APPLICATION OF SEISMIC REFRACTION TOMOGRAPHY TO DETECT ANTHROPGENIC BURIED CAVITIES IN PROVINCE OF NAPLES (CAMPANIAN PLAIN, ITALY)

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Introduction. The presence of near-surface buried cavities often poses serious hazards for human safety and infrastructures. Underground voids develop naturally in karst territories while are produced by human activities the cavities such as underground mines, tunnels, buried passage-ways, etcetera (Del Prete, 2008). The sudden collapse of the vault of these cavities is a recurring problem in landscape management and it is a main origin of sinkholes. If the collapses originate from man-made cavities, these phenomena can be classified as “anthropogenic sinkholes” (Guarino et al., 2012). Therefore, identification of these underground voids is an essential prerequisite for both minimization of risks arising from their presence, and for optimal planning of land use. The geophysics technologies are often the most convenient way to gather information aimed at the characterization of the subsurface and the search for underground voids. Up-to-date different geophysical prospecting methods have been tested for underground voids detection and their success is strongly influenced by local conditions and their ability in terms of penetration and resolution. The main difficulties in finding cavities using geophysical methods are generally related to the size and shape of the voids, and the subsurface lateral velocity variations that can create responses similar to those of underground voids (Riddle et al., 2010). The applications on synthetic models (Mandell, 2005a; Sheehan et al., 2005a, 2005b), in laboratory experiments on physical models (Grandjean and Leparoux, 2004; Grandjean, 2006) and the application on real data (Sheehan et al., 2005c; Cardarelli et al., 2010), have shown that the seismic refraction tomography represents a powerful tool for the detection of subsurface cavities. It has the advantages of being a non-invasive technique, of having a good penetrating power while maintaining a good resolution, and of allowing a three-dimensional reconstruction of the underground cavities. In this work we used a densely spaced grid of 2D seismic refraction profiles processed with first-arrival traveltime tomography to detect man-made cavities and to create a three-dimensional model of the subsurface in Casamarciano, in province of Naples. After modelling, some core-drillings have been made to compare and validate the seismic results.

Geologic contest and underground cavities. The area of present work is located in the central sector of the Campanian Plain. This latter occupies the bottom of a large structural depression (graben) oriented in NW-SE direction and bounded by carbonate ridges of Mt Massico to NW, of M.ti Lattari to SE and M.ti of Caserta and Partenio to NE and to E. The Campanian Plain graben began to form in the Late Pliocene as a result of tectonic activity that characterized the Apennines orogenic uplift (Bartole et al., 1984). The area was affected by intense volcanic activity and the graben was filled by the products of the nearby volcanism, i.e. pyroclastic deposits and lava, and by alluvial and marine deposits. Generally the stratigraphic series of the study area consist of volcanic deposits dating back to Upper Pleistocene - Holocene, such as the Neapolitan Yellow Tuff fm. (NYT: 12 ky b.p.) and the Campanian Ignimbrite fm. (CI; 37 ky b.p.) (Orsi et al., 1992, 1996). The stratigraphic series is completed to the top by loose pyroclastic deposits related to the subsequent post-Yellow Tuff activity (<10.5 ky b.p.) (Guarino et al., 2012; Di Vito et al., 2008; De Vivo et al., 2001; Bellucci, 1994).

Part of the survey area was investigated by four core drillings that reveal the stratigraphy down to depth of about 19 m. The stratigraphic series of the area consists of the following lithotypes (from top to bottom): pyroclastic deposits rich in yellow pumices down to depth of 6.5 m; between 6.5 and 11.5 m in depth there are alluvial gravel deposits in a grey pyroclastic...
matrix and from 11.5 m to the bottom (19 m) the well shows the Campanian Ignimbrite formation.

The NYT and CI fm. outcrops are associated to a high number of underground excavations (ancient aqueducts, tunnels, tombs, etc.). Good physical and mechanical properties of these tufa formations, wide distribution of these deposits, at depths and easy access, together with limited means of transportation available in the past centuries represented additional reasons that led ancient the communities not only to use the material quarried but also to take advantage of the excavations carried out accordingly (Vallario, 1992). The artificial caves were dug into the layers of pumice and tuff to reduce the cost of construction of the buildings, until the beginning of 1900. The building material was extracted widely from underground vertical shafts that reach the layers of loose pumice and the underlying tuff. Sub-horizontal tunnels were instead excavated within the layers of pumice. Once reached the tufa through vertical wells, sub-horizontal cavities of varying height and width (~ 4-8 m) were dug. After the extraction of the building material, voids were usually used as foodstuffs deposits and wine cellars. The vertical wells of the cavities, located outside of the towns such as the study area, usually were closed; therefore the knowledge about their presence in the subsoil was lost. The loss of maintenance of the cavities and water infiltration within them can result in instantaneous or progressive collapse.

Data acquisition and method. The investigated area, of ~10,000 m$^2$, is a private property and its aerial photography is shown in Figs. 1a and 1b.

Some surface evidences of sinkholes are clearly visible from aerial photography (red arrows in Fig. 1b and Fig.1c). For instance one the larger sinkholes in the area (red dashed line in Fig. 1b) has about 50 m in diameter and 20 m in depth. The analysis of visible evidences of sinkholes, together with the measurement of an accessible cavity, has allowed us to define the target of the investigation, namely the search of voids with lateral dimensions of about 10 m and heights of about 8-9 m located within 20 m of depth. In order to determine the optimal acquisition parameters and to test the accuracy of tomographic technique for the identification of these cavities into geologic contest investigated, we used the results of seismic refraction

Fig. 1 – a) Aerial photography with location of the survey area by Google Earth (yellow dotted line); b) survey area on Google Earth aerial photography (white dashed line) with some surface evidences of sinkhole (red arrows) and larger sinkhole in the area (red dashed line); c) photo of some surface evidences of sink-hole.
analysis of a synthetic model made by Cardelli et al. (2010), moreover we acquired a pilot profile, above a cavity with known size and position. The final velocity model resulting from the pilot profile (Fig. 3a) shows that in correspondence of the cavity there is an anomalous negative distribution of Vp velocity associated to the top of the tuff basement (about 1250 m/s) that is coherent with the size of the known cavity. **Model resolution is assessed** by a posteriori checkerboard test (Hearn and Ni, 1994), using an input perturbation values of ± 10 m/s in the cell with horizontal size 20 m and vertical size 10 m. Checkerboard test gives information on how data and the method used are spatially sensitive to the velocity variation in the final tomographic model (Improta et al., 2002). The anomalous velocity of Vp associated to the known cavity is in the resolved region of the model. **After this test, we acquired 20 seismic profiles with a total profile length of about 2 km.** The profiles are located as shown in figure 2 in the survey area. The employed acquisition system consists of two Geometric’s GEODE seismographs equipped with vertical geophones with a 40 Hz eigenfrequency, for a total of 48 channels. Seismic data were collected using an 8 kg sledgehammer. At each shot point we stacked 3 recordings to increase the signal and simultaneously to reduce random noise already in acquisition processing. Data were recorded by geophones placed at 2 m intervals, covering a distance of 96 m for each profile. **Source move-up was 4 m along all profiles, in order to obtain a dense network of seismic rays and consequently a high spatial resolution.** In order to increase the turning ray depth the penetration of the refracted waves offline shot were also acquired.

**Data processing.** After installing the geometry into trace header, a simple pre-processing aimed at improving the signal to noise on first arrivals was applied at recording data. This consisted of a frequency filtering, necessary to eliminate low-frequency noise caused by vehicular traffic, and a **manually checking trace by trace to remove dead or very noisy traces.** The main and longer part of refraction processing was the picking of the first arrivals, performed on the entire dataset, through the commercial Landmark software named ProMAX 2D.

The quality control on the readings was performed plotting time-distance curves and using the rules of parallelism and reciprocity described by Ackermann et al. (1986). The readings of the direct and refracted phases, after being checked for consistency, were inverted using a commercial software that is part of the package SeisImager®, distributed by Oyo Coroporation Ltd. and set on the work of Hayashi and Takahashi (2001). The inversion times algorithm is based on a tomographic technique of iterative reconstruction of image, known as “SIRT” [Simultaneous Iterative Reconstruction Technique; Gilbert (1972)]. The SIRT method requires an initial velocity model that was obtained by conventional procedures of refraction analysis (e.g. Burger, 1992). During inversions, ray tracing and SIRT are applied to the velocity model, until the root mean square (RMS) error on the difference between the observed and calculated travel times is minimized. **Horizontal cell size was 2 m. Velocity increased with depth from 200 m/s at the surface to 1500 m/s at a depth of 30 m.** On average 20 to 30 iterations of ray tracing and traveltine inversions were conducted. Running the inversions with 3 nodes, we obtained
a final velocity models that are characterized by an average RMS traveltime error of about 2.5 ms. Larger residuals, between 3 and 4 ms, are occasionally observed on some profiles with a smaller signal to noise ratio, as the profiles near the road. These profiles, contaminated by low-frequency random noise, are consequently characterized by a greater uncertainty on the first arrivals picking. Final tomographic velocity models, for each seismic line, were exported as ASCII files and velocity values were interpolated in the 3D space defined at the surface by the profile location. The ray coverage allowed determining the areas of the subsurface effectively resolved by the seismic inversion. All areas of the tomographic models outside the ray coverage have been blanked (Fig. 3).

Results. The resulting tomographic models (e.g. Fig. 2) show P-wave velocities that vary from a minimum of about 200 m/s at the surface and increase up to about 1500 m/s at the bottom where the CI basement is reached. It is evident the presence of many velocity lateral variations, which are generally located mainly at depths between 10-20 m from topographic surface. The profiles of group 1 and group 2 (see Fig. 2) show a very articulated CI basement, characterized by an average velocity of 1250 m/s. The velocity anomalies found in the basement, according with the anomalies found on the pilot profile, suggest the presence of underground cavities; in addition, they are consistent on adjacent profiles and appropriate in terms of location.

The tomographic models of group 3 (see Fig. 2) were acquired with a different azimuth (approximately WNW - ESE) are oriented approximately 90° to the direction of the profiles of the group 2. The tomographic sections related to these three profiles differ from the others by the absence of major and evident lateral variations of velocity. These profiles, in fact, show a sub-parallel velocity distribution, with a tendency of the faster layer (i.e. the top of the CI) to widen towards the end of the profiles. On this set of profiles, there is no evidence of voids in the CI tuff, as found on the other sets of profiles.

Spatial interpolation of the velocity information has allowed us to build a three-dimensional model the top of CI fm. (Fig. 3c), which clearly shows both location and dimensions of the voids. Four core-drillings were done in the area covered by the profiles of group 2, in order to validate the tomography results. These logs explorations are in perfect agreement with our results.
References


