A MULTIPLE HAZARD APPROACH TO SEISMIC AMPLIFICATION EFFECTS AND SEISMICALLY-INDUCED BOULDER FALLS AT CASENTINO CITY SITE (AQ)
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Introduction. The 2009 L’Aquila earthquake (5.9 ML) boosted seismic microzonation studies within the SE part of the Aterno Valley where seismic Intensities higher than 6 MCS have been recognized. During this seismic event several towns and villages were threatened by multiple co-seismic phenomena (local amplification, liquefaction, landslide). The Italian guidelines for seismic microzonation do not clearly suggest any procedure to combine multiple co-seismic effects although a few scientists are currently developing procedures to manage multiple hazards and risks (Liu et al., 2015 and references herein). The main aim of this study is to deal with two interfering co-seismic effects, namely the local seismic response LSR and the seismically induced landslides SL. To this end, LSR analyses carried out by a finite element method commercial code RSL_2D (Stacec, 2015) are planned to be combined to the seismically-induced rock sliding and falling at the study site of Casentino (located within Sant’Eusanio Forconese district, L’Aquila province). The scenario seismic event considered hereafter is the April 6, 2009 L’Aquila earthquake.

The seismic microzoning of Casentino town. Casentino is a little town in Sant’Eusanio Forconese municipal area. It is located in central Italy, in L’Aquila province, in the heart of the Apennine territory. It is set into the Aterno Valley along the Eastern slopes of D’Ocre mountain range, between the steep limestone walls of the “MuroMurato” and the valley of “Fosso di Fossa “ (this latter is a tributary of the principal Aterno river). The authors performed Local Seismic Response LSR analyses through numerical simulations by finite element method FEM calculations. 1D (one-dimensional) and 2D (two-dimensional) numerical analyses have been performed to investigate the filtering effects of soil deposits overlaying the seismic bedrock on the seismic body waves (namely SH waves propagating within vertical one or two dimensional sections) in terms of amplitude, amplified periods and increased duration (detected were shear wave velocity $V_s$ $>$ 800 m/s). These effects are estimated on the ground surface where urban structures are mostly affected by the seismic induced horizontal vibrations.

Fig. 1 – Two representative sections have been analyzed in order to obtain the amplification factors at Casentino urban area. Several geological, geotechnical and geophysical investigation campaigns have been used to reconstruct the stratigraphic successions and then the 2D sections. For each soil unit dynamic parameters have been measured and the equivalent linear behavior has been assumed.
Numerical simulations of RSL performed at Casentino used strong motion records of seismic events recorded at seismic stations belonging to national and international networks. In this study 1D and 2D numerical analyses have been carried out using the seismic input of the L’Aquila earthquake of April 6, 2009 (Pace et al., 2011).

Two-dimensional numerical simulations have been performed by the FEM commercial code LSR_{2D} (Stacec, 2015).

Results from FEM simulations are reported in Fig. 2: as can be noted the Casentino site amplifies the input accelerations up to 5 times. Compared with the spectra suggested by the Italian technical code (NTC08), 2D numerical analyses show higher amplifications for large period intervals, ranging between 0.2 and 0.9 s. The amplifications have been calculated according to factors suggested by “Indirizzi e Criteri per la microzonanzione sismica” (ICMS, 2010), in terms of the amplification factors FA. Considered Housner’s Spectral Intensity $H_x^A$:

$$H_x^A = \frac{1}{T_i} \int_{T_i}^{T_f} S_A(t) \, dt$$

where $S_A$ is the acceleration spectra and $T_i$ and $T_f$ are the lower and upper limits of the range of periods, the amplification factor FA is defined as the ratio between Housner’s Spectral Intensity of the output divided by the input at different calculation points:

$$FA_x = \frac{H_{x,o}^A}{H_{x,i}^A}$$

The FA values calculated through 1D simulations range from at least 1.6-1.8 up to at most 3.8-4. These results enable to state that the sections with a non-horizontal ground surface, show different amplification values depending on the investigated point. 1D simulations assume the ground conditions can be modelled as axial symmetric ones (both geometric and material). Whenever the preceding assumption is not properly verified 2D simulations must be undertaken. For this reason the present authors performed 2D numerical analyses alongside two representative sections (Fig. 1). The highest amplifications values have been calculated where topographic slopes change or where complex buried geometries are modeled.

**Seismically-induced rock falls instability.** For studying the slope stability of the limestone rocky wall (named MuroMurato), a survey of the falls or likely to fall rocky boulders has been undertaken. Thus, the study at the first step focused on the geometric characteristics of the rocky blocks and the downwards kinematic energy associated to the rolling and falling...
movements. Then, the second step was focused on the evaluation of the hazard associated with the preceding movements.

Using a probabilistic approach, according to the standard procedure R.H.A.P. (Rockfall Hazard Assessment Procedures), the authors tried to estimate the “maximum potential advancement run out” through the assessment of the maximum length of the potential paths of the blocks. This calculation enables to detect the areas characterized by the same probability of being reached by the boulders.

To undertake the numerical study, a GPS campaign has been carried out to have a census of blocks and to preliminary estimate their volumes. The laser scanner technology allows to overpass the limits in the accuracy of the aerial photos. Thus, the frames obtained from the laser scanner acquisitions were then analyzed by the software Image Master (Topcon, 2012) in order to obtain three-dimensional models for performing analyses, like calculating the precise magnitude of the boulder volumes. A preliminary back analysis has then been performed by using different values of the input parameters within the following formula used to estimate the velocity of the rocky boulders during the rolling movement after their detachment from the rocky wall:

\[ V = \sqrt{V_0^2 + 1.333 \cdot g \cdot l \cdot (\tan \beta - \tan \delta_{rol})} \] (1)

Keeping constant the values of the initial velocity \( V_0 \) and gravitational acceleration \( g \), the angle of the slope \( \beta \) and the dynamic rolling friction angle \( \delta_{rol} \) were derived from GIS spatial analysis tools and from literature data, respectively. In fact, the length of the slope \( l \) has been derived as raster file through the function cost distance belonging to the ArcGIS (Esri Italia, 2010) spatial analyst.

The resulting velocity values calculated by means of Eq. 1 were used within the formula of the kinetic energy:

\[ E_c = \frac{1}{2} m v^2 \] (2)

enabling to calculate a raster file with the kinetic energy values drawn from each boulder. This information layer has been mapped to provide preliminary information on the degree of LS hazard related to the run-out of the blocks. The parameter obtained by Eqs. 1 and 2 represents the intensity of the phenomenon (block rolling and falling) and it can be directly related to the seismically induced landslide hazard.

Although the preceding analysis is only “qualitative” estimates it enables to assess the extension of the area of Casentino urban territory where the blocks are likely to roll and fall,
named the “shadow cone”. In order to do a quantitative analysis of the rock fall hazard the preceding information were subsequently integrated with numerical models by using the commercial code ROTOMAP (Geoandsoft int., 2012). This part of the study is still on going.

Nonetheless, in order to combine the two main hazards that took place at Casentino urban area, the present authors are developing LS hazard analyses by ROTOMAP considering the amplified seismic signals drawn from FEM analyses of the MuroMurato rocky wall as additional load in Eq. 1. In this equation the dynamic acceleration contributes to the velocity of the detachment of the rocky blocks. The results of this study will enable the authors to draw combined hazard maps of LS and RSL effects at Casentino site.

**Conclusions.** This study is devoted to deal with multi-hazard scenarios that took place at Casentino urban center. Here, the seismic event of 2009 L’Aquila earthquake triggered local amplification effects and rock booulder rollings and falling within the urban territory of a small area (about 86.51 km²). Thus, in order to quantify the twofold hazard scenarios, at first two separate studies of rock slope instability and local amplification simulations have been carried out. Then, a non linear combination of the two hazards has been proposed by calculating the run-out of the rocky boulders due to both static and seismic horizontal loadings. The seismic loading should be calculated after a FEM study of the rocky wall model although the peak ground acceleration suggested by the Italian technical code (NTC08) can be preliminarily taken into account.

**References**


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