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Earth dams in near-fault areas: from the regional to the site model

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Abstract

The seismic response of large embankments in near-source conditions may be investigated by a multi-scale and multidisciplinary approach, where the seismological and geological aspects of the problem are firstly studied on a regional scale while the local and geotechnical aspects are studied on a detailed scale, including the structure of interest. A detailed knowledge of the basic seismological aspects of the area on a regional scale is necessary to properly simulate the seismic source and the wave propagation pattern within the rock basement to get the input motion at the bedrock formation for the reference site. The proper characterization of the motion at the bedrock level is crucial for large earth-dams or embankments for which a strong variability of the input motion may be dangerous, since differential settlements and fractures of the embankment may be promoted, with the consequent reduction of structure safety. Worth mentioning is the case-history of Conza Dam (AV) during the 1980 Irpinia earthquake: the embankment was partially jeopardized by the seismic event, being the dam site very close to the Irpinia source ($\approx$10 km). To merge the different scales of analysis (macro and micro) the mathematical formulation of the Domain Reduction Method (DRM), initially proposed by [1], has been recently implemented [14] in a FDM commercial code. One of the main advantage of the DRM procedure is the possibility of sub-structuring the real problem, dealing the generation and propagation of the seismic waves (model on a regional scale) separately from the seismic response of the specific site and structure, carried out on a reduced and detailed model (site model). According to the DRM approach, the dam is inserted in the refined internal domain and will receive the seismic motion from the external domain (which contains the source and propagation medium) through an interface boundary. To quantitatively evaluate the variability of the ground motion at the bedrock of the reference site, synthetic parameters were selected and suitable represented.

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1. Introduction

Earthquake response analysis in near-source conditions (i.e., at sites close to an active fault) cannot be separated from the simulation of the source mechanism and of the propagation process occurring in the rock basement. The variation of the seismic motion along the boundary of the analysis domain is, in fact, closely related to: (i) the geometry of the source (extension in plan and corners of the strike and dip); (ii) the direction and value of the sliding; (iii) the position and number of asperities on the fault surface; (iv) the mean rise-time; (v) the site-source distance; (vi) the propagation medium (number of layers and the mechanical properties of each layer); (vi) the extension of the study area.

A very promising approach to model ground response in near-source conditions is the so-called Domain Reduction Method (DRM) proposed by [1]. One of the main advantage of the DRM procedure is the possibility of sub-structuring the real problem, dealing the generation and propagation of the seismic waves (model on a regional scale) separately from the seismic response of the specific site and structure, carried out on a reduced and detailed model. In short, the problem is faced by generating two numerical sub-models characterized by different scale dimensions and solved in two different steps (Fig. 1).

Step 1. The first model (Fig. 1(a)), which may span thousands of meters, is an auxiliary one and represents a simplification of the real external domain. In this step the earthquake source and propagation path are simulated. As proposed by [1], a stratigraphic system (flat-layer scheme), solved by means of 3D Green function, is simulated.

Step 2. The second model (Fig. 1(b)) contains the domain of interest with reduced spatial dimensions (internal domain), including the structure and the surrounding soil. The seismic source and most of the propagation path from the source to the site are now excluded. The input is given as a set of equivalent nodal forces applied to the interface elements Γ and able to reproduce the seismic source modelled in the first step.

A few applications of the DRM approach may be found in literature [2,3,4,5].

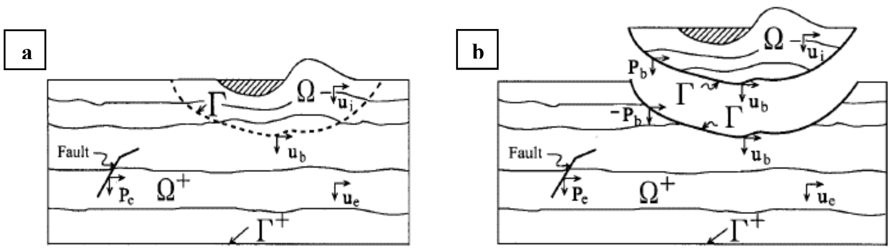

Fig. 1. Scheme of the seismic region including the causative fault, geological structure and local features. (a) Outer boundary Γ^+ restricts computation to a finite domain; fictitious interface Γ divides the region into two subdomains: Ω^+ which includes the seismic source (represented by the nodal forces Pe) and the propagation medium (rock basement); Ω containing the local geological features in the domain, the surface soils and the structure of interest [1].

In the present study, the DRM procedure was applied to define the input motion at the Conza Dam site (Italy) during the 1980 Irpinia earthquake (November 23, 1980; Mw=6.9). Due to the short distance of the site from the fault area, the Conza Dam is representative of several large dams placed in near-source area in Italy and worldwide. The paper illustrates (i) the reconstruction of the velocity structure of the Campania-Lucania region on the basis of former literature studies and on a new calibration of the 1-D velocity model at the regional scale; (ii) the definition of the reference input motion at the site of the Conza Dam with highlights on the spatial variability of the ground motion below the dam foundation.

2. Regional scale model

As preliminary steps of the DRM procedure, it is necessary to establish a velocity model for the propagation medium and a source model of the selected earthquake. In the case at hand, a one-dimensional layered stratigraphic model was adopted to represent the seismic wave propagation inside the rock basement of the Campania-Lucania region. To calibrate the model, a back-analysis on records of recent weak earthquakes provided by the ISNet (Irpinia Seismic Network) was carried out. Calibration of the stratigraphy at regional scale was performed with reference to seismic events of low magnitude (magnitude < 2.5) to avoid that events of medium-high intensity could affect the estimation of rock stiffness.

At present, a 3D velocity model for the Irpinia region does not exist. Conversely, since 1989 many 1D velocity models have been developed at different spatial scales. These velocity models differ in the P-wave velocity values and in number and depth of interfaces. This is due to the different predictive tools and data set used by the authors in each study, as well as to the actual complexity of the propagation medium. In particular, in the present study reference was primarily made to the Matrullo et al. [5] model (Fig. 2), representing the most updated evolution of the Campania-Lucania rock stratigraphy. Other velocity models were, however, considered as reported in Figure 2 [6,7,8].

Simulation of synthetic signals at the regional scale was carried out by implementing an algorithm based on empirical Green functions for the estimation of the propagation term and a kinematic source model. The Green functions are computed using the Discrete Wave-number Method (DWM) [9,10]. This method introduces a spatial periodicity of the sources to discretize the radiated wave field and uses the Fourier transform in the complex frequency domain to calculate the Green functions. Once the source and propagation terms are known, it is possible to determine the motion at the specific site by their convolution. This numerical formulation is implemented in the Axitra code [11].

Unfortunately, the synthetic signals reproduced by implementing the original Matrullo et al. [5] stratigraphy have pulse-like waveforms in correspondence to the individual arrivals of the various phases (reflected, refracted and converted waves) because the model does not account for the reverberations caused by the superficial layers in the upper part of the earth crust or local anomalies attributable to bi- and tri-dimensional effects. A pulse signal or a signal with multiple peaks in time, even if characterized by the same frequency content, induce different response in a soil deposit: signal duration and energy distribution in time are key features of the input motion due to nonlinearity of the soil behavior. The original Matrullo et al. [5] model was thus enriched with a random variation of stiffness in the upper part of the stratigraphy, between the depths of 0 and 1.5 km. The range of imposed variation corresponds to ±50 % of the P-wave velocity that the original model provides at the same depth (Fig. 2).

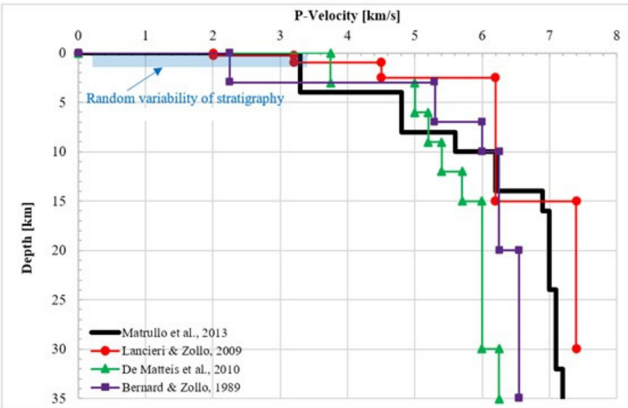

Fig. 2. Comparison between the most significant P-wave velocity models proposed for the Campania-Lucania region.

2.1. Validation of the proposed velocity model for the rock basement

Figure 3(a) shows a comparison between the elastic response spectra of the acceleration (East-West component) predicted and recorded at the ISNet Caggiano station (code: CGG3). The insertion of a random V_P variability in the upper crust of the original Matrullo model provides a remarkable improvement of the fitting on spectral components, especially at lower periods. The signal obtained considering the original Matrullo stratigraphy [5] tends to strongly underestimate the predicted spectral components with respect to the recorded signal. The improvement in terms of spectral ordinates was achieved not only for the station of Caggiano but also for other stations of the ISNet network, here not shown for the sake of brevity. Figure 3(b) shows the comparison in terms of PGA attenuation law between the predicted and measured signals. It is worth noting that observing the data between 20 and 25 km or between 27 and 28.5 km, higher values of PGA are observed, contrary to a general trend of intensity decrease with the distance from the source. These peaks are well reproduced by the numerical simulations for all the examined velocity models. Since the same trend is obtained also by using the original Matrullo model [5], this implies that these peaks are not linked to the random variability introduced in the upper part of the crustal model but to a deeper interface, which is a peculiarity of the regional velocity model.

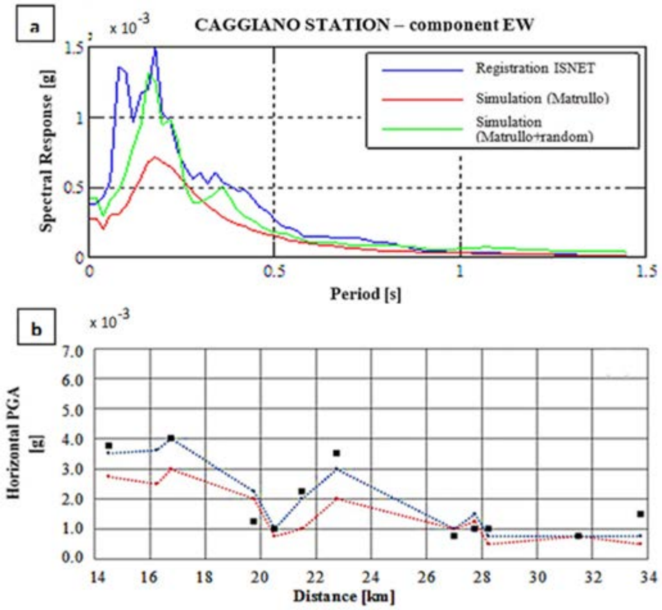

Fig. 3. (a) Comparison between the elastic spectra of the recorded and simulated E-W acceleration at the Caggiano ISNet station. Simulations refer to the original Matrullo velocity model [5] and to the randomly modified version proposed in this study. b) Observed vs. simulated PGA attenuation law in the horizontal direction (the horizontal motion was obtained by vector composition of the recorded NS and EW components).

2.2. Source model

The 1980 Irpinia earthquake ($M_w = 6.9$) is one of the most studied normal faulting event in the world. Surface faulting was identified over a broader area by [12]. The accelerograms recorded at several sites clearly show three distinct seismic events separated by a time lag of 20 s. The seismic radiation of the first 20 s sub-event is not clearly visible on all strong motion recordings because it is probably superimposed on the seismic radiation of the main rupture (first event) [8].

In this research work, to model the first fault mechanism of the 1980 earthquake reference was made to the inversion studies by [13]. For the second and the third fault mechanisms, a map of slip almost uniform was considered as suggested by [6], with a unique asperity at the hypocenter. The source model is built by positioning a series of equally spaced, point sources along the fault surface. The sum of point source seismic moments was set to be equal to the event seismic moment. The rupture velocity (V_r) was assumed constant and equal to the 80% of the shear wave velocity in the investigated area. The elementary point source spacing depend on the maximum frequency chosen for the numerical computation (the minimum wavelength given by $\lambda=V_r/f$, with f is the selected Nyquist frequency).

3. Site scale model

As stated above, the final goal of the overall research work is the assessment of the seismic response of the Conza Dam to the 1980 Irpinia earthquake. By applying the Domain Reduction Method (DRM), the dam will be later inserted in the internal domain (Figs. 4 (a)-(b)) and will receive the seismic motion from the external domain (which contains the source and propagation medium previously defined) through the interface boundary Γ (Fig. 1). A novel algorithm, recalling the procedure proposed in [1], was encoded by Dello Russo [14] in the commercial code FLAC 3D [15], which implements the finite difference method (FDM) as spatial solution technique of a continuous medium. An explicit finite difference formulation was adopted to solve the boundary value problem in the time domain. The engineering implications of the spatial variability of the ground motion at the base of the dam are out of the scope of this paper, which is primarily aimed at reproducing the 1980 earthquake scenario and quantifying the spatial variability of the motion at the bedrock of the specific site. Being the Conza Dam very close to the Irpinia 80 fault system, each node placed on the roof of the bedrock could have experienced a markedly different seismic motion.

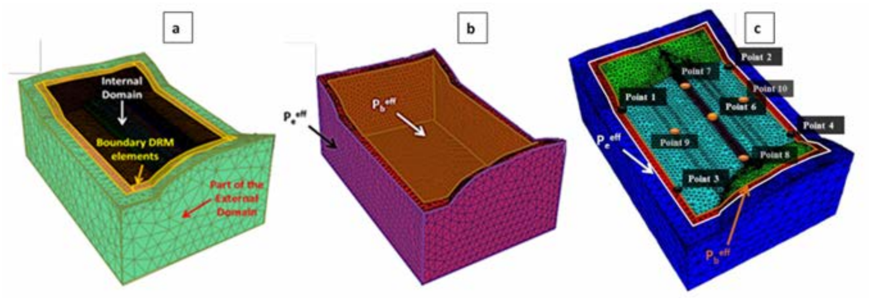

Fig. 4. DRM scheme for the application of the nodal forces from the external to the internal nodes of the interface region: (a) external and internal domain; (b) interface elements. (c) Reference points on the bedrock roof where the spatial variability of the ground motion was assessed.

To quantitatively evaluate the variability of the motion at the bedrock of the reference site, Figure 5 shows synthetic parameters (only for the first and second mechanisms of the 1980 Irpinia earthquake) characterizing the ground motion in correspondence to the previously selected monitoring points shown in Figure 4(c). With reference to Figure 5(a), it is possible to observe that the PGAs induced by the first two fault mechanisms are markedly different in each point of the upper boundary of the model, representing the bedrock roof at the site. Similar observations may be done for the values of PGV, here not shown for the sake of brevity. In the plots of Figure 5, the instants at which the acceleration peaks were attained in each location are also reported to highlight the asynchronism of the motion on the bedrock roof, i.e. below the dam embankment. All data highlights the strong spatial variability of the bedrock motion and the necessity to account for this phenomenon in the future seismic analysis of the dam, due to possible and important engineering implications [16].

4. Conclusion

The paper illustrated a multi-scale procedure developed to analyze the bedrock motion at the Conza Dam site during the 1980 Irpinia earthquake. Through a multidisciplinary approach, the spatial variability of the seismic motion at the bedrock level was evaluated. The ground motion thus predicted will be later adopted to back-analyze the seismic response of the dam to the 1980 Irpinia earthquake. The seismic source (extended) and the propagation path of the elastic waves from the source up to the site were simulated. Former regional stratigraphic models of the Campania-Lucania region were revised to match the ISNet available recordings of the recent Irpinia seismicity. Finally, the seismic hazard at the Conza Dam site was obtained and the spatial variability of the seismic motion at the bedrock formation below the dam was quantitatively assessed.

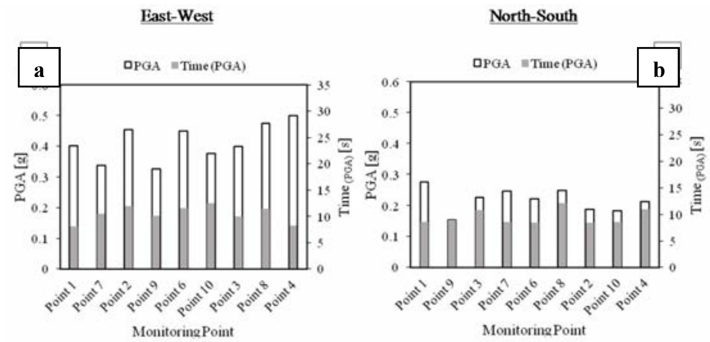

Fig. 5. Synthetic parameters for the signals computed at different points of the bedrock roof at Conza Dam site due to the first and second mechanisms of the 1980 Irpinia earthquake scenario.

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References

[1] J. Bielak, K. Loukakis, Y. Hisada, C. Yoshimura, Domain reduction method for three-dimensional earthquake modeling in localized regions. Part I: theory. Bull. Seism. Soc. Am. 93 (2003) 817-824.
[2] M. Corigliano, L. Scandella, C.G. Lai, R. Paolucci, Seismic analysis of deep tunnels in near fault conditions: a case study in Southern Italy. Springer Science+Business Media B.V., Bull Earthquake Eng., 2011.
[3] L. Scandella, Numerical evaluation of transient ground strains for the seismic analysis of underground structures. PhD Thesis. Politecnico di Milano, 2007.
[4] C. Yoshimura, J. Bielak, Y. Hisada, A. Fernandez, Domain reduction method for three-dimensional earthquake modeling in localized regions. Bull. Seism.Soc. Am. 93 (2003) 825-840.
[5] E. Matrullo, R. De Matteis, C. Satriano, O. Amoroso, A. Zollo, An improved 1-D seismic velocity model for seismological studies in the Campania–Lucania region (Southern Italy). Geophys. J. Int. 195 (2013) 460–473.
[6] M. Lancieri, A. Zollo, Simulated shaking maps for the 1980 Irpinia earthquake, Ms 6.9: Insights on the observed damage distribution. Soil Dynamic sand Earthquake Engineering 29 (2009) 1208-1219.
[7] R. De Matteis, A. Romeo, G. Pasquale, G. Iannaccone, A. Zollo, 3D tomographic imaging of the southern Apennines (Italy): a statistical approach to estimate the model uncertainty and resolution. Stud. geophys. Geod. 54 (2010) 367-387.
[8] P. Bernard, A. Zollo, The Irpinia (Italy) 1980 earthquake: detailed analysis of a complex normal fault. J. Geophys. Res. 94 (1989) 1631-1648.
[9] M. Bouchon, K. Aki. Discrete wavenumber representation of seismic source wave filed. Bull Seismol. Soc. Am. 67 (1977) 259-277.
[10] M. Bouchon, A review of the discrete wavenumber method, in Seismic Motion, Lithospheric Structures, Earthquake and Volcanic Sources: The Keiiti Aki Volume. Pageoph Topical Volumes, 2003, pp. 445-465.
[11] O. Coutant, Program de simulation numerique AXITRA. In Rapport LGIT. Universiteè Joseph Fourier, Grenoble, 1989
[12] R. Westaway, J. Jackson, The earthquake of 1980 November 23 in Campania-Basilicata (Southern Italy). Geophy. J.R. astr. Soc. 90 (1987) 375-443.
[12] D. Pantosti, G. Valensise, Faulting mechanism and complexity of the 23 November 1980, Campania-Lucania earthquake, inferred from surface observations. J. Geophys. Res. 95 (1990) 15319-15341.
[13] M. Cocco, F. Pacor, The rupture process of the 1980 Irpinia, Italy, earthquake from the inversion of strong motion waveforms. Tectonophysics 218 (1993) 157-177.
[14] A. Dello Russo, Seismic response of soil embankments in near-source conditions. PhD Thesis. University of Naples Federico II, 2015.
[15] Itasca Consulting Group. FLAC3D - Fast Lagrangian Analysis of Continua in Three-Dimensions, Ver. 5.0, Manuals. Minneapolis, 2012.
[16] E. Bilotta, L. Pagano, S. Sica, Effect of ground-motion asynchronism on the equivalent acceleration of earth dams. Soil Dyn. Earthq. Eng. 30 (2010) 561-579.