The role of underground cavities on ground motion amplification

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SUMMARY:
Subsurface cavities represent mechanical discontinuities for the seismic wave propagation. They can modify the propagation pattern of seismic waves and alter soil response in correspondence to building foundations or ground level. In literature, different analytical and or numerical solutions have been proposed to describe the effect of underground cavities or inclusions on the ground motion generated by P, S or R waves. In these former studies, the subsoil is assimilated to a homogeneous, isotropic and linear elastic halfspace containing one or more cavities. In the present study the effect of subsurface cavities on ground motion amplification has been analysed accounting for the nonlinear behaviour of soil. Furthermore, the propagation medium is a stratified subsoil with a hill shape. The analysed model was inspired to a real case represented by the village of Castelnuovo in Italy, which during the April 6th, 2009 Abruzzo mainshock suffered huge damage. Castelnuovo is located on a hill. In its subsoil there are many cavities with roofs 2-3 m below the ground level. The longitudinal NW-SE section of the hill has been investigated by 2D nonlinear site response analysis. A preliminary analysis was performed without modelling cavities, to detect ground motion amplification due to mere stratigraphy and topography factors. The numerical model was later refined inserting: (i) a single cavity, (ii) multiple cavities placed below the hill surface, (iii) multiple cavities filled with concrete.

Keywords: site response analysis, underground cavities, ground motion amplification.

1. INTRODUCTION

In the present study the effect of subsurface cavities on ground motion amplification has been analysed by referring to the real case of Castelnuovo village (Italy), which during the April 6th, 2009 Abruzzo earthquake suffered huge damage. Castelnuovo is located on a hill at around 800 m a.s.l.; its subsoil has been deeply investigated soon after the Abruzzo earthquake to produce microzonation maps for reconstruction planning (Working Group, 2011). In its subsoil there are many underground cavities which have been enlarged in the years by the inhabitants and used as cellars. Since the roofs of these cavities are very close to the ground surface (typically 2-3 m below the ground level), some of them collapsed during the main shock of the Abruzzo earthquake, thus contributing to increase the level of structural damage observed in the village. The estimated MCS intensity was IX-X grade.
The paper describes the 2D numerical model developed to analyse the seismic response of the longitudinal section of Castelnuovo hill, accounting for the presence of underground cavities. This study differs from the previous ones since: (i) soil nonlinearity has been accounted for by the equivalent linear technique; (ii) the subsoil is not homogeneous with respect to stiffness; (iii) the free surface of the domain is not horizontal and topography effects occur as well. All these factors could make the results obtained in this study not immediately and easily comparable to most of the theoretical studies present in literature.
For reference, a preliminary site response analysis without modelling cavities was performed to evaluate ground motion amplification due to stratigraphy and topography factors. The numerical model was later refined inserting: a single cavity, multiple cavities placed below the hill surface, multiple cavities filled with concrete (inclusions), a concrete carpet connecting all cavities.

2. STATE-OF-THE-ART

Subsurface cavities or inclusions represent mechanical discontinuities for the seismic wave propagation. They can modify the propagation pattern of the seismic waves and, hence, soil response in correspondence of building foundations or ground level. In literature different analytical and/or numerical solutions have been proposed to describe the effect of underground cavities on the ground motion produced by both volume (P, S) and surface waves (R). In all former studies, the subsoil is assimilated to a homogeneous, isotropic and linear elastic (infinite)half space containing one or two cavities.
One of the first studies on such an issue is by Pao & Mow (1973), who studied the diffraction mechanism caused by a cylindrical tunnel embedded in an ideal infinite elastic medium, subjected to the horizontal (anti-plane) component of the S wave. The main goal of the former researches on cavities is to provide indication for the design of underground pipes and tunnels under SH waves (these structures are rarely designed to withstand the transverse loads due to the SV component (in-plane) of the shear wave). Dravinski (1983) reports a review on ground motion amplification caused by elastic inclusions in a halfspace. Wong et al. (1985) show that when P, SV and Rayleigh waves are incident on embedded cavities or inclusions, the surface displacements can be significantly modified by the "obstacle": the shape, size, orientation and depth of cavities below the ground level contribute towards the amplification of the motion at the surface. Moreover, it was found that scattering by more than one inclusion can change considerably the ground motion at the free surface. Lee (1988) analysed the 3D elastic diffraction caused by a cavity in a halfspace.
Recently Smerzini et al. (2009) presented a theoretical approach to study the anti-plane seismic response of inclusions or cavities considering the incidence of plane or cylindrical SH waves. The analytical solution is obtained using expansions of wave function by Bessel and Hankel series. The effects of underground cavities on surface earthquake motion are studied as a function of the size of the cavity, its embedment depth, the frequency content of excitation, the incidence angle and the distance from the axis of symmetry of the cavity itself. They found that the surface ground motions are controlled by the vibration modes of the portion of soil between the cavity and the free surface. An approximate relationship for the fundamental vibration frequency as a function of the ratio of the cavity embedment depth to the radius of the cavity itself has been provided. It turns out that the dominant wavelength associated with the fundamental vibration mode is about 6 times the cavity embedment depth, i.e. it is dependent only on the geometry of the problem at hand. The work by Smerzini et al. (2009) is limited to SH wave propagation. For SV and P wave incidence, the maximum amplification at the surface is expected at larger horizontal distance (about 3 times the characteristic dimension of the cavity) from the cavity centreline.
As stated above, all theoretical studies available in literature do not account for factors which could be important from an engineering point of view in regulating seismic site response, such as soil nonlinearity, stiffness inhomogeneity, topography effects. All these factors could make the results obtained by solving a more complex boundary value problem not immediately and easily comparable to the available theoretical solutions, obtained assuming simplified hypotheses on the domain subjected to the seismic wave propagation.

3. CASE-HISTORY AND NUMERICAL MODEL

3.1. Castelnuovo

At 3:32 am of April 6th, 2009, the city of L'Aquila and its surrounding region were shocked by a strong earthquake.
According to the National Institute of Geophysics and Volcanology (INGV), the main event has been generated by a normal fault (NW-SE) with magnitude M_L=5.8 and M_W=6.3. The city of L'Aquila and the border villages of the Aterno valley (SE of L'Aquila) were affected by huge damage.

Castelnuovo (800 ÷ 860 m a.s.l.) is a hamlet of San Pio delle Camere municipality (Figure 1). It lies at about 22 Km far from the epicentre. The old village is settled on a hill, elongated in the NW-SE direction, and rising 60 m above the surrounding alluvial plain. It was one of the most damaged sites after the main shock of the Abruzzo earthquake (I_{MCS} IX-X). In the historical centre some underground cavities collapsed (the roofs are typically 2 ÷ 3 metres below the ground level), so that the sinking of the ground level contributed to increase the level of damage observed in the historical centre, where most of buildings are made of poor un-reinforced masonry.

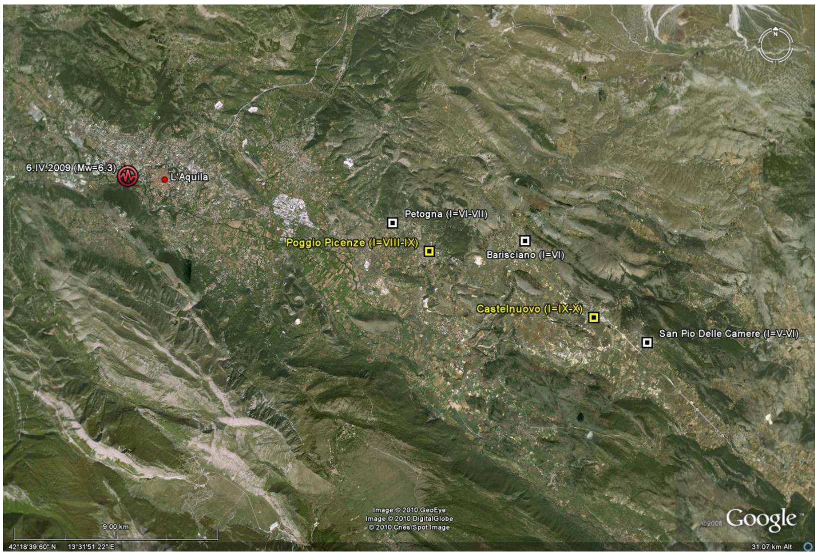

Figure 1. Location of Castelnuovo in the epicentral area of the Abruzzo earthquake (2009).

About 2 months later the main shock of the Abruzzo earthquake, the Italian Civil Protection Department promoted a Seismic Microzonation study (WG, 2011) on about 30 towns within the Aterno Valley. These studies were based on detailed geological, geophysical and geotechnical investigations. Data were also integrated with few stratigraphic logs already available from previous studies. The geological map and the longitudinal (WNW-ESE) section produced by the WG (2011) for Castelnuovo are reported in Figures 2 and 3, respectively. It could be observed that the subsoil is primary made of a white carbonate silt (L), also called “Creta Bianca”, resting on a thin layer of breccia (B) and finally on a stiff calcarenite (M), representing the bedrock formation. In the lower parts of the hill, thin layers of debris (d) and terraced alluvial deposits (b3) may also be found. For the microzonation study (WG, 2011), a very accurate geotechnical characterization of the white silt was achieved by performing down-hole measurements to obtain Vs and cyclic torsional shear (CTS) tests on undisturbed blocks to obtain the nonlinear soil behaviour in terms of variation of the normalised shear modulus, $G(\gamma)/G_0$, and damping ratio, $D(\gamma)$, with the shear strain (Figure 4).
The silt deposit (L), due to its lacustrine origin, is characterized by a shear wave velocity V_S significantly increasing with depth, starting from a value of 300 m/s at the surface up to 600 m/s at a depth of about 200 m below the ground level.
Below the free surface of the hill, underground cavities may be found. This happens for Castelnuovo village as well as for other surrounding towns like San Pio delle Camere, Poggio Picenze or the city of L’Aquila itself.
As can be seen from Figure 5, in Castelnuovo cavities are mostly concentrated in the historic centre of the village, i.e. at the top of the hill, and are almost perpendicular to its longitudinal (NW-SE) section. For this reason, this cross section has been considered in the numerical study described henceforth. The embedment depth of the cavity roof varies between 2 ÷ 4m below the ground level. The inspected cavities typically have cross sections of 3m (height) x 5m (width). The relative spacing between cavities varies between a few meters up to 17 m. In some cases, cavities are so close each other to become a unique system (see, for example, cavities C_{XI}, C_{XII}, C_{XIII} in Figure 5).
The plan extension and number of cavities shown in Figure 5 should, therefore, be intended as an underestimation of the real data. Many cavities are still unknown, as they are cellars of private houses and, for this reason, difficult to catalogue and inspect.

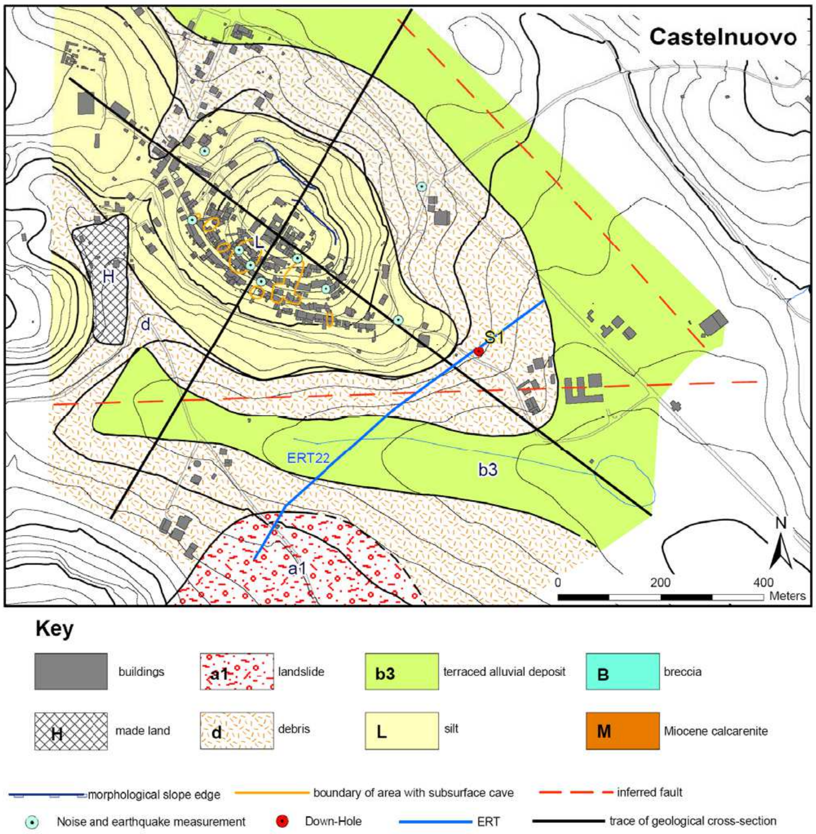

Figure 2. Castelnuovo: geological map (WG, 2011)

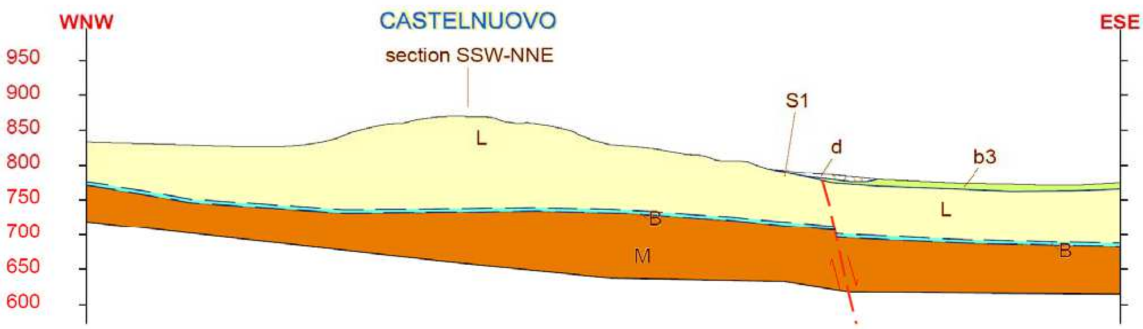

Figure 3. Longitudinal cross-section (WG, 2011)

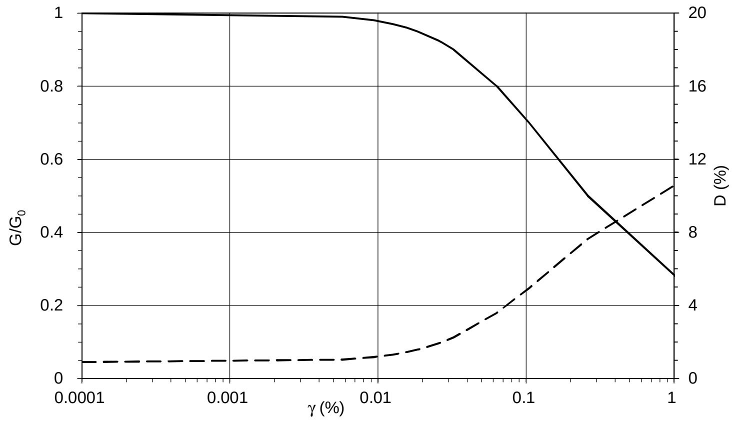

Figure 4. Experimental nonlinear behaviour of the white silt (L) present in the subsoil of Castelnuovo

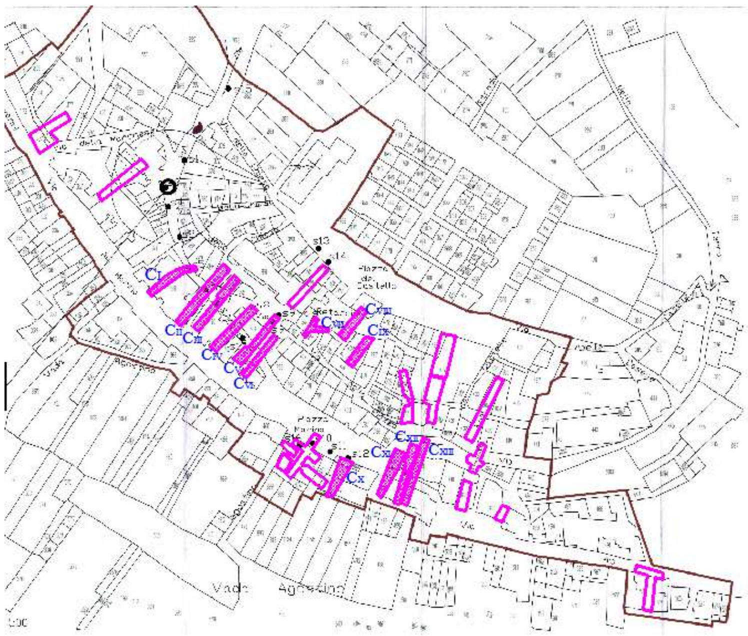

Figure 5. Plan location of the main cavities detected in the centre of Castelnuovo

3.2 Numerical model and input motion

The seismic response of the hill longitudinal cross-section shown in Figure 3 was investigated by 2-D FEM analyses through the code QUAD4M (Hudson et al. 1994), which operates in the time domain, by assuming vertically incident SV waves. The code allows modeling the radiation damping by introducing viscous dampers at the bottom of the mesh (absorbing boundaries). By contrast, side boundaries are perfectly reflecting; therefore, in order to reduce the influence of artificial reflected waves, side boundaries were extended far enough in both directions from the region of interest. The maximum thickness of mesh elements, h_{max}, for all materials was fixed according to the well-known indication by Kuhlemeyer and Lysmer (1973), on the basis of soil shear wave velocity Vs and the maximum frequency of the input to be transmitted.

Soil response was modelled by the equivalent linear procedure. For the white silt (L), the curves G/G_0-γ and D-γ described in Figure 4 were implemented. The soils called Breccia (B) and Calcarenite (M) were assumed to have a linear visco-elastic response. As a matter of fact, just the shear wave velocity, Vs, and the initial damping, D_0, were required for these materials. For the sake of simplicity, in the numerical model the presence of the thin layers of debris (d) and alluvia (b) towards the ESE side of the longitudinal section (Figure 3) was disregarded.

Table 1 reports the values of the unit weight γ, shear wave velocity Vs, Poisson ratio ν, and initial damping D_0, assigned to the soils of Castelnuovo in the numerical study. To account for the increase of Vs with depth, the white silt (L) was divided in two homogeneous layers: an upper one having Vs = 370 m/s and a lower one characterized by Vs = 495 m/s. The assigned velocities are respectively the mean values of the experimental values measured between 0 and 35m (upper silt) and between 35 and 110 m (lower silt), as reported in the WG (2011). The final model adopted for the numerical study is shown in Figure 6. The mesh is very refined in the upper part of the hill, where the element height is of the order of 3 m.

Table 1. Soil properties adopted in the numerical study

material	***γ*** ***[kN/m³]***	***V_S*** ***[m/s]***	***ν***	***D_0***
Silt (L)	18	*from 0 to 35 m* 370 *from 35 to 110 m* 495	0.38	0.009
Breccia (B)	22	1250	0.34	0.008
Bedrock (M)	22	1250	0.34	0.01

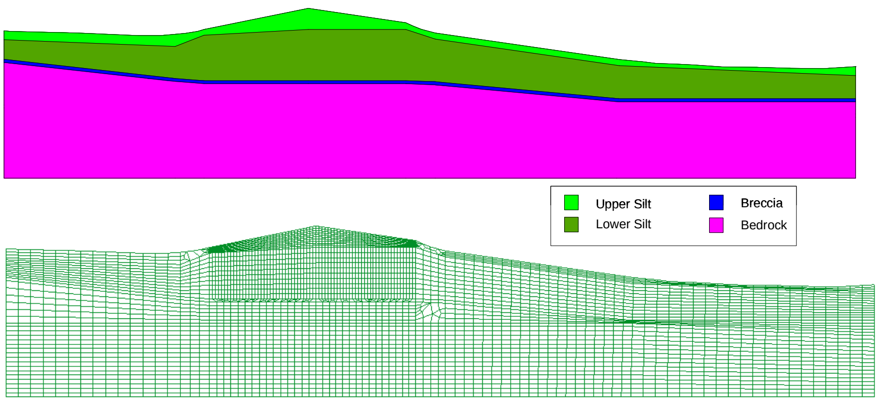

Figure 6. Model geometry with material identification (top); finite element mesh (bottom)

Reference input motions for the numerical analyses were provided by an *ad hoc* study by the Department of Civil Protection within the microzonation project (WG, 2011). The Working Group adopted three alternative hazard approaches to derive the reference acceleration response spectra: probabilistic, deterministic and the National Technical Code (Ministero delle Infrastrutture e dei Trasporti, 2008). In the present study, the accelerogram NTC (Figure 7), providing the smooth spectrum of the National Technical Code (2008) for a return period of 475 years and a PGA = 0.22g, was considered as the horizontal input motion for site response analyses. A low-pass filter was preliminary applied to the input signal to remove frequency higher than 15 Hz and assure an accurate simulation of the seismic wave propagation within the discretized model shown in Figure 6.
Preliminarily a site response analysis has been carried out on the reference model of Figure 6, without introducing the cavities. This analysis will provide the reference solution for assessing the effects of cavities on the seismic response of the Castelnuovo hill.
As QUAD4-M does not have the “null” element in its library, it was necessary to understand how to simulate cavities in it. Two different procedures were tested. First, cavities were simulated by simply decreasing stiffness and density of those elements occupying the cavity sections. This procedure has the advantage to allow ones operating directly on the reference mesh without necessity of re-numbering the elements. Second, cavities were simulated by removing the corresponding elements from the reference mesh. This procedure is much more accurate but time-consuming as re-numbering of the mesh elements is required. The two procedures are in all equivalent since they provide the same results (Rotili, 2010). The final model including cavities is shown in Figure 8. The horizontal spacing

between cavities (varying from 1 to 15 m), the embedment depth below the ground level (≈ 3 m) and cavity dimensions are as representative as possible of the real problem (Rotili, 2010).

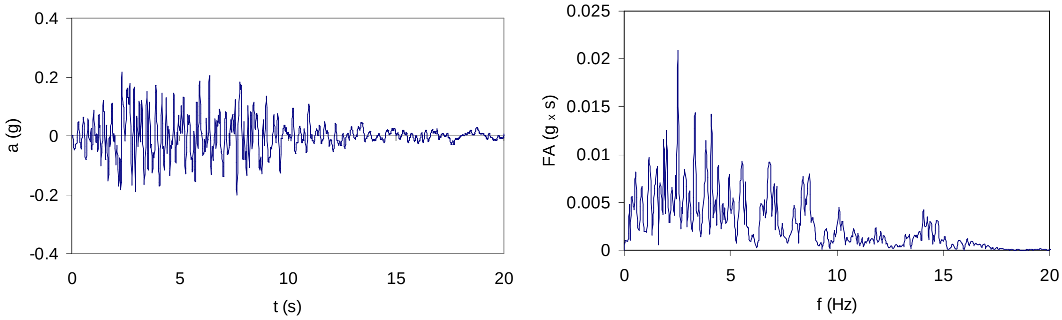

Figure 7. Time history and Fourier amplitude of the horizontal input accelerogram (NTC)

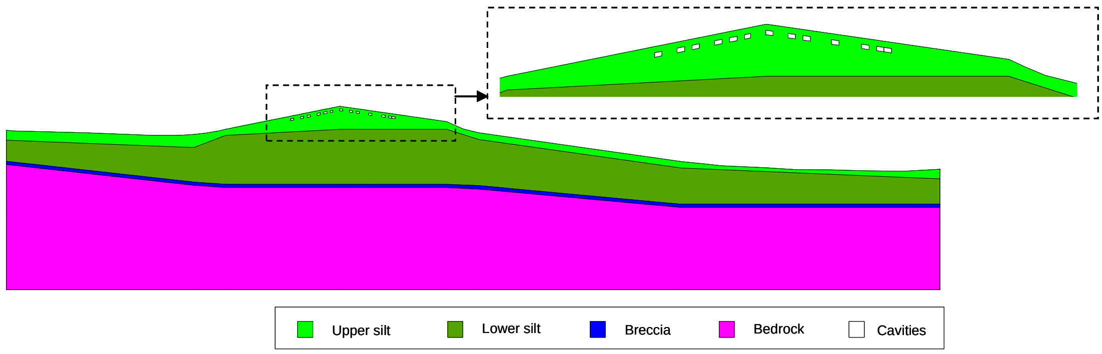

Figure 8. Location of cavities in the numerical model with a zoom at the top of the hill

4. MAIN RESULTS AND DISCUSSION

Once the numerical model was optimized, the following analyses have been carried out:

a) Reference analysis (no cavities);
b) Analysis with 1 cavity below the top of the hill (by removing one element of the mesh);
c) Analysis with 13 cavities (by removing 13 elements of the mesh);
d) Analysis with 13 cavities (13 elements of the mesh with reduced stiffness and density);
e) Analysis with 13 deeper cavities (cavities were simply translated in the vertical direction to match the interface between the upper and lower silt);
f) Analysis with spaced cavities (starting from the model with 13 cavities, these were alternatively filled with soil so that the relative spacing between consecutive cavities was increased);
g) Analysis with 13 cavities filled with concrete;
h) Analysis with a continuous carpet of concrete, connecting all cavities.

In Figure 9 the results obtained from the analyses at the items a), b) and c) have been compared in terms of peak ground acceleration along the free surface of the hill and acceleration amplitude factor, $F_{PGA,}$ computed as the ratio between the peak acceleration at the ground level and the peak acceleration of the input motion (0.22g). From Figure 9 it can be observed that at the top of the hill the reference analysis (no cavities) provides an amplification in PGA of about 3.3, due to a combination of stratigraphy and topography factors. The insertion of 1 cavity below the top of the hill is rather negligible, but the insertion of 13 cavities produces a significant amplification of the ground motion in all the upper part of the hill. The amplification factor at the top of the hill (abscissa x=520m) increases of 12.3 % with respect to the reference analyses.

In Figure 10 the effect of two important geometrical factors is accounted for: the embedment depth of cavities below the ground surface and the relative spacing between cavities (comparison among analyses at the items a), c), e) and f).

It could be observed that if cavities are ideally translated from the top to the lower part of the hill, that is to say, increasing embedment depth, the amplification of the ground motion due to cavities is suppressed and a slight deamplification in PGA is observed with respect to the reference analysis. On the other hand, increasing the spacing among cavities provides a lower amplification with respect to the real case. Both embedment and spacing of cavities actually control the wave propagation phenomenon in the hill, indicating the occurrence of a complex interaction among the cavities themselves and, in addition, between cavities and topography of the hill. As well known from theoretical studies, the interaction among soil and cavities is regulated by the dominant wavelengths of the seismic waves propagating in the subsoil. In this case, due to material non linearity and consequent stiffness inhomogeneity, it is quite huge establishing the representative wavelength to be compared to the characteristic dimension of the cavity and/or to the relative spacing among cavities, as typically done in literature studies for the idealized case of a homogeneous, isotropic and linear elastic half-space.
Figure 11 compares the profile along the hill free surface of the peak accelerations computed by filling the cavities with concrete, i.e. replacing cavities with inclusions stiffer than the surrounding soil. As can be observed, there is a reduction in ground motion amplification with respect to the case of void cavities, a result rather unexpected considering that “void” is the best isolating system. It should be, however, considered that in correspondence to the top of the hill the seismic motion is affected by the waves reflected from the hill slopes (SV and P, as well as, R) and trapped between the hill free surface and cavities. When cavities are replaced by solid inclusions part of this trapped energy may be sent back downward, thus causing less amplification. The final analysis is purely ideal and refer to the case of a continuous concrete carpet connecting the existing cavities. The aim is of enhancing what happens to the ground motion if the interaction among the cavities or inclusions is prevented: as can be seen the ground amplification at the top of the hill is completely suppressed, as most of the energy carried out by the impinging SV waves are reflected downward by the carpet and only a small amount is transmitted to the hill crest.

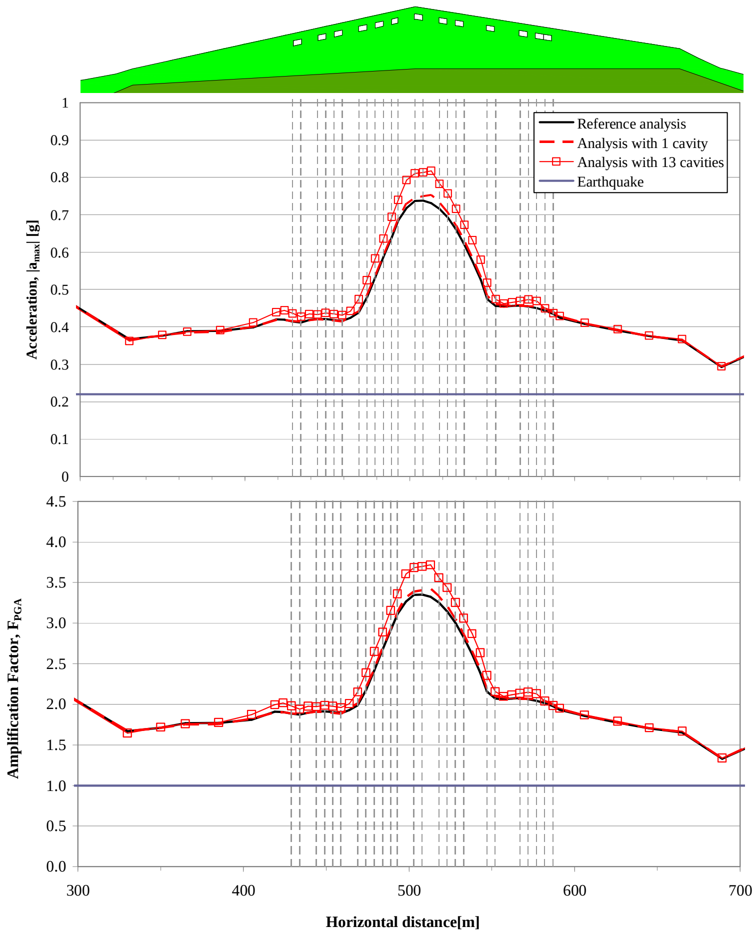

Figure 9. Peak acceleration (top) and PGA amplification factor (bottom) along the free surface of the hill

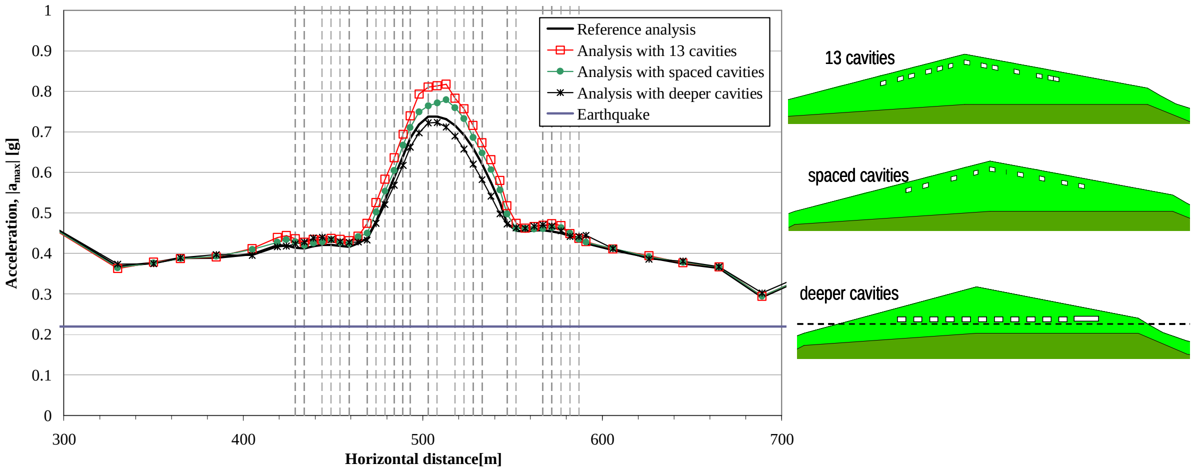

Figure 10. Peak acceleration along the free surface of the hill: effect of horizontal spacing among cavities and of cavity depth below the hill surface

Finally, Figure 12 shows only some of the above results in the frequency domain. As can be seen from Figure 12a, the fundamental frequency of the upper part of the hill is around 1 Hz, in accordance with microtremor measurements carried out by the WG (2011) for the microzonation project. Cavities amplify the frequency range 3-5 Hz, as it can be observed from the transfer function in Figure 12b.

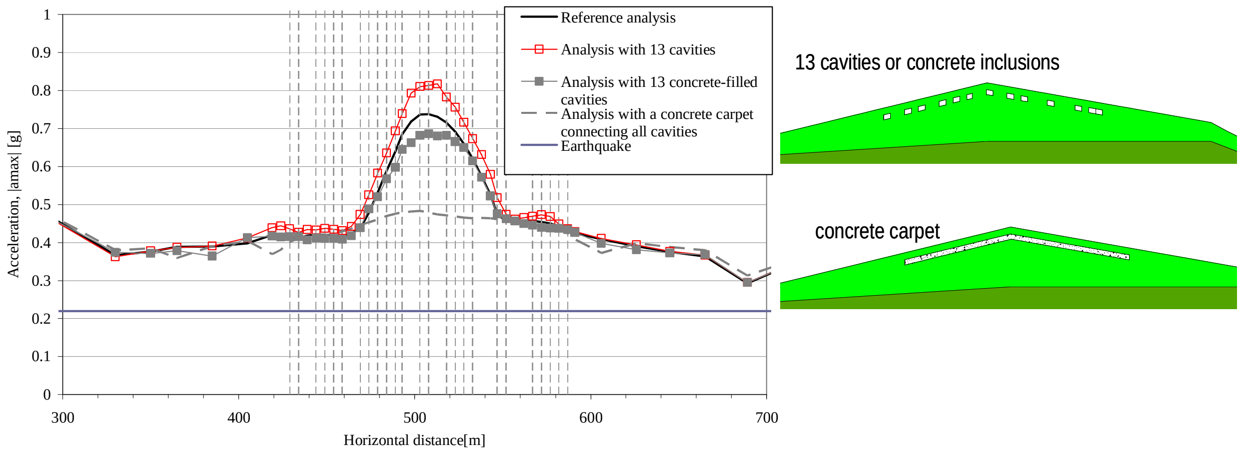

Figure 11. Peak acceleration along the free surface of the hill: effect of cavities, concrete inclusions and of a continuous concrete carpet

5. CONCLUSIONS

This work focused on the effect of underground cavities on the ground motion amplification along the free surface of a hill. The investigated model inspires to a real case, Castelnuovo (Italy), which experienced huge damage after the mainshock (April 6, 2009) of the Abruzzo earthquake.

In the subsoil of Castelnuovo there are several underground cavities, whose roofs are quite superficial (about 2-3 meters below the ground level). In order to evaluate the role of cavities on ground motion amplification, seismic site response analyses have been carried out by the f.e.m. code QUAD4-M. From the numerical study it emerged a relevant effects of cavities on the ground motion computed along the free surface of the hill. The interaction between consecutive cavities and topography could justify the high level of damage caused by the mainshock in the village and, specially, in the historic centre placed at the top of the hill. Further investigation is required to interpret the obtained results in the light of the available theoretical solutions. Soil nonlinearity, stiffness inhomogeneity and topography effects, accounted for in this work, will make this further step not straightforward.

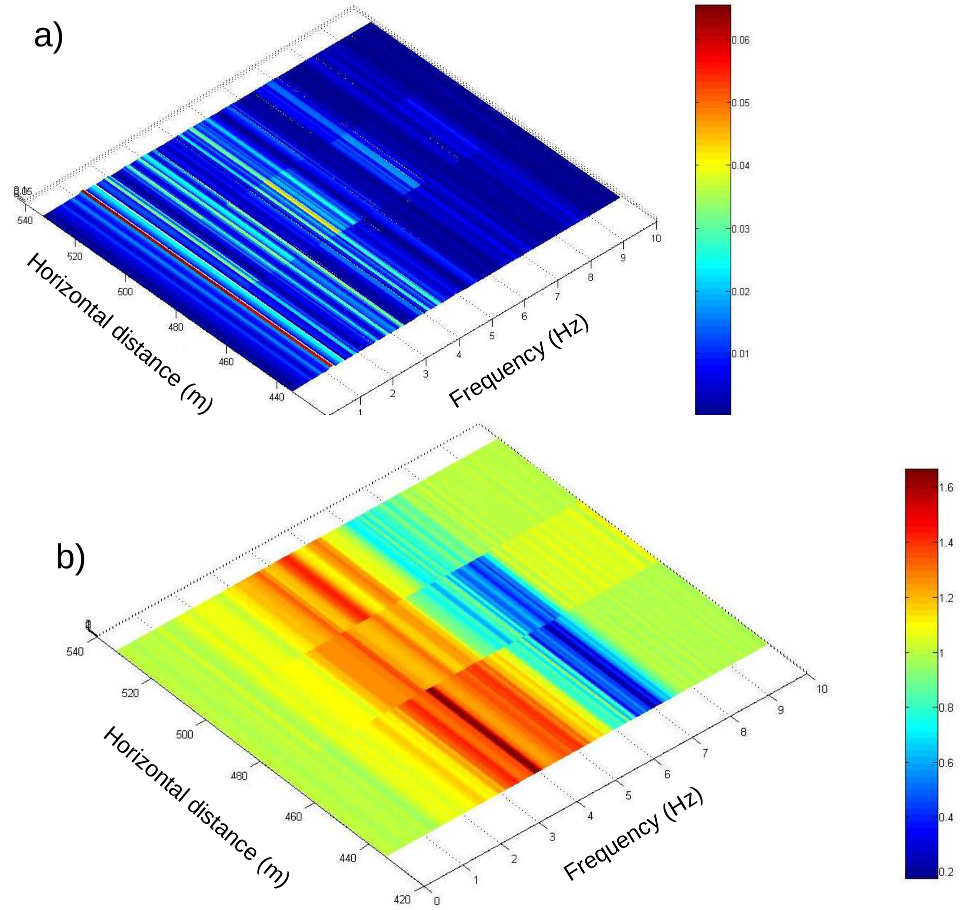

Figure 12. In (a) acceleration Fourier amplitude along the top of the hill for the reference analysis (no cavities); in (b) transfer function between the surface accelerations computed from the analysis with 13 cavities and from the reference analysis (no cavities)

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