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Surface topography and site stratigraphy effects on the seismic response of a slope in the Achaia-Ilia (Greece) 2008 M_w6.4 earthquake

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ABSTRACT

Following an overview of the state of knowledge on the effects of slope topography on the seismic ground response, the results of numerical analyses of the response of a 28° slope, with a height of 24 m, located in the meizoseismal area of the Achaia-Ilia (Greece) 2008 M_w6.4 earthquake, are presented. The 2-D and 1-D FEM equivalent-linear analyses were based on the results of an extensive geotechnical investigation and on input motions estimated on the basis of recorded acceleration time histories in the broader area of the slope. The results of analyses were (a) found to be in a good agreement with the observed distribution of structural damages in the area of the town, (b) used to separate the effects of pure topography from the effects of soil stratigraphy, and (c) used to check the validity of a simplified prediction of topography effects, by superimposing the decoupled 1-D and 2-D amplification of motions.

1. Introduction

The ground surface morphology (i.e. such topographic features as ridges, hills, slopes, cliffs and canyons), Fig. 1, has been known to play an important role in the seismic response of a site, generating amplification of the intensity and modification of frequency content of ground motion, compared to the case of flat terrain [36]. The above effects (known as topography effects) were recognized and analyzed numerically for the case of slopes in the 1960's [25,26], whereas observational evidence (from earthquake records of instrumented topographic features) started accumulating since the 1970's [21]. A general definition of the effects of surface topography on the seismic ground response is given in NEES [35] as follows: “Focusing, defocusing, diffraction and scattering of seismic waves by irregular surface geometry, affecting amplitude, frequency and duration of ground motion compared to flat ground conditions”. It has also been recognized that topography effects should be introduced to Ground Motion Prediction Equations (GMPE's) [41]. In addition, the topographic amplification of motion has been found to produce the spatial concentration of rock/soil slides (Murphy, 2006; [27]).

The seismic ground response has also been found to depend on the subsurface topography, i.e. the shape and depth of the seismic bedrock underlying the surficial soil layers. The effects of subsurface topography (encountered in sedimentary basins and alluvial valleys), Fig. 2, are known as “basin effects” and they are characterized by the amplification of motion at the basin edges as well as the elongation of shaking duration ([1], Makra and Chavez Garcia, 2016). Theoretical analyses of basin effects started appearing in the 1980's [12], whereas instrumental data started becoming available in the 1990's. In the last few years significant progress has been made in realistic and reliable numerical simulations of the behavior of 3-D basins under earthquake shaking [18,32].

The topographic amplification of earthquake motion was analyzed in the past mainly by modeling the actual (or simplified) surface geometry and assuming 2-D homogeneous subsurface conditions (e.g. [9,47]). The aim of this type of numerical studies was the development of simple methods for predicting the topographic amplification (or aggravation) of motion in terms of surface morphology and earthquake input motion characteristics (i.e. without considering the soil stratigraphy). In a second step, the 1-D soil amplification function was

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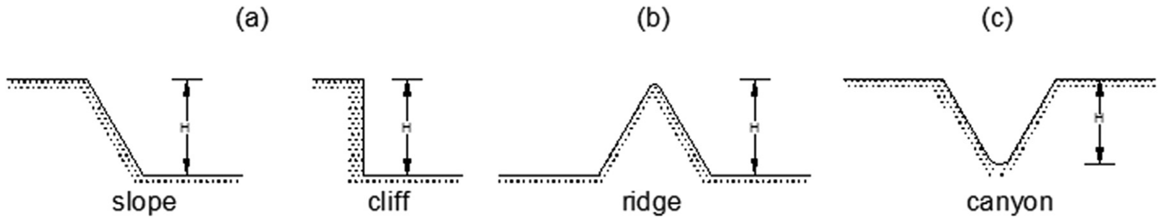

Fig. 1. Types of surface irregularities: (a) slope (or cliff-type topography), (b) ridge-type topography, and (c) canyon-type topography.

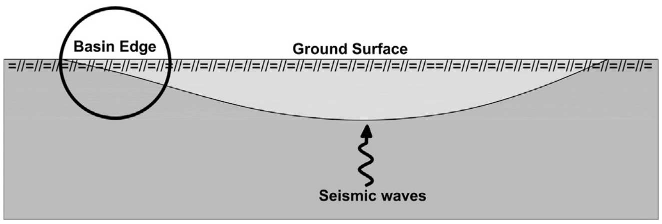

Fig. 2. Schematic illustration of a sedimentary basin / alluvian valley.

estimated on the basis of the site-specific flat stratigraphy which was then superimposed to the previously derived 2-D topographic amplification function to derive the combined amplification function to be used in the design. This approach is actually proposed in the two seismic codes (EC-8 [22] and AFPS [2]) that include provisions for topography effects. A number of recent (and few older) numerical and instrumental studies, however, have shown that the superposition of the two decoupled sources of amplification is not valid and more importantly, it may be unconservative [6,8]. Current research on this subject is focusing on the development of methods for simplified coupling between topographic and soil stratigraphy effects as well as on the effect of soil nonlinearity and parasitic vertical component of motion [34,35,4].

Despite the significant progress that has been made on the subject of topographic amplification of earthquake ground motion in the last 10–15 years, there still exist several unresolved issues that require further research, including studies of relevant case histories of observed vs. computed behavior. This paper presents such a case study involving the case of a slope in the K. Achaia (Greece) 2008 M_w6.4 earthquake [31].

The available data for this case study include 1) the slope geometry, 2) the pattern of observed structural damage, 3) the results of a geotechnical investigation, with measurements of V_s-depth profiles of the site and 4) earthquake recordings at three accelerograph stations surrounding the slope site at distances ranging from 19 to 27 km. 2-D finite element analyses were performed with input motions derived from the recorded motions and assuming both: an average homogeneous subsurface material as well as the measured layered soil profile. 1-D response analyses were also conducted using the actual soil stratigraphy at the site. The nonlinearity of soil behavior was taken into account in the above analyses and the results were utilized in order to quantify the deviations between the fully coupled and de-coupled combination of topography and stratigraphy effects on the amplification of motion.

2. Overview

A brief literature review (focusing mainly on recent advances) is presented in this section regarding (a) the methodological approach to the problem of topography effects, (b) the case of slope-type topography, and (c) a summary of findings.

2.1. Methodological approach

The pertinent research generally follows three directions:

1. *Analyses of observational data,* such as the spatial pattern of structural damages or of rock/soil instabilities occurring in the vicinity of surface irregularities. This type of studies indicate that the structural damages or rock/soil slides are concentrated at the crest of slopes and the top of ridges, hills and canyons [24,33]. The above findings suggest that the intensity of motion is amplified at the particular locations of surface irregularities.
2. *Experimental studies,* involving (a) the instrumentation of topographic features for the simultaneous recordings of earthquake (or induced seismicity) motions at the top, base (and intermediate elevations) of the topographic feature [17,21,44,46]. These recordings are used for determining the amplification of motion in the time and frequency domains, (b) the performance of ambient noise (or weak earthquake motion) measurements at selected elevations [16,39] which are used for estimating values of amplification of motion by applying the Standard Spectral Ratio (SSR), Horizontal to Vertical Spectral Ratio (HVSR) and polarization techniques, and (c) testing of small scale physical models of topographic features in shaking table or centrifuge facilities to obtain measured values of amplification of motion [19].
3. *Theoretical studies* (including analytical solutions and numerical analyses) which are validated against the observed or/and measured behavior of surface irregularities and allow the performance of parametric analyses of topographic effects. Analytical solutions for simple geometries of surface irregularities have been developed by several researchers, e.g. [28]. Numerical 2-D analyses of the effects of topography on seismic ground motion date back to the 1960's and 1970's [25,26]. Subsequent developments have made possible the numerical simulations of complex topographies and realistic constitutive modeling of soil behavior (including 3-D analyses) regarding case studies of topographic amplification [10,11,39,40,6,7,9].

2.2. Effects of slope-type topography

Idriss and Seed [26] and Idriss [25] were the first to present results of FEM analyses indicating the amplification of horizontal motion (as well as the generation of a vertical component of motion) at the crest area of a homogeneous slope – with linear-elastic soil behavior – under an earthquake excitation. Subsequently, Sitar and Clough [43] using FEM analyses with equivalent-linear soil behavior found that the horizontal motion at the crest of steep slopes under earthquake excitation may be increased by up to 70%. More importantly, however, they noted that the amplification due to the slope topography may be small compared to the amplification due to soil stratigraphy at the far field.

Numerical analyses for the effects of both slope topography and subsurface inhomogeneity (assuming linear-elastic soil behavior and the incidence of SV and Rayleigh waves) on the dynamic amplification of motion at the crest of slopes were conducted by Ohtsuki and Harumi [38]. They reported amplification values (for both horizontal and vertical motion) in the vicinity of the crest ranging from 2.5 to 3 times the incident motion (with the higher values corresponding to R-waves). These amplifications were developed for incident wave lengths 2–4 times the height of the slope (i.e. $\lambda/H = 2–4$ or $H/\lambda = 0.25–0.5$). The effect of incidence angle of input motion plays a major role with great