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# Numerical Assessment of Sinkhole-induced Damage to Buildings

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## Abstract

In this paper, an advanced chemo-hydro-mechanical (CHM)-coupled numerical model for soft rocks is used to predict the temporal evolution of settlement damage to buildings on cavities subject to weathering. By using surface differential settlements obtained by CHM coupled finite element (FE) analyses a building damage index is used (BDI) to assess serviceability conditions. By modelling the reactive transport of chemical species in 3D and using a coupled CHM constitutive and numerical model, it is possible to simulate weathering scenarios and monitor the temporal evolution of surface settlements making the BDI time dependent. This approach is applied to evaluate BDI evolution of a building lying on two anthropic caves in a calcarenite deposit belonging to the *Calcarenite di Gravina* Formation. The soundness of both constitutive relationship and reactive transport solver are tested by simulating laboratory-scale boundary value experiments. The first is a model footing test on dry and wet calcarenite, while the second is a small-scale pillar that, after the saturation-induced short-term water weakening, fails due to a long-term dissolution weathering process. Finally, both 2D and 3D coupled FE analyses simulating different weathering scenarios and corresponding settlements affecting the buildings above the considered cavities are presented.

Keywords: geo-structural resilience, weathering, soft rocks, soil structure interaction

## 1. Introduction

Sinkholes, of both natural and anthropogenic origin, represent an important geological hazard worldwide. Their formation is often the result of physical hydraulic chemical phenomena (weathering) inducing detrimental changes of the earth crust hydro-mechanical properties. From a geotechnical engineering perspective, weathering induced degradation of mechanical properties, may affect the stability of various geotechnical systems. For instance, the interaction of water with the gypsum pillars of an abandoned mine can transform this rock into a much weaker and compressible material, which can eventually collapse under the weight of the overburden (Castellanza et al., 2018). Even the simple saturation of dry porous carbonate rocks, limestones or other karstic formations can lead to considerable changes in strength and stiffness that may cause large surface settlements unacceptable for the service life of existing structures (Parise and Lollino, 2011).

In engineering practice, to assess the safety of a geosystem the safety factor $F_s$ is commonly used. $F_s$, is usually determined as the ratio between the initial strength parameters and the reduced strength parameters causing the system to collapse (Potts et al., 1990). This method, also known as $c$-$\phi$ reduction method, assumes a strength reduction that is equal for all points of the domain and usually requires the use of Mohr-Coulomb failure criterion. However, weathering induced material degradation is not homogeneous in space and evolves in time. Typical spatial-temporal evolution patterns of weathering induced damage can be determined thanks to long-term monitoring and mechanical testing (Lawrence at al. 2013, Ciantia et al. 2015a, Bhowmik et al.2020). Recently, Castellanza et al. (2018) presented a methodological approach showing how the $F_s$ can be linked to time using 3D FE simulations employing simple elastic-perfectly plastic Mohr–Coulomb type constitutive models. However, despite the considerable progress made in recent years in the study of the interactions between earth crust and the environment (Gens, 2010), the application of advanced models to perform 3D numerical simulations to assess the safety conditions of geotechnical systems is rare.

In the following, the approach proposed by Ciantia et al (2018), to incorporate the effect of weathering on the safety factor is presented and used to predict the damage evolution of a building on a cavity subject to weathering. Instead of assuming a strength profile and then performing strength reduction analyses, a weathering scenario is simulated and, by means of the reactive transport of contaminants, the spatial-temporal evolution of rock strength and stiffness are modelled. The results show that slight changes to the aggressiveness of the environmental boundary conditions largely affect the service life of a structure. The numerical approach is hence a powerful and promising tool for geo-structural resilience assessment.

## 2. A time dependant Service Safety Factor $SSF$

The formulation of the $SSF$ is inspired by the work of Boscardin and Cording (1989) and uses the surface differential settlements obtained by *FE* analyses to assess how far a building is from a non-acceptable service condition. By modelling the reactive transport of chemical species and using a coupled HCM constitutive model, it is possible to simulate weathering scenarios and monitor the temporal evolution of surface settlements. In this way the temporal evolution of horizontal strain and angular distortion at the base of the building, are then used to enter the well-known Boscardin and Cording abacus. $SSF(t)$ is hence defined as:

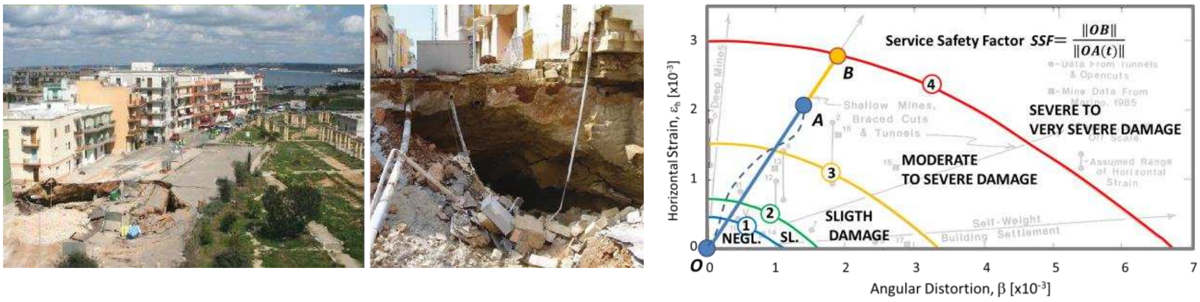
$$SSF(t) = \|OB\| / \|OA(t)\| \tag{1}$$

where $\|OA(t)\|$ is the distance of the current state from the origin, while $\|OB\|$ is the distance from level of damage 3 to the origin obtained as an extension of *OA* (Figure 1b). The assumptions made to calculate $SSF(t)$ are that:

i) weathering causes surface settlements (subsidence) like those induced by tunnelling excavation,

ii) the building stiffness is not considered as it is assumed not to affect the subsidence profiles and the building displacement and deformations are assumed to coincide with the ones of the rock, and

iii) the building is assumed to comply with the Boscardin and Cording (1989) mechanical and geometrical assumptions.

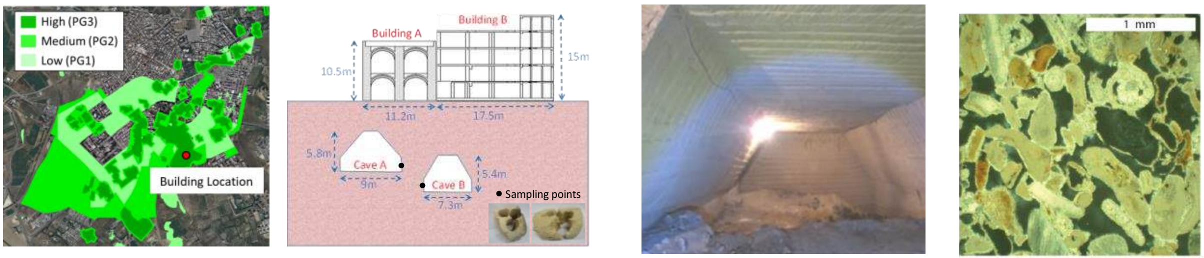


a) b)

**Figure 1**: a) Pictures of a sinkhole in Gallipoli occurred in 2007 (Ciantia et al., 2015c) and b) definition of $SSF(t)$ in the Boscardin & Cording (1989) plot.

## 3. Case study

In the following the $SSF(t)$ of two buildings in Canosa di Puglia (Italy) built on a complex cavity excavated about two centuries ago (Figure 2a) and is numerically predicted. The cave is in a carbonate rock belonging to the Calcarenite di Gravina Formation. The rock has a porosity of 59% and a unit weight in a dry condition of 11.1 kN/m$^3$. Several experimental tests performed to adequately characterize the material, including triaxial and SEM imaging (Figure 2b,c), and detailed results are reported in Ciantia *et al*. (2018).



a) b) c)

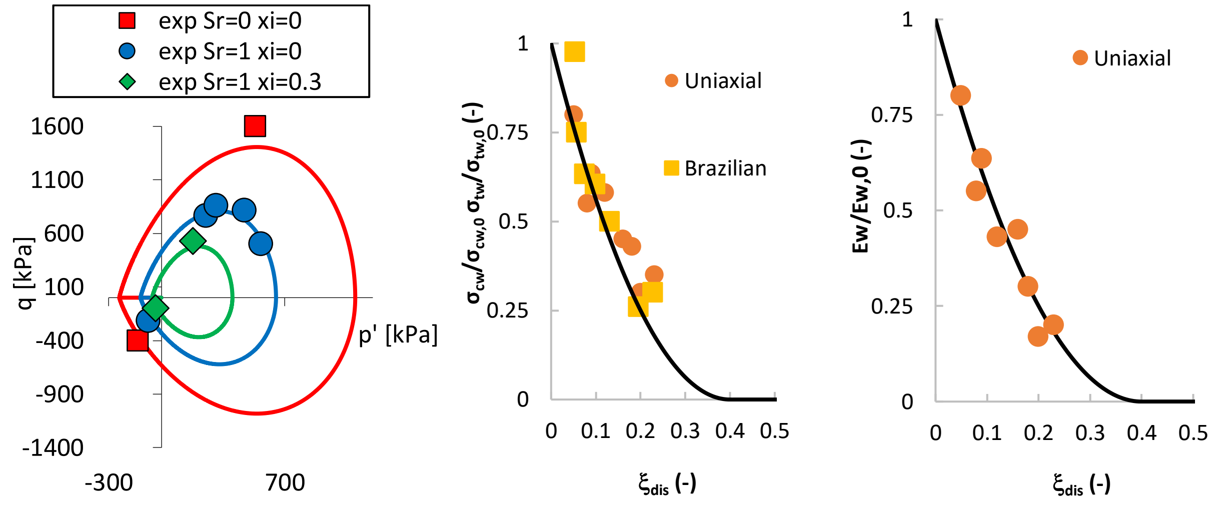
**Figure 2**: a) Map of Canosa di Puglia with the highlighted High, Medium and Low risk zones and Case Study section view of cave interacting with building, b) Picture of the cavity and c) optical microscope images of thin sections of the in situ calcarenite.

## 3.1 Constitutive model for carbonate rock

To model the coupled hydro-chemo-mechanical behaviour of the soft rock, the constitutive model by Ciantia and Di Prisco (2016) was used. The model is of the family of modified cam clay extended to structured materials and modified to be able to describe suspension and dissolution induced damaging phenomena by means of rock strength evolution laws that describe material behaviour during suspension and dissolution effects. The core of the model are the hardening variables that control the evolution of the yield surface. They evolve with plastic strains (mechanical damage) and because of saturation effects (in the short term) and dissolution effects (in the long term). The evolution of the hardening variable related to the rock tensile strength reads:

$$\dot{p}_t = -\rho_t p_t \left( \dot{\epsilon}_v^p + \xi_t \dot{\epsilon}_s^p \right) + \frac{p_t}{Y} \dot{Y} \tag{2}$$

where $p_t$ is the initial tensile strength $\rho_t$ and $\xi_t$ are parameters of the model controlling mechanical softening and $Y$ is the weathering function (a scalar that goes from 1 to 0) that depends on degree of saturation $S_r$ and the normalised dissolved mass $\xi_{dis}$. To calibrate $Y$, non-standard experimental tests whereby the strength along with weathering induced mass loss are measured are necessary. Details on such calibration procedures are in Ciantia et, al 2015a,b. By performing triaxial compression tests at various levels of weathering rock it is possible to identify the evolution of the yield surface, strength, and stiffness of the rock (Figure 3).



a) b) c)

**Figure 3**: a) Yield surface calibration of the rock for dry to saturated and weathered (30% dissolved mass) conditions. Evolution of strength (b) and stiffness (c) with normalised dissolved mass, $\xi_{dis}$.

## 3.1 Weathering scenario

The weathering scenario considers the cave boundaries exposed to a slightly acidic pH environment, resulting in the development of a coupled chemo-mechanical diffusion and deformation process. To consider the real geometry of the problem and realistic building loads a 3D numerical analysis is performed and the mesh and problem definition are shown in Figure 3b.

Standard displacement boundary conditions have been applied to the external boundaries, with fixed horizontal and vertical displacements at the bottom and fixed horizontal displacements on the lateral boundaries. The external loads (i.e. the foundation loads) acting at the ground surface are kept constant while the weathering process evolves from the inner boundary of the cave. To represent building A, a pressure of 150 kPa is imposed under each of the 9 square footings, while a pressure to represent building B, a uniform pressure of 40 kPa is imposed under the area covered by it. On the cavity surfaces, a fixed constant concentration of [$H_3O^+$] ions, corresponding to a wanted pH is imposed. They will propagate into the rock by means of a diffusive phenomenon causing the long-term dissolution of $CaCO_3$. A parametric study considering variable levels of boundary acidity are performed and pH values of 7.5, 6.7 and 6 will be used. Details of the reactive transport model are described in Fernandez-Merodo et al. (2007).

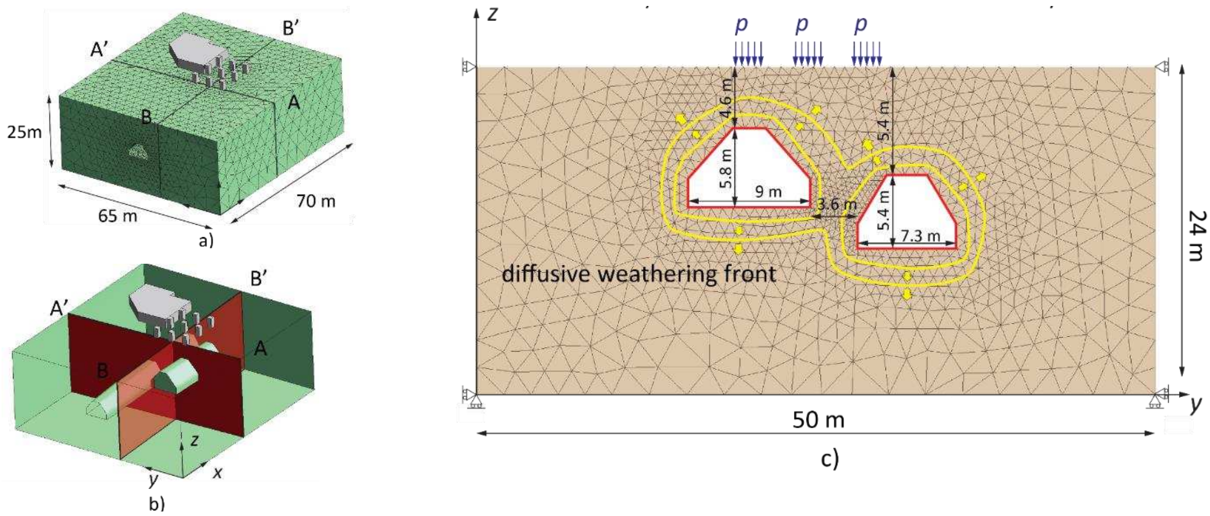


**Figure 4**: a,b) 3D mesh and sections considered for the *SSF* calculation, and c) section, mesh, boundary and initial conditions and environmental loads.

## 4. Results

Figure 5 reports the main results as a function of physical time (days) from the beginning of the weathering process assumed for the 3D numerical simulations. The dissolution process that evolves from the inner boundary is shown in the first column of Figure 5 by the contour in time and space of the contaminant ion $[H_3O^+]$. As the contaminant concentration increases, the dissolution process evolves causing a mass reduction and a consequent increase of the scalar $\xi_{dis}$ leading to a reduction of the bonding related variables $p_t$ of the model. This strength reduction causes yielding of the rock to concentrate in correspondence of the partition wall. As the exposure time with the $[H_3O^+]$ ions increases the plastic strains localize into a shear band (3rd column) and the displacements increase (4th column). Nevertheless, before plastic strains localize into a shear band, material degradation developing from the wall boundaries induces a stress redistribution in the partition wall. Although non-local approaches (e.g. Manica *et al* 2020) should be adopted to avoid mesh dependency when looking at the failure mechanism, it was observed that further mesh refinement did not change the results of the simulation in terms of surface displacement with time. Interestingly, the failure of the partition wall doesn't cause a global failure mechanism, and this is due to the residual frictional strength within the shear band combined with the rooftop geometry. The stress corresponding to a point within the shear band, starts from an initial elastic state, yields after about 120 days of acid exposure, and evolves until critical state is reached.

The chemo-mechanical coupled induced displacements are well documented in terms of the displacement plots in Figure6a. In Figure6b the angular distortion horizontal strain paths for the numerical analyses are reported. By means of eq.(1), in Figure 6c, the service factor of safety SSF(t) is also reported. The time needed to attain a SSF(t)=1 results to be 1080, 200 and 60 days for the 7.5, 6.7 and 6 pH case respectively. The plot also shows how the three-dimensional effect delays the SSF attaining a value of unity from 165 to 200 days for the 6.7 pH simulation. In this contribution only two sections were considered for the SSF assessment of building A, however any section can be analysed and the final SSF(t) would be the first one (section A-A' in this simulation) reaching a value of 1.

## 4. Conclusions

In this work a numerical approach to assess the safety conditions of geotechnical systems found in porous carbonate rock formations which are susceptible to weathering processes is presented. The approach requires the use of reactive transport of chemical species and an advanced strain hardening plasticity constitutive. Standard mechanical and advanced hydro-chemo-mechanical (HCM) experimental tests on the in situ rock are required to calibrate the evolution laws of the constitutive model which account for the hydro-chemical damage effects induced by weathering. The reactive transport of chemical species plays a fundamental role as it enables us to physically describe the spatial-temporal evolution of weathering. The numerical results show that weathering triggers a progressive failure of the porous rock causing large displacements at the ground level. Plastic strains begin to develop at the corners of the cavity by the partition wall and before they localize into a shear band, then a lot of stress redistribution develops within the rock. Such local failures can be very useful as collapse premonitory signs as they can start developing few months before failure and, at the same time, displacements are also recorded. A simple procedure to calculate the Service Safety Factor, *SSF* is used. The temporal evolution of horizontal strain and angular distortion are used to assess the time evolution of the *SSF* that, for the case study considered, attains a value of 1 well before the collapse of the cavity and sinkhole development. The numerical results also show how the failure mechanism is affected by the three dimensionality of the problem. Such result is important, if sinkhole design charts are defined using numerical simulations (Lollino et al 2019). Interestingly, despite the non-symmetric geometry of the two cavities, the subsidence basin assumes a circular shape, which is typical for the sinkholes observed in these rock formations.

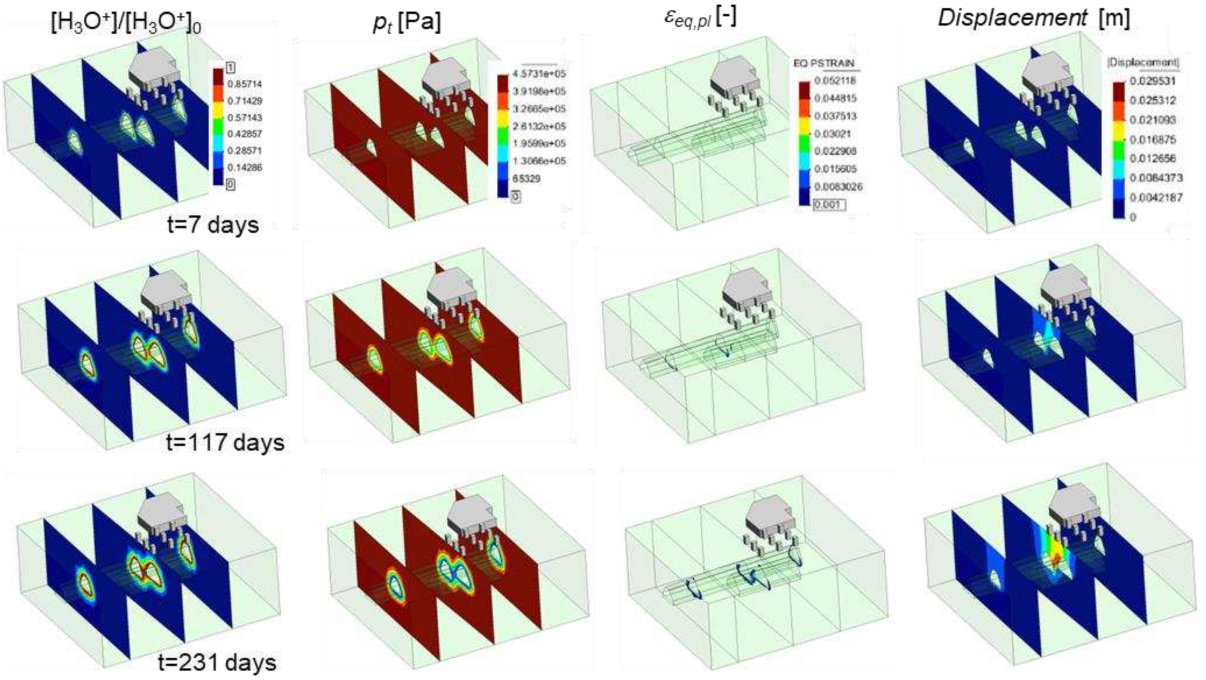
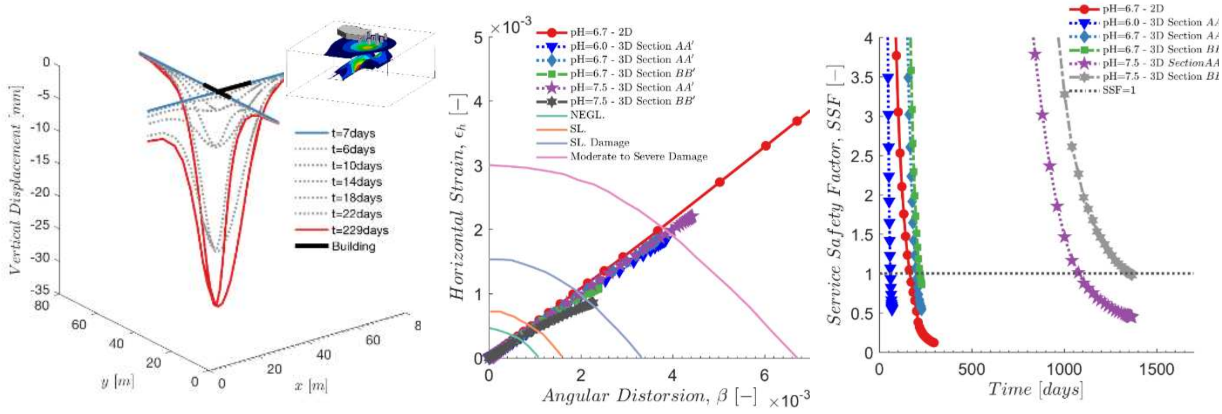


**Figure 5**: FEM results: Contour results by increasing time for the long-term weathering process (considering column): #1 evolution of [H3O+] contaminant; #2) internal variable related to bond strength $p_t$; #3) equivalent plastic strains; #4) displacement modulus.



a) b) c)

**Figure 6**: a) Displacement contours of 3D FEM results showing subsidence basin induced by partition wall failure and corresponding vertical displacements curves used to calculate SSF, b) Building angular distortion – horizontal strain paths for the 2D and 3D FEM simulations in the Boscardin & Cording (1989) abacus and c) corresponding temporal evolution of the Service Safety Factor, *SSF(t).*

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