6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch, New Zealand

Site effects due to the presence of cavity near the cliffs

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ABSTRACT

The paper reports a numerical evaluation of seismic site effects from an underground cavity in Sant'Agata de' Goti, a typical medieval town of south Italy, perched on a tuff ridge. The cavity, located along the edge of *Martorano* ridge and interconnected to the historical center, was analyzed with the 2D FLAC code. A dynamic analysis was carried out with seven spectrum compatible accelerograms according to Italian code. In order to distinguish the site effects, the analysis was done with and without the cavity. From comparison of the two cases, expressed by maximum acceleration on the ground surface, it was observed that the presence of the cavity leads to higher acceleration towards the edge of the cliff with respect to a 1D analysis and to simplified procedures according to the Italian National code.

Introduction

Seismic and landslide hazards affect the historical towns in the Central-Southern Italy resting on soft rock slabs, lying on thick deformable soil layers (Fenelli et al. 1988). In many of such towns, the rocky ridges are crossed by anthropic cavities which affect their static and seismic stability. The aim of the paper is to evaluate the site effects due to surface topography and due to the presence of the cavity systems, referring to the case study S. Agata de' Goti (Figure 1a), perched on the top of a steep ridge crossed by numerous cavities. The National seismic hazard map (MPS working group, 2004) specifies a moderate amplitude of the reference ground motion, i.e. a peak ground acceleration a_g=0.16g on a stiff rock outcrop with a return period of 475 yrs (Figure 1b). Nevertheless, significant topographic amplification due to the site morphology is expected. Thus, in this study dynamic analyses using a 2D model of the ridge were first performed neglecting the cavities. To evaluate the topographic and stratigraphic effects, the results were compared with those obtained using simplified 1D equivalent linear analyses carried out in previous works (de Silva et al. 2013; Scotto di Santolo et al., 2014). The variation of the surface and in-depth ground motion was then analyzed introducing in the 2D model the presence of a cavity.

Subsoil characterization

The rock formation constituting the ridge of Sant'Agata is the Campanian Ignimbrite in its

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yellow and grey tuff lithofacies, lying on a thin loose layer of pyroclastic soil and a Miocene flysch formation (Figure 2b). The 160 hypogean cavities detected in the historical centre (Figure 2a) were excavated for the extraction of the yellow tuff (LYT) and mainly utilized as storage.
The interaction between cavity, foundation and building is more hazardous along the Martorano creek, where most of the cavities directly overlook the valley (Figure 1a). Their precarious stability is testified by the damages, consisting of block detachment from the roof and the walls, that occurred during the 1980 Irpinia earthquake (de Silva et al., 2013).

The subsoil model proposed was based on a comprehensive investigation carried out through the whole historical centre in 1994, when 40 boreholes, georadar measurements and down-hole tests were performed. The boreholes, drilled down to 40 m, intercepted about 4 m of made ground, sometimes mixed to pyroclastic soil (MG-PS), about 10 m of Lithified Yellow Tuff (LYT) and the Welded Grey Ignimbrite (WGI), without reaching the Miocene flysch formation (MFF). Both the grey and the yellow tuff lithofacies are crossed by joints belonging to various sets, which are evident along the slopes of the cliff (Figure 2c) and inside the cavities. The discontinuities are partly syngenetic (i.e. the result of the sudden cooling of the volcaniclastic formation), partly related to mechanical processes, such as stress relief due to the proximity to the slopes, excavation and overburden load. A total of 64 discontinuities were detected in the cavities and interpolated in the equal angle or stereographic projection (Figure 2d).

1D and 2D seismic response analyses

A typical cavity, located along the western cliff of the town and indicated with a red square in Figure 1, was studied. Figure 3 reports the plan and sections of the cavity that extends over an area of 130 m^2 below an ancient building. It comprises three main rooms (A, B, C), one tunnel and two stairwells, accessed from the superstructure and reaching the main rooms at different elevations. The roof of room A is a lowered vault presenting a cylindrical well, covered with tuff bricks. The tunnel is 3 m wide and 3.4 m high and extends for about 20 m parallel to the slope, connecting the two main rooms A and B. Due to its regular shape, plane strain static and dynamic analyses were performed on the section A-A of the tunnel (Figure3b) with the finite difference code FLAC 2D (Itasca 2007).

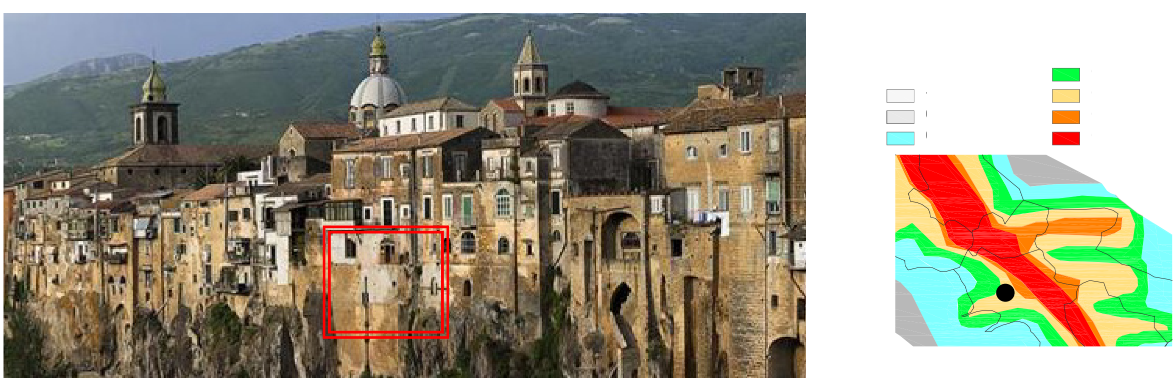

Figure 1. Sant'Agata de' Goti: western cliff (a), location on the Italian seismic hazard map (b).

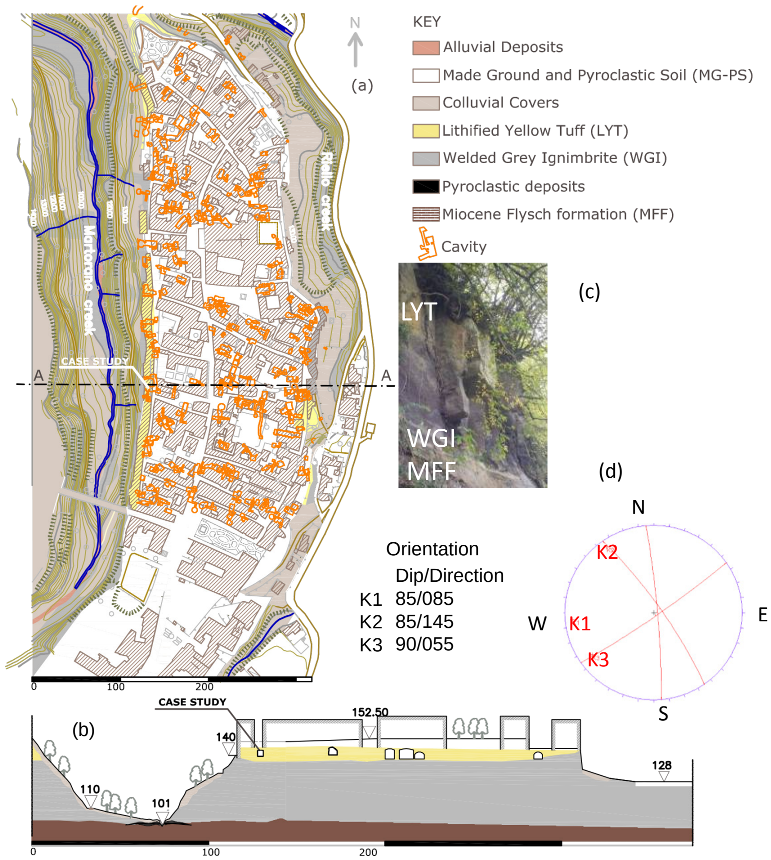

Figure 2 - Geological map showing the location of the cavities (a); A-A stratigraphic section (b); picture showing the typical aspect of the cliff (c); families of discontinuities (d).

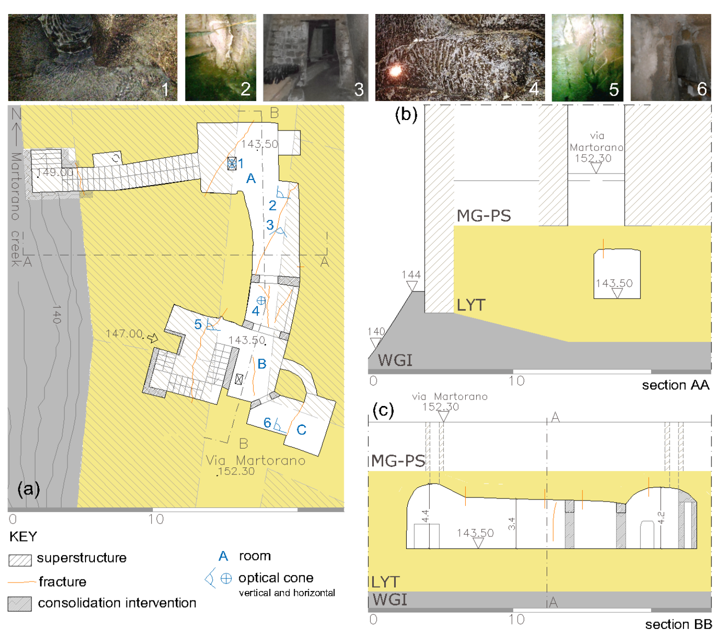

Figure 3. Plan (a), sections (b and c) of the studied cavity.

The model was limited in depth to the LYT assuming a rigid base as shown in Figure 4b and considering the superstructure as an overburden load. The initial stress state was evaluated by assuming a value of the coefficient of earth pressure at rest, k_0, equal to (1 - sinφ) for the MG-PS formation and (ν/(1-ν)) for the rock. The rock mass was assumed to be continuous with an elastic - perfectly plastic behavior following the Mohr-Coulomb failure criterion. The parameters used for the rock and soil are shown in Table 1. The volumetric bulk modulus, B, and the shear modulus, G_0, were derived from the P and S wave velocities resulting from down-hole tests. The unit weight, γ, and the uniaxial compression strength, σ_c, were taken equal to the mean values measured on 21 samples; whereas, the tensile and shear strength parameters (σ_T, c and φ) were derived from typical values reported in the literature for pyroclastic weak rocks (Aversa and Evangelista, 1998) and for pyroclastic soils (Picarelli et al., 2006). The results of the static stability condition was reported in Scotto di Santolo et al. (2014).

Table 1. Mechanical parameters adopted in the numerical model.

Soil	γ (kN/m^3)	σ_c (MPa)	σ_T (MPa)	φ (°)	c (MPa)	V_P (m/s)	V_S (m/s)	G_0 (MPa)	B (MPa)
MG-PS	14,9	-	-	33	0,1	435	211	70	198
LYT	15,2	4	0,1	29	0,9	886	556	480	579

The dynamic analyses were subsequently addressed to investigate the stability conditions and site effects, expressed by the acceleration amplitudes in two cases: with and without cavity. In order to minimize the effects of wave reflection, the model was widened inwards the ridge and an absorbing ‘quiet’ boundary was assumed. Rayleigh damping was assumed for the LYT formation, considering a damping ratio D = 5% corresponding to the frequency f = 1Hz. The input motion at the base of the 2D model was computed from one-dimensional seismic response analyses using the EERA code (Bardet et al., 2000), as illustrated in Figures 4a and 4b.

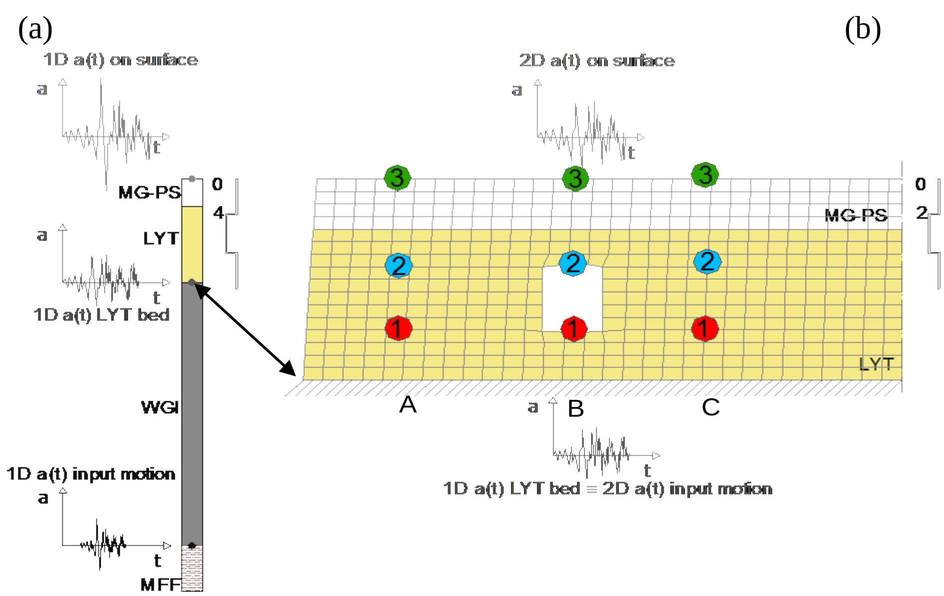

Figure 4. 1D (a) and 2D (b) models for the dynamic analyses.

The seismic response analyses were performed using the shear wave velocity profile shown in Figure 5b, provided by the Down Hole tests. To model the non-linear and dissipative behaviour of the soils, the variation with the shear strain, γ, of the equivalent shear modulus, G (normalized with respect to its small strain value, G_0) and the damping ratio, D, were taken from literature data (de Silva et al., 2013).

According to the disaggregation map annexed to the MPS (Spallarossa & Barani, 2007), the local seismic hazard is caused by two ranges of magnitude ($5.5 < M_L < 6.0$ and $6.5 < M_L < 7.0$) and epicentral distance (10km < R < 20km and 20km < R < 30km) corresponding to two seismogenic sources. Referring to the ranges M_L =5.5-7.0 and R=10-30 km, seven spectrum-compatible accelerograms were selected from the Italian Accelerometric Archive (Pacor et al., 2011) through the Rexel code (Iervolino et al., 2009). The record properties are listed in Table 2, while in Figure 5d the mean response spectrum at 5% structural damping is compared to that specified by the National Technical Code (NTC, D.M. 14/1/2008) for soil class ‘A’. Figure 5c shows the vertical profiles of the maximum acceleration, a_{max}, induced by the selected earthquakes. Due to the stratigraphic amplification, the seismic motion increased gradually in the tuff formation, and sharply across the loose soil cover, attaining an average value of 0.27*g* at the ground surface.

Table 2. Properties of the selected records.

Earthquake	M_w	Date (day/month/year)	Station	Epic. distance (km)	Comp.	Median Period (s)
Irpinia	6.9	23/11/1980	ALT	24	WE	0.52
Gran Sasso	5.4	09/04/2009	ANT	23	NS	0.54
Val Comino	5.9	07/05/1984	PNT	27	WE	0.49
Umbria-Marche	5.6	14/10/1997	CSC	22	NS	0.44
Friuli	5.6	11/09/1976	SRC	26	NS	0.50
Irpinia	6.9	23/11/1980	BSC	28	NS	1.16
Val Nerina	5.8	19/09/1979	ARQ	21	NS	0.25

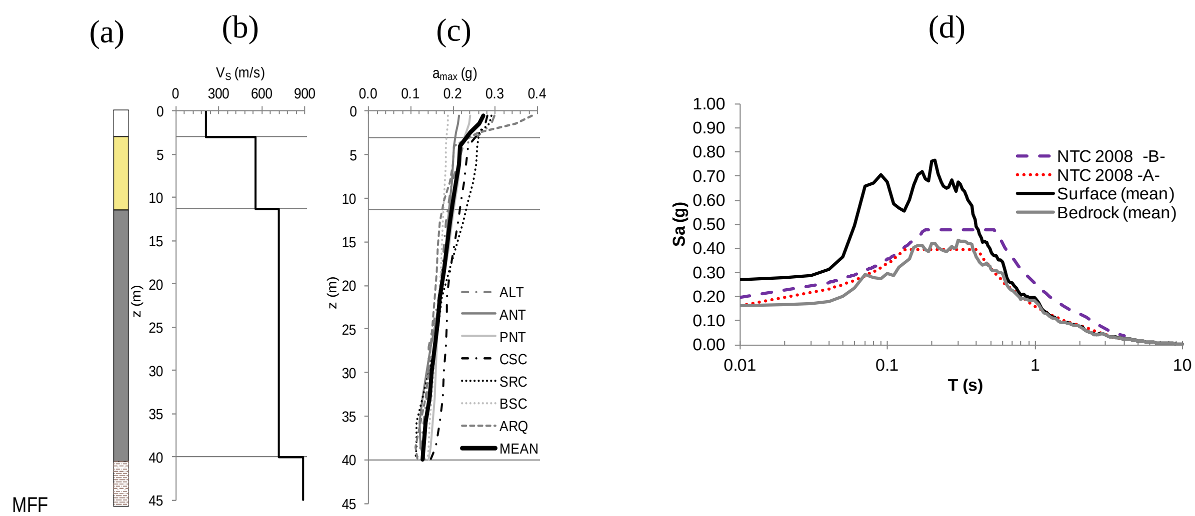

Figure 5. Layering (a) and V_S profile at the site (b) and peak acceleration profiles resulting from the different input motions (c). Mean spectra resulting from the seismic response analyses and mean reference input motion (bedrock) compared with the NTC spectra for class A and B (d).

Figure 5d shows the average response spectrum at the surface, resulting from the s.r.a., compared to the mean input spectrum and that specified by NTC for a soil class 'B', corresponding to the shear wave velocity profile in Figure 5b. It is worth noting that the latter underpredicts the spectral ordinates for a period *T* lower than about 0.4 s, while it overestimates the expected ground motion for higher periods.

2D Dynamic results

The results of the dynamic analyses are reported here for the SRC input, which produces the maximum acceleration at the interface between the grey tuff (WGI) and yellow tuff (LYT) in the 1D analysis, in Figure 5c, utilized as input in the 2D analysis.

Figures 6a and 6b show the comparison of the results obtained in the 2D analyses with and without the cavity. Figure 6a shows the iso-contours of the amplification factor, in terms of the ratio between the acceleration amplitude at a generic time and the input value. It is observed that the presence of the cavity modifies the iso-contours; in detail, the void causes a higher amplification of the acceleration towards the edge of the slope and an increase of the zones with comparable acceleration.

Figure 6b reports the profile of the maximum accelerations attained on the surface during the earthquake in the presence (Surf. 2D cav.) and in absence (Surf. 2D no cav.) versus the maximum acceleration from the 1D analysis (Surf. 1D). Comparing 1D and 2D results, the increase of the seismic acceleration due to the topographic irregularities can be clearly recognized. As expected, the trend of the maximum accelerations on surface is attenuated where the cavity is located, according to the studies by Landolfi et al. (2011). It is observed that the topographic amplification factor of the peak accelerations at the edge of the slope (obtained as the ratio $a_{max,\ 2D}$ / $a_{max,\ 1D}$) is equal to 1.20 and 1.38 respectively for the cases without and with the cavity; in the first case, it is therefore equal to that specified by the National code (DM 14/1/2008) for these geometric conditions.

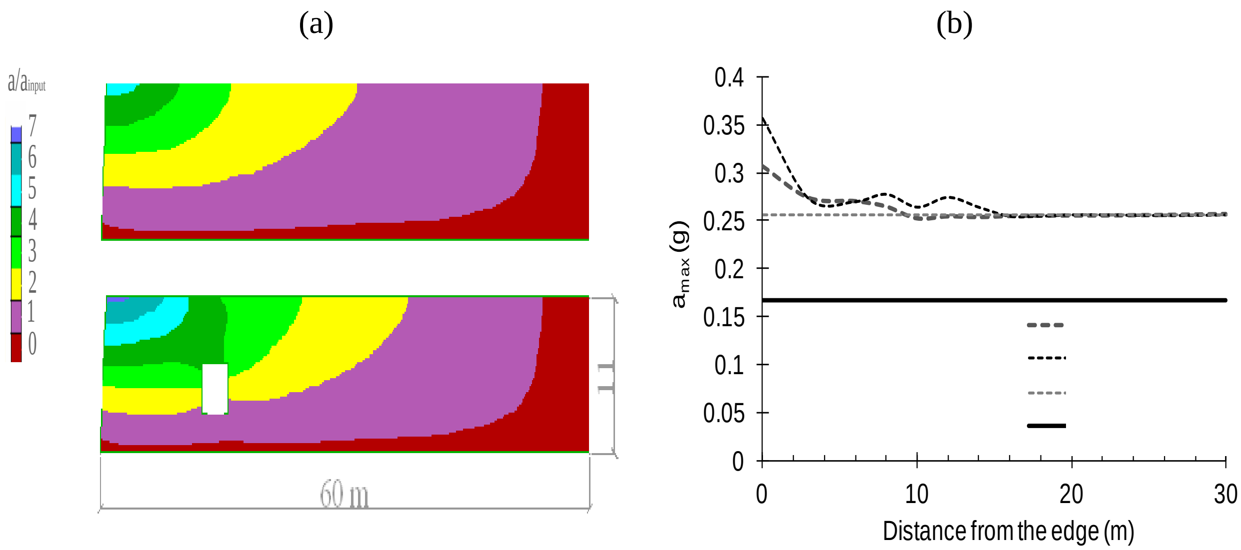

Figure 6. Isocontours of the acceleration at the same instant (a) and a_{max} on surface in 1D and 2D conditions along the distance from the edge (b) without and with cavity.

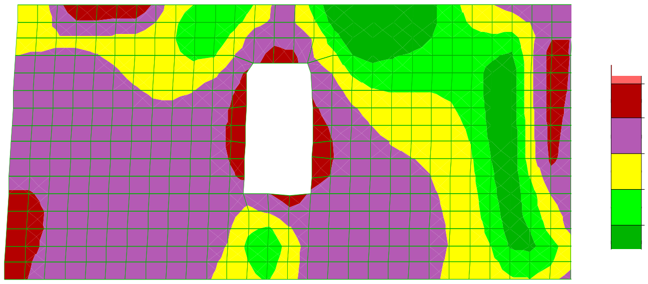

Figure 7. Strength to stress ratio (SF) in the LYT after theearthquake.

Finally, Figure 7 shows the safety factor SF (evaluated as strength to stress ratio) at the end of the earthquake. It is observed that critical conditions are reached mainly along the vault and the cavity walls and locally at the foot of the slope.

Conclusions

Sant'Agata de' Goti is a small town resting on a rocky relief between two creeks, where many anthropic cavities, due to tuff quarrying activities, are present. The tuff roof is only few meters deep, so that the open-pit excavation technique adopted led to a building heritage strictly connected to the underlying cavities.

The research is focused on the investigation of the static and seismic stability conditions of a typical cavity, located close to the edge of the cliff. After the collection and the interpretation of the geological and geotechnical data, static, pseudo-static and dynamic analyses were carried out. The static analyses, carried out by continuous and discontinuous rock mass models, confirmed that the fissuring pattern observed in the field affects the instability mechanisms of the cavity vault (Scotto di Santolo et al. 2014). The seismic response in presence of the cavity, simulated using the FLAC code, was significantly affected by the complex interaction between the presence of the void and the proximity to the rock cliff.

The interplay between the different factors can therefore significantly affect both the stability of the slope and the seismic actions on the overlying buildings. This study was focused mainly to evaluate the entity of the amplification induced by the presence of the cavities near the cliff. Starting from the static condition, the dynamic analyses were carried out with seven spectrum-compatible accelerograms according to the Italian code. Preliminary one-dimensional linear equivalent analyses were carried out in order to evaluate suitable input motions at the interface between the two rocky formations assumed as the base of the numerical model. The analyses highlight that the cavities near the cliff induce higher amplifications in terms of peak ground acceleration compared with the analysis carried out without the cavity. A reduction of the acceleration in the area on the top of the cavity and amplification at distance from the cavity centre was observed, due to the geometry of the problem rather than the dynamic input (frequency content, energy, see Table 2).

Further analyses are currently in progress to consider the whole hill and the presence of other cavities with constitutive models based on laboratory investigations. Moreover, additional work is needed in order to find a methodology for assessing the stability conditions of the cavity considering the interaction with the superstructure.

Acknowledgements

The authors warmly thank the owners of the cavity, mr and mrs Viscusi, who kindly allowed this study.

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