

## UNDERGROUND CAVITIES AND THEIR AGGRAVATION EFFECTS ON THE LOCAL SEISMIC RESPONSE: A PARAMETRIC ANALYSIS

VERONICA GREGORI<sup>(\*)</sup>, GUGLIELMO GRECHI<sup>(\*)</sup>, MATTEO FIORUCCI<sup>(\*\*\*\*)</sup>, SEBASTIANO D'AMICO<sup>(\*\*)</sup>, EMANUELE COLICA<sup>(\*\*)</sup>, LUCA LENTI<sup>(\*\*\*)</sup>, NATHALIE GLINSKY<sup>(\*\*\*)</sup> & SALVATORE MARTINO<sup>(\*)</sup>

<sup>(\*)</sup>Sapienza University of Rome - Department of Earth Science - Rome, Italy

<sup>(\*\*)</sup>University of Malta - Department of Geosciences - Msida, Malta

<sup>(\*\*\*)</sup>CEREMA / Géoazur - Valbonne, France

<sup>(\*\*\*\*)</sup>University of Cassino and Southern Lazio - Department of Civil and Mechanical Engineering - Cassino, Italy

Corresponding author: veronica.gregori@uniroma1.it

### EXTENDED ABSTRACT

Le cavità sotterranee, naturali o antropiche, diffuse in numerosi contesti naturali e urbani, rappresentano un potenziale fattore di rischio per edifici e infrastrutture, soprattutto in aree sismicamente attive. Nei contesti urbani, tali strutture sono spesso il risultato di attività estrattive storiche o di opere ipogee, mentre in ambienti naturali possono svilupparsi a seguito di processi carsici; in entrambi i casi, condividono meccanismi di instabilità e di risposta dinamica analoghi. Oltre ai problemi legati alla loro stabilità strutturale, quali il collasso delle volte e la formazione di sprofondamenti (*i.e.*, *sinkhole*), la presenza di cavità può influenzare in modo significativo la propagazione delle onde sismiche, alterando ampiezza, contenuto in frequenza e durata dello scuotimento sismico in superficie rispetto a condizioni di campo libero. La valutazione delle modificazioni del moto sismico associate alla presenza di cavità sotterranee ha assunto un ruolo crescente negli studi di microzonazione sismica. Tuttavia, molti studi numerici si basano su modelli bidimensionali semplificati e su analisi non integrate con osservazioni sperimentali, limitando la comprensione dei principali meccanismi di interazione tra onde sismiche e strutture ipogee, quali diffrazione, riflessione e amplificazione. In questo contesto, il lavoro propone un approccio integrato che combina la modellazione numerica bidimensionale della propagazione delle onde sismiche con analisi vibrazionali *in situ*. Tale approccio è applicato a un singolo caso di studio rappresentativo di un contesto naturale, caratterizzato dalla cavità Il-Latnija (Malta), con l'obiettivo di caratterizzare la risposta dinamica di cavità e il loro potenziale effetto aggravante sulla risposta sismica locale. La modellazione numerica 2D è stata condotta utilizzando un modello concettuale rappresentativo, caratterizzato da una cavità circolare di dimensioni medie ( $d = 20$  m) ubicata in un mezzo stratificato tipico del contesto geologico dei casi di studio. Le modellazioni sono state eseguite in condizioni elastiche lineari, utilizzando una funzione Gabor con un contenuto in frequenza fino a 20 Hz, rappresentativa di un'onda di taglio SV che si propaga dalla base del modello verso la superficie. La risposta dinamica (*i.e.*, serie temporali di velocità nelle componenti  $x$  e  $y$ ) è stata monitorata nel modello mediante una rete di punti di controllo distribuiti lungo la superficie libera e il contorno della cavità. I risultati delle modellazioni mostrano che la risposta in superficie è dominata dalla componente orizzontale del moto, coerentemente con la natura dell'onda incidente. In prossimità della cavità, invece, si osservano effetti di amplificazione locale ed una maggiore durata delle oscillazioni, con la comparsa di componenti verticali del moto comparabili a quelle orizzontali. La risposta dinamica, in termini di ampiezza e durata delle oscillazioni, è fortemente variabile in funzione della posizione lungo il contorno della cavità, evidenziando la complessità del campo d'onda. Nell'ambito di un approccio integrato che combina modellazione numerica e osservazioni sperimentali, è stato inoltre analizzato un caso di studio reale rappresentato dalla grotta di Għar il-Latnija (Malta). Il comportamento dinamico del tetto parzialmente collassato della cavità è stato analizzato mediante registrazioni di rumore sismico ambientale e tecniche di Analisi Modale Operativa (OMA). L'elaborazione dei dati ha consentito di identificare quattro principali frequenze di risonanza, con un primo modo ben definito e caratterizzato da deformazioni modali prevalentemente verticali e concentrate nelle porzioni centrali della volta. A supporto dell'interpretazione sperimentale, è stata condotta un'Analisi Modale Numerica (NMA) basata su un modello tridimensionale semplificato della cavità, che ha riprodotto con accuratezza la frequenza e la forma modale associate al primo modo di risonanza. Nel complesso, i risultati ottenuti mostrano come la modellazione numerica 2D consenta di analizzare i principali fattori di triggering legati all'input sismico, mentre le analisi vibrazionali contribuiscono alla caratterizzazione del comportamento dinamico naturale della cavità e al perfezionamento del modello geologico di dettaglio, anche in un'ottica futura di trasferibilità ai contesti urbani. L'integrazione tra approcci numerici e sperimentali si conferma quindi essenziale per una valutazione più realistica degli effetti sismici associati alle strutture ipogee. Futuri sviluppi prevedono l'estensione della modellazione numerica mediante l'analisi di un numero maggiore di configurazioni geometriche e stratigrafiche e l'applicazione di metodi tempo-frequenza avanzati, quali il *Normalized Inner Product* combinato con la *Stockwell Transform*, per l'analisi dell'evoluzione spettrale del moto e il miglioramento della caratterizzazione dei meccanismi di interazione tra moto sismico e cavità sotterranee.

## ABSTRACT

Underground cavities are widely distributed in urban areas and pose a significant risk to buildings and infrastructures. Beyond structural instability issues, cavities can significantly affect seismic wave propagation, modifying the amplitude, frequency content, and duration of ground motion. This study presents an integrated approach to investigate the dynamic response of underground cavities, combining two-dimensional numerical modelling of seismic wave propagation and *in situ* ambient vibration measurements. The numerical analyses, performed under linear-elastic conditions, aim to explore the interaction between seismic input and underground cavities. In a similar way, ambient vibration measurements carried out at the Ghar il-Latnija cave (Malta) were analysed using Operational and Numerical Modal Analysis techniques. The results highlight local amplification effects and marked spatial variability in the dynamic response, providing a preliminary framework for assessing the seismic response of underground cavities.

**KEYWORDS:** numerical modelling, parametric analysis, ambient seismic noise, local seismic response

## INTRODUCTION

Underground cavities, formed by anthropic activities or natural processes, pose a significant geohazard for buildings and infrastructure, particularly in seismically active areas. Due to complex geological and environmental interactions, these structures can evolve over time and eventually collapse under earthquake-induced stresses exceeding the rock strength of their vaults. In addition to their role in causing structural instability, seismic waves propagating inside underground cavities can be modified in terms of frequency content, ground shaking amplitude, and duration, thereby influencing the local seismic response relative to free-field conditions (FABOZZI *et alii*, 2024). For these reasons, the investigation of such complex structures is considered paramount when they actively interact with urban settings. Several studies have investigated cavity mapping (ZALAGHAIE *et alii*, 2022) and conducted geological, geomorphological, and geotechnical analyses aimed at understanding rock mass stability around underground cavities (LOLLINO *et alii*, 2013). In the Italian context, the Department of Civil Protection has promoted the use of numerical modeling approaches to assess earthquake-induced ground instabilities at the urban scale within the framework of Seismic Microzonation (SM) studies (FABOZZI *et alii*, 2024). Additionally, several studies have investigated the interaction between earthquakes and underground cavities using two-dimensional numerical modeling approaches (LANCIONI *et alii*, 2016; ALIELAHI *et alii*, 2016). Nevertheless, the study of the seismic response of underground cavities re-

mains challenging and limited. Numerical studies are often based on two-dimensional models and simplified material property assumptions (*e.g.*, homogeneous and isotropic material properties), without accounting for structural complexities typical of fractured rock masses (FARAONE *et alii*, 2023). In the present study, we propose an integrated approach coupling parametric numerical analysis with ambient vibration measurements to investigate the dynamic response of underground cavities. The parametric analysis is based on systematic variations of cavity geometry, depth, and stratigraphic configuration, whereas material properties and seismic input are kept constant. The Operational and Numerical Modal Analyses (OMA and NMA) enable the identification of resonance frequencies and deformation patterns associated with the natural response of cavities, providing information on their dynamic properties. Wave propagation numerical modeling, instead, allows the analysis of triggering effects related to the seismic input and their interaction with underground cavities under controlled parametric conditions. A representative cavity configuration, inspired by the geometry of Ghar il-Latnija cave, was adopted as a conceptual model to investigate the fundamental dynamic mechanisms of cavity-wave interaction under controlled numerical conditions.

## METHODOLOGICAL APPROACH AND PARAMETRIC DEFINITION

A preliminary statistical analysis of an inventory of cavities in the Maltese Archipelago enabled the definition of 60 parametric scenarios based on geometry, size, depth, and stratigraphic setting. Among these, a single representative model corresponding to a typical cavity configuration was selected and used for the numerical simulations and integration with ambient vibration measurements. The aim of this parametric approach is to establish a preliminary methodological framework useful for categorizing the local seismic response of underground cavities as a function of their physical and mechanical characteristics.

## SELECTION OF THE REPRESENTATIVE CASE

Among the 60 parameterized configurations, a representative model was selected because it reflects a typical stratigraphic sequence in the Maltese geological context. In particular, the selected model is characterized from top to bottom by Upper Coralline Limestone (UCL), Blue Clay Formation (BCF), Globigerina Limestone (GLO), and Lower Coralline Limestone (LCL) formations (PEDLEY, 2002). The examined cavity is circular, with a 10 m radius, and is located within the uppermost layer of the Upper Coralline Limestone (UCL). The selection of this scenario was guided by the need to define a conceptual reference model for integrating the numerical results with the vibrational analysis conducted on the real case

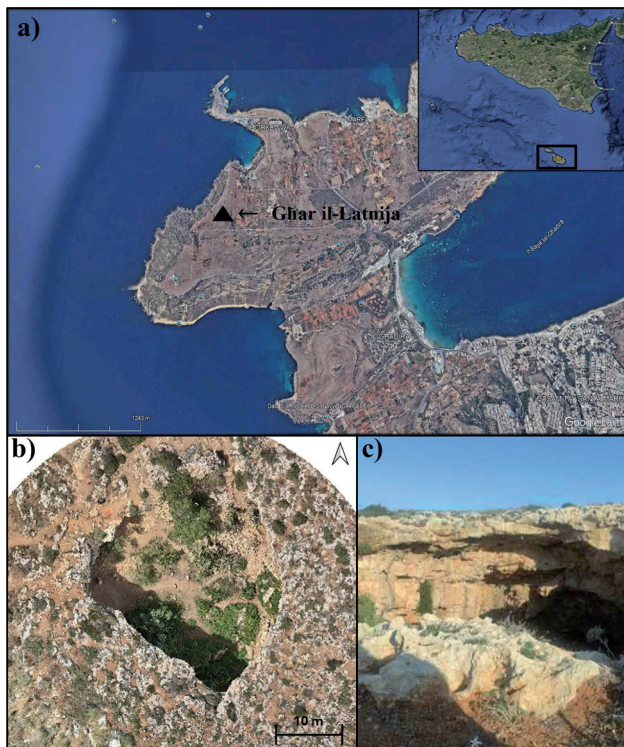


Fig. 1 - (a) Satellite view of the north-western sector of Malta with the location of the Ghar il-Latnija cave. (b) Plan view of the cave derived from the 3D model. (c) Field photograph of the cave and the overhanging rock roof, illustrating its geometry

study of Ghar il-Latnija, located in the northwestern sector of Malta (Fig.1). Although the selected model does not reproduce the exact geometry of the real site, it still represents a configuration that matches, in terms of stratigraphy and geometry, the values derived from the sinkhole inventory.

## NUMERICAL MODELING

The model geometry and stratigraphy were first designed in AutoCAD and then imported into FLAC2D 8.0 (Itasca Consulting Group), where a parametric analysis was carried out under linear-elastic conditions with no damping. The domain was assumed to be linear-elastic and without damping, adopting a conservative assumption aimed at enabling a consistent comparison, under identical stratigraphic conditions, between the transfer functions of domains with and without cavities. The resulting numerical domain is 273 m deep and 500 m wide (273×500 m), discretized with a uniform 1×1 m grid spacing. Each lithological layer is characterized by representative values of soil density ( $\rho$ ), shear-wave velocity ( $V_s$ ), Poisson's ratio ( $\nu$ ), shear modulus ( $G$ ), and bulk modulus ( $K$ ), derived from literature data. To prevent spurious wave reflections at the model boundaries, absorbing boundary conditions are assigned to the lateral sides of the domain (e.g., LYSMER & KUHLEMEYER, 1969; ITASCA, 2011). The adopted ap-

proach aims at determining the seismic frequency spectrum of shear waves at the ground surface. At the model base, a seismic input in the form of an upward-traveling SV shear wave was imposed, represented by a Gabor function applied to the horizontal component, with significant frequency content up to 20 Hz. No vertical input component is imposed; the vertical motion observed at the surface and along the cavity boundary therefore arises from wave-cavity interaction. Seismic wave propagation was monitored through multiple control points distributed within the model. A total of 500 control points were located along the ground surface with 1-m spacing. 16 additional, equally spaced control points were placed at the cavity boundary, along the cavity's vertical and horizontal axes, and along a vertical line on the right-hand side of the model. In this work, only a subset of representative control points located at the ground surface and along the cavity boundary was analyzed, with the full dataset reserved for future developments.

## AMBIENT MEASUREMENTS AND MODAL ANALYSIS

### *Ambient seismic noise measurements*

The Ghar il-Latnija cave is a surviving portion of a collapsed doline, located in the southern sector of the Paradise Bay promontory, in the northwestern sector of Malta. Entirely formed within the UCL formation, the structure extends over a perimeter of about 90 m, covering approximately 380 m<sup>2</sup>, with a maximum depth of 10 m and a relatively regular circular geometry. Although about 90% of the vault has collapsed, residual portions of the original roof remain along the southern and eastern margins, with average thicknesses of 1–2 m. Along the southern edge of the cave, ambient seismic noise measurements were conducted using an array configuration of five ultra-low-power GEOBit digital seismometers, deployed along a 20 m transect with an average spacing of 5 m (GRECHI *et alii*, 2025). All sensors were installed on bedrock, leveled, and oriented toward magnetic north. Ambient vibrations were recorded for 1.5 h at a sampling frequency of 250 Hz.

### *Operational modal analysis (OMA)*

Ambient vibration data were analyzed using the Frequency Domain Decomposition (FDD) technique, introduced by BRINKER *et alii* (2001). This approach allowed extracting the dynamic properties of the overhanging roof by exploiting non-localized ambient vibrations (*i.e.*, white noise) at the site. To ensure accurate analyses, time windows containing transient signals were removed. The data were then bandpass-filtered between 0.5 and 100 Hz, and the horizontal components rotated to transverse and radial directions relative to the southern edge of the roof.

The processed signals were divided into 100-s Hanning-tapered windows, and the cross-power spectral density (CPSD)

matrix was computed among all recorded channels. Singular Value Decomposition (SVD) was applied to the CPSD to identify the dominant structural modes. Finally, the Modal Assurance Criterion (MAC), a correlation coefficient quantifying the similarity between two mode shapes at different frequencies (ALLEMANG, 2003), was used to validate the observed modes when the MAC value exceeded 0.8.

### NUMERICAL MODAL ANALYSIS (NMA)

To support the dynamic and structural characterization of the cave, a 3D eigenfrequency numerical model of the cavity was implemented. The geometry was reconstructed using aerial drone photogrammetry, enabling the generation of a high-resolution mesh of the cavity. The model was then imported into COMSOL Multiphysics and discretized using a mesh composed of approximately 25,000 tetrahedral elements. In the numerical model, the rock mass was assumed to be continuous, homogeneous and isotropic. A density of 2300 kg/m<sup>3</sup>, a Poisson's ratio of 0.25, and a Young's modulus of 9.5 GPa were assigned based on values reported in the literature for the same Maltese rock formations, obtained by averaging data from multiple published studies (FARRUGIA, 2016; FARRUGIA, 2017; PISCHIUTTA, 2016); the latter calibrated on the first measured resonance mode. Relative modal displacements were computed in the transverse, radial, and

vertical directions at the geophone locations and compared with experimental modal shapes using the MAC to assess the level of agreement between in situ observations and the numerical model.

### RESULTS

The preliminary results of the 2D numerical modeling are presented for the case characterized by a medium-sized circular cavity (d = 20 m and depth = 3m), with the aim of evaluating the influence of the cavity on the local seismic response. Figure 2 shows the velocity time histories recorded at the five control points (CP1–CP5), considering the horizontal (x) and vertical (y) components of motion, measured at the ground surface and along the cavity boundary.

Relative to the incident motion, the recorded responses exhibit significant variations in amplitude, waveform, and phase, which can be attributed to wave reflection, refraction, and scattering induced by the presence of the cavity and the ground surface. Differences among the control points highlight a pronounced spatial heterogeneity of the dynamic response, related to the relative position of the monitoring points and to the cavity geometry. Near the cavity boundary, the velocity time histories exhibit more articulated behavior, characterized by persistent oscillations and increased signal complexity compared to the surface response. These features contribute to the varia-

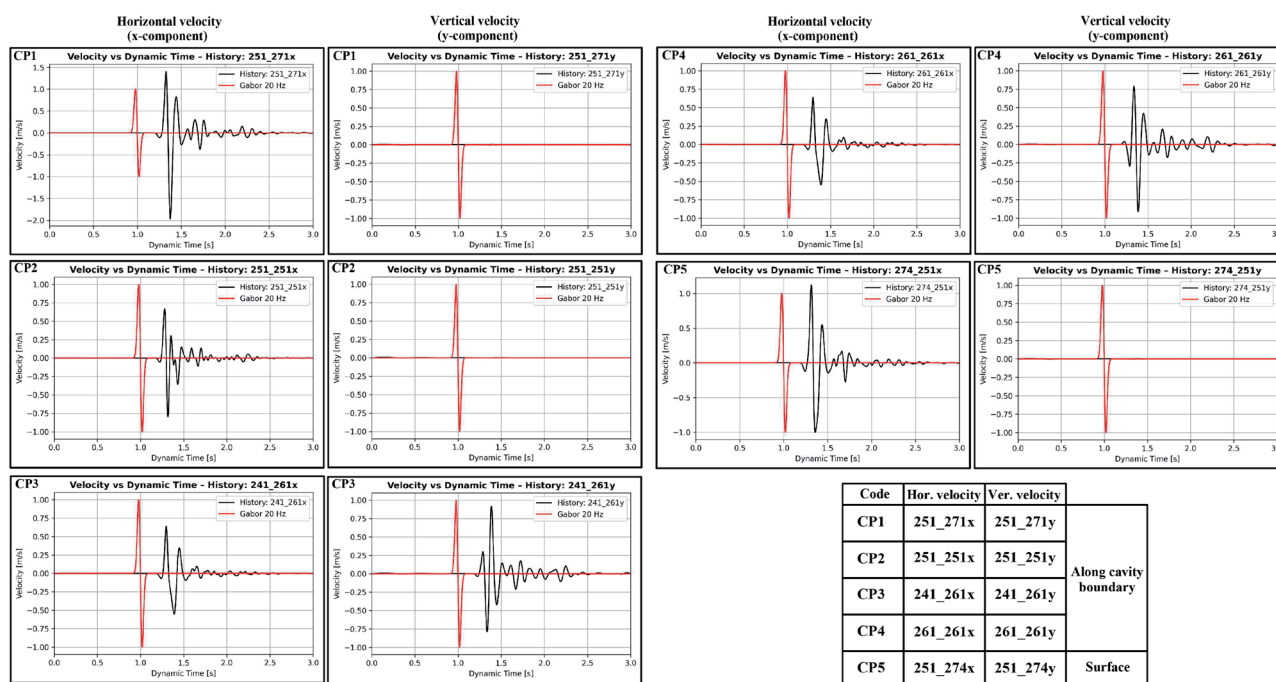


Fig. 2 - Velocity time histories at the five control points (CP1–CP5). Horizontal (x) and vertical (y) components are shown in the left and right columns, respectively. Black curves show the velocity response at the ground surface and along the cavity boundary, while red curves represent the incident Gabor function applied at the model base. The input motion is applied only to the horizontal component. Control point locations are listed in a reference table

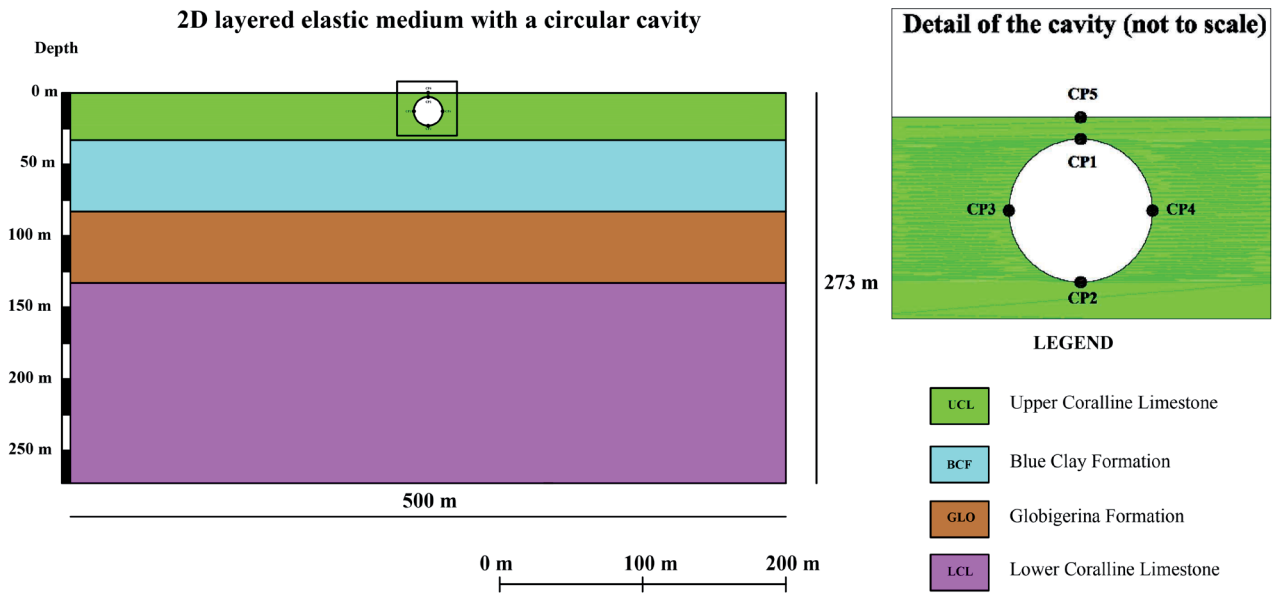


Fig. 3 - Geometry and stratigraphic setting of the 2D model with a circular cavity (left). An enlarged view of the cavity is shown on the right (not to scale), highlighting the location of the representative surface and cavity control points (CP1–CP5) used for the analysis and discussed in Fig. 2. Colours and the legend indicate the different lithological units

bility observed among the control points in terms of amplitude, phase, and motion duration. Although the excitation is applied only in the horizontal direction, consistent with the propagation of incident SV waves, a non-negligible vertical velocity component develops at all control points and becomes particularly evident near the cavity boundary. Overall, the velocity time histories illustrate how the presence of the cavity significantly modifies the dynamic response of the system, leading to local amplifications and a redistribution of kinetic energy. A schematic view of the numerical model, showing the locations of the selected surface and cavity control points, is shown in Fig. 3. Overall, the results of the 2D numerical modelling indicate that the cavity acts as a strong geometric heterogeneity capable of significantly modifying the local wave field, even in the absence of material damping. The complex wave field observed along the cavity boundary, characterized by local amplification, mode conversion, and marked spatial variability, is consistent with previous numerical studies that highlight the role of strong heterogeneities in modifying seismic wave propagation (MEZA-FAJARDO *et alii*, 2019).

The dynamic behavior of the southern overhanging roof of the Ghar il-Latnija cave was analyzed using OMA and NMA techniques applied to ambient seismic noise recordings (GRECHI *et alii*, 2025). Data processing using the Frequency Do-main Decomposition (FDD) method allowed the identification of the main resonance frequencies and corresponding modal characteristics of the structure (Fig. 4a). The first resonance mode is characterized by

a well-defined peak in the first singular value plot at 16.8–17 Hz, while the second and third modes, identified at 33.5 Hz and 37 Hz, are closely spaced in frequency, suggesting the possible presence of complex modes; the fourth mode is clearly defined at 45 Hz. To verify whether the closely spaced peaks between 33 and 37 Hz represented distinct resonance modes, the analysis of the Modal Assurance Criterion (MAC) was performed (Fig. 4b). Frequencies with MAC values greater than 0.85 were assigned to the corresponding modal shapes. The results show that the two peaks are associated with broad frequency bands (> 3 Hz), without overlap and with high mode shape coherence, confirming their interpretation as distinct modes. The first resonance mode is identified as a first-order bending, with predominant vertical deformations (Fig. 4c). As shown by the model, modal displacement is maximum at the two central stations (S3 and S4) and progressively decreases toward the roof edges (S1 and S5). The vertical bending of the roof indicates greater sensitivity to vertical loads, thus representing a critical factor for the structural stability of the cave. The first resonance mode was then used to calibrate the numerical eigenfrequency model. Numerical Modal Analysis (NMA) accurately reproduced only the first resonance frequency (Fig. 4d), while higher-order modes showed poorer agreement. Comparison between experimental and numerical modes using the Modal Assurance Criterion (MAC) shows that only the first mode is effectively resolved by the numerical model (MAC > 0.7), whereas the others exhibit lower MAC values, indicating weak modal correspondence (Fig. 4e).

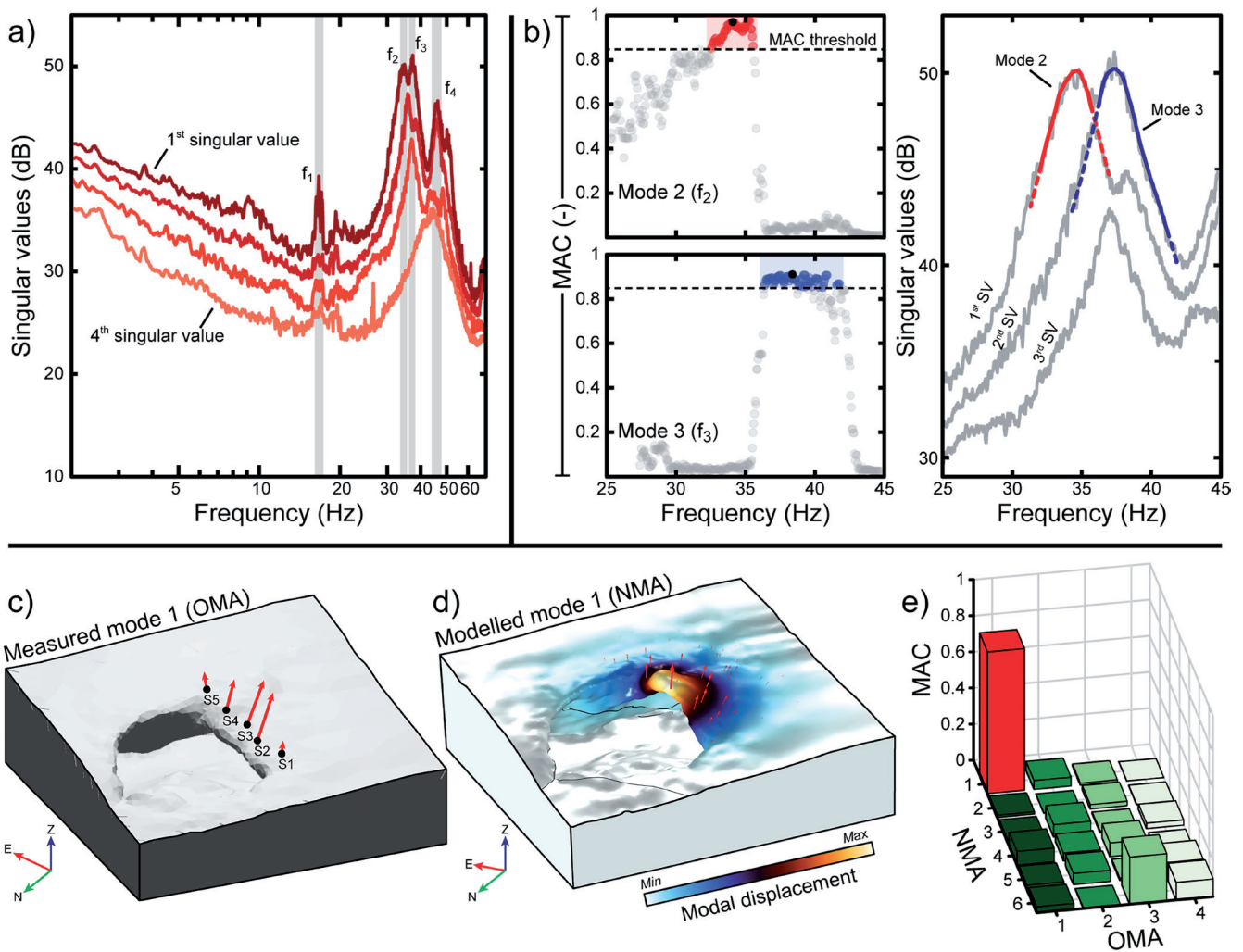


Fig. 4 - Results of operational and numerical modal analysis of the southern overhanging roof of the Ghar il-Latnija cave. (a) First four singular values obtained from Frequency Domain Decomposition (FDD), showing the identified resonance frequencies; (b) Modal Assurance Criterion (MAC) values used to discriminate closely spaced resonance modes; (c) Experimental mode shape of the first resonance frequency obtained from Operational Modal Analysis (OMA); (d) Numerical mode shape of the first resonance frequency obtained from Numerical Modal Analysis (NMA); (e) MAC matrix comparing experimental and numerical mode shapes

**DISCUSSION AND CONCLUSIONS**

This study proposed an integrated approach to investigate the dynamic response of underground cavities, combining two-dimensional numerical modelling of seismic wave propagation with in situ ambient vibration analyses using Operational and Numerical Modal Analysis techniques. Ambient vibration measurements and modal analysis are included to provide an experimental reference for interpreting the results of the parametric numerical analysis, which represents the core contribution of this work. The results of the 2D numerical modelling show that the presence of an underground cavity modifies the seismic wavefield, inducing local amplification and marked spatial variability in the dynamic response along the cavity boundary. The adopted

modelling framework is based on a simplified two-dimensional circular configuration with homogeneous mechanical properties and without explicit representation of fractures or structural heterogeneities. This conceptual setting is intended to isolate and analyse the fundamental mechanisms governing wave-cavity interaction under controlled conditions. The ambient vibration analysis carried out on the Ghar il-Latnija cave provided a preliminary characterization of the dynamic behavior of the residual roof under ambient conditions, identifying four resonance frequencies and deformation patterns dominated by vertical motion for the first mode. These results allow us to discuss the role of seismic vibration in influencing the dynamic response of the cavity, supporting interpretation of its observed dynamic behaviour. The

eigenfrequency numerical model reproduced the first resonance mode accurately, whereas agreement with higher-order modes was limited, potentially highlighting the limitations of simplified numerical models in representing the structural complexity of fractured rock masses. Overall, the integration of numerical modelling and vibration analyses proves to be an effective approach for improving the understanding of the fundamental mechanisms governing the dynamic response of underground cavities, which can influence their stability, and for seismic risk assessment in urban contexts. Future developments will include the extension of the numerical modelling through the analysis of a wider range of cavity geometries and stratigraphic

configurations and the application of advanced time–frequency techniques, such as the Normalized Inner Product combined with the Stockwell Transform, to investigate surface wave propagation and wave–cavity interaction mechanisms.

### *Acknowledgements*

The study is part of the PhD research of Veronica Gregori at the Vito Volterra PhD School of the University of Rome Sa-pienza. This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005).

### REFERENCES

- ALIELAHI H., ADAMPIRA M. & VENTURA G. (2016) - *Numerical modeling of seismic wave propagation around underground cavities*. Engineering Geology, **206**: 12-24.
- ALLEMANG R.J. (2003) - *The modal assurance criterion - Twenty years of use and abuse*. Sound and Vibration, **37**(8): 14-23.
- BRINCKER R., ZHANG L. & ANDERSEN P. (2001) - *Modal identification of output-only systems using frequency domain decomposition*. Smart Materials and Structures, **10**(3): 441-445.
- FABOZZI S., DE SILVA F., TOMMASI P., BILOTTA E. & MOSCATELLI M. (2024a) - *New proposal to assess the seismic stability of shallow underground cavities in soft intact rocks*. Engineering Geology, **324**: 107408.
- FABOZZI S., VARONE C., LENTI L., MARTINO S. & SEMBLAT J.F. (2024b) - *Numerical modelling approaches for seismic-induced instabilities in urban underground cavities: Implications for seismic microzonation*. Bulletin of Earthquake Engineering, **22**: 1-25.
- FARAONE C., COLANTONIO F. & VESSIA G. (2023) - *Seismic amplification effects induced by ancient shallow cavities under-neath the urban area of the historical center of Chieti, Italy*. Engineering Geology, **318**: 107259.
- FARRUGIA D., D'AMICO S., PAOLUCCI E. & GALEA P. (2016) - *Inversion of surface-wave data for subsurface shear-wave velocity profiles characterised by a thick buried low-velocity layer*. Geophysical Journal International, **206**: 1221-1231.
- FARRUGIA D., GALEA P., D'AMICO S. & PAOLUCCI E. (2017) - *Sensitivity of ground motion parameters to local shear-wave velocity models: The case of buried low-velocity layers*. Soil Dynamics and Earthquake Engineering, **98**: 196-205.
- GRECHI G., GREGORI V., MARTINO S., COLICA E., D'AMICO S. & GALONE L. (2025) - *Analysis of the dynamic behaviour of an underground cavity roof via operational and numerical modal analysis*. Proc. Eurock 2025 - Expanding the Underground Space, Trondheim, Norway, ISRM.
- ITASCA CONSULTING GROUP (2019) - *FLAC (Fast Lagrangian Analysis of Continua)*, Version 8.0.463. Itasca Consulting Group, Minneapolis, United States.
- LANCIONI G., BERNETTI R., QUAGLIARINI E. & TONTI L. (2016) - *Numerical analysis of the seismic response of underground cavities*. Soil Dynamics and Earthquake Engineering, **90**: 287-300.
- LOLLINO G., ARNONE E., MANUNTA M. & PARISE M. (2013) - *The role of geological factors in the propagation of sinkholes and underground cavities*. Geomorphology, **201**: 21-31.
- LYSMER J. & KUHLEMEYER R.L. (1969) - *Finite dynamic model for infinite media*. Journal of the Engineering Mechanics Division (ASCE), **95**(4): 859-877.
- MEZA-FAJARDO K.C., VARONE C., LENTI L., MARTINO S. & SEMBLAT J.F. (2019) - *Surface wave quantification in a highly heterogeneous alluvial basin: Case study of the Fosso di Vallerano, Rome, Italy*. Soil Dynamics and Earthquake Engineering, **119**: 186-199.
- PEDLEY M., CLARKE M.H. & GALEA P. (2002) - *Limestone Isles in a Crystal Sea: The Geology of the Maltese Islands*. P.E.G. Publishers, San Gwann, Malta.
- PISCHIUTTA M., VILLANO F., D'AMICO S., VASSALLO M., CARA F., DI NACCIO D., FARRUGIA D., DI GIULIO G., AMOROSO S., CANTORE L., MERCURI A., FAMIANI D., GALEA P., AKINCI A. & ROVELLI A. (2016) - *Results from shallow geophysical investigations in the northwestern sector of the island of Malta*. Physics and Chemistry of the Earth, **98**: 41-48.
- ZALAGHAI S., HEIDARI M. & NIKUDEL M. R. (2022) - *Engineering geological factors affecting loess caves susceptibility mapping in Gorgan Plain, Golestan Province, northeastern Iran*. Italian Journal of Engineering Geology and Environment, **1**: 15-30.

*Received January 2026 - Accepted March 2026*