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Influence of the soil-atmosphere interaction on the collapse of sand in the Valle dei Templi in Agrigento

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Abstract

The sacral complex of the Valle dei Templi in Agrigento, belonging to the UNESCO Heritage Site List, stands over the crest of a stiff calcarenite bench, which overlies a layer of partially saturated carbonate sand. The retrogression of slopes and toppling phenomena that have occurred in the past, caused by the undermining combined with the discontinuity pattern, threaten some of the more relevant archaeological structures. Recent studies identified an open and metastable structure, typical of collapsible soils, for the sand layer under the calcarenite bench. In the sandy collapsible layer, significant vertical strains occur rapidly when the water content changes locally, decreasing suction and causing differential settlement and an increment of tensile stresses in the above calcarenites, where discontinuities might arise or increase their opening, resulting in possible progressive failure. By using meteorological and rainfall events data, the research presented here is focused on the study of the evapo-transpiration of a one-dimensional model of sand which was carried out in order to predict the water content change in the sandy layer. Successively, by calibrating the results through oedometer tests, the increments of water content were correlated to the amount of collapse. A first assessment of the influence of the soil-atmosphere interaction on the mechanism of collapse is then proposed.

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1. Introduction

Recent studies on the morphological evolution of slopes and on the stability and safety conditions in the temples area consider the open metastable structure of the sand, interposed between calcarenite and clays, as the main cause of the block failures [1,2]. The mechanism of progressive failure described by the above authors is based on the volumetric change in the sand, upon wetting (i.e. inundation through rainfall), which is considered a structural collapse characterised by low to moderate severity [3]. In a collapsible soil, on wetting, suction will be lost or highly reduced, whereas chemical bonding is likely to be less affected by the change in water content. As is well known, the principle of effective stress is not fully applicable to partially saturated soils (e.g. [4]) and in the case of net effective stress (σ_f-u_a) constant, an increase in suction always corresponds to a volume reduction, while a reduction of suction might correspond to an irreversible volumetric strain (i.e. collapse).

In the case of the *Valle dei Templi* in Agrigento, these local collapses cause differential settlements, which develop high tensile and shear stresses in the calcarenite bench and consequent new sub-vertical discontinuities defining rock blocks [2]. These unstable blocks, characterised by great volumes, might be involved in rotation or toppling phenomena. Furthermore, these discontinuities cause an increase of secondary permeability in the calcarenite bench and allow the rainwater to flow directly into the underlying sands in which, as a consequence, the water content increases. Ercoli et al. [2] suggested that change in water content in the sand is a fundamental parameter to be monitored, for its main role in the retrogression process. The advanced thermo-hydro-mechanical coupled modelling of the slope-atmosphere interaction requires an assessment of both the geo-mechanical and the hydraulic soil features such as the morphology of the slope, soil stress-strain behaviour that might be more complex for partially saturated soils, hydraulic properties and boundary conditions. With the aim of a first attempt, the influence of sand-atmosphere interaction on the collapse potential CP of a one-dimensional model of the sand was investigated, considering simplified boundary conditions and vertical flows only. Justified by the outcropping of the sandy layer in infrequent and restricted portions in the area, a direct contact between the sandy one-dimensional layer and the atmosphere was assumed. Therefore, for the infiltration and evapo-transpiration flows a standard "sandy soil" was selected. Its hydro-mechanical properties were statistically estimated from the literature of similar soils by Allen at al. [5]. The work, indeed, simulates the responses to changes in the water contents induced by rainfall events and evapo-transpiration phenomena processes over different timescales, relatively to three peaks in cumulative yearly rainfall occurring in the last 40 years. The resulting cumulative collapse for the one-dimensional model was then calculated starting from the estimated water contents according to the experimental correlation between collapse potential and water content on specimens of the sand of Agrigento.

2. Methods and data

2.1. Monitoring data, one-dimensional model and soil-atmosphere interaction

Meteorological data regarding rainfall, temperature, sun radiation, wind and relative humidity were used to estimate the evapo-transpiration and the flow at the model boundaries. In Figure 1 the evolution of the cumulative yearly rainfall is given over the last 40 years; the trend highlights the tendency to a new increase of precipitation, after a period of lower peaks. Data are referred to two atmospheric monitoring stations close to the considered area (i.e. "Osservatorio Acque" and "Agrigento Scibica"). Among the peak values, three of them (2003, 2009 and 2013) were considered for the analysis here presented. According to the data, 823.4mm, 755.4mm and 771.6mm are the cumulative yearly rainfall that occurred in 2003, 2009 and 2013 respectively. Although a model as much as possible faithful to the reality should take into account the boundary conditions in situ, where the calcarenite bench and its discontinuities patterns are involved in the inlet/outlet flows and the sand is outcropping rarely, a simplified one-dimensional model of sand directly in contact with the atmosphere was considered, as a first attempt of the study.

The vertical dimension of the model was chosen according to the height of the sandy stratum, which was estimated to be 4m on average. Following the FAO approach [5] the daily crop evaporation under standard conditions E_{Tc} was estimated as the product between the reference crop evaporation E_{T0} according to the FAO-Penman-Monteith formula [5] [6] and the crop coefficient K_c which, following the second approach for its determination [5], was split into two factors that separately describe the evaporation (K_e) and transpiration (K_{cb}) components. Hence, from the daily precipitation P, the value of the inlet flow q_s was estimated following equation (1):

$$q_S = P - E_{Tc} \tag{1}$$

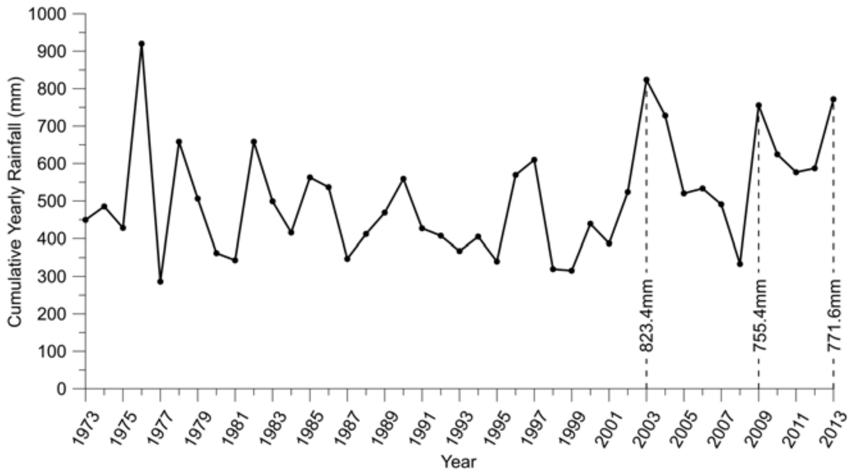

Fig. 1. Evolution of cumulative precipitation over forty years. Data from "Osservatorio acque" (1973-1983) and "Agrigento Scibica" station (1983-2013).

As for the water balance in the column, the inlet quantity of water q_s was corrected by means of a surface runoff coefficient RO, that was assumed equal to 0 for the simplified boundary conditions. For the boundary conditions at the base of the column, the system was considered as "closed" without any capillary rise or deep percolation from or to the deepest clays, respectively. This last hypothesis can be partially justified by the very low permeability of clays. For the "field capacity" and the estimation of water content variations *w*, according to the precipitation (P) and to evapo-transpiration processes (E_{Tc}), an average void ratio e_0 of the sand stratum equal to 0.85 was evaluated from specimens. Measuring the water content after 24 hours at 105°C on specimens, a residual water content w^* equal to 1.5% on average was then considered.

Hence in (2), the current water content w can be estimated as:

$$w = \frac{M_{w^*} + M_w(q_S)}{M_S} \tag{2}$$

where M_{w^*} is the mass of the residual water in the vertical column of volume $4x1x1m^3$, $M_w(q_s)$ is the mass of the water resulting from the equation (1) flowing in the vertical column and M_s is the mass of the solids in the considered volume according to specific gravity of the sand of Agrigento $G_s = 2.647$ and the void ratio e_0.

2.2. Laboratory testing

Three sandy specimens from the *Valle dei Templi* in Agrigento, sampled in the sandy stratum below the *Porta VII*, were taken to the laboratory for collapse testing. Jennings and Knight [3] classified the potential severity of collapse based on the collapse potential, defined in equation (3).

$$CP = -\frac{\Delta H}{H_0} = -\frac{\Delta e}{1+e_0} \cdot 100 \tag{3}$$

where ΔH and Δe are the change in height of the sample and in void ratio respectively, upon flooding, H_0 is the initial height of the specimen, and e_0 is the void ratio at the natural water content. It is clear that the CP value depends on the vertical stress at which the flooding is applied and Jennings and Knight [3] suggested a standard procedure to estimate it, flooding the specimen when a pressure of 200kPa is applied (see also ASTM D 5333-03 [7]). In the case being studied, the vertical stress assumed at the mid-height of the sandy layer is indeed about 200kPa [3], because of the calcarenite bench weight and the assumed water table, located below the sandy stratum in the clayey layer. Unlike the standard procedure [7], the collapse potential was considered in its evolution, through several steps of flooding under a constant value of vertical stress σ_n =200kPa. For this reason it is a cumulative collapse potential and, hence, is referred as CP_0: for each step of flooding, it was always referred to the initial void ratio e_0.

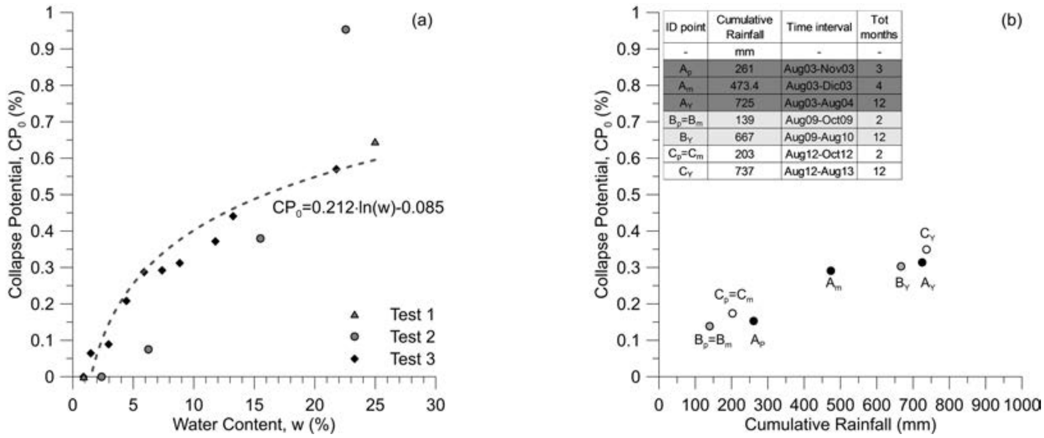

Fig. 2. (a) Collapse Potential CP_0 against controlled water content; (b) Cumulative rainfall against collapse potential CP_0 for the simulations.

Figure 2a illustrates the CP_0 plotted against the water content variations induced by controlling the amount of water flowing into the sandy samples, set in a conventional oedometer preventing the flow from the sample towards the drainage at the base by means of an impermeable film, similarly to what was assumed for the one-dimensional model. Hence, the influence of water contents on the collapse occurring was investigated flowing controlled amounts of water from the top of the samples in several steps: 2 for steps for test1, 3 steps for test2 and 9 steps for test3. The data points were fitted using the logarithmical correlation given in the equation highlighted in Figure 2a and characterized by a correlation coefficient equal to 0.76. Although more tests should be carried out in order to assess the effectiveness of this correlation, the relatively low value of the correlation coefficient might be due to an anomaly of test 2, which showed rather a hyperbolic trend and higher values for larger water contents. The maximum value of CP_0 that occurred is about 0.95%. This value is lower than 2.3% estimated by Nocilla et al. [1] under the same vertical stress (i.e. 200kPa) on a sandy sample taken from the foundation sandy layer close to the temple of Vulcano. The initial void ratio being very similar for the two samples, this difference could be due to the different locations of sampling, to different amounts of collapse already occurred and/or to the differences in the nature of collapse, that can be the result of the erasing of suction forces only or also to the dissolution of other bonds (e.g. [8]). Jennings and Knight [3] classify soils with collapse percentage greater than 1% as metastable and collapse percentage from 0% to 1% from low to moderate. However, low to moderate values of CP combined with the heterogeneity of the flooding phenomena in the sandy layer could generate differential settlements that might introduce intolerable stress states for the overlying calcarenite bench [2].

2.3. Simulations and effects of water content variations on collapse

For the three different years, the daily water content was considered calculating the effects of precipitation and evapo-transpiration (eq. 2) in three different time periods. The years for the simulations were chosen among the peak values on Figure 1 recorded by the “Agrigento Scibica” station. The time “zero” was set at the 1st of August for all simulations.

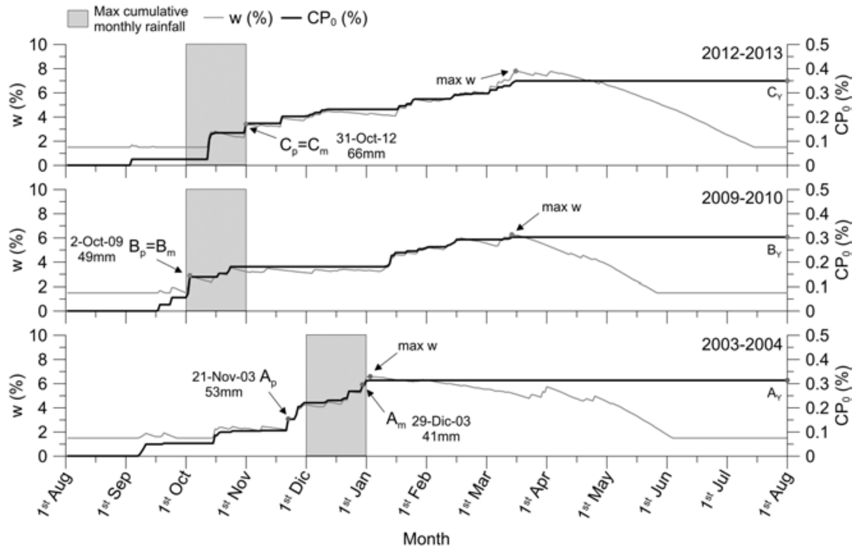

Fig. 3 Water content w and Collapse Potential CP_0 against time in the simulations.

The 1st of August is assumed as the “driest condition” and it represents the “zero” condition, i.e. the starting point of the water balance and the “virginity point” for the collapse. The influence of limited climate trends on the collapsing behaviour over different time periods was analysed rather than a response over the last 40 years. In other words, each timescale, each simulation returns to the “zero”. This way to proceed in the analysis, due also to the discontinuity of the data, is partially justified by the nature of the evapo-transpiration process, which usually goes back to “dry conditions” in terms of water content. The presence of the calcarenite bench and the evolving secondary permeability might open to new virgin paths for the flow so that the sand can be considered to be flooded for the first time. Taking into account the precipitation and evapo-transpiration processes, the daily water content was estimated using Equation (2) over different simulations based on distinct intervals of time. Values of CP_0 were estimated according to the logarithmic correlation on Figure 2a and results were plotted on Figure 2b. In detail three peaks in cumulative yearly rainfall occurring in the last 40 years were considered (Fig. 1) and 12 month time periods have been taken for three timescales of one year spanning two solar years. For each reference timescale (A:2003-2004; B:2009-2010; C:2012-2013), a first simulation considers the time up to absolute rainfall peak of the yearly timescale (points A_p, B_p and C_p), the second simulation considers the time up to peak in the max cumulative monthly rainfall (points A_m, B_m and C_m) and the last simulation considers the 12 month timescale (points A_y, B_y and C_y).

Figure 2b highlights the difference of the timescales on the collapse potential CP_0. While for simulations B and C the absolute peak values and peaks in the max cumulative monthly rainfall perfectly coincide, for simulation A the peak in the max cumulative monthly rainfall can be distinguished from the absolute peak value. As for the values of CP_0, the influence of number of months considered can be highlighted: CP_0 values at the absolute peaks (corresponding to a time period of 2 or 3 months at least) are low (in the region of 0.15%) and reach the maximum value (around 0.3-0.35 %) considering the yearly timescale only (A_y, B_y and C_y), except for the simulation A where this maximum value was obtained almost at the peak in the max cumulative monthly rainfall (A_m). The collapse being irreversible, the estimation of CP_0 took into account positive increments of water content only and not its fluctuation: the value of CP_0 increases only when the water exceeds a previous maximum value. The values of CP_0 recorded are, on the whole, low (about 0.35 %) and they never reach the maximum value (0.6%) given by the equation on Figure 2a for w=25%.

3. Conclusions

The amount of cumulative rainfall cannot be considered as the only factor acting on the collapse potential CP_0; values of CP_0 do not exclusively depend on the amount of cumulative rainfall and similar values of CP_0 occur for very different values of cumulative rainfall: indeed points A_m and A_y correspond to similar values of CP_0 (about 0,3%) and to very different values of cumulative rainfall (473.4mm and 725mm, respectively). The key features of the collapsing behaviour can be better explained in Figure 3, in the which trends of water content and relative collapse potential CP_0 were plotted against time. When the interval of time to the peak in the max cumulative monthly rainfall is small (B_m, C_m), further rainfall events, although less intense, produce an accumulation of water contents; the evapo-transpiration processes occurring in the rest of the year and the meteorological conditions do not contrast as much as in the driest periods the increase of P in the balance of Equation (1) resulting in a further increment of water contents (and CP_0) up to the value corresponding to the maximum *w* highlighted in Figure 3. In contrast, for simulation A, the maximum cumulative monthly rainfall occurs later (December 2003) and no further collapse was recorded since then, because of the nature of evapo-transpiration processes in the remaining months which, although there are further rainfall events, do not allow any increase of the water contents. Therefore, from simulation A in Figure 3, the influence of the position of the max cumulative monthly rainfall (A_m), rather the absolute peaks (A_p), can be highlighted. It is possible to conclude that the rainfall regime and the evapo-transpiration process influenced by the climate fluctuations, before and after peak events, have a more important role on the CP_0 than the millimetres of rainfall occurring during the event itself. Despite these differences over the smaller timescale, the CP_0 value over the 12 month time period simulations, always reaches a similar maximum (between 0.30% and 0.35%), corresponding to the higher water contents, which are quite low (less than 8%), though a rainfall regime through the year. The one-dimensional model, although assumed to be impermeable at the bottom, never saturates completely and the maximum value of CP_0 estimated by laboratory testing is never obtained. This seems to be a key feature of the collapse behaviour of the sand of Agrigento, for which it might be assumed that the maximum collapse potential CP_0 is never totally reached because no high or full saturation is achieved during the year, even for the rainiest years that occurred in the past in this arid area.

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