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EVALUATION OF THE SEISMIC STABILITY OF UNDERGROUND CAVITIES IN NAPLES

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Abstract

The paper proposes a closed-form solution to preliminary assess the safety of the roof of shallow underground anthropic cavities in seismic conditions. The roof is modelled as a fully restrained beam element characterized by constant thickness and mechanical rock properties, loaded by a rotation of the restraint. The rotation is linked to the peak ground acceleration through the 1D wave equation of motion. The damage condition is assumed to be achieved when the loading moment is equal to the resistant moment in the extreme sections of the roof. According to the closed-form solution, the seismic load affects more the cavities characterized by the lowest ratio between the width and roof thickness, that are the safest under gravity loads. The formula is applied to a large number of underground cavities in Naples, in the south of Italy, detected and well characterized during an extensive urban-scale survey in Nineties. The results revealed that most of the cavities are expected to be damaged under the peak ground acceleration associated with a return period of 475 years.

Keywords: underground cavity, safety factor, 1D wave equation of motion, urban-scale seismic assessment.

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1. INTRODUCTION

In presence of seismic actions, underground cavities can be subjected to deformations in the overlying rocks/soils or in correspondence of the cavity pillars due to changes in the mechanical properties of rock/soil beneath. These mechanisms can produce local or global cavity instabilities, as well documented in the recent works [1] that carry out an Italian database of earthquake-induced instabilities in underground cavities, counting 97 instability events due to seismic actions (43 certain events and 54 uncertain events).

Overall, technical literature reports many events of cavity instabilities occurred during recent and historical earthquakes (e.g.[2][3]), reported also in some Italian database of co-seismic effects (i.e.,[4][5]).

This occurrence represents, from one hand, a risk for the cavity itself that is an abject exposed to the seismic risk and thus can be damaged, from another hand it represents a serious geotechnical hazard for civil constructions and urban development that can be enter in interaction with areas influenced by cavity damages/collapse after an earthquake, especially in densely urbanized and historical areas where many structures, infrastructures, strategic and historical monuments are located and thus more exposed to seismic risk ([6][7]).

In similar urban environments like many Italian ones, it is very appealing the possibility to adopt simply methods to preliminary asses the seismic stability of cavities in seismic conditions at areal scale, especially in consideration of the fact that this issue is little covered in the technical literature from engineering point of view.

With this aim, the present work proposes a simplified closed-form solution for rectangular single cavity for which the roof is modelled as a fully restrained beam element characterized by constant thickness and mechanical rock properties. The proposal represents an attempt to frame the problem at territory scale (e.g. urban scale) to detect the vulnerability of the selected area to cavity collapse risk under seismic action for both planning and management issues and to plan subsequent insights.

The procedure is well described in §2, bearing in mind the limitations in the applicability of the method connected to the basis hypothesis. Anyway, they can be considered a sufficient and acceptable approximation for the considered problem scale and for the expected use (i.e. preliminary assessment).

The city of Naples, in the south of Italy, was selected as case study since it turned out very interesting for the relevant presence of cavities in the subsoil. Furthermore, in most cases the cavities are rather shallow and this condition made the cavities more vulnerable to the seismic actions compared with deeper ones. The application of the proposed method, limited to the case study, puts in evidence that (i) the seismic load affects more the cavities characterized by the lowest ratio between the width and roof thickness, that are the safest under gravity loads.

2. THE UNDERGROUND CAVITIES IN NAPLES

The shallowest subsoil of Naples is characterized by a pyroclastic rock, namely tuff. Since in many areas of the town tuff outcrops or is at a rather shallow depth, it has been excavated since very old times. Nowadays a dense network of more than 900 cavities is known underneath the city, for a total excavated volume of tuff of about 7106 m^3, and new cavities are currently found, indicating an even larger underground world [8].

Figure 1 (a) shows a schematic cross section of a typical Neapolitan cave. A layer of cohesionless (mostly pyroclastic) soils is typically on the top of the tuff mass with a thickness p variable between 5 and 25 m. The roof is close to be flat and the walls are generally vertical or slightly inclined.

Figure 1 (b) shows some statistics for 123 cavities inspected during an extensive survey in 2000. The span length L mostly ranges from 2 m to 8 m, the thickness of the tuff on the roof, t, is typically low, between 1 m and 6 m, leading to a ratio L/t mostly varying between 1 and 6.

The height, h, is generally comparable to the sum of the thickness of the roof and the upper loose soil.

(a) (b)

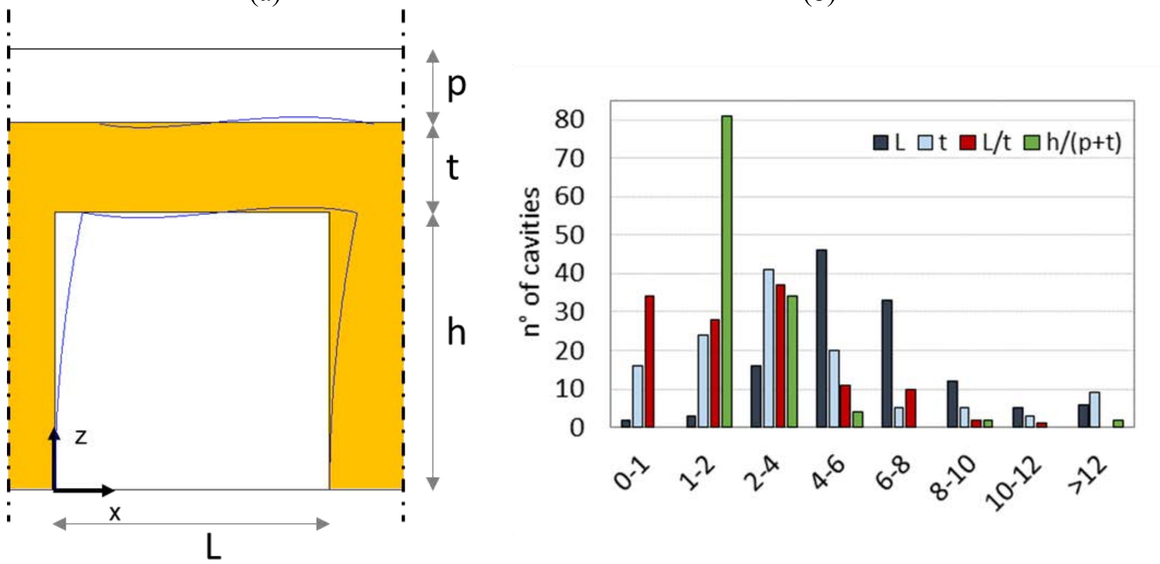


Figure 1: Typical geometric layout of an underground cavity in Naples (a) and cavity statistics from available geometric data (b).

3. METHOD OF ANALYSIS

The safety of the cavity roof under gravity loads is usually assessed in literature with reference to the idealized equivalent fix ended beam in Figure 2, characterized by the same span length L and thickness t of the roof and supporting a uniformly distributed load equal to the vertical lithostatic stress at the same depth of the cavity ceiling, σ_{vR}. The latter includes the weight of the equivalent beam and the weight of the loose soil covering the rock.

(a) (b)

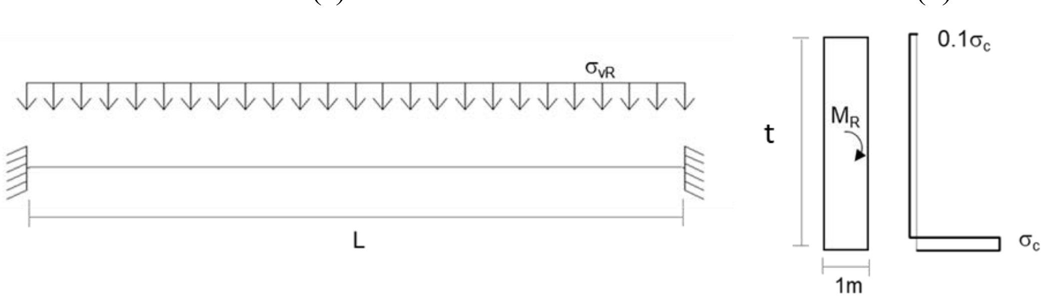


Figure 2: Equivalent beam model (a) and strength distribution for the calculation of the resistant moment (b) of the cavity roof.

In this loading condition, the bending moment acting on the equivalent beam is maximum at the extremities and increases during the earthquake, because the extremities are forced to rotate, as shown by the qualitative deformed cavity shape in Figure 1a.

The amount of the rotation can be estimated by exploiting the well-known 1D wave equation of motion:

$$V_S^2 \frac{d^2u}{dz^2} = \frac{d^2u}{dt^2} \quad (1)$$

in which V_S is the rock shear wave velocity while the other terms are the second order derivative of the displacement, u, with respect to the depth, z, and the time, t.

Assuming that the acceleration is constant in the time, as usual in pseudo-static analyses, the right-side term is constant and equal to PGA.

The rotation at a depth equal to the cavity roof, i. e. z=(t+p), obtained from the integration of equation (1), results in

$$\theta = \frac{PGA}{V_S^2}(t+p) \quad (2)$$

The increment of the bending moment ΔM associated with the simultaneous rotation of both extremities is consequently equal to:

$$\Delta M = \frac{6EI}{L}\theta = \frac{Et^3}{2L}\frac{PGA}{V_S^2}(t+p) \quad (3)$$

in which E is the Young modulus of the rock, $I=t^3/12$ is the moment of inertia of the cavity roof and θ is the rotation coming from eq. (2).

By writing E as a function of the shear modulus G and the Poisson coefficient ν as well as V_S as a function of G and the density ρ, equation (3) becomes

$$\Delta M = (1+\nu)\frac{t^3}{L}\rho(t+p)PGA \quad (4)$$

The total moment acting on the beam extremity is therefore

$$M_S = \frac{\sigma_{vR}L^2}{12} + (1+\nu)\frac{t^3}{L}\gamma(t+p)\frac{PGA}{g} \quad (5)$$

where the rock unit weight γ and the gravity acceleration g are introduced instead of ρ.

The term $\gamma(t+p)$ in equation (5) is the lithostatic stress at a depth equal to that of the cavity ceiling, σ_{vR}. By introducing $\gamma(t+p)=\sigma_{vR}$; equation 5 becomes

$$M_S = \sigma_{vR}\left(\frac{L^2}{12} + (1+\nu)\frac{t^3}{L}\frac{PGA}{g}\right) \quad (6)$$

To prevent the failure of the beam extremities, M_S needs to be compared with the resistant moment, M_R. This last can be estimated according to the equilibrium of the section in Figure 1b:

$$M_R = \sigma_c \frac{t^2}{22} \quad (7)$$

where the tensile strength is equal to 1/10 of the compression strength, σ_c [8].

The section failure is achieved when the ratio between the resistant and loading moment is equal to one. Such condition leads to the following expression:

$$\frac{\sigma_c}{\sigma_{vR}} = 22\frac{t}{L}\left(\frac{1}{12}\left(\frac{L}{t}\right)^3 + (1+\nu)\frac{PGA}{g}\right) \quad (8)$$

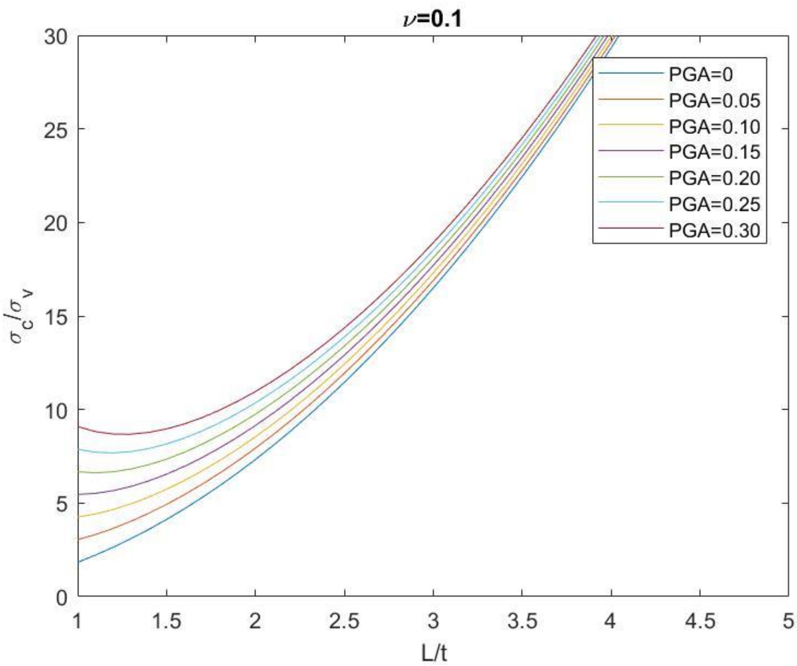
Equation 8 represents the cavity stability curve that distinguishes the safe (area above the curve) from the unsafe (area below the curve) condition.

Figure 3 shows the predictions of the Equation 8 for different values of ν=0.2 and PGA expressed in g. The selected ranges of L/t are the most representative of the geometric features of the Neapolitan cavities as discussed in §2 (see Figure 1). The curve associated to PGA=0 refers to the stability under gravity loads.

The seismic increment of the critical σ_c/σ_v ratio increases with the PGA and it is higher for the lowest L/t ratio and tends to the curve at PGA=0 when L/t increases. This trend makes the cavities that are safer under gravity loads to be the most affected by the seismic actions.

Conversely the effect of the Poisson coefficient is secondary.

It also should be noted that the considered mechanism is a local mechanism that does not lead to the global instability of the cavity roof, for which the additional failure of the central section is needed. The mechanism can be consequently intended as a damage state since it deteriorates completely the rotation restraints at the extremities.



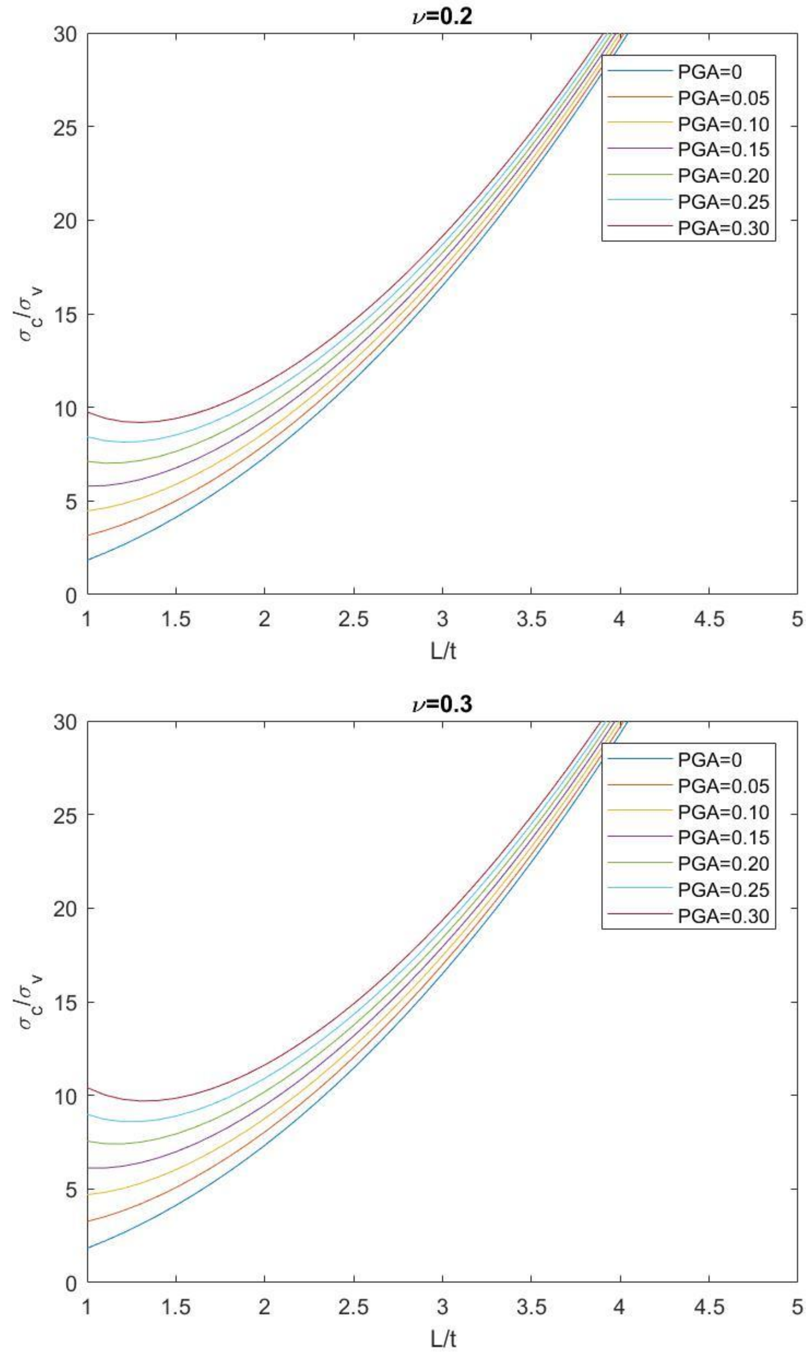


Figure 3: Variability of the cavity stability curves with the L/t, ν and PGA.

4. EXAMPLE OF APPLICATION

Figure 4 compares the stability curve provided by the proposed closed-form-solution described in Section 3 to that obtained by Evangelista et al. (2000) [8] and by de Silva et al. (2023)[9]. [8] modelled the roof through an arch scheme and applied a limit equilibrium analysis to derive the critical σ_c/σ_v ratio, while [9] executed finite difference analyses to several cavities in jointed rock to derive the stability curves for different probability of failure, p_f. The stability curve proposed in this study is significantly more conservative than that proposed by [8] and quite close to that proposed by [9] for p_f=10%. Such difference depends on the facts that this study considers the failure of the extreme roof sections that does not correspond to the collapse of the roof analyzed by the other referenced studies.

The black line is the minimum σ_c/σ_v ratios provided by Equation 8 for the PGA=0.17g expected in Naples with a return period of 475 years. If the obtained minimum σ_c/σ_v ratio is lower than the σ_c/σ_v ratio acting in the roof, the cavity extremities are expected to be safe, otherwise, they fail. The green markers plot the cavities resulted safe, while the red ones are associated with the unsafe. The plot shows that most of the cavities are expected to be damaged in seismic conditions.

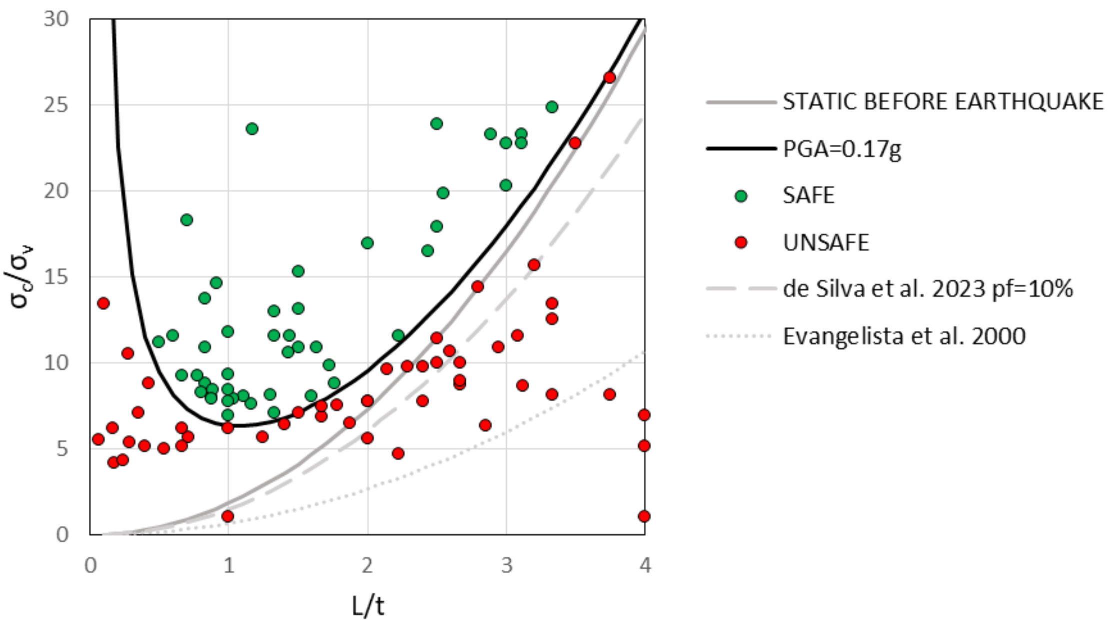


Figure 4: Case study: application of the proposed closed-form-solution to assess the safety condition of some Neapolitan cavities.

5. CONCLUSIONS

The paper derives a closed form solution to quantify the minimum σ_c/σ_v ratio to prevent the failure of the extreme sections of the roof of a rock cavity in static and seismic conditions. Such mechanism can be interpreted as a significant damage for the roof but does not correspond to its full collapse. As expected, the curve obtained in the σ_c/σ_v – L/t plane for the static conditions is more conservative with respect to the others existing in literature and associated with the full collapse of the roof. The minimum σ_c/σ_v ratio in seismic conditions increases with respect to the static case with increasing the PGA and with reducing the L/t ratio. This means that the lowest L/t ratio, generally safe in static conditions, are the most prone to be affected by earthquake. The formula herein proposed represents a simple yet sound tool for a first investigation at the urban scale.

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