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Vulnerability assessment of reinforced concrete buildings at precarious slopes subjected to combined ground shaking and earthquake induced landslide

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ABSTRACT

At present, the seismic vulnerability of reinforced concrete (RC) buildings standing in the vicinity of the slope's crest is assessed ignoring, in most cases, the effect of topography and the potential slope instability. This study aspires to investigate these effects by proposing a methodological framework for assessing the vulnerability of typical RC buildings subjected to combined ground shaking and earthquake induced landslide hazards. The method is based on a two-step numerical analysis procedure. First, the acceleration time histories and the permanent differential ground displacement time histories are evaluated employing dynamic non-linear analysis. Then, a series of nonlinear dynamic and static time history analyses are performed for a reference low rise, code-conforming RC frame building located at varying distances from the slope's crest to compute the fragility curves for the two loading conditions i.e. ground shaking considering topographic amplification and seismic permanent landslide displacements. The derived fragility curves, described as a function of peak ground acceleration (PGA) at the rock outcrop, are compared to provide insight into the primary damage mechanism while, in the end, coupled fragility curves are generated to account for the combined potential damages due to ground shaking and seismically induced landslide considering or not the interaction between the two hazards. The proposed coupled fragility curves could be used within a probabilistic risk assessment framework to evaluate the structural vulnerability of specific RC building typologies at precarious slopes due to ground shaking and seismically induced slope displacements.

1. Introduction

A building standing near the cliff would be impacted by ground shaking influenced by the topography. The co-called "topographic effect" may significantly affect the amplitude and frequency content of the free-field seismic response along slopes leading to an amplification or de-amplification of the horizontal ground motion and the generation of a parasitic vertical ground motion component e.g. [1]. This is due, among other factors, to the scattering and diffraction of the seismic waves at the surface irregularities and surface wave generation. The aggravation of seismic motion in the vicinity of slopes is evident both in the time domain, i.e. as an increase in the maximum observed amplitude near the crest with respect to the maximum observed amplitude of the free-field, and in the frequency domain, i.e. as a spectral amplification over a narrow band of frequencies corresponding to wavelengths similar to the horizontal dimension of the slope. Studies on the influence of topographic effect on the ground motion, e.g. [1–15], have lead in certain cases to the proposition of topographic amplification factors, which have been also reflected to few seismic design codes [16,17]. Few studies have considered the influence of a structure standing next to the slope's crest in further modifying the seismic response along slopes. Among them, Assimaki et al. [11,12] investigated the additive role of topography, stratigraphy, soil heterogeneity, material nonlinearity and soil-structure interaction in aggravating the seismic input motion in the vicinity of the crest using elastic parametric and nonlinear site-specific two-dimensional finite element simulations. Although they offer a significant contribution on this field, the used simplified model of the structural configuration as a linear elastic continuum of equivalent reduced density can only capture kinematic interaction phenomena while inertial interaction effects and the potential damage to the building members cannot be considered. The modification of the ground motion characteristics in the vicinity of a slope might affect the seismic vulnerability assessment of a typical structure located next to the slope's crest considering that at

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present the available seismic fragility curves are derived assuming at best horizontal soil layering [18]. This is an important issue for many communities in Europe (e.g. Central Italy, Epirus in northwestern Greece) and worldwide considering also that documented observations from previous destructive seismic events have shown that buildings located on hilltops and slope crests exhibit more significant damages compared to those located near the toe, e.g. [11].

In addition to the ground shaking, a building standing in the vicinity of the crest of a precarious slope would also be potentially subjected to the seismically induced permanent ground deformation due to the landslide hazard. The magnitude of the seismically induced displacements is shown to correlate well with observations of seismic performance of slopes, and thus it has considered a useful parameter in seismic design and hazard assessment. For instance, Jibson et al. [19] have shown good correlations between the modeled displacements estimated based on Newmark's permanent-deformation (sliding-block) analysis and the digital inventory of landslides triggered by the 1994 Northridge earthquake and he constructed a probability curve relating the predicted displacement to the probability of slope failure. Various Newmark-type displacement models are available that may predict the seismically induced permanent slope displacement as a function of different ground motion and site parameters, e.g. [20]. Analytical predictive expressions of the co-seismic slope displacements with the best-correlated scalar and vector intensity measures (IMs) describing seismic hazard and site effects have been recently suggested based on advanced statistics of a comprehensive set of numerical results [21]. While there has been extensive research into quantifying landslide hazard, e.g. [22], research into consequences and vulnerability of the exposed civil engineering structures and infrastructures is limited, e.g. [23–25]. Recently, Fotopoulou and Pitilakis [26,27] proposed an analytical method to evaluate the vulnerability of RC buildings subjected to earthquake induced slope displacements. Generic fragility functions as a function of peak ground acceleration (PGA) at the rock outcrop and permanent ground displacement (PGD) at the slope area have been suggested based on the most influential parameters, i.e. the slope inclination and soil material. In these studies the building's vulnerability is assessed only for the effect of the permanent co-seismic displacement. Thus, the potential structural damage due to ground shaking (including also the effect of topography) as well as the combined damages due to ground shaking and seismically induced slope displacements have not been taken into account in the evaluation of building's vulnerability.

Under these considerations, this paper is a continuation of the authors' previous studies [26,27] proposing an original methodology for the vulnerability assessment of typical RC buildings subjected now to combined ground shaking, considering also potential topographic effects, and earthquake induced landslide, employing advanced numerical computations and statistical analysis. A flowchart of the proposed methodology is shown in Fig. 1.

The damages for the two loading cases (i.e. ground shaking and earthquake induced permanent slope displacement) are initially assessed separately and combined at a later stage applying a two-step uncoupled analysis procedure.

First, two-dimensional dynamic non-linear computations are employed using an adequate non-linear finite-difference slope model and properly selected progressively scaled acceleration time histories as input motion. The results are extracted in terms of horizontal and vertical acceleration time histories and the permanent differential ground displacement time histories to account for the response to ground shaking and earthquake induced landslide respectively. A representative reference building located at varying distances from the precarious slope's crest is then subjected to the computed ground shaking time histories explicitly affected by the topography and the subsequent differential permanent ground displacements. Thus, a series of nonlinear dynamic and static analyses are carried out respectively for the two loading cases using a fiber-based finite element structural model. The building's response to the two loading modes of failure assessed using appropriate engineering demand parameters (EDPs) [26–28] is statistically correlated with predefined damage states to construct the fragility functions. Log-normally distributed fragility functions as a function of PGA at rock outcropping conditions are first constructed separately for the two loading modes of failure. Moreover, for completeness, the seismic fragility functions for the same structure founded on 1D horizontally stratified layered media are also provided to compare and illustrate the addictive role of the topography and slope instability in terms of permanent co-seismic slope displacements in altering the structure's fragility. Finally, the combined damages due to combined effects of ground shaking and seismically induced slope displacements are calculated considering or not the possible interaction between the two hazards. In the following, the proposed framework is described through an example application.

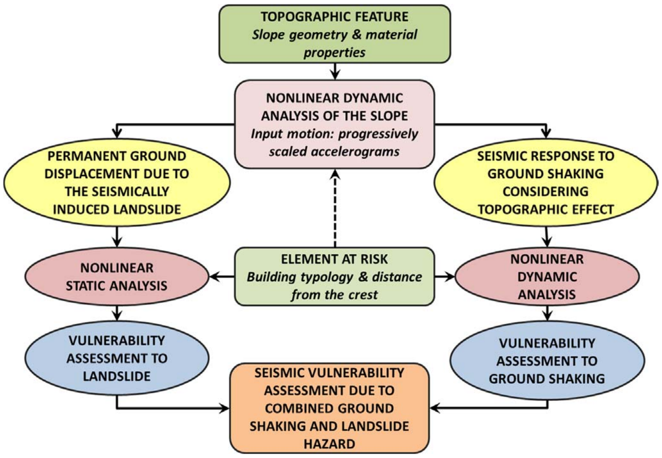

Fig. 1. Flowchart of the proposed framework.

2. Numerical analysis

2.1. Soil dynamic model

Dynamic non-linear computations are performed using the finite difference code FLAC 7.0 [29]. The assumed two-dimensional (2D) plane strain soil model (Fig. 2) has a total length of 1200 m and an upslope thickness of 160 m, while the slope height (H) and inclination (i) are 40 m and 45° respectively. Kuhlemeyer and Lysmer [30] showed that for accurate representation of wave transmission through a model, the element size must be smaller than approximately one-tenth to one-eighth of the wavelength associated with the highest frequency component of the input wave. Following this suggestion, the model consists approximately of 22,000 four-node quadrilateral elements the size of which was determined on the basis of the frequency content of the incident motions and the dynamic soil properties, to ensure detailed representation of the propagating wavelengths. The discretization allows for a maximum frequency of at least 10 Hz to propagate through the grid without distortion. A discretization of 1 m×2 m is adopted in the slope area, whereas towards the lateral boundaries of the model the mesh is coarser (2.5 m×2 m). Free – field absorbing boundaries [31] are applied along the left and right sites whereas quiet (viscous) boundaries [32] are applied along the base of the mess to reduce the effect of artificial wave reflections from the boundaries. For the same purpose, the absorbing boundaries are placed at sufficiently large distance compared to the dimensions of the slope.

The soil materials are modeled using Mohr–Coulomb elastoplastic constitutive model characterized by its yield function and flow rule [29]. The failure envelope corresponds to the Mohr–Coulomb criterion (shear yield) with tension cutoff (tension yield function) assuming a nonassociated flow rule for shear failure, and an associated rule for