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Dynamic properties of earth-core Italian dams from field and laboratory tests

Propriétés dynamiques des barrages de terre Italiens à partir d'essais in situ et en laboratoire

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ABSTRACT: The seismic design of new earth-core dams as well as the seismic re-assessment of existing ones with advanced numerical simulations require the knowledge of dynamic properties of core materials in a wide range of shear strains. The key parameters to be determined are the shear wave velocity Vs (or the maximum shear modulus G_0) and the normalized modulus reduction and damping ratio curves (G/G_0-γ_c and D-γ_c). Indeed, limited data do exist in the scientific literature on the in-field measured Vs profiles and on the laboratory cyclic/dynamic tests on undisturbed core samples. In this paper the dynamic properties of core materials of six zoned Italian dams are described and the main peculiarities are discussed, also in the light of the dynamic behaviour of natural soils.

RÉSUMÉ: Le comportment sismique des nouveaux barrages en terre ainsi que la réévaluation sismique des barrages existants avec des simulations numériques avancées nécessitent la connaissance des propriétés dynamiques des matériaux de noyau de la terre des barrages dans une large gamme de deformations de cisaillement. Les paramètres les plus important sont la vitesse d'onde de cisaillement Vs (ou le module de cisaillement maximal G_0) et les courbes de réduction de module normalisés et d'amortissement (G/G_0-γ_c et D-γ_c). En effet, il existe des données limitées dans la littérature scientifique sur les valeurs de Vs et sur le courbes G/G_0-γ_c et D-γ_c réalisée sur des échantillons non perturbés de les noyaux de terre. Dans cet article, les propriétés dynamiques des matériaux du noyau argilleuse de six barrage en terre italiens sont décrites et les principales particularités sont discutées, également à la lumière du comportement dynamique des sols naturels.

Keywords: Italian earth-core dams, core materials, Vs profiles, normalized modulus reduction and damping curves

1 INTRODUCTION

Advanced dynamic analyses are nowadays increasingly used in engineering practice for the sesmic design of new dams and for the evaluation of the seismic safety of existing dams. They have been proven to be a valuable tool for a more realistic seismic assessment as they provide several insights (e.g., patterns of elastic and permanent deformations, pore water pressure increments, influence of ground motion characteristics, etc.) that simpler methods cannot.

Advanced analyses of earth dams require key input dynamic parameters, usually expressed in terms of shear wave velocity Vs (or maximum shear modulus G_0) and normalized shear modulus reduction (G/G_0-γ_c) and damping ratio (D-γ_c) curves, being γ the shear strain amplitude.

This paper will focus on the dynamic properties of the core material of earth-core rockfill dams (ECRD). It is evident that meaningful results will be obatined only when realistic values of dynamic properties of core materials are introduced in the analyses.

The main factors influencing Vs (or G_0) of natural and reconstituted fine-grained soils as well as their the nonlinear properties, described by the G/G_0-γ_c and D-γ_c relationships, are well established in the literature. Shear modulus at very small strains, G_0, is associated with state parameters such as void ratio (*e*), mean effective confining pressure (σ'_m) and overconsolidation ratio (OCR). Empirical correlations expressing G_0 in terms of the above mentioned parameters have the following functional form:

$$G_0 = S\,F(e)\,OCR^m\,(\sigma'_m)^n \qquad (1)$$

where F(*e*) is a void ratio function, and S, n and m are empirical coefficients that depend on the plasticity of soils.

At present, there are very few studies in which the sher wave velocity of core materials have been determined from field tests. Sawada and Takahashi (1975) recommended an empirical correlation for the estimation of the Vs profile in the core zone. This correlation is based on the results of Vs profiles measured in boreholes and on back analyses of seismograph records of three dams in Japan. More recently Park and Kishida (2018) measured shear wave velocity profiles of fill dams from different geophysical tests. The Authors, based on the collection and statistical analysis of test results of 28 fill dams, propose an empirical relationship of the Vs profile as a function of vertical effective stress. The empirical correlations of Sawada and Takahashi (referred as S&T), in terms of upper and lower bounds, and Park & Kishida (referred as P&K), in terms of average and average ± standard deviation σ, are both plotted in Figure 1. It can be seen that the S&T profiles are characterized by higher Vs profiles as compared to P&K, with the lower bound of S&T close the the average profile of P&K.

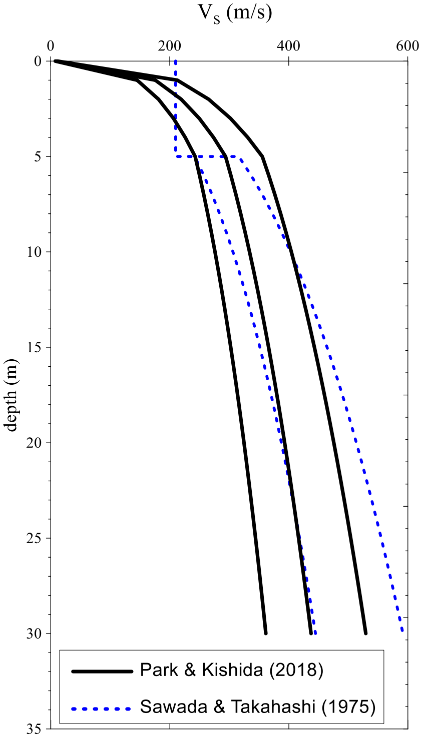

Figure 1. Empirical correlations for estimating the shear wave velocity profiles of the core zone

As the G/G_0-γ_c and D-γ_c curves is concerned, key parameters identified based on laboratory tests are plasticity index (PI) and mean effective confining stress (σ'_m). Empirical relationships have been proposed since nineties for fine grained soils (e.g. Vucetic and Dobry, 1991) or the beginning of the new century (e.g. Darendeli, 2001).

On the contrary, experimental results on the dynamic properties of earth-core field-compacted materials are limited. Most of the experimental studies concern laboratory-compacted soils, usually intended to be used for the contruction of the core, tested under full saturation (e.g., Kallioglou et al., 2002; Xenaki and Athanasopulos, 2008) of partially saturated (e.g. Vinale et al. (1999) conditions. In this latter study it is reported that the effects of saturation and confining pressure on the G/G_0-γ_c and D-γ_c curves are negligible.

Experimental studies on undisturbed samples retrieved from the core of the dams are seldom available. A recent study shows the results of laboratory tests on the shear modulus reduction and damping ratio curves of core materials of 13 earth-core Korean dams (Park and Kishida, 2019). Alltogether 31 resonant column (RC) tests have been conducted, 17 on undisturbed samples and 14 on reconstitued ones. Based on tests results, an empirical correlation for G/G_0-γ_c and D-γ_c curves is also proposed based on the statistical regression analyses of experimental data.

From the above considerations it turns out that new data on the dynamic properties of earth-core materials could be particularly useful because they will increase the database of existing experimental results and, moreover, they can be compared with the new empirical correlations *ad-hoc* developed by Park and Kishida for earth-core materials. Therefore, it seemed appropriate to collect and illustrate the dynamic properties of the core materials of some italian dams, most of which are currently undergoing a seismic reassessment.

2 ITALIAN DAMS CONSIDERED

Six italian dams have been considered in this study, whose location is reported in Figure 2. All dams are earth-core rockill dams, constituted by a central core of fine-grained material flanked by shells of cohensionless materials. Table 1 reports the name of the dam, the construction period and the maximum height. The dams are aged between 30 and 60 years since their construction. Maximum height is comprised between about 20 and 65 m, with the exception of San Pietro in Villa (H_{max}=6.3 m). In the same table, in-situ and laboratory cyclic/dynamic tests available for each dam are also indicated. It must be noted that data for Angitola, Montedoglio and San Pietro in Villa dams were obtained from the consultant activity of one of the Authors (Ground Engineering srl) whereas the data of the other dams have been taken from the literature, i.e. Bilancino dam (Mancuso & Silvestri, 1993), Camastra dam (Pagano et al., 2008) and San Pietro dam (Calabresi et al., 2004). It must be noted, also, that in-situ and laboratory measurements at Bilancino dam were carried out during construction, and therefore the corresponding material properties are not affected by ageing phenomena.

Figure 2. Location of the earth-core rockfill dams considered

2.1 Geotechnical investigations

For most of the Italian dams considered, results of in-situ and laboratory investigations carried out on the core materials during the design and construction phases were available.

Table 1. In-situ and laboratory tests available for the core materials of six Italian zoned dams

#	**Dam**	**Construction period**	**H_{max} (m)**	**In situ geophysical tests**	**Laboratory tests**
1	Angitola	1960-1966	28.8 (right) 22.6 (left)	DH SCPT	DSDSS
2	Bilancino	1988-1995	42	DH	RC/TS
3	Camastra	1963-1964	54	SDMT	-
4	Montedoglio	1977-1986	64.3	CH	DSDSS
5	San Pietro	1958-1964	49	-	RC
6	San Pietro in Villa	1980-1993	6.30	CH	DSDSS

The data collected and elaborated, although in some cases extremely numerous, refer essentially to the physical and "standard" mechanical (e.g., compressibility and shear strength) core properties. However, as mentioned in the Introduction, the geotechnical characterization for advanced dynamic numerical simulations require further and more detailed investigations. Therefore, additional campaigns have been conducted in the framework of the seismic reassessment of the dams, on one hand to confirm the geotechnical characterization based on already available data and, on the other hand, to acquire information on their dynamic properties.

In Figure 2 and Figure 3 the grains size composition and plasticity chart, respectively, of the core materials of five dams are illustrated. In Figure 2, the shading adopted for the different distributions refer to the upper and lower bounds determined on the samples subjected to laboratory tests. According to this diagram, core materials of the dams have similar composition, as they are mainly composed of sand, silt and clay in variable percentages. For Montedoglio and San Pietro in Villa sandy fraction is lower than for the other dams; clay fraction is always present and varies between 20 and 40%. The plasticity chart (Figure 3) indicate that core materials have generally a medium plasticity (PI≅15-30), even if in some cases (San Pietro dam) some data point fall in the region of low plasticity.

As indicated in Table 1, the definition of the shear wave velocity profile (Vs) along the vertical axis of the core was carried out by different in-situ geophysical surveys. In some cases conventional drilling was carried out and therefore cross-hole (CH) or down-hole (DH) tests were performed; in some other cases seismic dilatometer (SDMT) or seismic cone (SCPT) tests were conducted.

Nonlinear deformation properties (G/G_0-γ_c and D-γ_c) have been determined in the laboratory on undisturbed samples retrieved in the core of the dams during the execution of boreholes. In particular, dynamic resonant column (RC) tests and cyclic simple shear tests using a dual specimens device named the DSDSS apparatus (Doroudian and Vucetic, 1995; D'Elia et al., 2003) have been conducted. Properties of the core materials have been determined in the small-to-medium strain range from resonant column tests and from small-to-large strains with the simple shear testing.

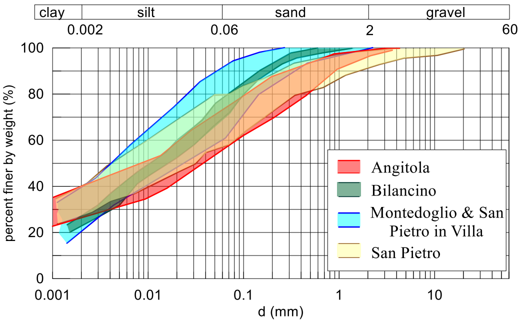

Figure 2. Grain size distributions of core materials

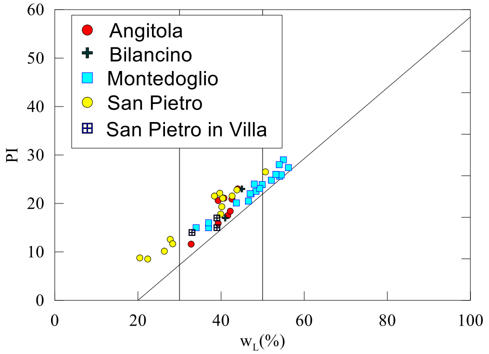

Figure 3. Plasticity chart of core materials

3 DYNAMIC CORE PROPERTIES FROM IN-SITU AND LAB TESTS

3.1 In-situ geophysical tests results

The results of the different geophysical survey methods are plotted in Figure 4 as a function of depth from the dam crest. Notwithstanding the different field tests, Vs profiles are quite similar and fall in a narrow range. It particular, Vs increases very slightly with depth. More specifically, in proximity of the crest, Vs values are approximately constant and comprised between 200-300 m/s whereas at 30-40 m depth the Vs values vary approximately in the range 250-400 m/s.

This observed behaviour is not surprising considering the overconsolidation state of the core due to compaction and the possible small variation of the mean effective stress with depth. This latter circumstance, for instance, has been observed by Pagano et al. (2008) showing, based on the results of numerical simulations corroborated by results from dilatometer tests, the small increase of the mean effective stress with depth from the crest of the Camastra dam.

In the same figure the experimental results are compared with the P&K empirical correlation. It is clear that, at least for the Italian earth dams under consideration, the P&K formula significantly overestimate the average stiffness of the core materials.

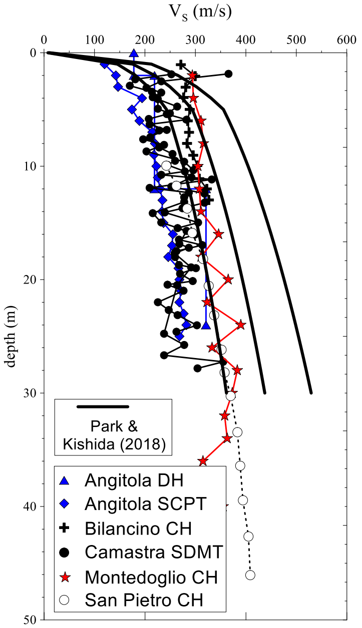

Figure 4. Vs profiles of core italian dams based on in-situ geophysical tests

3.2 Laboratory cyclic and dynamic tests results

In Table 2 the main physical characteristics of the core samples tested are reported. Samples were retrieved at different depths from the crest of the dams, close to the surface (e.g. Bilancino and San Pietro in Villa) and up to 30 m depth (e.g. Montedoglio). Unit weight is quite constant (γ=20.1-21.3 kN/m^3) and also water content do not show significant variations (w=15.4-23.3%); plasticity index PI varies between 15 and 29.

As indicated in Table 1, for Bilancino and San Pietro dams, dynamic RC tests have been conducted whereas for Angitola, Montedoglio and San Pietro in Villa dams cyclic DSDSS were performed. Usually the samples have been considated at the in-situ vertical or mean effective stress but in some cases (e.g. Montedoglio) very high confining pressure were also applied (up to 1500 kPa). The confining stress (vertical or mean) in all tests varied in the range 50-1500 kPa.

Table 2. Main physical properties of core materials

Dam	depth (m)	γ (kN/m^3)	w (%)	PI (-)
Angitola	18.9	20.3	20.8	23
Bilancino	1.0	20.1	18.0	23
Montedoglio	4.7	20.2	23.3	29
Montedoglio	23	21.3	17.2	16
Montedoglio	30	21.2	15.4	15
S.Pietro in V.	3.0	20.4	19.4	15
San Pietro	15.0	20.1	23.0	21.5

The G/G$_0$-γ_c e D-γ_c of the tested core samples are illustrated in Figure 5. Several considerations can be done. Like the Vs profiles, it can be noted that the curves of the undisturbed materials fall in a very narrow range, apparently independent on the soil plasticity in the range investigated. The more nonlinear G/G$_0$-γ_c curve pertains to Bilancino core material, whose sample was retrieved during the construction of the dam (not-aged nmaterial). The effect of confining pressure is also negligible, regardless of the very high confining range investigated (50-1500 kPa). These observations indicate therefore, differently to what is well established for natural fine grained soils, that the influence of plasticty and confining stress on the curves for core materials is not evident and significant. An analogous consideration was also made by Park and Kishida (2019). Damping ratios follow a trend similar to normalized stiffness experimental data points.

Figure 6 illustrates the comparison between the normalized stiffness and damping curves carried out on the samples retrieved from the dams core and the data extracted from literature on laboratory-compacted samples of similar plasticity, to be used for the construction of the core of dams. It is evident that field-compacted core materials exhibit a much slower decay in terms of G/G$_0$-γ_c curves as compared to the laboratory-compacted samples. The difference between field- and laboratory- compated soils has been already highlighted for others geotechnical properties (e.g. Prapaharan et al., 1991) and can be ascribed to different energy levels used for compaction that induce differences in the soil fabric. Damping ratios are much more scattered, especially at very small strains where also too high damping values comprised between 5 and 8% can be recognized. At strains larger than 0.1%, the damping ratios of laboratory- compacted samples (even if only few data from Xenaki and Athanasopoulos are available) are lower than field-compacted ones.

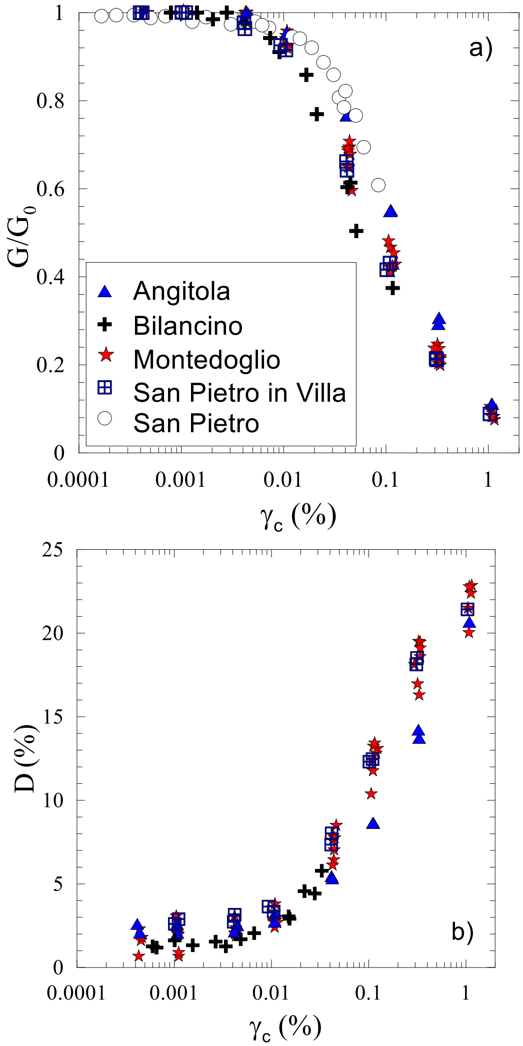

Figure 5. Normalized shear modulus (a) and damping ratio (b) data of core samples as a function of shear strain amplitude γ_c

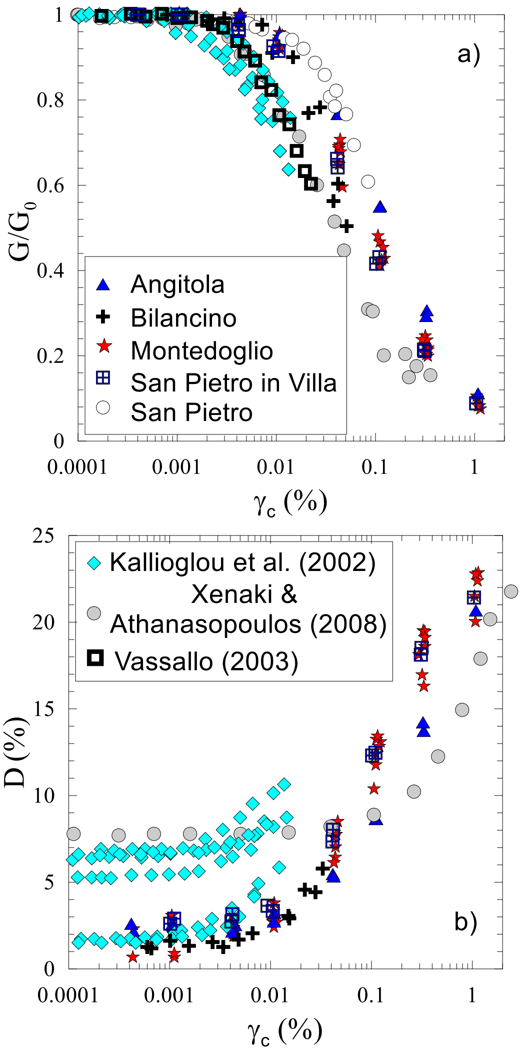

Figure 6. Normalized shear modulus (a) and damping ratio (b) data as a function of shear strain amplitude γ_c: comparison between field-compacted undisturbed core samples and laboratory compacted soil samples

In Figure 7 the G/G_0-γ_c and D-γ_c data points are finally compared with empirical curves from literature for similar PI, namely Vucetic and Dovry (1991) and Darendeli (2001). It can be seen that neither Vucetic & Dobry nor Darendeli are able to capture the variation of normalized stiffness with shear strains, at least up to about γ_c=0.05%; at larger shear strains experimental data fall within the band identified by Vucetic & Dobry for soils of similar plasticity. Furthermore, even when considering the effect of confining stress, Darendeli predictions are still well below the experimental data. Comparison in terms of damping ratio shows that at small strains experimental data are higher than predictions; at small-to-medium strains (0.005-0.05%) Darendeli curves show better agreement with experimental data as compared to Vucetic & Dobry while the opposite is true at higher strains.

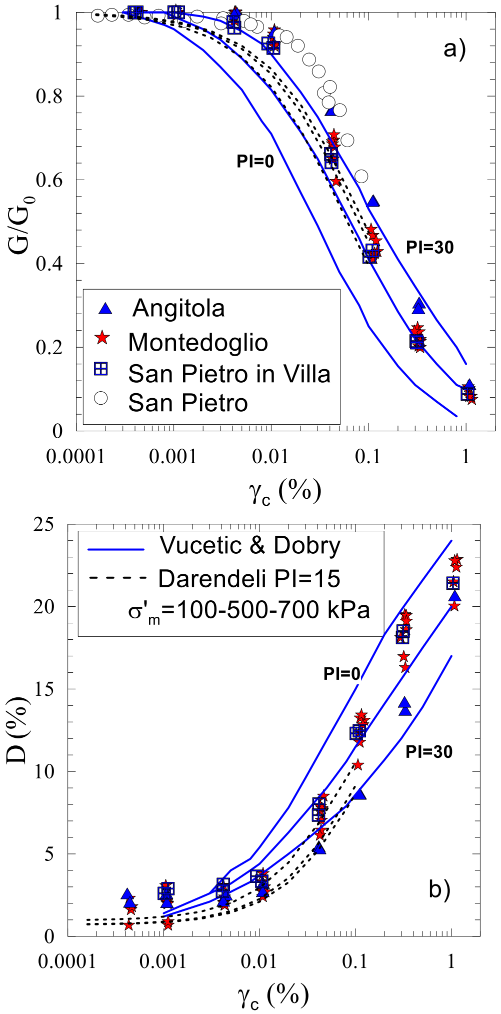

Figure 7. Normalized shear modulus (a) and damping ratio (b) curves: comparsion between data form the core zone of Italian dams and the empirical correlations of Vucetic and Dobry (1991) and Darendeli (2001)

4 CONCLUSIONS

In this study, focus is on the key parameters needed for dynamic analyses of ECR dams, i.e. shear wave velocity, modulus reduction and damping ratio curves. Based on the results of field and laboratory investigations carried out in the core zone of six Italian dams, it is shown that shear wave velocity profiles fall in a narrow range, gradually increasing with depth. The empirical correlations available on Vs of core zone overestimate the stiffness of Italian dams. Normalized modulus reduction and damping curves obtained from dynamic/cyclic laboratory tests on undisturbed core samples do not seem to follow the well-established trend for natural fine grained soils in terms of plasticity index and confining stress.

More field and laboratory investigations are in progress for other Italian dams in order to provide a greater generality to the results obtained.

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