

# Dynamic characterisation of an earth dam in eastern Sicily (Italy)

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**ABSTRACT:** Eastern Sicily (Italy), characterized in the past by large and destructive earthquakes (1169, 1542, 1624, 1693 and 1818) with magnitude between 5.5 and 7.4, is one of the most active regions in the Mediterranean area. The last significant seismic event ( $M_w = 5.6$ ) that occurred in this area was on December 13, 1990. The epicenter of this earthquake was located in the sea offshore the city of Augusta and maximum intensity values of VII-VIII were felt in the municipalities of Augusta, Carlentini, Lentini and Mineo. The 1990 seismic event caused damage and deformation to an earth dam in the city of Lentini. In particular, Sicily has a total of 47 large dams, of which 10 are regularly in use. In this context, it becomes crucial to evaluate the seismic risk of existing earth dams and determine their level of safety. Earth dams are large-scale engineering projects that are typically designed differently for each situation. For this reason, a site-specific assessment is often required. In this paper, the dynamic characterisation of an earth dam located in the central-eastern part of Sicily was developed. Moreover, the seismic hazard assessment was performed according to the current Italian seismic code. The findings presented in this work contribute to the existing knowledge on earth dam analysis.

**KEYWORDS:** earth dams; dynamic characterization; seismic hazard assessment.

## 1 INTRODUCTION

Large earth dams represent crucial infrastructure, providing local communities with water resources for various uses. Simultaneously, the safety and security of a dam have significant implications for the lives of people (Masini et al. 2021, 2022).

Various approaches can be employed for the evaluation of the seismic safety of earth dams. These include pseudo-static methods, which determine the stability of the dam with respect to boundary equilibrium conditions by using a global safety factor. Additionally, dynamic methods can be employed, where the stability is assessed by comparing the displacements accumulated during an earthquake to the corresponding admissible values (Castelli et al. 2016; Lombardo et al. 2018).

Many existing earth dams in Italy were designed prior to the establishment of a seismic code or with an underestimated degree of seismic hazard compared with the current Italian seismic code (NTC 2018). Therefore, conducting an accurate dynamic characterization of the earth dam and foundation soils and appropriately defining the most critical seismic scenarios at the dam site is of vital importance (Lanzo et al. 2017; Biondi et al. 2021).

This study focuses on the dynamic characterisation of the “Pietrarossa” dam located in the central-eastern part of Sicily (Italy) at the confluence of Acquabianca and Pietrarossa rivers. Furthermore, the seismic hazard was evaluated at the dam site according to the current Italian seismic code (NTC 2018).

## 2 DESCRIPTION OF THE CASE STUDY: “PIETRAROSSA” DAM

The “Pietrarossa” dam is an earth dam located in the municipality of Mineo, in central-eastern Sicily (Italy). It is part of a hydraulic system intended for the irrigation of the Catania plain (Figure 1).

The dam construction began in 1989, but it was interrupted a few years later due to the discovery of Roman era archaeological remains. In 2017, the Sicilian Region decided to complete the dam works, simultaneously planning the establishment of a museum for the archaeological finds. The dam, presently 97% complete, was constructed with a

capacity of 32 million  $m^3$  and a design height of 50 m dam on a site with an average elevation of 170 m above sea level and (Bertini et al. 2020).



Figure 1. Location of “Pietrarossa” dam (from Google maps, modified).

Eastern Sicily is characterized by a high seismic hazard as shown by historical seismic events (1169, 1542, 1624, 1693 and 1818) (Cavallaro et al. 2024; Grasso and Sammito 2025). The strongest earthquake hit Eastern Sicily on January 11, 1693 with a moment magnitude  $M_w=7.23$ . The most recent significant seismic event to occur in the investigated area was on December 13, 1990, with a moment magnitude  $M_w=5.6$ . The map with the intensity values felt during the 1693 seismic event is reported in Figure 2. An intensity value of X-XI was reached in the municipality of Mineo (Locati et al. 2022).

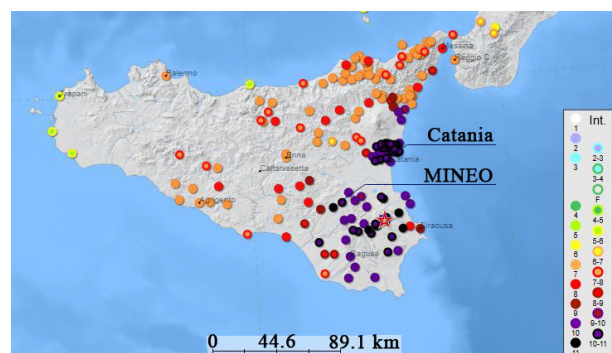


Figure 2. Intensity map for the 1693 earthquake (from Rovida et al. 2020, 2022; modified).

### 3 EXPERIMENTAL TESTING PROGRAM

In order to determine the static and dynamic properties of the foundation soil, three boreholes were performed, named S0, S1 and S2. Four undisturbed soil samples were retrieved at different depths to be subjected to laboratory tests (Table 1).

Table 1. List of the soil samples.

Sample	Depth [m]	Soil description
S0C1	24.00-24.50	Clay with silty sand
S1C2	36.00-36.50	Sand with clayey silt
S1C3	48.00-48.50	Clay with sandy silt
S2C4	22.50-23.00	Silt with clay and sand

Standard classification tests were carried out to obtain the physical parameters of the investigated soils, including the soil unit weight,  $\gamma$ , the specific weight,  $\gamma_s$ , the natural moisture content,  $w_n$ , the liquid limit,  $w_L$ , the plastic limit,  $w_P$ , the plasticity index,  $I_P$  and the consistency index,  $I_C$ , as reported in Table 2. In particular, it is possible to observe that  $\gamma_s$  values range between 25 kN/m<sup>3</sup> and 26 kN/m<sup>3</sup>,  $w_n$  values range between 17% and 25%,  $I_P$  values are variable between 23% and 29%, and the  $I_C$  values range between 1.1 and 1.4.

Table 2. Index properties for the investigated soil.

Sample	$\gamma$ [kN/m <sup>3</sup> ]	$\gamma_s$ [kN/m <sup>3</sup> ]	$w_n$ [%]	$w_L$ [%]	$w_P$ [%]	$I_P$ [%]	$I_C$ [%]
S0C1	19.3	24.9	21.1	54.4	27.5	26.8	1.1
S1C2	19.7	24.9	19.9	47.2	24.1	23.1	1.2
S1C3	20.1	25.0	17.4	57.8	29.1	28.7	1.4
S2C4	19.2	26.0	25.2	54.4	27.5	26.8	1.1

The dynamic soil behaviour was described by the variation of the shear modulus,  $G$ , and damping ratio,  $D$ , with the cyclic shear strain amplitude,  $\gamma_c$ . In this work, the non-linear behaviour was investigated in laboratory from cyclic triaxial tests (CTX) performed on S0C1, S1C2 and S2C4 samples. The CTX apparatus at University “Kore” of Enna was employed (Figure 3).



Figure 3. CTX device at University “Kore” of Enna.

The cyclic triaxial (CTX) apparatus has three main components with different purposes. A computer-controlled servo-pneumatic system manages vertical loading, displacement, cell pressure, and back pressure. A microprocessor-driven system controls a double-acting pneumatic actuator with an integrated LVDT displacement transducer. A compact unit oversees vertical load, displacement, cell pressure, and back pressure (Castelli et al. 2019; Lentini and Castelli 2019).

CTX tests were performed on specimens with nominal dimension of 70 mm in diameter and 140 mm in height. Cyclic triaxial test consisted of three main stages. The saturation was carried out by applying back pressure increments and maintaining a 10 kPa difference between the cell pressure and the back pressure. Values of the Skempton parameter,  $B$ , greater than 0.95 were considered for the complete saturation of the specimen. After the saturation phase, the specimens were isotropically consolidated for effective confinement mean stress representative of the in situ  $p_0$  range. Finally, displacement controlled modulus and damping according to the ASTM D 3999 standard were performed. The axial loading was applied through uniform sinusoidal cycles with constant amplitude at a defined frequency (e.g. 0.5 Hz).

The hysteresis cycles as the shear strain  $\gamma$  varies, obtained for the S0C1 and S1C2 specimens as examples, are shown in the Figures 4 and 5. Values of shear modulus  $G$  [MPa] and damping ratio  $D$  [%] versus  $\gamma$  obtained from CTX tests are showed in Figures 6 and 7.

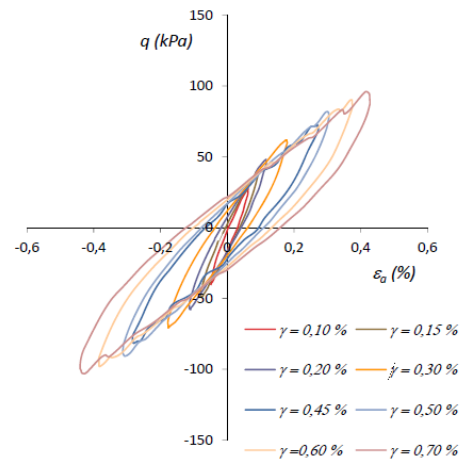


Figure 4. Variation of the deviator stress,  $q$  [kPa], with the axial strain  $\epsilon_a$  [%] for the S0C1 specimen.

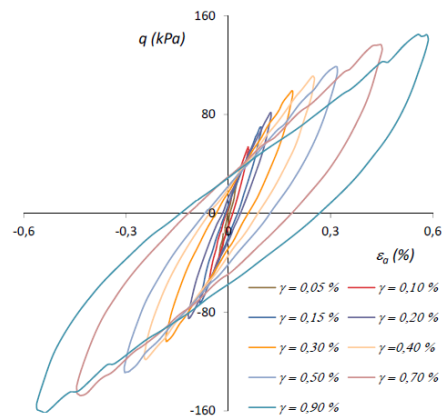


Figure 5. Variation of the deviator stress,  $q$  [kPa], with the axial strain  $\epsilon_a$  [%] for the S1C2 specimen.

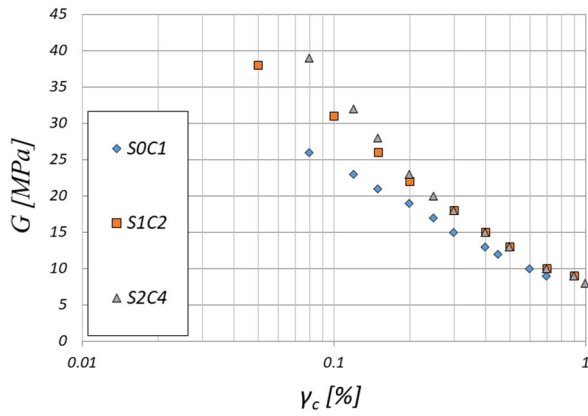


Figure 6.  $G$  [MPa]- $\gamma_c$  [%] curve for S0C1, S1C2 and S2C4 samples.

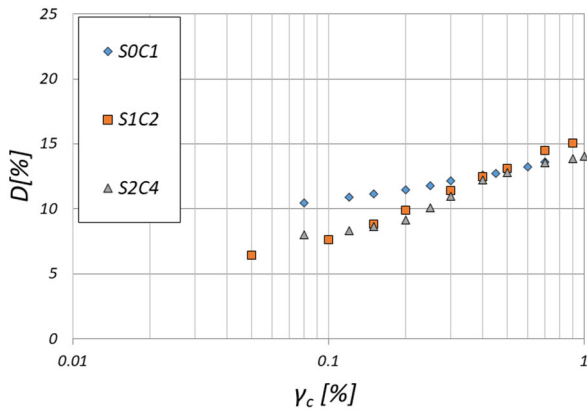


Figure 7.  $D$  [%]- $\gamma_c$  [%] curve for S0C1, S1C2 and S2C4 samples.

#### 4 SEISMIC HAZARD AND DEFINITION OF THE SEISMIC ACTION FOR “PIETRAROSSA” DAM

For the evaluation of the seismic hazard, the current Italian seismic code (NTC, 2018) employs a probabilistic approach (Probabilistic Seismic Hazard Analysis - PSHA).

In this work, a set of seven accelerometric waveforms compatible on average with the target spectrum build according to NTC (2018) was extracted. The target spectrum was defined for soil class A (outcropping rock) and a return period,  $T_R$ , of 1460 years. Indeed, a nominal life,  $V_N$ , equals to 50 years, a coefficient of use  $C_U$  equal to 1.5 (functional type III) and a reference period  $V_R$  of 75 years were considered. According to the NTC (2018), the functional type III includes “dams relevant for the consequences of their possible collapse”. The seismic hazard was assessed for a Collapse Limit State (CLS) corresponding to a probability of excess of 5% in 75 years.

The set of seven unscaled accelerometric waveforms was selected from the Engineering Strong-Motion (ESM) Database (Luzi et al. 2016; Lanzano et al. 2021), which includes events with magnitude greater than or equal to 4.0, mainly recorded in the European-Mediterranean regions and the Middle-East, using REXEL web tool (Version 2.1.9) (Sgobba et al. 2019). The compatibility was ensured in a range of period,  $T$ , equal to 0.15-2.0 s considering a lower threshold of 10% and an upper threshold of 30%.

Finally, the magnitude-distance criterion was employed considering the disaggregation data available at <https://esse1-gis.mi.ingv.it/>. The input parameters inserted in REXEL web tool are summarized in Table 3.

Table 3. Input parameters inserted in REXEL web tool.

Parameter	Value
Latitude	37.363
Longitude	14.585
Nominal life (years)	50
Functional type	III
Soil class	A
Limit State	CLS
$T_1$ [s]	0.15
$T_2$ [s]	2.0
Minimum magnitude	5.6
Maximum magnitude	6.6
Minimum epicentral distance [km]	0
Maximum epicentral distance [km]	36
Lower threshold [%]	10
Upper threshold [%]	30

Figure 8 and Table 4 show the set of seven unscaled accelerometric waveforms compatible to the reference spectrum defined according to the NTC (2018) using REXEL web tool.

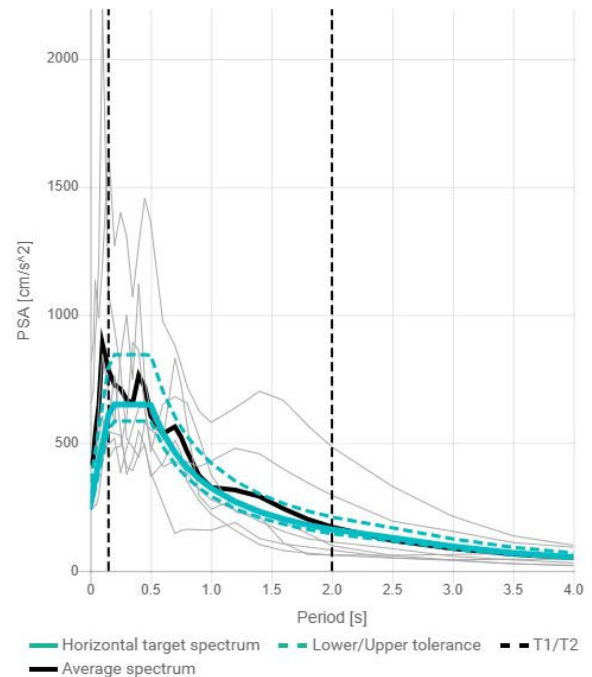


Figure 8. Combination of accelerometric waveforms selected using REXEL web tool for the “Pietrarossa” dam.

Table 4. Features of the selected accelerometric waveforms for the “Pietrarossa dam”.

Waveform ID	Magnitude, Mw	Epicentral Distance [km]
SM.106.00.HN.IS-2000-0048	6.5	22.7
SM.112.00.HN.IS-2008-0054	6.3	4.3
SM.502.00.HN.IS-2000-0053	6.5	6.5
8P.T1212..HN.EMSC-20161030_0000029	6.6	11.6
E.SRC.00.HN.IT-1976-0030	6.0	15.8
SM.113.00.HN.IS-2008-0054	6.3	7.5
8P.T1212..HN.EMSC-20161030_0000029	6.6	11.6

## 5 DEFINITION OF NON-LINEAR PARAMETERS IN THE HS SMALL MODEL

In the Hardening Soil model with small-strain stiffness (HS small model), the soil stiffness is stress-dependent and characterized by three different input parameters at the reference pressure,  $p_{ref}$ : the secant stiffness in standard drained triaxial test,  $E_{50}^{ref}$ , the unloading/reloading stiffness,  $E_{ur}^{ref}$ , and the tangent stiffness for primary oedometer loading,  $E_{oed}^{ref}$ . Moreover, in order to consider the soil non-linearity, the HS small model includes two additional parameters: the reference shear modulus at very small strain,  $G_0^{ref}$ , and the shear strain level,  $\gamma_{0.7}$ , at which the secant shear modulus,  $G_s$ , is reduced to 72.2 % of  $G_0$  (Benz, 2006; Benz et al. 2009). In the HS small, the stress dependency of  $G_0$ , is considered through the following equation:

$$G_0 = G_0^{ref} \left( \frac{\sigma'_3}{p^{ref}} \right)^m \quad (1)$$

In this work, the non-linear parameters in the HS small model were derived from the CTX test results (Section 3). Table 5 reports the non-linear parameters of the HS small for the following soil layers (Table 1): “Clay with silty sand”, “Sand with clayey silt” and “Silt with clay and sand”.

Table 5. Non-linear input parameters in the HS small model.

Soil Description	Parameter	Value	Unit
Clay with silty sand	$G_0^{ref}$	26	MPa
	$\gamma_{0.7}$	0.002	-
Sand with clayey silt	$G_0^{ref}$	38	MPa
	$\gamma_{0.7}$	0.015	-
Silt with clay and sand	$G_0^{ref}$	39	MPa
	$\gamma_{0.7}$	0.015	-

## 6 CONCLUSIONS

The main aim of this work is to provide a methodological approach for the safety evaluation of earth dams in seismic conditions. Indeed, many existing earth dams were designed prior to the establishment of seismic codes, making it of significant interest to evaluate their seismic performance.

The paper focuses on the dynamic characterisation of the “Pietrarossa” dam located in the central-eastern part of Sicily (Italy). The seismic hazard was evaluated according to the current Italian seismic code (NTC 2018) for a Collapse Limit State (CLS) with a return period,  $T_R$ , of 1460 years. The REXEL web tool was used to search for seven unscaled accelerometric waveforms compatible to the reference spectrum provided by the NTC (2018) in the range of periods of 0.15-2.0 s.

Results of cyclic triaxial (CTX) tests conducted on isotropically consolidated specimens are presented, focusing on the variation of the shear modulus ( $G$ ) and damping ratio ( $D$ ) with strain. The Hardening Soil model with small-strain stiffness (HSsmall) was considered to simulate the non-linear soil behavior of the investigated area.

## 7 ACKNOWLEDGEMENTS

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).

## 8 REFERENCES

- Benz, T. 2006. Small-Strain Stiffness of Soils and its numerical consequences. PhD Thesis. University of Stuttgart.
- Benz, T., Vermeer, P.A., Schwab, R. 2009. A small-strain overlay model. *Int J Numer Anal Methods Geomech* 200933(1), 25–44.
- Bertini, C., Buonora, L., Ridolfi, E., Russo, F. and Napolitano, F. 2020. On the Use of Satellite Rainfall Data to Design a Dam in an Ungauged Site. *Water* 12, 11: 3028. <https://doi.org/10.3390/w12113028>
- Biondi, G., Cascone, E., Aliberti, D., Rampello, S. 2021. Screening-level analyses for the evaluation of the seismic performance of a zoned earth dam, *Engineering Geology* 280, 105954, <https://doi.org/10.1016/j.enggeo.2020.105954>.
- Castelli, F., Cavallaro, A., Grasso, S., Lentini, V. 2019. Undrained Cyclic Laboratory Behavior of Sandy Soils. *Geosciences* 9(12):512. <https://doi.org/10.3390/geosciences9120512>
- Castelli, F., Lentini, V., Trifarò, C.A. 2016. 1D Seismic Analysis of Earth Dams: The Example of the Lentini Site. *Procedia Engineering*, 158, 356-361. <https://doi.org/10.1016/j.proeng.2016.08.455>.
- Cavallaro, A., Fiamingo, A., Grasso, S., Massimino, M.R., Sammito M.S.V. 2024. Local site amplification maps for the volcanic area of Trecastagni, south-eastern Sicily (Italy). *Bull Earthquake Eng* 22:635–1676. <https://doi.org/10.1007/s10518-023-01834-4>
- Grasso, S., Sammito, M.S.V. 2025. Assessment of 2D site effects for seismic microzonation studies: application to Eastern Sicily (Italy). *Bulletin of Earthquake Engineering* <https://doi.org/10.1007/s10518-025-02217-7>
- Lanzano, G., Luzi, L., Cauzzi, C., et al. 2021. Accessing European Strong-Motion Data: An Update on ORFEUS Coordinated through Services. *Seismological Research Letters* 92 (3): 1642–1658. <https://doi.org/10.1785/0220200398>
- Lanzo, G., Verrucci, L., Pagliaroli, A., Scasserra, G. 2017 Seismic safety assessment of a concrete gravity dam in Southeastern Sicily. Roma: *Proc. XXVI Convegno Nazionale di Geotecnica*; 2017. p. 1087–95.
- Lentini, V., Castelli, F. 2019. Liquefaction Resistance of Sandy Soils from Undrained Cyclic Triaxial Tests. *Geotech Geol Eng* 37, 201–216. <https://doi.org/10.1007/s10706-018-0603-y>
- Locati, M., Camassi, R., Rovida, A., Ercolani, E., Bernardini, F., Castelli, V., Caracciolo, C.H., Tertulliani, A., Rossi, A., Azzaro, R., D’Amico, S., Antonucci, A. 2022. Database Macrosismico Italiano (DBMI15), versione 4.0 [Data set]. Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.13127/dbmi/dbmi15.4>
- Lombardo, C., Greco, M., Lentini, V., Castelli, F. (2018). Seismic hazard and vulnerability of three Sicilian earth dams. *Proc.16th ECEE European Conference on Earthquake Engineering*, 12-17). Springer.
- Luzi, L., Puglia, R., Russo, E. et al. 2016. The Engineering Strong-Motion Database: A Platform to Access Pan-European Accelerometric Data. *Seismological Research Letters* 87 (4): 987–997. doi:<https://doi.org/10.1785/0220150278>
- Masini, L., and S. Rampello. 2022. Influence of Input Assumptions on the Evaluation of the Seismic Performance of Earth Dams. *Journal of Earthquake Engineering* 26 (9): 4471–4495. <https://doi.org/10.1080/13632469.2020.1835747>.
- Masini, L., Rampello, S., and Donatelli, R. 2021. Seismic performance of two classes of earth dams. *Earthq. Eng. Struct. Dyn* 50, 692–711
- NTC New Technical Standards for Buildings 2018. Available online: <https://www.gazzettaufficiale.it/eli/gu/2018/02/20/42/so/8/sg/pdf>
- Rovida, A., Locati, M., Camassi, R., Lolli, B., Gasperini, P., Antonucci, A. 2022. Catalogo Parametrico dei Terremoti Italiani (CPTI15), versione 4.0 [Data set]. Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.13127/cpti/cpti15.4>
- Rovida, A., Locati, M., Camassi, R., Lolli, B., Gasperini P. 2020. The Italian earthquake catalogue CPTI15. *Bulletin of Earthquake Engineering*, 18(7), 2953-2984. <https://doi.org/10.1007/s10518-020-00818-y>
- Sgobba, S., Puglia, R., Pacor F. et al. 2019. REXELweb: a tool for selection of ground-motion records from the Engineering Strong Motion database (ESM). *Proc.7th International Conference on Earthquake Geotechnical Engineering (ICEGE)* 17 - 20 June 2019, Roma, Italy.