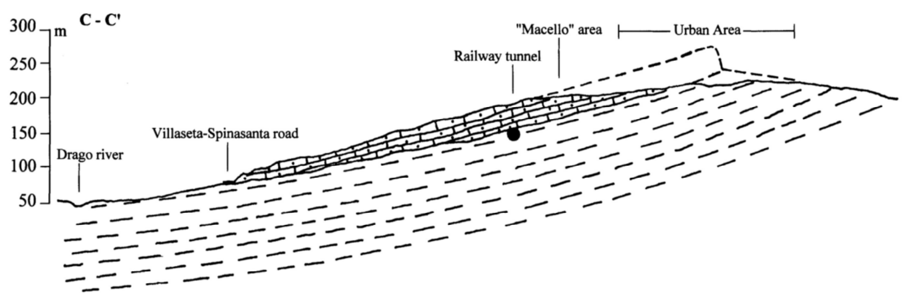

Fig. 12 – Geological section across the area involved in the landslide of 1966.

The observations showed that the location of the 1966 landslide was determined by a negative local combination between structural layout of the terrain and the morphology, which made movement kinematically possible; moreover, the phenomenon constituted the reactivation of a previously existing landslide body, as morphological and structural observations have evidenced.

Final Remerks

From the overall analysis of the geological and morphological characteristics of the Valley of the Temples it can be seen how natural and man-made factors of differing types come together to create favorable conditions for the development of erosion and landslides. The often irrational action of man adds to this, giving rise to overloading due to buildings, opening of large quarries for extracting calcarenite material in the middle of the built up area, lack of control of the surface and underground water, all of which trigger landslides and reduce the stability of the town.

The main landslide typologies are the (rock) topple, (rock) slide, involving the biocalcarenite outcrops; rotational and translational slides occur when failure develops mainly in the soil below biocalcarenite levels, involving wide areas.

Fig. 13 - Edge of the modern town facing the Valley of Temples along the 1966 landslide

Any improvement project has to consider the geometry and kinematics of the landslides, to design appropriate and environment-friendly intervention (Cotecchia et. al, 2000).

The main risk areas would appear to be:

- the southern scarp (between the Temple of Concordia and the Temple of Hera), where toppling phenomena have reached and affected the local archaeological ruins (ancient wall, Temples, catacombs, road) in some places;
- the eastern scarp, where deep-seated landslides (rotational slide) limit road function for access to the town;
- the western sector of the town, where a deep translational slide affects a wide area sector of the urban area.

Amongst the natural causes, highlighted by man-made modification which produces mass movements, the seismic activity of the area probably has an important role in controlling ancient building stability and landslide activity. Written sources say nothing about many events even though historical sources report persistent destruction of buildings in the area from the 12th century onwards. Moreover, it seems that the Temple of Zeus collapsed long before the construction work ended, as a probable effect of an earthquake. It has to be considered that the seismicity of this area induces a greater risk than in the past, considering the current condition of the temples.

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