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Selection of spectrum- and seismo-compatible accelerograms for the Tuscany region in Central Italy

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ABSTRACT

This article illustrates the results of a study aimed at developing a methodology for the automatic identification of the seismic input at outcropping rock sites and flat topographic conditions necessary to carry out non-linear dynamic analysis of structures and geotechnical systems. The seismic input is provided in terms of a set of 7 natural accelerograms recorded on outcropping rock and satisfying the average spectral compatibility requirements prescribed by the Italian seismic code (NTC08).

The study focuses on the territory encompassing Tuscany region in Central Italy and it has been carried out for six return periods, which are 50, 75, 101, 475, 712 and 949 years. The procedure involved four main steps: (1) grouping of the response spectra with similar features; (2) definition of the reference response spectrum for each group; (3) selection of spectrum-compatible accelerograms using the reference response spectrum of each group; and (4) linear scaling of the accelerograms to satisfy the compatibility requirement with respect to other response spectra of the group. The last step is implemented through an interactive, user-friendly program named SCALCONA 2.0, which provides the seismic input in agreement with the site location and return period specified by the user. The program is freely available at the following web site: http://www.rete.toscana.it/sett/pta/sismica/01informazione/banchedati/input_sismici/progettazione/index.htm.

1. Introduction

Nonlinear, time-history analysis represents the most advanced method to assess the response of structures and geotechnical systems to seismic loading. Despite the computational and modelling improvements achieved during the last decade, the use of nonlinear dynamic analysis is still restricted in most circumstances to the solution of research problems. This despite certain typologies of structures would require the adoption of such type of analysis. On the other hand, the assessment of ground response is becoming increasing widespread in the engineering practice. For instance, local administrators require the use of ground response analysis for the purpose of microzonation of a territory. The seismic input for nonlinear dynamic analysis is represented by properly defined time series (e.g., accelerograms), which need to be defined consistently with the expected seismic hazard at the site of interest. The selection of time series is a fundamental activity also because the results of non-linear dynamic analyses of structures and geotechnical systems are strongly affected by the adopted input signal. However, the identification of a group of accelerograms complying with the seismic hazard expected at a site is a complicated matter. It requires skills in engineering seismology and usually it is very time consuming.

The current Italian building code (NTC08 [1]) and its Commentary [2], defines the seismic action in terms of acceleration response spectra specified over a grid of points covering the entire Italian territory. However, their use is limited to pseudo-static and dynamic linear analyses. To encourage the use of nonlinear dynamic analyses, several regional administrations in Italy have funded research projects aimed at defining, in their territory, appropriate sets of spectrum-compatible natural records.

This paper describes a methodology developed in the framework of one of these projects, specifically the project funded by Tuscany Region, aimed at identifying the seismic input in the Tuscan territory in agreement with the prescriptions of the Italian building code [1,2]. The seismic input has been defined, for each location within the Tuscany Region, in terms of sets of 7 natural accelerograms recorded on outcropping rock (i.e., soil category A as per NTC08 [1]), spectrum-compatible with the response spectrum of

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the Italian building code [1,2]. The number of accelerograms in a set has been restricted to 7 in accordance with the prescriptions of the NTC08 [1], which permits to use the mean results of the analysis instead of the most unfavourable ones if the analysis carries out at least 7 independent dynamic analyses. The study has been carried out considering the following 6 return periods: 50, 75, 101, 475, 712 and 949 years.

Like other building codes worldwide, NTC08 [1] allows the adoption of three categories of accelerograms, namely natural, artificial and synthetic records. Natural (or real) accelerograms are signals recorded during real seismic events and they are available from accredited strong-motion databases. Artificial accelerograms are signals generated using stochastic algorithms and possibly constrained to be spectrum-compatible with a target response spectrum. This category includes also hybrid accelerograms, which are records obtained by appropriately modifying real seismograms in such a way to enforce spectrum-compatibility. Finally, synthetic accelerograms are signals generated through a kinematic and/or dynamic model of the seismic source coupled with an elastodynamic idealization of the Earth crust from the source to the site of interest.

The superiority of natural accelerograms over artificial and synthetic records is widely recognized in the scientific community for both structural and geotechnical applications. Natural accelerograms have a correct duration in relation to the earthquake scenario, frequency content and correlation between the vertical and horizontal components of ground motion and between the phase and the amplitude of the record [3,4]. For these reasons, some buildings codes like the NTC08 [1], do not allow the use of artificial records for the assessment of local site effects, slope stability and other geotechnical applications.

According to NTC08 [1], recorded accelerograms to be used for dynamic analysis need to be representative of the seismicity of the site and adequately justified in terms of the characteristics of the seismic source, the geological and geotechnical conditions of the recording site, the expected magnitude, the distance from the source and the peak horizontal acceleration expected at the site. They may be linearly scaled to match the code-based elastic response spectrum in the range of periods of interest for the problem under examination.

These prescriptions represent the current practice in the selection of natural records, in which the accelerograms should reflect the magnitude, distance and other earthquake-related parameters that are believed to dominate the hazard at the site. However, some studies [5] demonstrated that, in some cases, compliance with the magnitude and the epicentral distance of the earthquake scenario, which might be named *seismo-compatibility*, is not a sufficient criterion to guarantee a correct estimation of the structural response and the *spectrum-compatibility* also needs to be enforced. For these reasons, the Commentary [2] of the NTC08 [1] recommends that the selection of natural accelerograms should take into account the compatibility of the average spectrum of the selected records with respect to the code-based elastic spectrum, within a prescribed range of periods. Specifically, the code states that no value of the average response spectrum computed from the selected accelerograms should be less than the ordinates of the corresponding code-based elastic response spectrum by more than 10% in a predefined range of structural periods. The latter is calculated as the larger between the interval $0.15\,s \div 2.0\,s$ and $0.15\,s \div 2T$, for ultimate limit states, or $0.15\,s \div 1.5T$, for serviceability limit states, with T the elastic fundamental structural period. Furthermore, the Commentary [2] of the NTC08 [1] prescribes that, if the records are linearly scaled to satisfy spectrum-compatibility, the scaling factor must be limited in case of accelerograms originated from events characterized by small magnitude.

The identification of the seismic input for the Tuscan territory would require a selection of time series for each response spectrum defined by the NTC08 [1] within the region, for each of the 6 return periods considered in this study, resulting in over 5500 selections. Therefore, a procedure to reduce this computational effort has been developed. The methodology is based on the implementation of a number of steps which can be summarized as follows: (1) grouping of the response spectra in clusters with similar shape and amplitude; (2) definition of a reference response spectrum for each cluster; (3) selection of a set of 7 accelerograms spectrum-compatible with the reference response spectra only; and (4) linear scaling of the selected accelerograms so to satisfy the spectrum-compatibility at a specific site, where the code-based response spectrum is generally different from the reference spectrum, although it belongs to the same cluster. A Fortran code, named SCALCONA 2.0 (SCALing of COmpatible Natural Accelerograms, version 2.0) has been purposely developed and it is available at the following web site: http://www.rete.toscana.it/sett/pta/sismica/01informazione/banchedati/input_sismici/progettazione/index.htm. In a matter of few seconds, SCALCONA 2.0 yields the seismic input at a specific site and for a specific return period prescribed by the user.

The methodology is based on linearly scaling real accelerograms. However, big efforts have been made to obtain acceptable values for the adopted scaling factors. It is well known, in fact, that the duration of ground shaking and the frequency content of a seismogram are both strongly dependent on the magnitude–distance pair to which they are referred. Therefore, it is highly desirable to adopt scaling factors as close to unity as possible [4]. Formally, neither the NTC08 [1] nor the Eurocode 8 [6] prescribe specific bounds for the factors to be used to scale real accelerograms.

2. Definition of the target response spectra

2.1. Seismic input according to the Italian building code

The NTC08 [1] and its Commentary [2] define the seismic action in terms of elastic response spectra, using the results of the probabilistic seismic hazard assessment study for the Italian territory performed by the Italian Institute of Geophysics and Volcanology (INGV) in the framework of Project S1 [7]. The seismic hazard is estimated at 16921 nodes of a regular grid with a spatial distance among the nodes equal to $0.05°$, corresponding to an average distance of about 5–6 km. For each node, the seismic hazard is represented in terms of peak ground acceleration (PGA) and 10 different spectral ordinates between 0.1 and 2 s of structural period. The uniform hazard response spectra are defined for rock outcropping conditions and flat topographic surface and for 9 return periods (i.e. 30, 50, 72, 101, 140, 201, 475, 975 and 2475 years). All the data can be retrieved at the following web site http://esse1.mi.ingv.it. Disaggregation of the seismic hazard for the PGA has also been performed by INGV. The results of the study [8] are available in terms of magnitude, M, epicentral distance, d, and number, ε, of (logarithmic) standard deviations by which the (logarithmic) ground motion deviates from the median value predicted by a specific ground motion prediction relation for a given M–d pair.

The elastic response spectra defined by NTC08 [1] are site-dependent and match the probabilistic uniform hazard spectra for 10751 nodes of the reference grid and the 9 return periods adopted for the seismic hazard study. Moreover, for the islands belonging to the Italian territory, with the exception of Sicily, Ischia, Procida and Capri, a unique spectral shape has been defined throughout the territory of each island. Each response spectrum is defined, in the absence of site effects, by an equation depending on