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Interpretation of dynamic response of a very complex landslide (Latian-Tehran) based on ambient noise investigation

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ABSTRACT

Single station ambient noise measurements were performed in 122 points on a complex landslide at the left bank of Latian Dam reservoir in the north-east of Tehran (Iran), to investigate the seismic site response of a landslide, especially the nature and causative factor of directional site amplification. Recorded data were analyzed through the horizontal to vertical spectral ratio technique to obtain the resonance frequencies (f0), spectral ratio amplitude (A) and orientation and intensity of directional response over sliding and surrounding area. The results have a great coherence to geotechnical and geological investigation result and are tightly related to the landslide structure in such a way that outside the sliding area there is no or negligible sign of directional response. In general the result revealed two range of frequencies with high amplitude and directivity over the landslide mass; the first one around 1.2 Hz, ubiquitous, that seems to be related to normal mode vibration of the entire unstable mass, named as underlying layer in this paper. The second one at higher frequencies that is spatially variable over the landslide, which seems to be related to the effect of local surficial features (such as local sharp curvatures and ridges or blocks detached by tension fractures). Directional response pattern of both the underlying layer and surficial features is controlled by 2D or 3D features causing higher amplitude in the most kinematically free direction. It seems that the seismic response of the underlying layer at the surface is modified by directional filtering of the overlying superficial layer. This modification effects tightly related to the transfer function of surficial features especially their cross-coupling terms. Based on this study, a general rule is proposed to declare conditions which are essential to induce severe directional response at a specific site.

1. Introduction

During an earthquake, in the case of potentially unstable slopes or pre-existing landslides, input ground motion is possible to be significantly amplified, which can leads to landslides reactivation, even at unexpected large distances from earthquake epicenter. The most remarkable aspect of site amplification in landslide prone slopes is its azimuthal variation, which means the site response is amplified more significantly in specific azimuths in comparison to other orientations [1]. In several case studies, this directional response coincides with general direction of slope displacement (sliding direction) and in some cases is parallel to maximum slope direction, but it is not a general rule and some counterexample have been reported [2–4]. Therefore, assessment of site seismic response (especially its azimuthal dependency) of unstable slopes and its relation with slope geometry and internal structure can provide more detailed knowledge about the behavior of an unstable slope during an earthquake, which is important in landslide hazard assessment.

Although several studies [5–9] have been carried out to obtain clear interpretation of dynamic response (especially directional amplification) of marginally stable slopes and their causes, until now there is no general criterion to identify the causative factors and to recognize sites potentially exposed to directional amplification. This lack of knowledge on directional site response and its controlling factors is in part due to the scarcity of slope-specific ground motion recordings, and on the other hand to the complexity of landslide structure [1]. Many geometrical factors (such as local topography, discontinuities and cracks, 3-D individual blocks), or geomaterials properties variation (including thickness and mechanical properties of consisting materials) in a landslide may contribute individually to create directional seismic response or a complex interaction between them can result in concentration of spectral energy at specific orientation [2]. In the following section, some causative factors of directional amplification (including: topography, discontinuity systems, eigenmode vibration and attenuation anisotropy) and their effectiveness are discussed.

Regarding the effect of topography, several studies based on

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experimental recordings, as well as numerical modeling, have shown that ground motion can be significantly amplified at the mountains' crest and ridges or rim of canyon (as a topographical sharp curvature) [9–14]. This topography induced amplification linked directly to the sharpness (wedge angle) of the curvature [15,16] and usually has preferential orientation perpendicular to the topographical features elongation [12]. Coupling of the topographic effect with seismic velocity contrasts and internal fracturing may significantly enhance the site seismic amplification value even greater than 5 (depending on value of impedance contrast). However the topographical features without any impedance contrast display a much lower amplification (below 2 or less). This issue is proved by simple numerical modeling [17–19] as well as physical modeling [20,21].

Directional amplification may also result from lateral discontinuities (like open fractures) in landslides. The first study about relation between seismic wave properties and landslide open fractures was reported by Wada et al. [6] based on microtremor measurements over Kamenose landslide in Japan. He observed that the particle motion of microtremor is stronger perpendicular to cracks orientation. Directional amplification have also been observed on the Randa unstable rock slope, south of Switzerland [22] and on an active coastal spreading area at Anchor Bay, Malta [4], and was related to the internal structure of the unstable slope, specifically to the systematic open macro-fractures. This relation has been proved numerically for Randa rockslide by Moore et al. [5], comparing two models, one with high compliance values of discontinuities and another with very high stiffness values. In addition to landslides, fault zones show evidences of azimuth-dependent amplifications [23]. Pischiutta et al. [24,25] and Panzera et al. [26] interpreted this phenomenon as the effect of crack orientation, which causes a larger rock compliance perpendicular to predominantly oriented fractures.

Another hypothesis proposed for directional response in the unstable rock masses is the normal mode vibration of individual rock blocks, superimposed on that of the large unstable volume, rather than horizontal propagation of seismic waves [4,5,9]. Levy et al. [27] applied this hypothesis to interpret the dynamic response of a separated and collapsing rock column and attribute the ambient noise spectral peaks to eigenmode vibration of the rock column. He reported that the cliff resonance frequency progressively decreased as effect of the decrease of cliff bulk modulus as the damage developed in the rock column and of its bridge breakage prior to collapse. Pilz et al. [28] based on observation of ambient noise directivity in one azimuth at single resonance frequency for all parts of the Papan landslide (Kyrgyzstan), regardless of different thickness concluded that the total body of landslide can be viewed as an effectively reduced elastic moduli mass and that ambient vibration display the normal mode vibration of this mass.

Anisotropy of slope materials properties, associated with slope movements, have been proposed also as another causative factor of directivity by Del Gaudio [29] based on study on Caramanico landslide (Italy). However S-wave velocity measurements simultaneously at slope direction and perpendicular to slope direction by Coccia et al. [30] did not reveal any significant anisotropy of seismic wave velocity for this landslide. In another case study on the cracked part of Randa rock slope, Burjánek et al. [9] proposed an effective anisotropy in rock mass moduli, but they did not attribute such an effect to inherent seismic anisotropy of the rock (e.g., due to micro-fracturing), and related this anisotropy to the systematic orientation of open macro-fractures. He explained since the cracks have a preferred orientation sub-perpendicular to the direction of slope displacement, effective anisotropy in rock mass moduli arises. Specifically, he suggested that the bulk stiffness of the fractured rock mass drops significantly in the direction perpendicular to the trace of tension cracks. Moreover, Pischiutta et al. [25] and Panzera et al. [31], after studying several fault zones in Italy, concluded that wavefield polarization in those areas is produced by the existence of an anisotropic medium represented by fractured rocks. Such fractures make the medium more compliant perpendicularly to the faults strike.

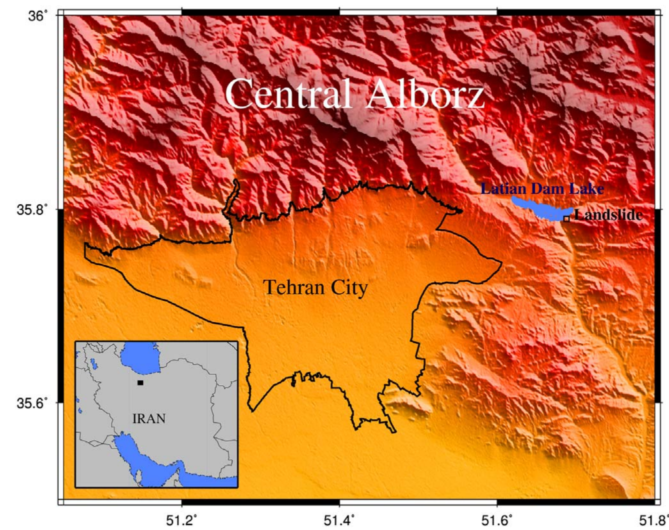

Fig. 1. The Latian landslide is located on a mountainous region of Central Alborz, nearby the Latian Dam, one of the main Tehran potable water resources. Black rectangle indicates the landslide area.

2. Latian landslide

The present paper concern the Latian landslide which is located at left bank of Latian Dam reservoir, 25 km north-east of Tehran (Iran) at 35.78 N and 51.68 E (Fig. 1). This complex landslide (a combination of rotational and transitional slide) with average length of 480 m and width of 210 m causes severe damages especially to the main access road of the region. Considering the high seismicity of this region and the close distance of landslide to Latian Dam (less than 500 m), a rapid failure of slope may create some threats for Dam structure and downstream areas.

From the geological point of view the landslide is situated in a crushed faulted zone of the Jajrood valley and several primary and secondary branches of Roodehen faults pass nearby the unstable slope (Fig. 2). This crushed zone is located on a mountainous region of Central Alborz, the main active tectonics province in northern Iran. Existence of numerous active faults and steep slopes, as well as landslide susceptible geological and geomorphologic condition, made this area, a hazardous region from the point of view of earthquake and landslide hazard. The current active landslide is part of a larger old landslide which reactivated at the end of winter (March) of 2006 with displacement rate between 1.5 m per year to 1.5 m per month. Slip velocity and displacement direction varies obviously in different parts of the landslide, based on its geometry and type of material involved, however its overall displacement is in northwest direction, perpendicular to dam reservoir shoreline (Fig. 3).

As delineated in Fig. 2, geological materials engaged in the landslides are very inhomogeneous (from a few m3 rock blocks to very fine grained material) and belong to an ancient large landslide that in turn engaged the green and gray tuffs of the Eocene (Karaj Formation). Due to the Roodehen fault and its sub-branches, as well as intrusion of some dikes and sills, the geological formation of the region is intensely crushed, pulverized and have been completely distorted [32]. The depletion created by the occurrence of the old landslide, as well as the orientation of faults and other fractures result in the concentration of groundwater flows toward the landslide centre zone, which created a local aquifer with a water table depth of 15–18 m. On the other hand, the ground leveling and manmade disturbance of natural drainage at the area cause more surface water infiltration into the slope subsurface layer. The existence of this aquifer together with sensitive tuffy rocks