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RESEARCH ARTICLE

Earthquake-induced paleo-landsliding in the Tehran Region and its role in assessing the seismic hazard, Iran

Solaymani Azad S[1], Entezam Soltani I[2], Hadi Tabassi[3], Mohamad-Javad Bolourchi[4]

[1] *Seismotectonics and Seismology Department, Geological Survey of Iran, P.O. Box: 13185 1494, Tehran, Iran.*

[2] *Management of Geohazard and Engineering, Geological Survey of Iran, P.O. Box: 13185 1494, Tehran, Iran. dr.entezam@gmail.com*

[3] *Islamic Azad University, Damavand Branch, Damavand, Iran, tabassi@damavandiau.ac.ir*

[4] *Zamin-Ab-Pey Consulting Engineers, Tehran, Iran, mj.bolourchi@gmail.com*

*** Corresponding author:** Shahryar SOLAYMANI AZAD, Shahryar.solaymani@gmail.com

ABSTRACT

In the central portion of the Arabia-Eurasia collision zone, the Tehran domain is positioned at a transitional boundary between seismotectonic zones of the Central Iranian lowland (to the south) and the Alborz highland (to the north). Consequently, numerous destructive seismic events have occurred in this active tectonic domain. This study delves into the tectonic geomorphology of the region within its northern highland domain, specifically focusing on the hanging wall of the E-striking north-dipping North Tehran fault (NTF) zone. Our findings in this northern domain emphasize several prominent topographic scars as significant co-seismic features. These include huge landslides, rockfalls, rock avalanches, and offset geomorphic surfaces and could be present as the main indirect co-seismic morphological features. Within this seismically active region, the extensive dimensions of these geomorphic pieces of evidence can indicate the seismic potential of the Tehran Region to experience really strong earthquakes (i.e. M>7.5). These results contrast with the previous Maximum Credible Earthquake (MCE) magnitude estimated for the Tehran Region (i.e. M~7.2) through different approaches in Seismic Hazard Assessments (SHAs). Consequently, the previous SHAs of the Tehran Region might have underestimated the seismic risk, and therefore, it is necessary to conduct an updated and complementary deterministic SHA based on the more detailed seismogenic geological features in this crucial area. This new approach can be employed in comparable active tectonic regions worldwide to assess existing SHAs.

Key words: coseismic landsliding; Paleo-landslides; seismic hazard; Tehran; Iran

1. Introduction

Landslides can be formed and then triggered by heavy rainfalls, earthquakes, and anthropogenic activities[1-4]. The extremely large landslides[5] associate mostly with strong earthquake-induced landslides[6-9]. Consequently, the large earthquake-induced landslides can trigger later by other quakes, environmental and or anthropogenic causes[10]. Then, it is well established that landslides may extensively formed and triggered as

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a result of large seismic events in upland areas[1]. Some authors have postulated that sediment moves through the drainage system as a 'slug', whilst others have noticed only limited impact as material remains stored in the drainage basin. What has almost never been addressed is the continued evolution of the landslides themselves after the seismic event, and their continued role in releasing slope materials[1].

In a general view, Iran is located in the central portion of the Alpine-Himalayan orogenic belt. The belt extends generally from West Europe to Southeast Asia[11]. Within the central portion of the belt, Persian semi-arid territory[12] is actively deforming in response to the ongoing northward motion of the Arabian plate[13-15] and its interaction with South Caspian Backstop[16]. Based on geodetic GPS measurements[17-21], the accommodation of Arabia-Eurasia plate convergence within the longitudinal zone of Iran occurs with a present-day shortening rate of about 25 mm yr^{-1}. The northward motion of the Arabian plate away from Africa started in the Upper Miocene with the opening of the Red Sea[22]. In response to the northward motion of the Arabian plate and its interaction with South Caspian Backstop, three main ranges of Zagros (to the southwest), Alborz (to the north) and East Iranian Mountain Chains have been formed and developed in Iran and the continental blocks forming Anatoly and NW Iran move aside in the collision zone[22-27]. In such an active tectonic context, numerous strong and moderate earthquakes have been recorded. Seismic records covering the central portion of the Arabia-Eurasia collision zone[28-30] indicate numerous destructive quakes in its different parts. Comparing pre-historical[27, 31-42], historical[28,43], and instrumental seismic records of Iran reveals the long return periods for active seismic clusters[29, 44], especially within the most populous region of N and NW of Iran[16, 45]. The long return periods of strong seismic events suggest a prevailing intra-plate tectonic regime in this domain[16, 27, 37, 46-49].

Within north of Iran, Tehran City locates in a transitional zone between the Central Iranian, and Alborz seismotectonic provinces to the south and north, respectively. Consequently, the seismotectonic characteristics of the Tehran Region affects from active deformation, and seismic interaction between these zones[50], and several earthquakes have been occurred (**Figures.1, 2,** and **3**). Since the Tehran's history, it has formed on the southern side of a large set of thick Pliocene-Quaternary alluvial fans, formed between the Alborz mountain (to the north) and Central Iranian plateau (to the south), and then it has expanded to the other geographical directions. In a geomorphologic view, the Tehran Region contains then all mountainous, piedmont, and plateau E-striking elongated topographic domains from north to the south, respectively. Based on previous studies[37,51-57] the topographic domains have generally been separated by E-striking major oblique-slip (reverse-sinistral) active fault zones such as the north-dipping NTF which traces the Tehran piedmont zone. The fault locates generally between the Eocene volcano-sedimentary rocks, to the north and the Pliocene-Quaternary alluvial, to the south[52]. In other words, all the mountainous, piedmont and plateau topographic domains have been developed in the Tehran Region, from the north to the south and they have been separated by E-striking structural zones. In addition to earthquake ground motion and vibration in both far- and near-field domains which menacing this capital city, it is able to face secondary earthquake hazards such as landslides[58-60] and liquefaction in its northern highlands and southern lowlands, respectively.

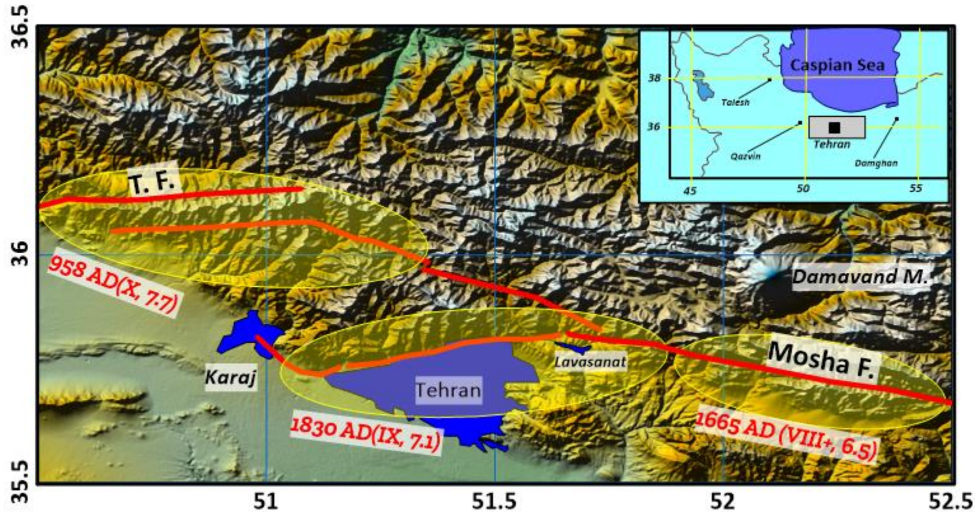

Figure 1. Major Seismogenic faults of the northern Tehran highland domain and their correlated historical earthquakes[38, 50]. In a general view, the Tehran City is located in the southern piedmont of the Alborz Mountain.

Based on literature review[35-38, 50-52, 54, 55, 61-62], the active tectonic deformation of the Tehran Region occurs along both dip-slip and strike-slip ~E-striking fault systems and folds. Consequently, the morphotectonic effects of both horizontal and vertical components of tectonic deformation have been formed and developed in this area. Within and around the Tehran Plain, several moderate to strong seismic events documented by instrumental seismicity[22, 63-68], historical catalogues[28, 43], and paleoseismological studies[31, 32, 34-38, 45, 69-71]. Based on the available seismic catalogues and the results of seismic hazard assessments, performed by using active fault database and paleoseismological studies, Tehran is menacing by earthquakes with magnitudes limited to 7.2[72, 73]. A part of the major seismic sources of the region locates within the northern highland domain of the Tehran Region (**Figure 1**). Consequently, their seismic events could be produced several landsliding events. Despite this finding, there is no sufficient information about earthquake induced paleo-landslides of the Tehran Region and their roles in assessing the seismic hazard. This paper aims to improve our general understanding of seismic hazard based on more detailed study on earthquake slope instabilities of this highly populated region of Iran by means of their geometric, dimensional, and dynamic characteristics. As a concise methodology and based on the characteristics of earthquake induced landslides[6, 74], we will discuss this type of slope instabilities of the Tehran Region to estimate the magnitude of their causative quakes.

2. Earthquake- induced slope instabilities

Seismic hazards are related with phenomena such as amplification of ground motion associated to soil parameters and liquefaction within lowlands, and amplification of ground motion associated to topography and landsliding within highland domains. Slopes failures during earthquakes have claimed a great number of casualties and can be a major cause of damage to structures and facilities constructed on or in nearby the slopes[75]. The scale of such landslides on natural slopes can be large enough to devastate entire villages or towns[5]. It is unsurprising that seismically induced landslides occur in mountain regions. In mountain regions, several types of slope instabilities can form and trigger by three different origins of environmental factors, earthquakes or by anthropogenic activities[1-4]. There, the main characteristic of the earthquake-induced landslides is generally their huge dimensions, which cause by the high measures of earthquake accelerations, especially along ridgetops of rock slopes. Consequently, they can 'form' and concentrate mostly within the meizoseismal zones of strong earthquakes in highland areas[1]. The intensity of ground shaking at a specific location is a function of the distance from the earthquake epicenter and the way in which seismic waves propagate through different kinds of subsurface materials[76]. At a given distance from the epicentral area in highlands, ground motion will be strongest in poorly consolidated deposits. Local topography can also increase the severity of ground shaking by focusing seismic waves onto narrow ridgetops[76]. This effect extends beyond the fact that steeper slope angles will generally give rise to higher shearing stresses on a potential sliding block. This effect, known as topographic amplification, means that there is considerable uncertainty about the magnitude of input ground motions for slope stability analysis[77]. The observation that different shaking intensities may exist between hill foot and hilltop was first reported towards the end of the 19th Century. However, the systematic study of this phenomenon is more recent [77]. Trifunac and Brady [78] observed on the basis of modeling 'canyon' topography that a critical angle existed between the incident wave and the slope for topographic amplification to occur. Usually the Peak Ground Acceleration (PGA) has been used in earthquake-induced hazard assessment; however, the earthquake capacity to trigger landslides depends not only on the seismic wave amplitude but also on the frequency content and strong motion duration[79].

Earthquake can contribute to long term erosion in mountain belts by triggering landslides or lowering the topographic surface and therefore producing “tectonic erosion” (i.e. tectonic exhumation or denudation) [80]. In a general view, landslides are an important part of the natural landscape system in dynamic mountain environments that experiences constant tectonic uplift[1]. These slope failures serve as efficient mechanisms for detaching and mobilizing slope-forming materials into the fluvial system, for eventual removal by channel flow processes. Most landslides require a triggering event to initiate movement. In many cases, this is a high intensity and/or long duration rainfall event. The other main cause for landsliding is the occurrence of a large seismic event [6] . The shaking associated with big earthquakes forms and triggers extensive landsliding. The release of sediments into the fluvial system may be highly episodic, with heavy rainfalls or seismic events causing the release from the slope of sediment, which is then removed by subsequent large flow events of the associated river system. Dynamic environments often experience simultaneous combinations of uplift, seismic events, and high precipitation within very short time intervals, and the interactions in terms of space and time between these events must be considered [1].

In a general view, according to the historical earthquake catalogs [28, 43] and the size of landslides[5] in Iran, many of them could be related to seismic events. In paleoseismic studies, the most difficult task is proving the relation between landslides with a certain seismic event, with proper degree of confidence[7]. Most paleoseismic landslide studies involve analysis of large group of landslide rather than individual features. The premise of this regional analysis is that a group of landslides of same age probably were formed or triggered by a single event of regional extend [7]. Crozier [81] cited six criteria to support a seismic origin for some landslides in New Zealand; These criteria can be applied generally (1) ongoing seismicity in the region ,which has triggered landslide (2) coincidence of landslide distribution with an active fault or seismic zone (3) geotechnical slope-stability analysis showing that earthquake shaking would have been required to induce slop failure, (4) large size of landslides (5) presence of liquefaction features associated with the landslide, and (6) landslide distribution that cannot be explained solely on the base of geological or geomorphic conditions. Obviously, the more of these criteria are satisfied, the stronger the case for seismic origin [7].

Two extensive statistical analysis of worldwide database published by Keefer [6, 74] and Rodriguez and colleagues [8] investigate the landslide types, their frequency, characteristic and geologic environment in historical seismic events, and the smallest earthquakes that cause landsliding in a region. They have also added the other effective factors to the aforementioned issues; distribution and seismic parameters, magnitude and area affected by landslide, maximum distance of landslide from epicenter and fault rupture, landslides and seismic shaking intensity. Earthquake can trigger all types of landslides, however some types tend to be more abundant in earthquakes than other types, keefer [6] ranked the relative abundance of landslides from 40 major earthquakes throughout the world accordingly: Very abundant (rockfall, disrupted soil slides, rock slides); Abundant (soil Lateral spread, soil slumps, soil block slide, soil avalanches); Moderately common (soil fall, rapid soil flow, rock slumps); Uncommon (subaqueous Landslides, slow earth flow, Rock block slide, rock avalanche). In a global view, there is a various type of coseismic landslide that observed in different seismic events. Generally, the single-event landslides have discussed as a resulting of massive rock slope failures. Yamada and colleagues [82] mention some coseismic landslide type in some more recent earthquake as follow: Mixture of surface failure and slide types (San Fernando USA 1994), Slide-fall mixture type and landslide dams (Jijizehen, Taiwan 1999, Kashmir, Pakistan 2005), Falls and rock avalanche type (Sichuan, china 2008), Shallow landslide and debris flow (Cinchona, Costa Rica 2009), Rock avalanche and flow slide after earthquake (Bandung, Indonesia 2009), Flow and Topple type landslide (Tohoku, japan 2011). However, Havenith and colleagues [83-85] proposed a seismically induced landslide event sizes follows an event by event approach rather than a statistical analysis of extensive database. It based on five main factors that at where combined to assess the size of an event in terms of potential number of triggered landslide and total affected area: intensity, fault factor, topography energy, climatic back ground, and lithological factors. Even years after occurrence of a great earthquakes we witness that many slopes which gone under effect of landslide and their factor of safety decrease may have activated due to different factors. The study of the 2015 Mw 7.8 Gorkha earthquake in Nepal during the 3.5 years after occurrence show that throughout this period both the number and area of mapped landslides have remained higher than on the day of the earthquake itself [86]. There are many studies that exploring rainfall induce landslide in earthquake-effected terrain [87], some researchers evaluated this effect between 1-4 years due to magnitude of earthquake [88]. The surface temperature is another factor that control pattern of post-earthquake landslide activity [89]. The studies show even low magnitude earthquake can increase landslide activity [90].

Logically, the large part of arid and semi-arid lowlands and highlands of Persian territory[12] cannot be mainly subject to environmental landsliding. Moreover, comparing northern and southern limbs of the Alborz Mountain Range shows completely different precipitation conditions and consequently different landsliding conditions. On the other hand, the seismic catalogues of Iran[28, 43] reveal several huge earthquake-induced landsliding events during the historical period within Iranian highland domains. Within highland areas, the large earthquake-induced landslides in rock slopes can trigger later by environmental causes and or anthropogenic activities, several times. However, for some huge landslides of Iran (e.g. Seimareh landslide as a Debris Flow, W Iran) there is a limited information about their seismic origins[91].

In a general scale, according to the size of about 3500 recorded landslides in landslide hazard zonation map of Iran [92], many of them may be related to earthquake events [93-97]. In this study, we consider mainly; the size of landslides [5, 98], their distance from active seismogenic faults [6, 8], the geological condition of them, and their surface morphology to discuss them as earthquake induced paleo-landslides in the Tehran Region. Then, we will compare the estimated magnitude of their causative quakes with the maximum magnitude of the assessed earthquakes of this crucial region.

3. Slope instabilities in the Tehran Region

In general, the main topographic contrast between the southern E-striking ridgetop of the Alborz faulted and folded range (~4000 m), as an accordant summit, and the Tehran piedmont (~ 1700 m) has a height of about 2300 m. Within the northern highland domain of the Tehran City, the southern slope of the E-striking Alborz Mountain Range is bounded to the south by the NTF zone and contains several small and large natural slope steps and instabilities as geomorphological topographic scars (**Figure 2**). In fact, the aforementioned geomorphological features have formed and developed within the faulted-crushed zones of the NTF, with an uplift rate of about 1 mm yr^{-1}`[57] and other old and young faults. The large geomorphological topographic features can define as an assemblage of dynamic gravitational scarps and their relevant slumps. In a geological-geomechanical view, the slope generally contains of Eocene volcano-sedimentary rocks of the Karaj Formation[99] (i.e. Tuffs and Andesitic Tuffs, with compressional strength of 700-1100 kg/cm^2;). In other words, the area contains several landslides, rock avalanches, and huge rockfall domains, which are concentrated on the northern highland domain of the Tehran Region [60, 100, 101].

By the means, according to the steep slope of the southern limb of the Alborz Mountain Range, the situation of faulted crush zones on the hanging wall of the NTF zone, the paleoseismicity of the Tehran Region, and etc. the area was and is a potential zone for occurring large earthquake-induced slope instabilities. Obviously, they were and are capable of being triggered successively by subsequent tectonic, environmental and or anthropogenic activities and causes.

From the west to the east of the study area, our discussed large slope instabilities are in two prominent categories; close to the northern piedmont of the Tehran Region on the hanging wall of the NTF, and settling in a same distance to the fault zone within the intersected N-striking valleys of the north Tehran Region (**Figure 3**). Within the massive rock slopes, according to their pattern and arranging to the NTF zone and their large dimensions as well as their morphology, they could be discussed as seismogenic paleo-slope instabilities. In other words, we consider these important criteria for a landslide to group in seismogenic slope instabilities; 1. Distance to the major active fault zones (e.g. the NTF zone), 2. Type of landslides, 3. The geological formations involve of the landslide movement (which are not easily to form by rainfalls), 4. The landslide area and volume, 5. The direction of landslide movement to the fault trend, 6. Be in a cluster compare with the causative fault zone. In this research, our estimation of landslide dimensions is generally on the basis of remote sensing (RS) and field analyses.

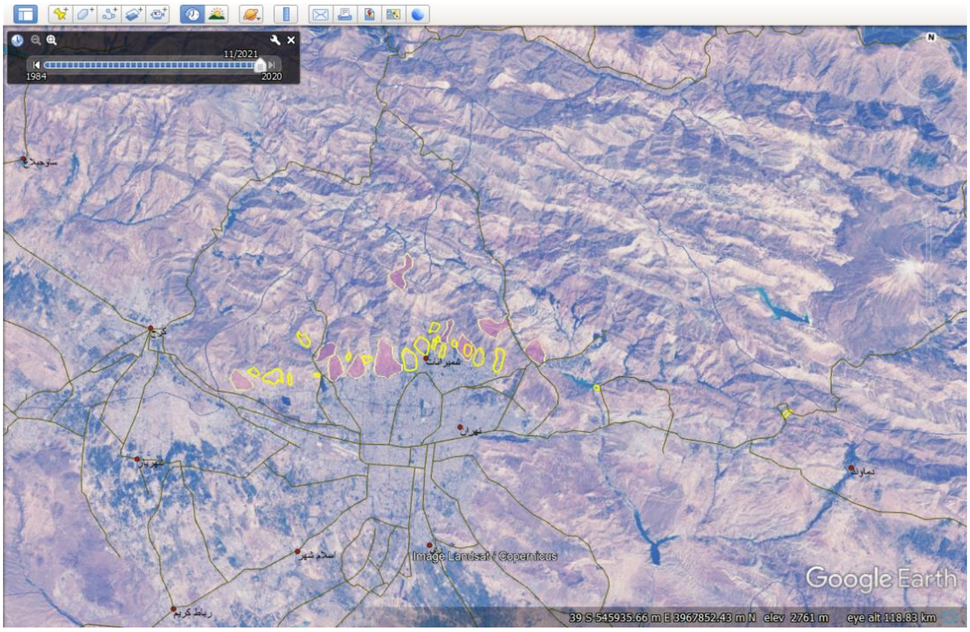

Figure 2. The Google Earth view of the Tehran Region on the Landsat 7 satellite imagery. The northern highland domain of the region contains a variety of small (marked by yellowish colour) and large (marked by pinkish colour) slope instabilities, along the southern Alborz Mountain. In this research study, we will discuss the potentially seismogenic large landslides of the region.

3.1. Large slope instabilities close to the northern piedmont of the Tehran City

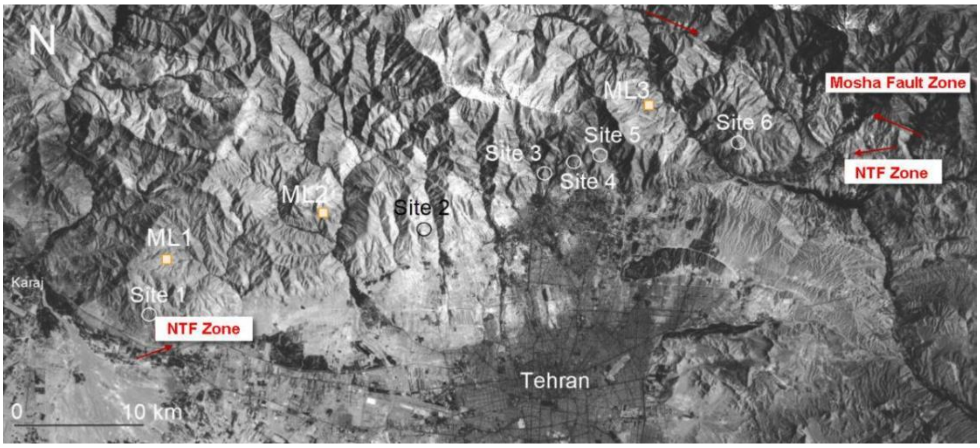

Figure 3. The IRS satellite image of the study area. In this image, our study sites are marked by circles. The yellowish rectangles are marked three huge landslides within intersected valleys of the north Tehran Region. The shorter and longer red arrows are marked the North Tehran and Mosha fault traces, respectively. Note the almost similar distance of the ML1, ML2, and ML3 from the NTF trace.

Parallel to the northern piedmont of the Tehran Region and close to the NTF trace, from Karaj to the Tehran City, there are several large natural slope steps as geomorphological scars on the hanging wall of the fault zone (**Figures. 1, 2,** and **3**). In this research, we will check out and discuss them from the west to the east of the study area. At the east side of the Karaj City and close to the north of Garmdarreh industrial town, an old landslide has been formed and developed along the southern south-facing slope of the Alborz Mountain

Range, on the hanging wall of the North Tehran north-dipping oblique-slip (reverse-sinistral) fault zone (**Figures 3** and **4**). It was moved as a complex of large boulders and Eocene volcano-sedimentary rock fragments of the Karaj Formation in a silty mud-sandy matrix (**Figure 3**). At this site, the slope of the ground surface is 26 degrees. The landslide covers an area of 45×10^5 m².

More to the east, the next old landslide at the NW of Tehran City is located in Farahzad Area (**Figure 5**). On the hanging wall of the NTF zone, it has moved to the south-south east. It was moved as a complex of crushed Eocene volcano-sedimentary rocks of the Karaj Formation (**Figure 5**). At this site, the slope of the ground surface is 25 degrees. The landslide covers an area of 12×10^5 m².

At the north of Tehran City, in Golabdareh Area the other old and large landslide is formed between the NTF zone, to the south and the Shirpala E-striking south-dipping dextral-normal old fault, to the north. In fact, the Shirpala fault could be act as a secondary antithetic fault of the NTF zone. On the hanging wall of the NTF zone, the landslide has moved to the south-south west. It was moved as a complex of crushed Eocene volcanic rocks of the Karaj Formation (**Figure 6**). At this site, the slope of the ground surface is 26 degrees. The landslide covers an estimated area of 48×10^4 m². At the north immediate vicinity of the Tehran Region, it is capable of menacing the city.

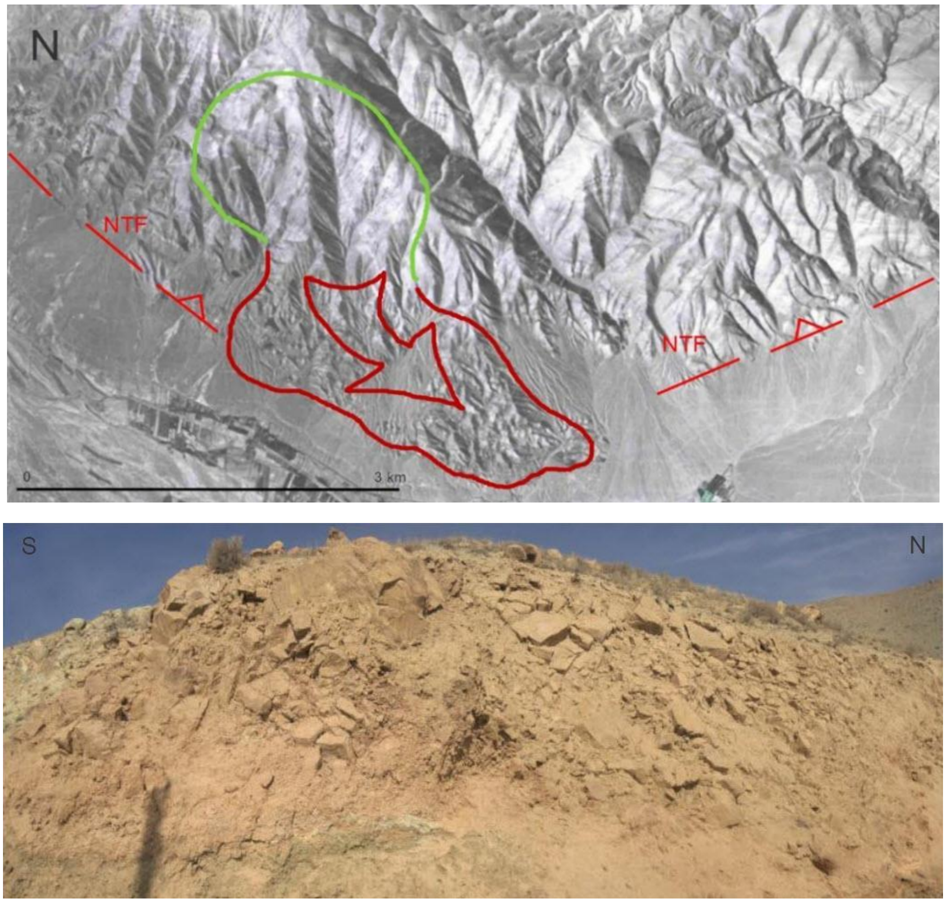

Figure 4. At the east side of the Karaj City and close to the north of Garmdarreh industrial town, an old landslide has been formed and developed along the southern slope of the Alborz Mountain Range, on the hanging wall of the North Tehran north-dipping fault zone. It was moved as a complex of large boulders and Eocene volcano-sedimentary rock fragments of the Karaj Formation in a silty mud-sandy matrix (Site 1 in Figure 3). In the field photo; note the bushes as scales.

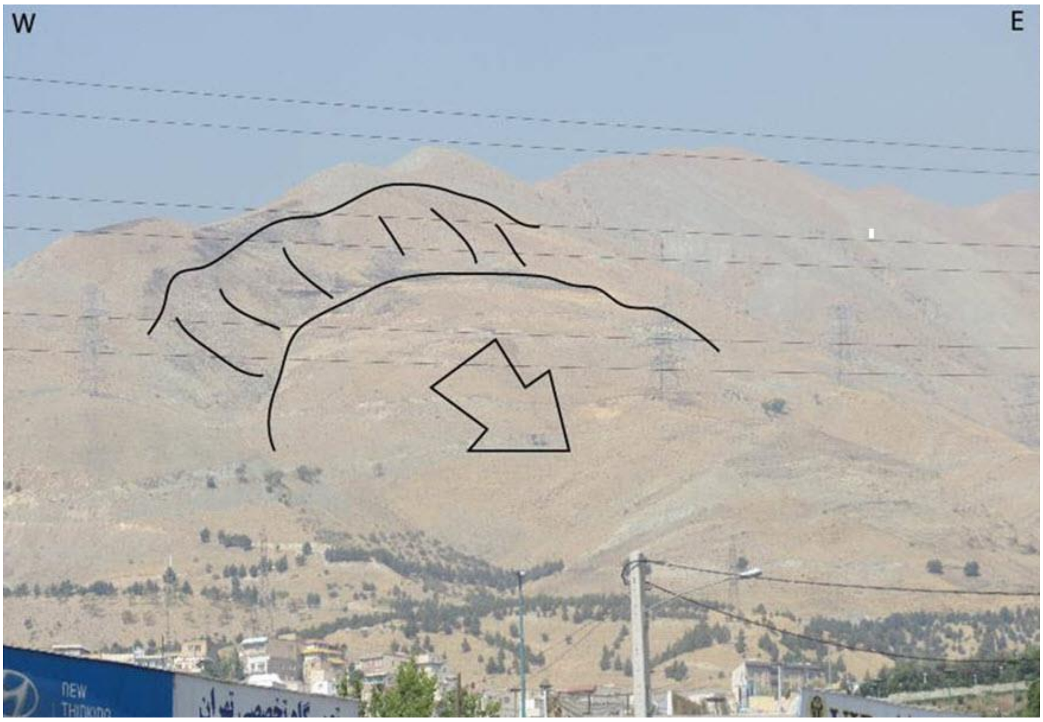

Figure 5. At the NW of Tehran City and on the hanging wall of the NTF zone, the Farahzad Landslide has been moved as a complex of crushed Eocene volcano-sedimentary rocks of the Karaj Formation to the south-south east. There, the mountain front is formed and developed by the NTF zone. The dashed area is marked the scarp of the paleo-landslide (Site 2 in Figure 3).

In the eastern vicinity of the Golabdareh landslide, a significant topographic scar corresponds to an ancient mega-rock avalanche in the Kolakchal area. The avalanche has moved towards the south on the hanging wall of the NTF zone (**Figure 7**). It involves the displacement and slump of a complex of crushed Eocene volcanic boulders of the Karaj Formation (**Figure 7**). At this site, the slope of the ground surface is more than 32 degrees. The giant paleo-rock avalanche has a volume more than 520×10^{6} m^3.

More to the east, the fifth old landslide at the NE of the Tehran City is located in the northwest side of Darabad Area (**Figure 8**). On the hanging wall of the NTF zone, it has moved to the south-south east. It was moved as a complex of crushed Eocene volcanic rocks of the Karaj Formation (**Figure 8**). At this site, the slope of the ground surface is 27 degrees. The landslide covers an estimated area of more than 2×10^{6} m^2.

Finally, along the eastern part of the NTF zone and at the left bank of Jajrud River in Zardband Area another landslide facing-south is formed and developed on the hanging wall of the fault zone. On the hanging wall of the NTF zone, it has moved to the south-south west. It was moved as a mass of crushed Eocene volcanic rocks of the Karaj Formation (**Figure 9**). The northern border of the landslide is bounded by a parallel fault strand of the NTF. At this site, the slope of the ground surface is 25 degrees. The large landslide covers an area of 26×10^{5} m^2.

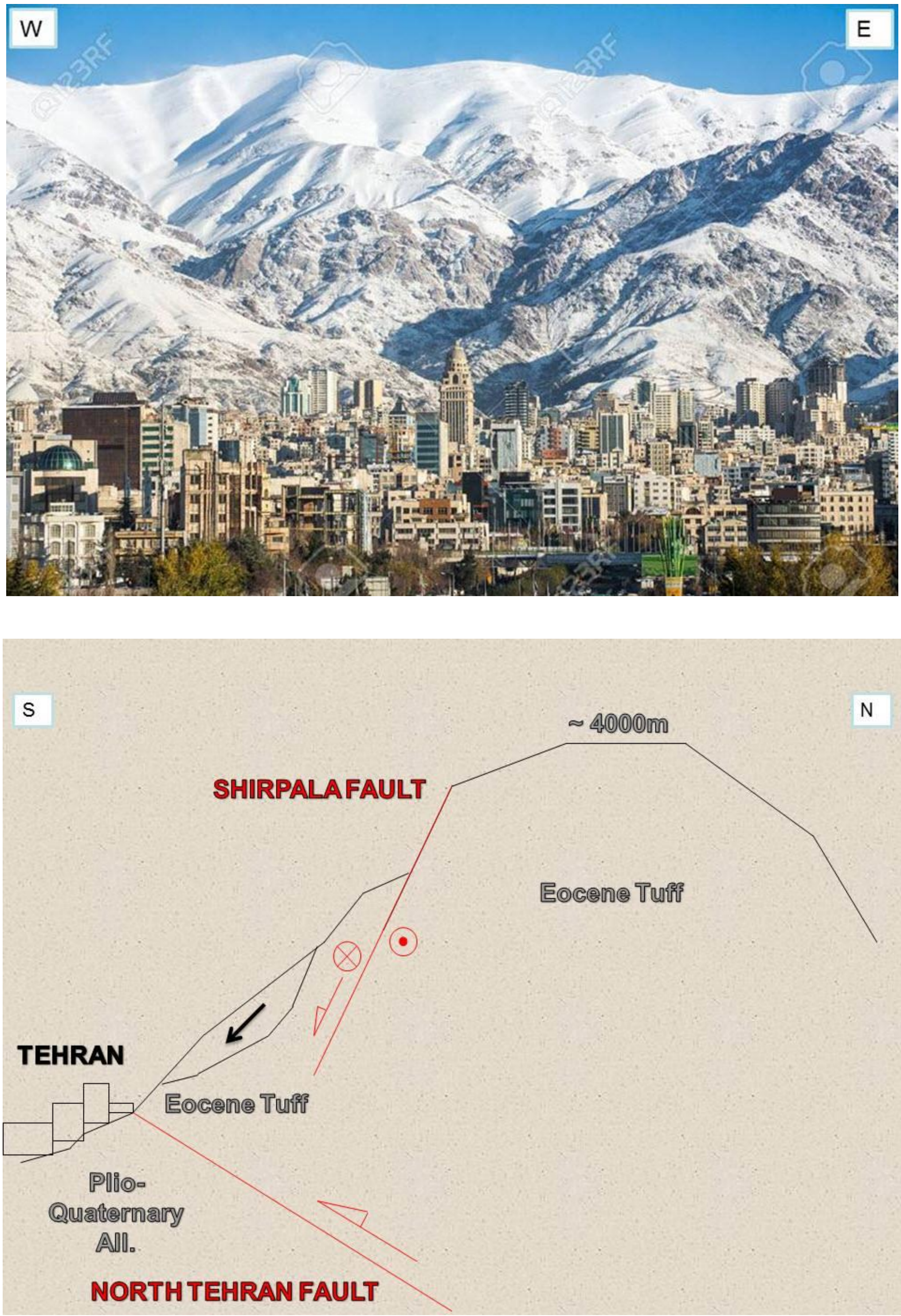

Figure 6. At the north of Tehran City, the old and sizable Golabdareh paleo-landslide has formed between the NTF zone, to the south and the Shirpala E-striking south-dipping dextral-normal old fault, to the north. It has moved towards the south-southwest direction on the hanging wall of the NTF zone, composed of crushed Eocene volcanic rocks of the Karaj Formation. This area displays the formation and development of the mountain front by the NTF zone. Situated in the immediate vicinity to the north of the Tehran Region, it poses a potential threat to the city (Site 3 in Figure 3).

Figure 7. At the eastside of the Golabdareh paleo-landslide, there is a huge topographic scar related to an old mega-rock avalanche in the Kolakchal area. On the hanging wall of the NTF zone, it has moved to the south. It was moved and evacuated as a complex of crushed Eocene volcanic boulders of the Karaj Formation. There, the mountain front is formed and developed by the NTF zone. The dashed area is marked the evacuated part of the slop (Site 4 in Figure 3).

Figure 8. The Darabad paleo-landslide is located at the NE of Tehran City. On the hanging wall of the NTF zone, it has moved to the south-south east. This paleo-landslide was moved as a complex of crushed Eocene volcanic rocks of the Karaj Formation. There, the mountain front is formed and developed by the NTF zone. The dashed area is marked the scarp of the paleo-landslide (Site 5 in Figure 3).

Figure 9. Along the eastern part of the NTF zone and at the left bank of the Jajrud River in Zardband Area another paleo-landslide was formed and developed on the hanging wall of the fault zone. In a general view, it has moved to the south-south west. The paleo-landslide was moved as a mass of crushed Eocene volcanic rocks of the Karaj Formation. The dashed area is marked the scarp of the paleo-landslide (Site 6 in Figure 3).

In general, the reactivation of this type of slope instability at the north immediate vicinity of the Tehran megacity can menace and endanger a large part of Tehran population and the most expensive buildings of the city as well.

3.2. Large slope instabilities arranged in a same distance to the northern piedmont of the Tehran City

Within the intersected river valleys that drain southward in the North Tehran highland domain, a series of three remarkably large paleo-landslides has emerged in the Eocene Tuffic rocks of the Karaj Formation. These landslides extend eastward and are evenly spaced, approximately 5 km from the NTF zone. The presence of well-defined incised drainages in their upstream areas indicates substantial erosion over a significant period. From the west to the east of the study area, these paleo-slope instabilities as the Vardij, Kan, and Galukan landslides with an almost similar areas have been arranged in the northern side of the NTF zone. At the east side of Karaj, the Vardij landslide is located on the western limb of Vardij Valley (**Figure 10**). The landslide was moved as a mass of Eocene volcano sedimentary crushed rocks of the Karaj Formation from the west to the east (**Figure 10**). At this site, the slope of the ground surface is 22 degrees. In general, the landslide has been affected an area of more than 13.4×10^{6} m^2. According to the situation of the landslide toe on the eastern limb of the valley, this valley has been dammed by the mass. At the central part of the landslide, its thickness is at least 120 m. Within the toe sector of the landslide, the height of runup is more than 100 m.

Figure 10. The Vardij landslide is located on the east side of Karaj region. The landslide was moved as a mass of crushed Eocene volcano sedimentary rocks of the Karaj Formation from the west to the east (ML1 in Figure 3).

At the north side of Tehran City and inside the Kan river valley, another huge landslide is located on the western limb of the Valley (**Figure 11**). At this site, the slope of the ground surface is 25 degrees. The landslide was moved as a mixed mass of Eocene volcano sedimentary crushed rocks of the Karaj Formation from the west to the east across the valley (**Figure 11**) and affects an area of more than 13.2×10^{6} m². According to remained lake deposits on the north-immediate side of the landslide in upstream ward of the Kan Valley, as well as the situation of the landslide toe on the eastern limb of the valley, this valley had been dammed by the mass and a lake was formed in its northern side. Subsequently, the natural dam was crushed by the river floods and overflowing. At this site, the thickness of the sliding materials is ca. 140 m. At the left bank of the valley, the height of runup at the toe part of the landslide is about 120 m. Actually, there is just a single dating result concerning to the landslide; OSL date shows the time about 1 kyr calendar years BP [59]. It can be correlated to the occurrence of a major earthquake on a fault zones associated with the North Tehran region in the historical time period[54].

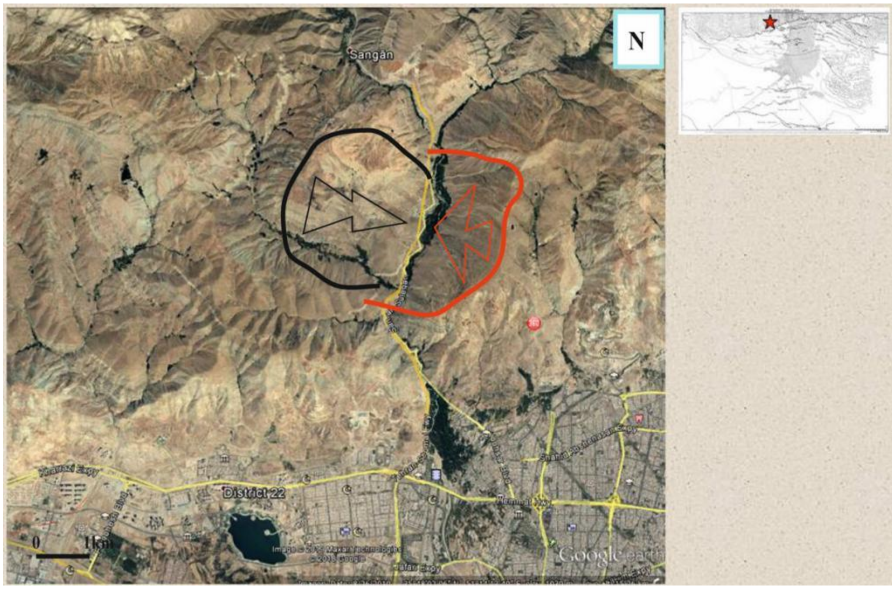

Figure 11. At the north side of the Tehran City and in the Kan Valley, a large landslide is located on the western limb of the valley. The Kan landslide was moved as a mixed mass of Eocene volcano sedimentary crushed rocks of the Karaj Formation from the west to the east of the valley (ML2 in Figure 3).

Finally, at the northeastern side of the city of Tehran and inside the south-draining Jajrud river valley-close to the Galukan area, an extremely large paleo-landslide is located on the western limb of the Valley (**Figure 12**). The landslide was moved also as a mixed mass of Eocene volcano sedimentary crushed rocks of the Karaj Formation as well as older rock units from the west to the east of the valley (**Figure 12**) and contains several large boulders. At this site, the slope of the ground surface is 22 degrees. The landslide affects an area of about 11.2×10^{6} m². Based on observed lake deposits on the north-immediate side of the landslide in upstream ward of the Jajrud river valley, as well as the situation of the landslide toe on the eastern limb of the valley, this valley had been dammed by the mass and a lake was formed in its northern side. Subsequently, the natural dam was crushed by river floods and overflowing. At this site, the thickness of the landsliding materials is then visible as 147 m. Actually, some patches of the fin grain laminated lake sediments can be found at the north of Galukan area, as an evidence. At the left bank of the valley, the height of runup at the toe part of the landslide is at least 150 m.

Figure 12. At the northeastern side of the Tehran City and in the south-draining Jajrud Valley, a large paleo-landslide is formed on the western limb of the valley. The landslide was moved as a mixed mass of Eocene volcanic crushed rocks of the Karaj Formation from the west to the east (ML3 in Figure 3).

The extremely large, geometrical aligned, and clustered slope instabilities in the rock slope of the NTF hanging wall could be assessed as the effects of strong paleo-seismic events. Within the higher parts of the NTF hanging wall and a little far from the fault trace, the effects of topographic amplification could be played a crucial role in forming of this type of slope instabilities. All these type of landslides in the study area, were subsequently affected by river captures and floods. Consequently, a large part of their slide materials has been washed and removed later by over following of the river floods. This helped us to observe more carefully their thicknesses in our field studies.

4. Discussion and conclusion

In this study, all the discussed extremely large slope instabilities of the Tehran arid-semi arid region have arranged and clustered around the seismically active zones; close to the NTF, and arranged in a same distance far from the NTF zone. In addition, most of these morphologically old landslides have been formed and developed in the Eocene hard-semi hard bedrock units, and then they are most probably the earthquake-induced paleo-landslides rather than environmental type. Obviously, these landslides could be triggered later by heavy rainfalls, quakes and or anthropogenic causes.

Close to the North Tehran seismogenic fault zone, landsliding and sliding orientation of the large slopes (i.e. Garmdarreh, Farahzad, Golabdareh, Kolakchal, Darabad, and Zardband landslides from the west to the east, respectively) could be related to their distance-topographic conditions (e.g. slope of the ground surface > 25 degrees) as well as the fault's movement direction. However, huge landslides of the Vardij, Kan and Galukan with slopes less than 25 degrees and at a greater distance from the fault zone could be related to path-site effects such as wave propagation and topographic conditions (e.g. the height of landslides).

The large studied landslides can be triggered or induced later by quakes, heavy rainfalls, and anthropogenic causes. Specifically, the Garmdarreh, Zardband, Vardij, Kan, and Galukan landslides pose threats to roads. Meanwhile, the Farahzad, Golabdareh, Kolakchal, and Darabad landslides have the potential to pose risks to urban areas in the Tehran City.

Based on sparse available dating analysis[59], and geometrical characteristics of the earthquake-induced paleo-landslides of the Tehran Region, we are not yet able to assess their precise forming dates. The huge, arranged and clustered paleo-landslides of the Vardij, Kan and Galukan are positioned at a similar distance to the NTF zone (see **Figure 3**). Consequently, the age proposed by Torabi and colleagues[59] for the Kan landslide might be linked to a strong historical earthquake associated with the NTF or other parallel E-striking fault zones in the North Tehran Region. However, the Taleghan fault zone is situated at varying distances from the aforementioned landslides. In other words, three paleo-landslides of the Vardij, Kan, and Galukan, as huge rock avalanches with high runup domains, have almost similar areas and have been formed at a distance of about five kilometers from the NTF trace. Consequently, they could have resulted due to the topographic strong motion of a paleoseismic event related to the NTF or the other parallel E-striking fault zones of the North Tehran Region. A more comprehensive dating analysis focused on coseismic landsliding in the region is imperative for accurate interpretations.

In the study area, the recent results (such as; the large dimensions of the landslides, their orientation and pattern to the active seismogenic fault zones, their localities in hard-semi hard geological rock units, and the tall runup sectors of the three huge landslides of Vardij, Kan and Galukan) could be attending as indirect geological features of strong paleo-earthquakes and their related slope instabilities. According to Keefer [74] equations, the large paleo-landslides of the Tehran highland domain can be formed by really strong earthquakes (Mw>7.5). This differs from the most of previous maximum credible earthquake magnitude estimated for the

Tehran Region (Mw~7.2) by using Seismic Hazard Assessments. Consequently, the previous results of seismic hazard studies for the Tehran City could be still under estimated and a new seismic hazard assessment according to the more detailed seismogenic geological features needs to be run for this important area. The most probable ignored factor to estimate the MCE magnitude in the SHAs of the Tehran Region could be related to using incomplete seismic source maps, especially within its northern highland domain. It's important to recognize that earthquakes that can cause large and extensive landslides are not necessarily the same as maximum credible earthquakes. Our innovative method is applicable to comparable active tectonic regions worldwide for reassessing previous seismic hazard assessments.

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Conflict of interest

The authors declare no conflict of interest.

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