Engineering Geology 192 (2015) 129–138

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Evaluation of cliff recession in the *Valle dei Templi* in Agrigento (Sicily)

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ARTICLE INFO

Article history:
Received 12 June 2014
Received in revised form 31 March 2015
Accepted 3 April 2015
Available online 16 April 2015

Keywords:
Archaeological site
Collapsible sand
Suction
Remote sensing monitoring

ABSTRACT

The sacral complex of the *Valle dei Templi* in Agrigento, added in the UNESCO Heritage Site List, stands over the crest of a rigid calcarenite cuesta, which overlies a layer of partially saturated (S = 6–12%) carbonate sand. In turn, the sand stratum lies on a thick stratum of clays. The environment is highly prone to landslides as highlighted by several previous studies that identify the undermining of slopes and the discontinuity pattern, occurred in the late Neotectonic phase, as causes of cliff failure. For wider and less exposed areas, where the undermining local instabilities can be present because of the specific morphology of the site, a recent research has proposed a new interpretation of the failure general mechanism. The new hypothesis here proposed would ascribe to the collapsible behaviour of the sand; both the failure mechanisms of the cliffs and the development of the discontinuities in the rock mass. A unitary framework is then proposed. A series of direct shear and oedometer tests was performed on the collapsible sand samples and values of collapse potential were estimated. As typical for collapsible soils when flooded, vertical strains occurred rapidly causing an increase of shear stresses in the upper calcarenite, characterised by low values of yielding and low values of tensile strength. As a consequence, additional discontinuities occur, volumes of rock fall and cliffs move back. Both by means of in situ surveys and the analyses of involved rock deformability and strength characteristics, a soil model was considered and a modelling process developed. The model results were compared with measurements of displacements as well as dimensions of fallen blocks and consequently the comprehension of the effect of sand collapse was then possible. The identification of the new mechanism key factors allows the definition of the soil parameters that need to be monitored. In order to prevent the cliff recession for the archaeological site, the work proposes a plan of monitoring methods. These methods will be able to estimate the cliff recession, to localize "sensitive areas" and to quantify the parameters that could activate the instabilities.

1. Introduction

The *Valle dei Templi* in Agrigento is one of the most outstanding examples of art and architecture in *Magna Graecia* so that the sacral complex has been added in the UNESCO Heritage Site List. A row of five Doric temples stands on the crest of a cuesta made of calcarenite which overlies a partially saturated sand layer. In turn, the sand overlies a stratum of clay. The preservation of these temples in the future is seriously threatened because their geomorphologic environment is highly prone to landslides and rockfalls. The recession of the slopes involves the hypogeic tombs of the sacred way and threatens the defensive walls and temple foundations. The whole area is shown in Fig. 1 where some instability zones are highlighted. Fig. 2a,b shows the Agrigento formation, with the four calcarenite levels (Fig. 2a). The cross section of the *Tempio di Giunone* area with its foundation soil is given (Fig. 2b).

In the current interpretation, these phenomena are due to the undermining of slopes, as a consequence of wind and splash selective erosion (Cavallari, 1883; Cotecchia et al., 1995; Cotecchia, 1996) and of the discontinuity pattern (Ercoli, 1985) together with the hydrogeological setting (Ercoli, 1994; Ercoli and Crouch, 1997). These studies on the mechanical behaviour of the calcareous–sandy–clayey formation in Agrigento and on its instability processes highlighted the influence of the discontinuities orientation, both in calcarenite and clay, on the morphogenetical processes of slopes, characterised by the alternation of low strength soils and rocks (Croce et al., 1980). The development of the discontinuities in the rock mass has been considered so far as an effect of differential uplifting occurred in the late Neotectonic phase from Pliocene to Quaternary (Diliberto, 1998). According to the author the uplift of the northern sector was greater than in the centre of the deposition basin.

In the last decades, a progressive enlargement of some sub-vertical discontinuities, with a N–S and NW-SE orientation, was observed and monitored by the *Ente Parco* and the University of Palermo (Grado, 2006) in the southwestern cliff area where the *Tempio di Castore e Polluce* and the *Tempio di Vulcano*, close to the *Kolymbetra* gardens, are

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http://dx.doi.org/10.1016/j.enggeo.2015.04.008
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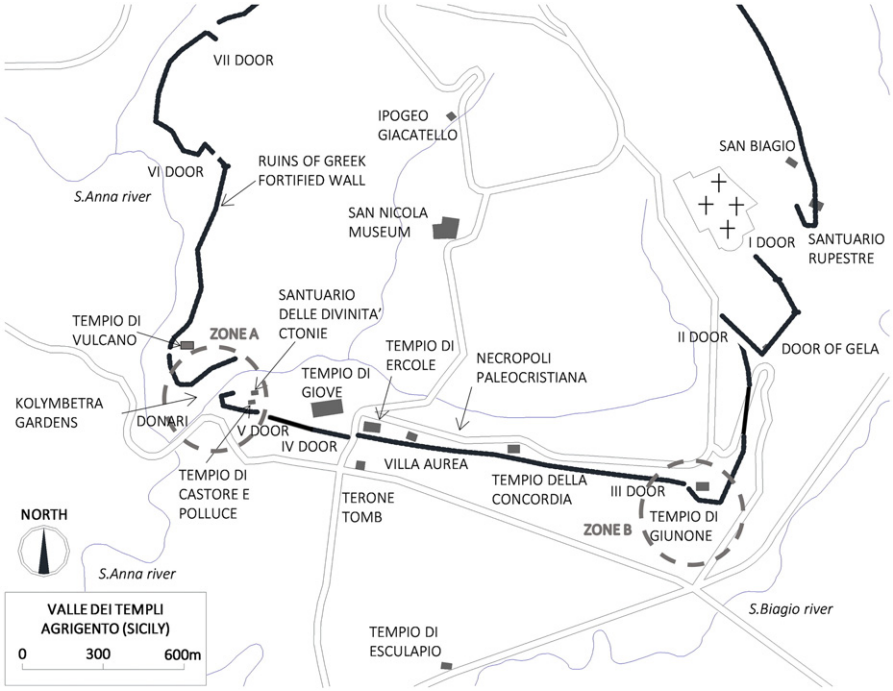

Fig. 1. Map of *Valle dei Templi* in Agrigento.

located. These discontinuities, in which apertures have increased with time, define rock blocks with dimensions of about 200 m^3. Some of these fractures have completely separated the blocks by the rock mass, as shown in Fig. 3a. New discontinuities (Fig. 3b) have been recently observed on the upper plane of the calcarenite bench. Recent studies on the morphological evolution of slopes and on the stability and the safety conditions in the temple areas consider the open metastable structure of the sand, interposed between calcarenite and clays, as the main cause of the block failures (Nocilla et al., 2013).

The research presented in this paper raises the question whether the collapsible sand stratum might have a role in the failure phenomena and whether a unitary framework might ascribe to the behaviour of the sand both in the failure mechanisms of the cliffs and the development of the discontinuities in the rock mass.

2. Morphological cliff evolution and laser scanner survey

The detailed survey of each block border with traditional topographic methods was performed (Ente Parco, 2013) and the monitoring of displacements was recorded from 2007 to 2010 in the limited "ZONE A", shown in Fig. 1. The monitoring was possible through the geodetic and georeferred net, owned by *Ente Parco*, on which the survey and alignment points are set. In detail, plano-altimetric apertures were recorded by 32 survey marks (Fig. 4).

Each block was labelled (Fig. 4) and, after proper horizontal scanlines, the apertures between rock mass and each block were estimated. These apertures are between 20 cm and 157 cm, increasing towards north and north-west, as they get closer to the *Kolymbetra* gardens.

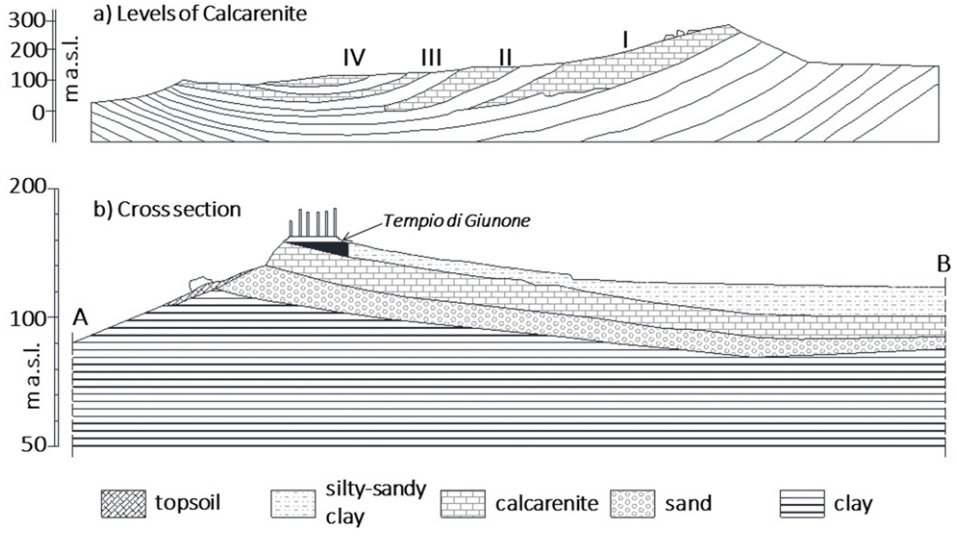

Fig. 2. Agrigento formation: (a) calcarenite levels; cross section of the *Tempio di Giunone* area and its foundation soil (b).