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THE EFFECT OF REDUCED PRECISION SEISMIC INPUTS IN THE CHARACTERIZATION OF THE SEISMIC RESPONSES FREE-FIELD

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Abstract

The increasing demand for a better knowledge of the earthquake effects on buildings and infrastructures is prompting the scientific research to further investigate the possibility of using large nets of low cost instruments in place of just few high precision, high cost sensors installed in a limited number of locations. Contrarily, seismic monitoring activities have been so far conceived only for very special purposes (survey of strategic buildings and or sites) and traditionally curried out with a limited number of high-precision sensors. In this study, data recorded from low cost, reduced precision accelerometers have been assumed as input data to run numerical simulation and calculate local seismic responses under free field conditions. These results have been later compared with those previously obtained on the base of input data taken from high cost, high precision accelerometers instead. Local seismic responses have been calculated and compared for different combinations of several variables. In particular, several earthquakes characterized from different ground motion parameters (intensity, duration, frequency content,…) have been considered. Two different soil profiles were assumed, representing real cases; the first one is characterized by regular gradient of the geotechnical properties (Vs increasing with depth) while the second one has a stratigraphy affected by an evident singularity in the Vs profile. The two soil profiles were also characterized by different bedrock depths were the above mention seismic inputs were applied. The results from the one-dimensional, equivalent linear numerical analyses performed so far show that the local seismic responses calculated using the reduced precision seismic inputs compare well with those calculated using the seismic inputs from high precision accelerometers.

Keywords: Reduced precision accelerometers; Local seismic response free-field; Non-linear numerical simulations.

1. Introduction

Social safety and building heritage along with the sustainable urban development are important issues in setting strategic priorities in European operational framework. To this end, evaluating the condition and performance of existing civil infrastructure is a crucial aspect that allows decision-makers to configure the best activity lines, in generic words, aiming people life-quality improvement [1].

This challenge reasonably embraces the efforts coming from different disciplines in order to create a suitable informative database and recognize preventive measures of risk mitigation for resilience improvement. Some perspectives involved are those of in situ inspection and investigation about mechanical properties of materials [2], or, for example, the characterization of the ground response for earthquake engineering applications [3]. In addition, depending on the purpose, one may move from a large-scale assessment [4] or, otherwise, analyze structural and dynamic properties referring to individual buildings [5], or conduct the analysis on a part of it [6].

In any case, vibrations induced by human activities or caused by natural and environmental actions are responsible for serious problems in a society, affecting not only the stability of critical infrastructures, such as lifelines and residential buildings, but also the comfort and safety of its inhabitants or compromising the functioning of critical activities and sensitive equipment (e.g. hospital surgery, nanotechnology industry, laboratory tests, etc.). The dependency of the community to critical networks, its complex interdependencies and the lack of real-time and effective communication of consequences, are aspects that severely contribute to cascade effects. These are indicators of a low resilient society and are associated with considerable and disruptive economic, social and physical damages and losses.

The possibility of using vibration monitoring as a tool to get information about the health status of building/infrastructure is now considered a “common general knowledge” and many examples can be found of particular applications, aiming to better understand the real conditions of a specific building/infrastructure, in order to set the needed actions for status improvement of the structure itself.

In case the aim of the analysis is enlarged and more general modeling and simulation tool of structures are requested for urban reliability improvement in the whole and to create reliability models of general validity, a more complete approach is needed. It has to take into account the complexity of the urban fabric, variable depending on the techniques of construction of buildings, on the local soil response, on the interaction among several factors which are difficult to predict in a complete way.

Therefore, procedures finalized to buildings diagnostics allowing us to operate in a selective manner and preferring the most critical situation will require a distributed sensor network, but also contemporaneous attention to geotechnical and structural aspects.

The novelty lies in the simultaneous monitoring of ground and building structure and on the further transfer of the so-built information towards assessment procedures of the structural criticalities. That surely implies the need of a greater number of measuring sensors together with the need of different installation and processing techniques, but it seems to be promising from a point of view of the information capacity.

This innovation, together with the will of covering wide areas in regard to different buildings by this multi-sensors network, sets the requirement of lower-cost solutions able to ensure the requested uncertainty of measurements anyway.

2. Motivations

In decision making procedures the usefulness of information given by measurements strongly depends on their uncertainty, if the approach according to the product and process conformity check is taken into account [7]. Therefore uncertainty evaluation plays a fundamental role with respect to the efficaciousness of the whole methodology.

The end users should cooperate in setting the uncertainty requirements of experimental data. In fact, they don’t have to ask that the uncertainty of measurements has to be set as low as possible to finally get reliable reference data for their prediction models. In this view, uncertainty limit should be set in order to get a validation of prediction models to be used by end users, so that these models can be considered reliable. This trade-off approach is expected to allow the possibility of reducing the cost of the apparatuses, making the whole process feasible.

Due to different reasons, achieving an adequate level of uncertainty is not a trivial result because of many factors including:

- different quantities to be measured (acceleration, tilting, mechanical properties of soil,…);
- different type of structures to be modeled for monitoring purposes;
- the need of using low cost measuring apparatuses in most of the measuring points;
- realization technology of the sensors;
- the time stability of instrumentation during the monitoring period and the methods to guarantee it at the installation time and during the in field operation period;
- the procedure of installation of sensors, depending on the type of structure and of their number;
- the characterization of the loads acting on structures;
- the great amount of experimental data to be acquired, processed and synthesized in order to get experimental indicators to be easily managed for decision about the intervention level;
- the need of integrating advanced procedures and methodologies in a remarkably interdisciplinary context (structural engineering, geotechnical engineering, measurement techniques, data mining and information technology, risk management, etc.).

Taking into account all the sources of uncertainty and their effects is obviously a process involving a long effort, but there are some aspects that could be considered “sine qua non” condition, in order to consider the process feasible. In particular a coherent approach is very promising, that is all the involved aspects should be considered as subsequent steps of the same knowledge process, that has to be faced in an integrated way from the beginning, (i.e. the sensors), to the end (i.e. data presentation, fusion, and synthesis).

Bearing in mind these considerations, the first aspect which is considered is the limit that could be achieved with reference to the uncertainty of sensors to be used for acceleration measurements, taking also into account cost requirements.

If technological aspects are taken into account, most of the above measurement and cost requirements could be satisfied by the well known Micro-Electro-Mechanical Systems (MEMS) and Fiber Optic Sensors (FOS) technology and some examples of its use for these applications could be found in literature [8], [9], [10], [11], [12] even though careful attention should be paid to many possible causes of errors [13], especially when low-cost and low-precision MEMS accelerometers are considered.

Recently, specific attention has been paid in literature to the cross sensitivity effects in three-axis accelerometers [14], [15].

The aim of the present research work is to investigate if records of seismic event characterized by a reduced precision may yet be considered useful to final users (engineers and/or public institutions) involved in structural safety assessments and in urban planning. In particular, this study focuses on the possibility of using reduced precision seismic records as input signal for running numerical reconstruction of the local seismic response free field. Demonstration that a positive answer exists to this possibility would help conceiving large networks of reduced cost accelerometers distributed at territorial scale.

The issues of the problem are very wide, concerning many characteristics of new low-cost sensors like: dynamic range, frequency bandwidth, achievable signal to noise ratio, sensor design and production quality assurance, digitisation errors. Also the way the installation of the sensor network is carried out is of concern. As a first step of the approach a synthetic representation of a reduced global measurement performance is assumed, by consdiering simulation data of reduced resolution, by missing a figure in the acceleration representation. The research is expected to take into account the other aspects in the future.

3. Seismic inputs selection

Acceleration time histories for use in this study were selected from records of real events generated by different seismic sources and having different levels of magnitude. In particular three different records have been selected: the Chichi (Taiwan) earthquake of September 21, 1999; the Loma Prieta (USA) earthquake of October 18, 1989 (Emeryville recording station); the Friuli (Italy) earthquake of May 6, 1976.

In terms of magnitude the Chichi earthquake reached values of Ms = 7.3 and Mw = 7.6-7.7, the Loma Prieta event reached a moment magnitude M = 6.9, the Friuli earthquake reached a Richter magnitude Mr = 6.4.

Data on the soil conditions at each recording station and the characteristics of the station itself were not retrieved nor sought for. In fact, given to the scope of the present study, this information is considered of no interest and negligible importance.

As shown in Fig. 1 the selected records are characterized by different accelerations at period T = 0 s, with peak horizontal accelerations of the recorded data equal to 0.8082 g, 0.2498 g and 0.4788 g for Chichi, Loma Prieta and Friuli respectively. Fig. also shows that the three seismic inputs are characterized by different energy contents: at low periods for the Friuli record, at low-medium periods for the Chichi record and at medium-high periods for the Loma Prieta record. Maximum spectral accelerations for 5% damping are equal to 1.74 g at T = 0.26 s (Friuli), 2.48 g at T = 0.58 s (Chichi), 0.72 g at T = 1.18 s (Loma Prieta).

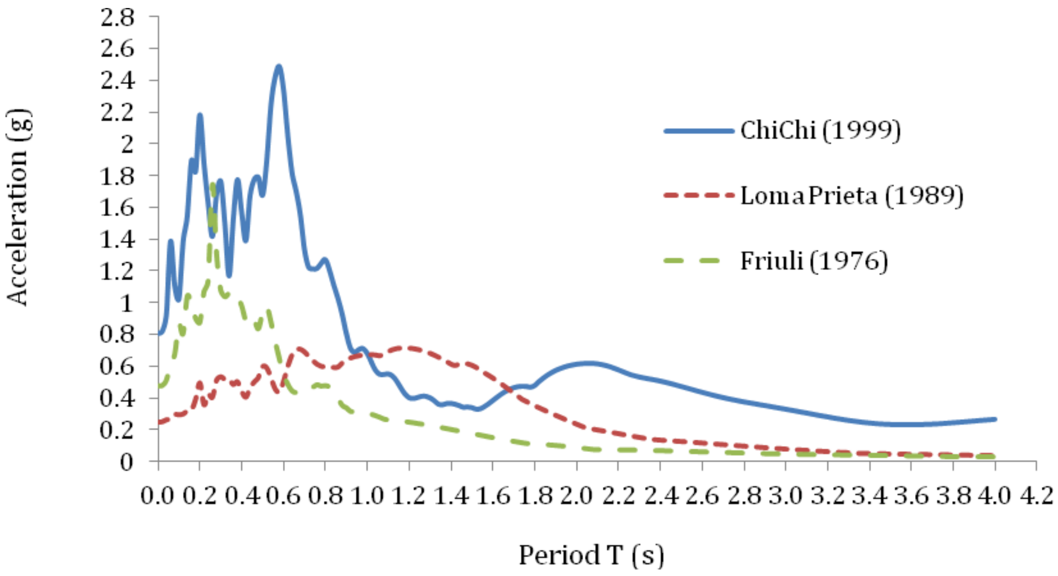

Fig. 1 - Elastic response spectra calculated at 5% damping

In the original records, the ground acceleration values were registered with an accuracy of four decimal digits. New seismic inputs were derived from the original ones, by rounding off to the second decimal digit. In this manner the accuracy of each original record was artificially reduced to obtain realistic input data as they would be eventually recorded by low cost accelerometers.

Subsequent analyses were then carried out considering a total of six input signals: one high precision record (4 digits) and one low precision record (2 digits) for each of the three selected earthquakes, Chichi, Loma Prieta, Friuli respectively.

4. Sites selection and soil properties for site response analyses

Concerning the stratigraphic conditions considered for the site response analyses, two different soil profiles were assumed, both representing real cases.

The first profile, shown in Fig. 2, is characterized by an increase of the geotechnical parameters with depth, namely the stiffness of the soil expressed by the shear wave velocity Vs. The second profile, shown in Fig. 3, is affected by evident singularity in the soils properties. It is worth noting that both profiles were selected from sites that are comprised within the town of L'Aquila (Italy) and suffered severe damage under the April 2009 earthquake. In particular the first one represents the subsoil conditions in the area of Pettino, on the North-West edge of the town. The second one is representative of the soil condition in the central part of the town (L'Aquila). The two soil profiles differ also for the depth to bedrock, equal to 21 m at Pettino and equal to 350 m in the central city.

Evidence from damaged structures in the 2009 earthquake highlighted that both sites suffered from local site effects under seismic shaking. This was confirmed from preliminary studies on site effects in the urban area of L'Aquila [16]. Similar conclusions are reached herein after comparing spectral response relative to input motions used in this study with spectral response relative to motions calculated at ground surface, as shown later in the paper.

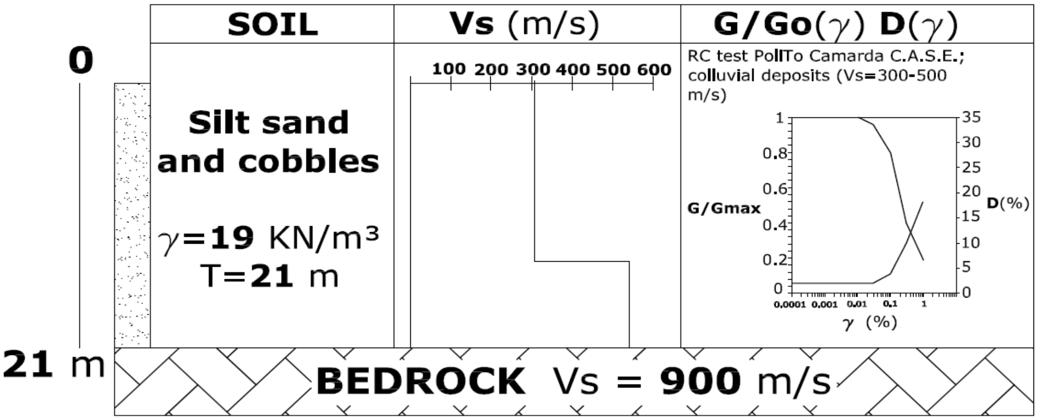

Fig. 2 – Soil profile and geotechnical properties for the Pettino site

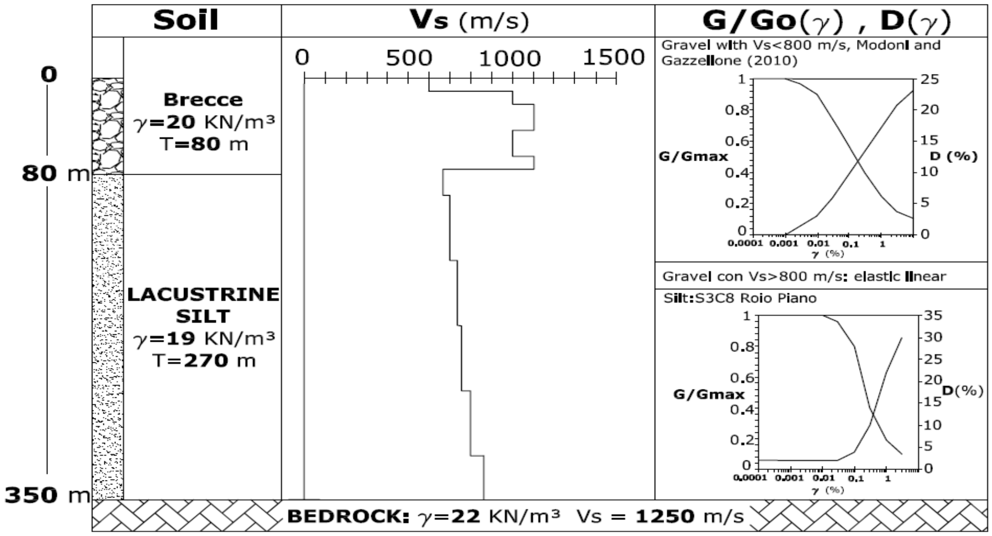

Fig. 3 – Soil profile and geotechnical properties for the central L'Aquila site

In order to evaluate the seismic response of the two sites, geotechnical investigations were carried out. In particular subsoil exploration and in situ testing allowed to reconstruct the stratigraphic conditions and the shear wave velocity profiles with depth. In addition laboratory tests were performed to obtain dynamic soil properties for analyses, in particular the curves of moduli reduction G/G_0 and increase of damping ratio D with increasing shear strain [17, 18, 19].

Data concerning the site of Pettino are summarized in Fig. 2. As can be recognized the subsoil consists of a single homogeneous layer of silts and cobbles, measuring 21 m in thickness. The profile of shear wave velocity with depth is characterized by a relatively constant value of Vs = 311 m/s from 0 m to 14 m in depth and Vs = 570 m/s from 14 m to 21 m, were the bedrock is reached.

Data concerning the central part of L'Aquila are summarized in Fig. 3. As can be recognized, in the ancient town area the depth to bedrock increases significantly and reaches 350 m. Here the subsoil consists of an upper layer of gravels and sands (brecce) with variable degree of cementation, having a thickness of 80 m, and a lower stratum of lacustrine silts with a thickness of 270 m. Accordingly the profile of the shear wave velocities with depth is characterized by a singularity. In the upper layer (brecce) Vs is equal to 600 m/s (first 20 m) and increases rapidly to values greater than 1100 m/s; in the lacustrine silt Vs drops to values ranging between 668 m/s and 878 m/s, due to the reduced stiffness of these finer soils. It is observed that the lacustrine silts shows a gradual increase of stiffness with depth.

Values of shear wave velocity within the bedrock (fractured limestone) ranged between 900 m/s and 1250 m/s at the two sites.

5. Site response analysis procedure

Site response analyses were performed using the ProShake code [20], developed as a professional software on the basis of the original SHAKE program [21], initially written at the University of California at Berkeley. ProShake features various numerical implementations and user friendly interface capabilities, compared with the codes SHAKE and the subsequent version SHAKE91 [22]. The professional code has been repeatedly tested against SHAKE91 with negligible differences between the twos.

Following the general approach described by Kramer [23], ProShake uses a frequency domain approach to solve the one dimensional ground response problem. In essence the code analyzes the motion of shear waves that propagate vertically through an horizontally layered deposit resting over an elastic bedrock. As usual the time history of the acting shear waves is calculated from an acceleration time history with data recorded at a constant time interval. Acceleration values, either generated artificially or copied from records of real events, may be applied at any depth within the soil deposit. For purposes of this study, the selected motions (Chichi, Loma Prieta, Friuli) were applied at top of bedrock, regardless of any kind of information concerning the site conditions at each recording station.

To approximate the nonlinear and inelastic response of soil, the code uses the largely adopted equivalent linear approach. Hence the soil properties, namely the stiffness and damping factor, are iteratively adjusted to be consistent with an effective level of shear strain induced by the pulsating load. In this approach the secant shear modulus is considered and its value is kept constant over an entire cycle of loading. For each iteration step, the effective level of shear strain caused by the seismic action is taken as 0.65 of the maximum shear strain induced during the previous step.

6. Results and discussion

The effects of the different site conditions on the propagation of the seismic actions are well described by comparing the acceleration response spectra of the input motions (top of bedrock) with those of the output motions, calculated after the upward propagation to ground surface as a result of the site response analyses.

As shown in Fig. 4 and Fig. 5 the site conditions can significantly modify the original input signal, in terms of acceleration amplification and also distribution of the energy content at the different frequencies.

Therefore, the selected soil profiles are considered representative of a variety of natural stratigraphic conditions for purposes of this study.

As a result of the present study it is demonstrated that the calculated local seismic response does not change when the accuracy of the input signal reduces from 4 decimal digits to 2 decimal digits. This regardless the characteristics of the input motion (duration, frequency content, peak acceleration,…) and site conditions (soil stratigraphy, equivalent elastic geotechnical parameters, depth of bedrock,…).

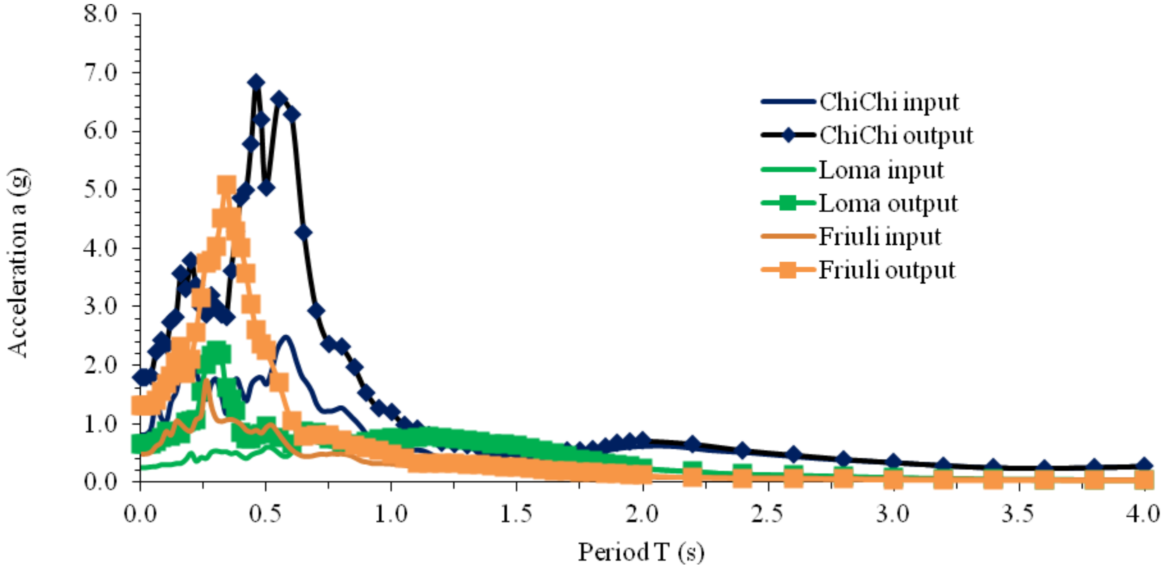

Fig. 4 – Spectral accelerations of motions at bedrock (input) and propagated to surface (output) for Pettino

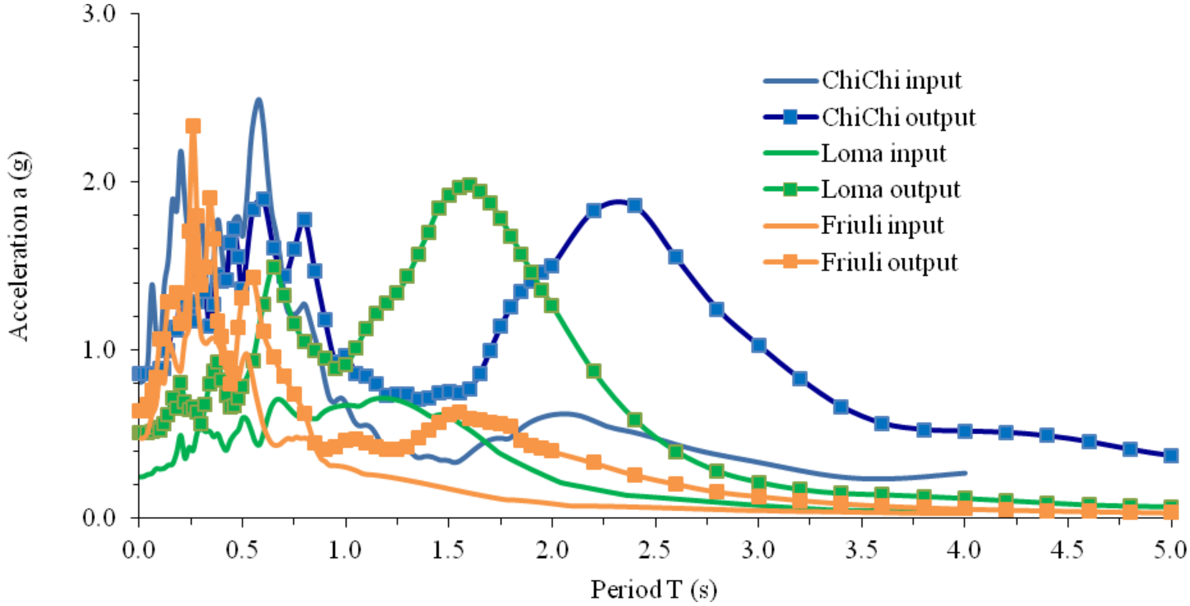

Fig. 5 – Spectral accelerations of motions at bedrock (input) and propagated to surface (output) for L’Aquila

As shown in Fig. 6 and Fig. 7, the curves representing the calculated response spectra at ground surface when the reduced precision signal is applied at top of bedrock, perfectly overlap the curves of the spectra calculated using the high precision signals as input.

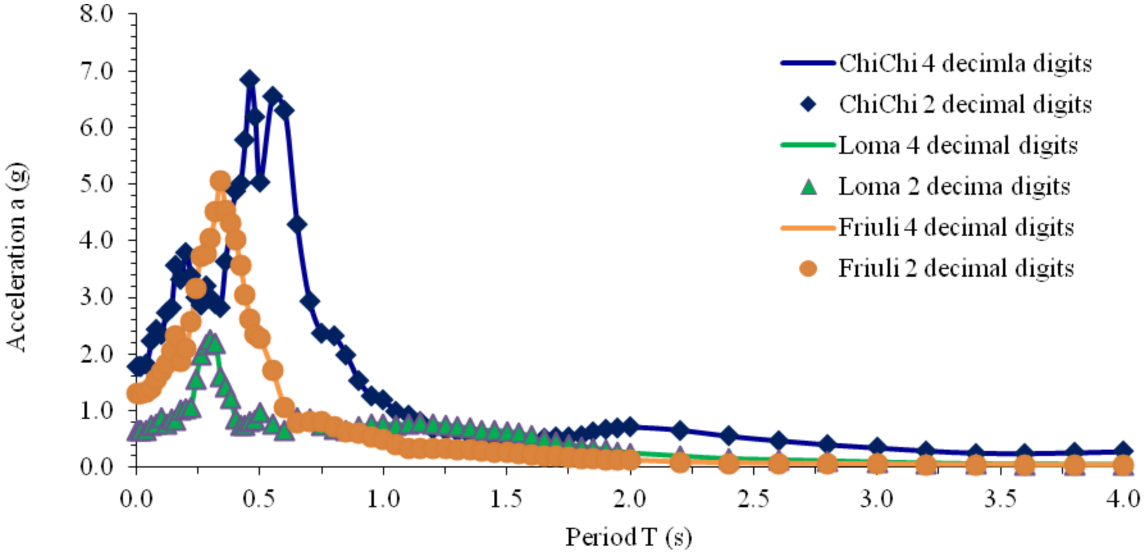

Fig. 6 – Spectral accelerations of motions propagated to surface for Pettino

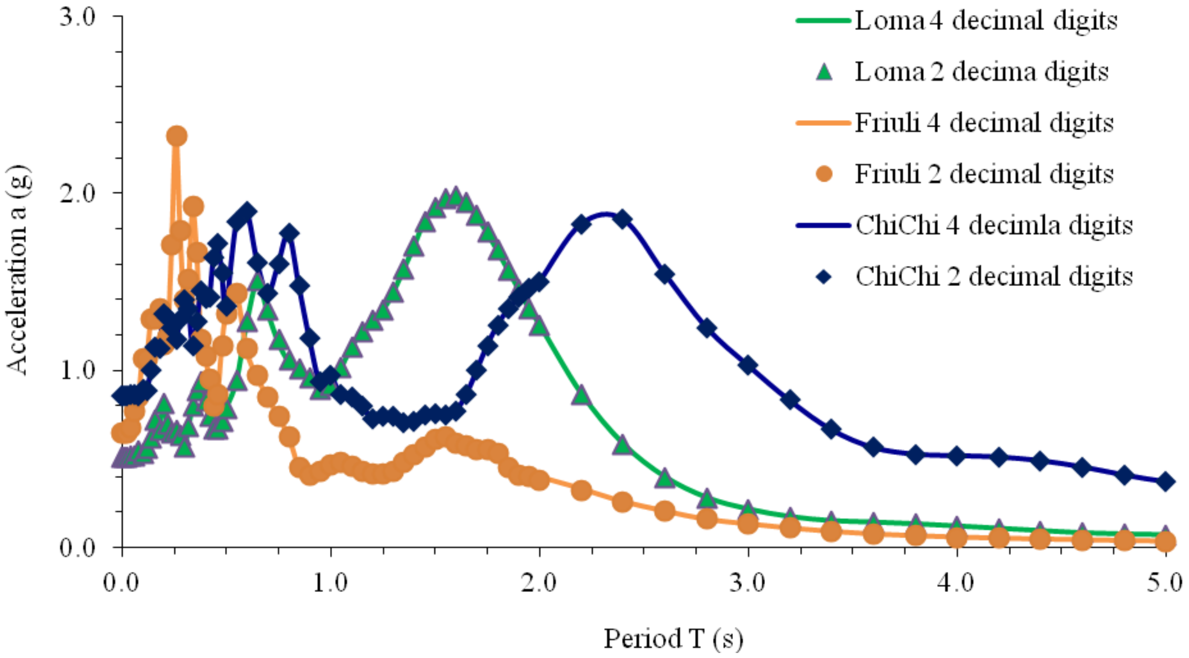

Fig. 7 – Spectral accelerations of motions propagated to surface for central area of L’Aquila

It is worth noting that the high values of spectral acceleration calculated for the site of Pettino (Fig. 4 and Fig. 6) when the Chichi and Friuli records are applied at bedrock, bear little significance from a practical point of view. In this respect it shall be reminded that these records were treated as if registered on outcropping rock, regardless the real site conditions at the two stations. In essence, the original acceleration data might carry the effects of the specific site conditions at each recording stations. These effects have been further amplified herein when the signals are propagated through the shallow deposit that characterizes the Pettino site. Considering the objective of this study, different from site response analyses, the deconvolution of the acceleration time histories was unnecessary. On the contrary, the significant amplification registered for the site of Pettino, together with the overlapped spectra obtained using the original and the truncated data records, are further validation of the present work.

6. Conclusions

The analyses performed in this study represent a preliminary investigation on the possibility to use acceleration data from natural earthquakes recorded by low cost accelerometers, having a reduced level of precision, for purpose of running site response analyses and evaluating the safety of structures under seismic actions.

The study was carried out using two sets of acceleration data from three earthquakes, thus a total of six input motions. The three events, having different magnitude and originated by different seismic sources, were selected in such a way to cover an ample range of ground motion parameters (peak acceleration, intensity, duration, frequency content). Thus acceleration data come from the Chichi event (Taiwan September 21, 1999), the Loma Prieta event (USA October 18, 1989), the Friuli event (Italy May 6, 1976).

The first set of data, representing the output of common high precision instruments, is a copy of the three original records, in which the acceleration values are registered with an accuracy of four decimal digits. The second set of data, representing the output of low precision accelerometers, was constructed from the same three records by truncating the acceleration values to the second decimal digit.

The six resulting motions (3 original data and 3 truncated values), from the three selected events, were then propagated through two real soil profiles. These were selected in the area of L’Aquila to represent very different site conditions in terms of soil properties and depth to bedrock.

The one-dimensional, equivalent linear, numerical analyses performed herein, yielded two sets of output motions at ground surface that superimpose completely for all practical purposes. Similarly, the acceleration response spectra at 5% damping calculated for the two sets of motions, the original data records and the truncated ones overlap completely.

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