EFFECTS OF GROUND MOTION CHARACTERISTICS ON SEISMIC RESPONSE OF EARTH DAMS: SOME REMARKS ON DURATION PARAMETERS AND VERTICAL SHAKING

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Abstract: Acceleration records used as input motion for nonlinear dynamic analyses of earth dams can significantly affect the outcome of the analyses. The selection of an adequate set of records is therefore an essential step of the study. Customary approaches rely on matching the target spectrum and the average response spectrum of the selected records. Furthermore, vertical motion is often considered to have a modest influence on dam response. In this paper, FLAC was used to conduct dynamic analyses of an earth dam located in Central Italy. The response was assessed in terms of permanent crest settlements and correlation were attempted with several IMs. The analyses were conducted with and without vertical component of motions. It was found that Arias Intensity may be considered an additional parameter to guide selection of input motions. The inclusion of the vertical components lead to a general increase, on average 75%, of the crest settlement.

Introduction

Nonlinear dynamic analysis of earth dams requires the definition of the input motion at the bedrock to be propagated through the foundation soils and the embankment dam. To this aim, ground motion time-histories are required which, on average, have to be compatible with a deterministic or probabilistic target response spectrum defined for the earthquake scenario considered. Presently, the extensive number of ground-motion records in internet-based depositories contribute to make more accessible signals that may satisfy the spectrum-compatibility requirements. Therefore, availability of suitable candidate records is no longer an issue. However, the selection criteria of an appropriate suite of records is still a challenging problem because there are no generally accepted criteria for selecting appropriate records for analyses.

As discussed by Bommer and Acevedo (2004), the current state of practice consists in conducting the selection in terms of seismological and geotechnical parameters such as tectonic environment, earthquake magnitude, fault characteristics, source-to-site distance and subsurface conditions. The selected records are then modified to match the target acceleration response spectrum: they may be simply scaled in intensity (linear scaling) or be spectrally modified (so called “spectral matching”). However, spectral parameters only address the peak response and therefore they offer a limited description of the seismic input and its potential consequences. This is especially true for embankment dam analyses when nonlinear behaviour is taken into account as time varying characteristics may significantly affect the computed response.

The need to consider additional intensity measures (IMs) of ground motion for dynamic analyses of dams has been first considered by Saragoni (1981) who suggested the use of the destructiveness potential factor P_D defined as the ratio between Arias intensity I_a and the intensity of zero crossings ν_0. This parameter was found to provide the greatest degree of information on the severity of ground motion for determining the cumulative displacements of a slope (Crespellani *et al.*, 1998). Von Thun *et al.* (1988) suggested a scalar descriptor based on the velocity spectrum intensity defined as the integral of the 5%-damping pseudo-velocity spectrum over the period interval 0.1-2.5 s. More recently, Yule *et al.* (2004), Perlea and Beaty (2010) and Armstrong *et al.* (2011) have investigated the possibility of using Arias

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intensity or significant duration as additional selection criteria for dynamic analyses of embankments dams. For instance, Armstrong *et al.* (2011) developed, for two earthquake scenarios, a suite of 40 ground motions constrained to both target acceleration response spectrum and target Arias Intensity. These motions were used as base input for the dynamic analysis of a 15 m high zoned embankment dam underlain by either a rock foundation or an alluvium layer. It was found a large variability in terms of crest displacements as a function of the ground motions selected and the foundation conditions modelled. On the same line of reasoning, Beaty and Perlea (2012) investigated the influence of several IMs parameters of the selected input motion on the crest settlement calculated from the dynamic analyses of two embankment dams. Both simple (e.g., significant duration d_s, Arias Intensity I_a) and composite (e.g., the product of Arias Intensity and significant duration) parameters were found to be efficient predictors of the computed response whereas peak response values (PGA, PGV, etc.), as expected, did not provide reasonable predictions.
Another important issue concerning the dynamic analysis of earth dams is related to the vertical component of ground motion. Traditionally, this component has been ignored most probably because (Bureau *et al.*, 2008): i) early equivalent-linear numerical site response studies did not show any significant effect on the response of the embankment dams (e.g., Seed *et al.*, 1973) ii) vertical motion occurs at high frequencies, of little significance to embankment dam analysis. The issue was first addressed by Von Thun and Harris (1981) and Bureau (1985), who introduced the vertical component for Newmark analyses and for dynamic analyses of concrete dams, respectively. More recently Bureau *et al.* (2008) and Bureau *et al.* (2009) conducted several dynamic response analysis for an earth dam with FLAC code, with and without vertical component. The authors concluded that peak crest settlements with vertical component may be as much as twice greater than without it. Similar results are obtained by Karimian *et al.* (2010) who showed that, by adding the vertical component of acceleration, the settlement of dam crest increased by as much as 85% for a 64 m high embankment dam.
It has to be remembered, however, that the vertical component may be especially important at short distances from causative faults, i.e. in the near-field, where vertical component dominates high frequencies, whereas it may have little impact at intermediate to large distance.
This paper illustrates the results of dynamic analyses conducted for an earth dam located in Central Italy. Attention is focused on the methodology used to define a set of natural accelerograms as input motion, considering in the selection IMs parameters not routinely taken into account such as significant duration and Arias intensity. Furthermore, all the analyses were run with and without applying the vertical ground motion excitation. The influence of the input motion parameters and the effect of vertical component on the computed results, expressed in terms of permanent settlements at the dam crest, are presented and discussed.

Description of Montedoglio dam and material characterization

Montedoglio dam is a zoned earth dam located on the Tiber River about 24 km northeast of the city of Arezzo, in Tuscany region (Central Italy). Construction of the dam began in 1970 and was completed in 1986, primarily to provide irrigation water storage.
Figure 1 shows the Google Earth view and main cross-section of the dam. The embankment dam has a crest length of 566 m, a crest width of 8 m, a maximum height of about 64.0 m high, and impounds a reservoir capacity of 153·106 m^3. The vertical core is made of compacted clayey silt of low plasticity flanked on both the upstream and downstream sides by compacted relatively pervious materials transported by the Tiber River. The core of the dam is directly founded on a formation made up of ophiolitic rocks while the shells underlain a thin layer of compacted alluvium soils superimposed on bedrock (Figure 1).
Extensive field and laboratory tests were carried out prior to, during and after construction to characterize the embankment and the foundation materials. Due to the lack of information on dynamic material properties, a supplementary field investigation was carried in 2013. This

investigation consisted of two cross-holes, one in the core and the other in the downstream shell, and one seismic refraction test along the crest. The cross-hole measurements allowed to obtain shear and compression wave velocity profiles (see V_S profile in Figure 1). In addition, undisturbed samples were also obtained in the core and were used for standard laboratory testing (physical tests, oedometer, triaxial, direct shear tests) and more sophisticated cyclic simple shear testing to determine modulus reduction and damping curves. Based on the above data, a geotechnical model of the dam and the subsoil was built and static as well as dynamic analyses of Montedoglio dam were carried out. Table 1 reports the physical and mechanical parameters assigned to the different materials.

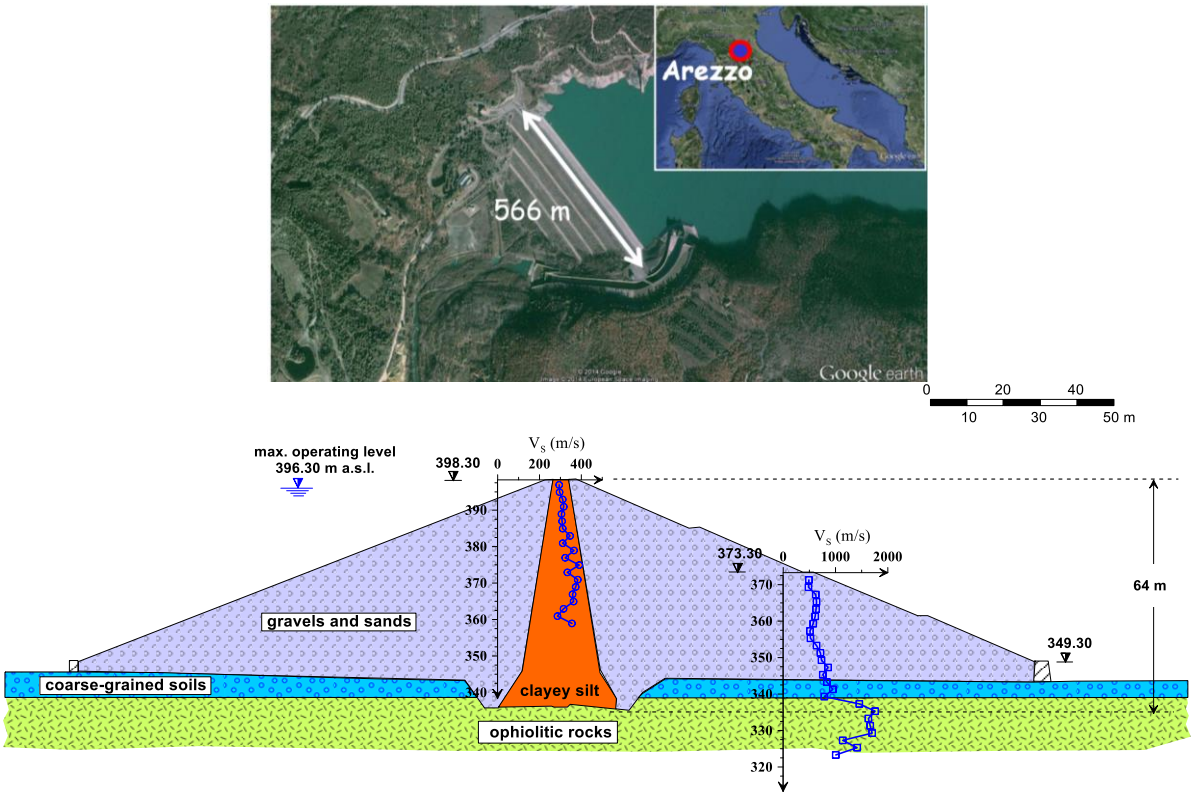

Figure 1. Google Earth view and main cross section of the Montedoglio zoned dam

Table 1. Physical and mechanical material parameters used in the static and dynamic analyses

parameter	core	shells	foundation alluvium	bedrock
γ (kN/m^3)	20.7	25	22	25
γ_{sat} (kN/m^3)	20.7	24.2	22	25
k (m/s)	$3\cdot10^{-10}$	$3\cdot10^{-5}$	$3\cdot10^{-5}$	$3\cdot10^{-10}$
c' (kPa)	10	0	0	-
φ' (°)	25	40	40	-
E' (MPa)	10	50	40	12550
G_0 (MPa)	$140+19.9z^{0.58}$	$92p'^{0.45}$	1450	4650
V_s (m/s)	280-380	480-850	800	1350
ν (-)	0.25	0.35	0.40	0.35

Seismicity assessment and seismic actions

The area where the dam is located (Valtiberina region) is characterized by moderate seismicity testified by both historical and instrumental earthquakes. The historical seismicity was defined based on the database of macroseismic observations DBMI11 (Locati et al., 2011). The Valtiberina region has a seismic record going back to the Middle Ages and

includes five I_o>VIII MCS earthquakes (1352, 1389, 1458, 1789, 1917), most of them extensively studied. The magnitude of these earthquakes was estimated to be between 5.9 and 6.5. The seismotectonic framework was defined by consulting the Database of Seismogenic Sources – DISS (Basili et al. 2008), supplemented by recent seismotectonic studies (e.g. Brozzetti et al. 2009). Based on the above information, all the earthquake sources with their fault mechanism and source-to-site distance that more strongly contribute to the seismic hazard of the area were determined. The magnitude and distance ranges corresponding to the main scenario event were assigned as M_w=6.0-6.6 and D=0-25 km. These ranges were directly used to select records from seismic web-site databases.
The seismic actions were defined in terms of elastic 5% damped acceleration response spectra according to the seismic Italian code NTC08 (Ministero delle Infrastrutture e dei Trasporti, 2008) for rock outcropping condition and flat surface topography. Assuming a reference life of 75 years and the tolerable probability of occurrence of 5%, a return period of 1460 years for the Collapse Limit State (SLC) was considered. The response spectrum of horizontal ground motion, presented in Figure 2, is characterized by a peak ground acceleration on rock outcropping PGA_h=0.312g while the maximum spectral acceleration is 0.75g. The vertical response spectrum, illustrated in the same figure, presents a peak ground acceleration PGA_v=0.237g and a maximum spectral acceleration of 0.57g.

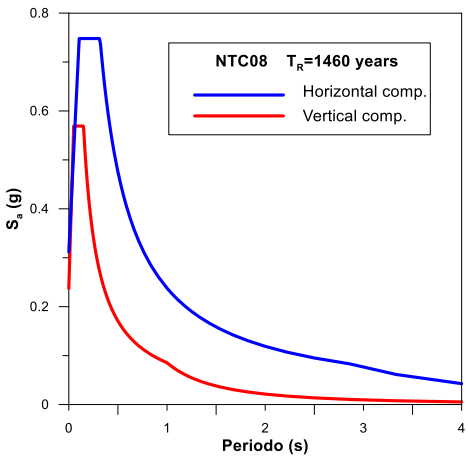

Figure 2. Horizontal and vertical acceleration response spectra from NTC08 for a return period T_R=1460 years

Time-histories selection and scaling

To define an appropriate suite of acceleration time-histories for dynamic analyses, an initial selection of candidate time-histories was carried out. Only time-histories from earthquake events similar in terms of magnitude and distance ranges to those obtained in the previous section (i.e., M_w=6-6.6 and D= 0-25 km) were considered. These constraints resulted in 48 ground motions selected from free-access internet databases, i.e. ITACA (http://itaca.mi.ingv.it/ItacaNet/), PEER (http://peer.berkeley.edu/) and ITSAK (http://www.itsak.gr). All candidate records were then linearly scaled to a value close to the target horizontal PGA applying a scaling factor SF. For each horizontal component of motion in this initial selection, the parameter D_{rms} (Bommer and Acevedo, 2004) was calculated:

$$D_{rms} = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(\frac{SA_0(T_i)}{PGA_0} - \frac{SA_S(T_i)}{PGA_S}\right)^2} \qquad (1)$$

where $SA_0(T_i)$ is the pseudoacceleration ordinate of the selected record at period T_i, $SA_S(T_i)$ is the target spectral acceleration at the same period, PGA_0 and PGA_S are the peak ground acceleration of the considered record and the zero-period anchor point of the target spectrum, respectively, and N is the number of periods at which the spectral shape is

specified. The calculation was performed in the range of periods 0.1-0.5 s (the elastic fundamental period of the dam is T=0.32 s), where we want to ensure a close match between the spectral shape of each record and the target spectrum. For each horizontal ground motion the scaling factor was plotted as a function of D_{rms}(0.1-0.5), as illustrated in Figure 3, and those recordings with the smallest D_{rms} and SF were selected, i.e only those records having D_{rms}<0.14 and SF<3.6. According to literature, suggested limit values for SF are comprised between 0.25 and 4 (Krinitszky and Chang 1979, Vanmarke 1979) while for D_{rms} are in the range 0.10-0.20 (Bommer and Acevedo 2004).

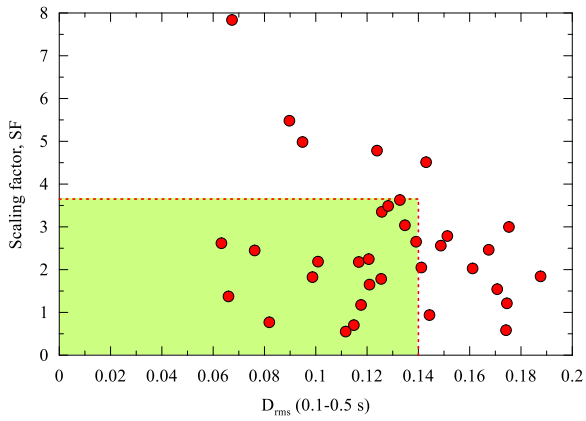

Figure 3. D_{rms} vs. SF for the acceleration records matching M-d ranges.

Based on this screening procedure, a subset of 18 accelerograms was obtained. The basic characteristics of the selected accelerograms along with the unscaled horizontal PGA and I_a are listed in Table 2. The main characteristics of the scaled ground motion records are reported in Table 3 and include Peak Ground Velocity (PGV), Peak Ground Displacement (PGD), Significant Duration (d_s), Arias Intensity (I_a), Predominant Period (T_p), Mean Period (T_m); in the table are also considered other two less common parameters, i.e. the Cumulative Absolute Velocity (CAV) and the Specific Energy Density (SED), defined as:

$$CAV = \int a(t)\,dt \qquad\qquad SED = \int [v(t)]^2\,dt \tag{2}$$

Table 2. Basic characteristics of 18 unscaled selected records (horizontal components)

GM #	Earthquake	Date	M	Station	Comp	D* (km)	EC8 soil class	PGA_h (g)	I_a (cm/s)
1	San Fernando	1971/02/09	6.6	Lake Hughes #4	201	24.2	A	0.153	20.7
2				Lake Hughes #4	111	24.2	A	0.192	24.8
3				Lake Hughes #9	021	23.5	A	0.157	7.6
4	Friuli	1976/09/15	6.0	San Rocco	NS	19.9	A	0.131	9.1
5				San Rocco	EW	19.9	A	0.250	24.4
6				Tarcento	EW	14.1	A	0.102	9.29
7				Tarcento	NS	14.1	A	0.129	15.8
8	Imperial Valley	1979/10/15	6.5	Cerro Prieto	237	26.5	B	0.157	134.0
9	Victoria	1980/06/09	6.3	Cerro Prieto	045	14.4	B	0.621	195.7
10	Morgan Hill	1984/04/24	6.2	Gilroy Array #6	090	11.8	B	0.292	87.1
11				Gilroy #1	320	16.2	A	0.098	5.94
12				Gilroy Gavilan	337	16.2	B	0.095	5.38
13	Palm Springs	1986/07/08	6.0	Silent valley	090	25.8	A	0.113	5.79
14	Kozani	1995/05/13	6.5	Kozani prefect.	Y	21.2	A	0.140	18.9
15				Kozani prefect.	X	21.2	A	0.208	25.6
16	Umbria-Marche	1997/09/26	6.0	Assisi	EW	22.1	A	0.188	22.6
17	L'Aquila	2009/04/06	6.3	AQG	EW	4.3	B	0.446	127.4
18				AQG	NS	4.3	B	0.489	127.2
*Closest distance									

Table 3. Main characteristics of 18 selected scaled records (horizontal components)

GM #	SF	D_{rms} (-)	PGV (cm/s)	PGD (cm)	I_a (cm/s)	d_s (s)	T_p (s)	T_m (s)	CAV (cm/s)	SED (cm^2/s)
1	2.25	0.121	18.88	4.25	104.72	12.89	0.2	0.257	817.1	216.9
2	1.78	0.126	9.96	1.60	78.70	12.71	0.12	0.197	703.7	92.6
3	2.18	0.117	9.78	2.71	71.77	4.7	0.08	0.138	585.8	100.1
4	2.62	0.063	27.63	6.25	62.70	4.36	0.14	0.506	441.8	569.4
5	1.37	0.066	27.57	7.83	45.78	2.66	0.2	0.453	327.6	344.3
6	3.35	0.126	13.12	2.62	104.25	7.42	0.12	0.231	673.6	192.4
7	2.65	0.139	16.49	2.90	110.82	6.88	0.12	0.217	682.7	179.6
8	2.19	0.101	40.76	17.48	642.63	36.23	0.3	0.568	3470.9	6644.5
9	0.55	0.112	17.42	7.48	59.49	8.57	0.06	0.509	536.3	461.6
10	1.17	0.118	42.93	7.17	119.22	6.47	0.22	0.613	707.8	1058.9
11	3.49	0.128	10.05	3.57	72.42	8.95	0.14	0.233	609.0	156.3
12	3.63	0.133	10.40	3.42	70.87	8.18	0.18	0.213	595.0	120.0
13	3.04	0.135	12.02	2.40	53.52	6.99	0.1	0.184	460.1	60.9
14	2.45	0.076	15.83	1.27	113.19	8.67	0.2	0.256	772.5	177.0
15	1.65	0.121	14.48	1.38	69.79	6.48	0.2	0.264	560.2	131.8
16	1.82	0.099	18.25	1.46	74.88	4.13	0.32	0.331	510.9	158.1
17	0.77	0.082	23.37	4.53	75.52	8.14	0.22	0.449	639.9	385.7
18	0.70	0.115	24.53	3.00	62.32	8.44	0.2	0.437	587.6	267.9

Numerical modelling

The computer program FLAC (ITASCA, 2011) was used to perform the dynamic analyses of Montedoglio dam. This program uses a 2D finite difference formulation that models the embankment dam and foundation with plane strain elements. FLAC solves the dynamic stress-strain problem using an explicit time-stepping procedure, well suited for nonlinear analyses. The program also includes the capability to model groundwater flow using a finite-difference formulation of seepage-consolidation.

The numerical analysis procedure consisted of three phases: (1) static analysis to establish the initial stress state of the model; (2) unconfined seepage analyses through the dam and (3) dynamic analysis to evaluate model response to input motions. More specifically, to establish a reasonable state of stress for use as initial condition in dynamic analyses the construction of the dam was first simulated. The soils were assumed to behave as elasto-plastic material characterized by a Mohr-Coulomb failure criterion. The stiffness moduli (E' in Table 1) were varied to back-calculate the displacements measured during dam construction. During the second phase the effects of the reservoir on the pore-water pressure conditions were evaluated by a steady-state seepage analysis condition assuming the reservoir surface elevation at the maximum operating level (396.30 m a.s.l.). Several changes were made to the model to adapt it from static analysis to dynamic analysis. Soil stiffness was updated from "static" values to small strain ones. In particular, the small-strain shear modulus G_0 (Table 1) was assumed variable with depth and confining stress according to the available in-situ geophysical tests. The Mohr-Coulomb elasto-plastic model was coupled with the sigmoidal3 hysteretic damping formulation available in the code library. The parameters of this model were calibrated by using the G/G0-γ and D-γ curves obtained from the laboratory cyclic simple shear tests for the core material whereas literature curves were assumed for the shells material. A small amount (0.3%) of Rayleigh damping was also added to provide a non-zero damping at very small strains. Water level located at the maximum operating level has been considered for the simulations.

The 18 scaled natural accelerograms were applied as seismic input at the base of the model. As mentioned in a previous section, the horizontal component of the ground motion was assumed as the primary component for linear scaling. The scaling factors for the horizontal component are then used for scaling of the vertical component. This is in fact what is suggested by the U.S. Army Corps of Engineers (2003) as a preferred option in order to preserve the relative amplitudes of the individual components present in the original record.

Dynamic analyses results

Dynamic analyses were performed on the main cross section of Montedoglio dam. As previously discussed, two set of analyses were carried out. In the first only the horizontal components of ground motion were used whereas in the second set of analyses the same suite of records was applied, but including the appropriate vertical components. The permanent settlement of the dam crest (w), results of plastic deformation induced by shaking, was primarily taken as indicative of the general response of the dam to seismic actions. The maximum permanent displacement (d_{max}) within the dam cross-section was also considered.

Figure 4 provides comparisons of crest settlements and selected IMs, with and without the inclusion of vertical component. The calculated crest settlement are generally less than 20 cm for the different input motions. The only exception is represented by the time-history of Cerro Prieto 237 (GM#8 in Table 2 and Table 3) which yielded the largest crest settlement (w=91.8 cm and w=60.2 cm with and without vertical component, respectively), well beyond the other computed results. It is interesting to remark that this signal presents a value of Arias Intensity (and duration) significantly larger than other input motions included in the dataset. For this reason Cerro Prieto data points are excluded from the plots in Figure 4.

In the range of computed displacements, the IMs that best correlate with the crest settlements are I_a and, to a lesser extent, CAV. On the other hand, PGV, d_s and SED as well as the composite parameter $(I_a \times d_s)^{0.5}$ showed little correlation. Figure 4 also reports the variation of crest settlements with the normalized predominant period T_p/T_0 and the normalized mean period T_m/T_0,being T_0 the fundamental period of the dam in the linear (small strain) range. The least scatter is found for T_m/T_0 correlation as illustrated in Figure 4h. With the exception of one point well outside the general trend (but characterized by the largest value of I_a), this figure indicates that the maximum crest settlement occurs at T_m/T_0~1 (i.e. when the mean frequency content of the acceleration time history is close to the fundamental period of the dam). Similar conclusions can be reached if maximum displacements d_{max} are considered for correlations with the different IMs. Again, it can be seen that I_a and CAV are the most promising parameters relating the dynamic response of the dam with the ground motion characteristics.

Based on the above observations, Arias Intensity targets for the present study were developed using the GMPE proposed by Travasarou *et al.* (2003) in the range of magnitude and distance of interest (Mw=6.0-7.0 and D=0-25 km). The values from the attenuation relationship are compared in Figure 5 with the I_a values of unscaled and scaled horizontal input motions. Most of the 18 recordings exhibit I_a unscaled values in the range predicted by the average curves plus one standard deviation, and scaled values still close to the upper limit. Only the two records coming from Cerro Prieto station have Arias intensities well above predictions, especially Cerro Prieto 237 for the scaled value.

An important conclusion is then related to the possible inclusion of Arias Intensity parameter within the input motion selection criteria, in order to exclude recordings inconsistent with the seismicity of the area of interest leading to a severe overestimation of permanent deformations.

Comparing the vertical displacement of the dam crest in Figure 4, a significant difference between the results obtained with and without the vertical component of ground motion can be recognized. With the exception of few recordings, there is a general increase of the crest settlement as evident from Figure 4. This increase is on average of about 75%, that is almost twice than the displacement computed with the horizontal component only. If the maximum displacement is considered, an average increase of about 50% with the inclusion of the vertical component can be obtained.

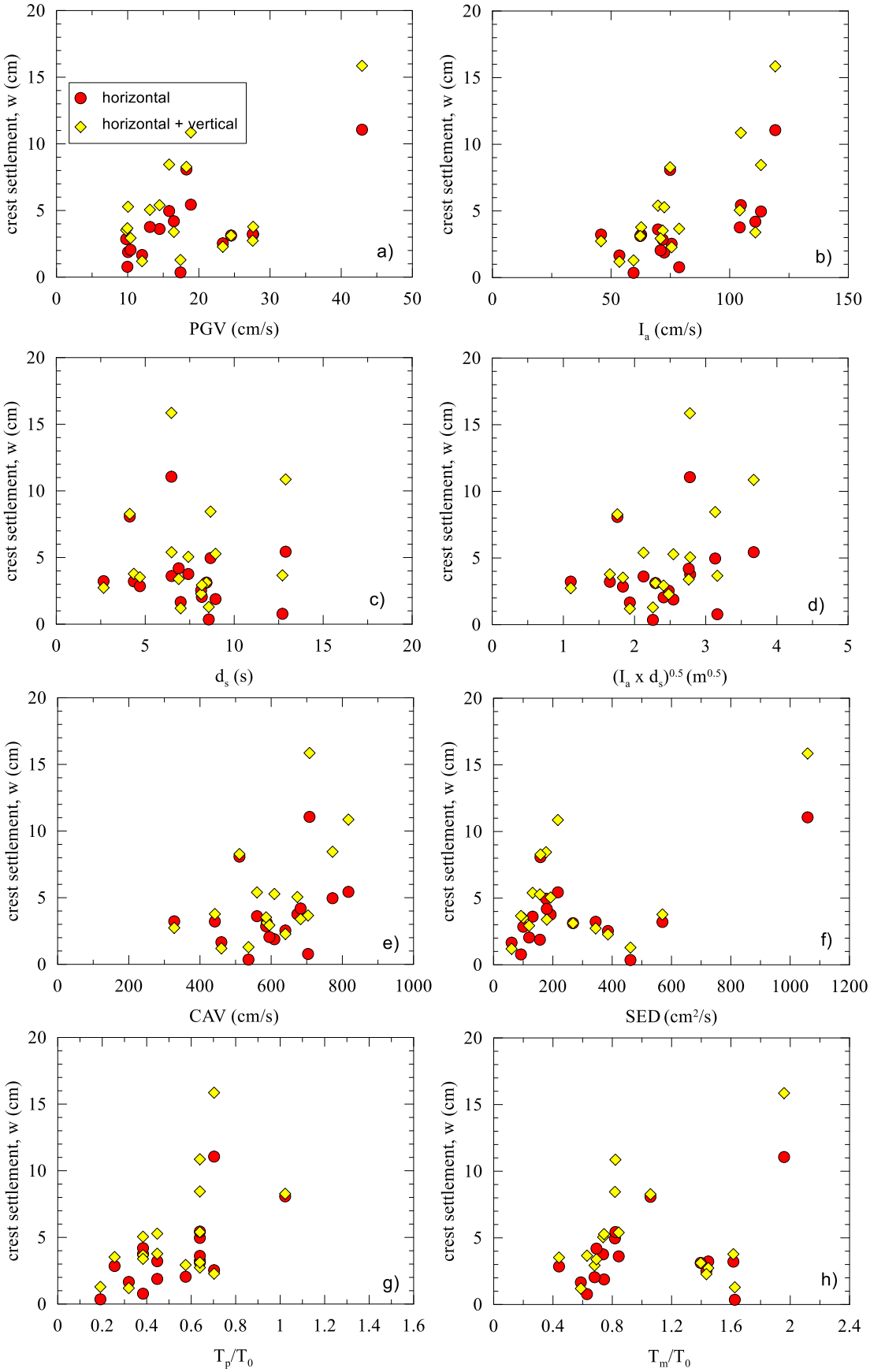

Figure 4. Crest permanent settlement vs. different IMs

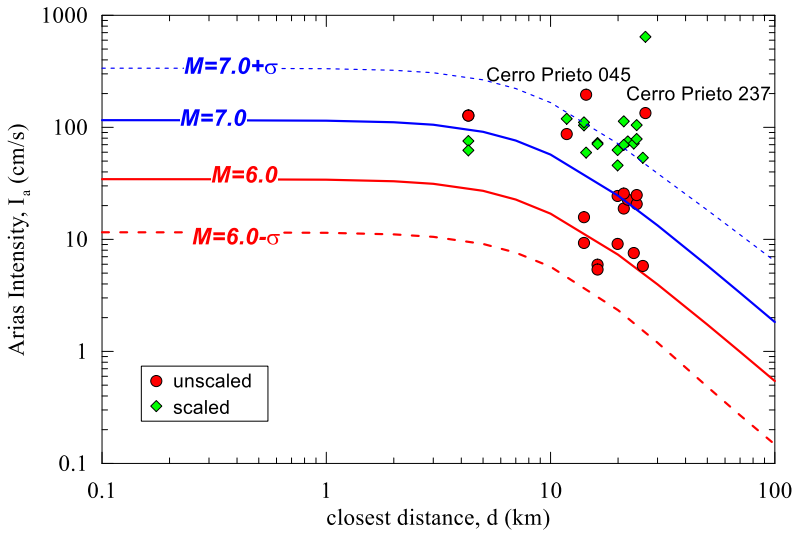

Figure 5. Arias intensity of unscaled and scaled accelerograms compared with values predicted by Travasarou *et al.* (2003) GMPE

Conclusions

A numerical investigation on the influence of the ground motion characteristics on the dynamic behaviour of an earth dam in Central Italy is presented. The study was carried out using the finite-difference computer program FLAC. A suite composed of eighteen records was selected as seismic input. Two set of analyses were carried out, one considering only the horizontal components of ground motion and the other including also the corresponding vertical components. The response of the dam was analysed in terms of permanent crest settlements and maximum permanent displacements. The calculated crest settlement and maximum displacements generally are not higher than 20 cm and 25-30 cm, respectively. For this range of predictions, which is actually rather small, a number of IMs were evaluated for their correspondence to the displacements values. It has been shown that duration parameters such as Arias intensity provides the more adequate prediction of the damage potential. Therefore, it appears that taking into account an additional parameter such as Arias Intensity may be a guidance for a suitable selection of input motion records for seismic analyses of dams. GMPEs of Arias Intensity applied to the seismicity of the studied area can be useful to discard unrealistic recordings. This conclusion may be weakened by the limited range of calculated displacements and for this reason a parametric investigation with increasing levels of seismic excitations is currently in progress.

Furthermore, the effect of adding the vertical component of motion was also demonstrated. The results of the analyses have shown, on average, an increase of crest settlements (approximately 75%) and maximum displacements (approximately 50%) with the inclusion of the vertical component. The usual practice of ignoring this component of motion when analysing the seismic performance of dams should be reconsidered, also bearing in mind the actual enhanced capability of conducting more sophisticated analyses.

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