LANDSLIDE HAZARD ZONATION OF THE TEHRAN METROPOLIS

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ABSTRACT

Landslide is one the most catastrophic geotechnical phenomena accompanying earthquakes, and is a very abundant geotechnical hazard during earthquakes. Iran locates in a highly seismic area of the world and its capital Tehran is surrounded by several active faults. In this article landslide hazard of Tehran is investigated by three methods of: Comprehensive Aerial Model of Earthquake-induced Landslide (CAMEL), Analytical Hierarchy Process (AHP), and Information Value (IV). AHP and IV use slope angle, ground class, DEM, distance from rivers, mean annual precipitation, landuse, earthquake acceleration, slope aspect, and distance from roads, as input data. CAMEL uses ground class, slope angle, slope height, ground roughness, soil moisture, vegetation, distance from disturbing elements, and earthquake intensity, as input data.

The results reveals that slope angle, ground class, DEM, and distance from rivers have the most effect on AHP model results, respectively, and the most important parameters in CAMEL model are ground class and slope angle. For verifying the results witness landslides map is used, where AHP model with 3.41 and CAMEL model with 3.15 have highest and lowest Quality Summation (QS) index, respectively.

INTRODUCTION

Population increase and development of urban areas, and therefore changing the landuse of natural slopes around cities has resulted in a considerable increase in losses due to landslides. This has introduced Landslide phenomenon as a potential hazard for the community. After Manjil (1990) earthquake, where many villages were destroyed by earthquake-induced landslide, the importance of this destructive geotechnical hazard was highlighted and many efforts were made to prevent and reduce landslide losses. The preliminary step for this purpose is to produce landslide hazard zonation maps in regional scale.

Many studies have been conducted on landslide hazard zonation all over the world. Mahdavifar (1385), Sangchini (1391), Ftemiaghda et al. (1391) are some examples of landslide hazard zonation studies in Iran.

Iran mountainous topography, high tectonic and seismic activities, and diverse geological and meteorological regions, provides appropriate conditions for different types of landslides occurrence. Tehran metropolis being near highly sloped mountains and active faults has a high potential for landsliding. Occurrence of several big landslides in northern and north-eastern parts of Tehran reveals the importance of landslide hazard zonation of this metropolis. (Safari & Moghimi, 2010)

The study area includes Tehran metropolis, and southern slopes of Alborz Mountains up to Tochal summit. The study area locates between 51000’ and 51045’ longitudes and 35030’ and 35052’ latitudes (Fig.1).

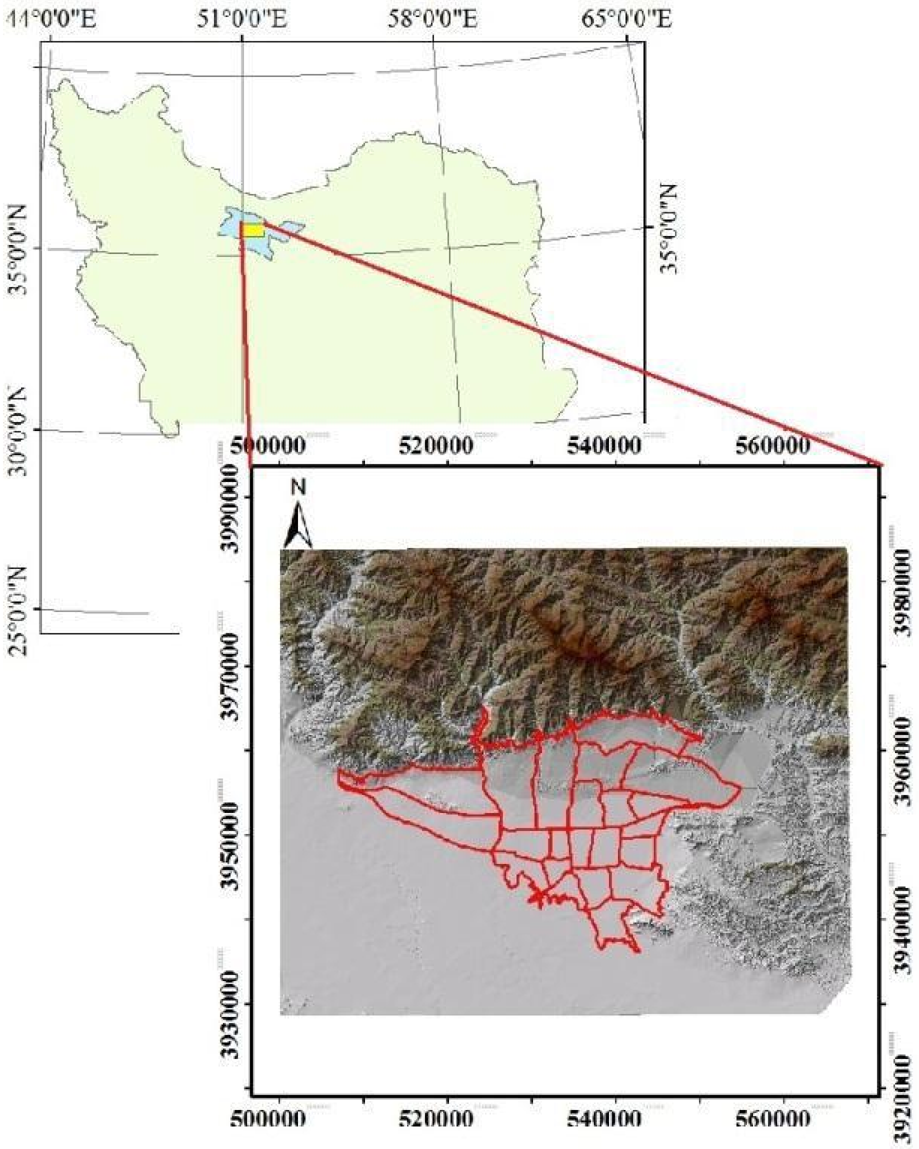

Figure 1. Study area boundary and Tehran metropolis

The study area locates at the north of central Iran tectonic area and near Alborz Mountains. The bed rock of the study area is composed of green Eocene tuff (Karaj formation), which is covered by four groups of Tehran sediments (Riben, 1955). Tehran is divided to two parts of foothills and Varamin plain. In the foothills area sediments of group A, and B predominates and group C sediments are found in lower parts. Sediments of Varamin plain are from group C, and D of Tehran sediments (Jafari & Asghari, 1376).

From seismicity point of view Tehran locates in the Alpine-Himalayan belt. Tehran region has been affected by tectonics since Neogene but mostly in Miocene when the overall faults system of the region has been changed to compressive and thrust faulting. North of Tehran fault, Mosha-Fasham fault, Kahrizak fault, and North and south faults of Rey are the most important faults of the region. Based on Berberian et al. Report (1371) seismic faults are those with more than 10 kilometers of length and historical evidences of activity, which has cut the quaternary sediments. The seismic faults of Tehran region are used for seismic hazard zonation of the region. In seismic hazard maps the maximum acceleration due to the activation of all seismic faults is calculated for each point (Berberian et al., 1371).

In this research, AHP, IV, and CAMEL models are used for landslide hazard zonation. Firstly tow methods of AHP, and IV are discussed in the next section, and after all the CAMEL model is explained.

LANDSLIDE HAZARD ZONATION METHODS

A. ANALYTICAL HIERARCHY PROCESS (AHP)

Analytical Hierarchy Process (AHP) is a decision making method with multiple criteria which helps to generate an importance scale between a number of variables. This method is widely used in susceptibility analysis of landslides (Ayalew et al., 2005).

For criteria weights of AHP method, a paired comparison matrix must be constructed. With paired comparison matrix, each parameter influence on landslide occurrence in comparison with other parameters is evaluated assigning a number between 1 and 9. The resulted matrix is a 9 by 9 matrix with values between 1 and 9 chosen based on expert judgment. The results of paired comparison matrix are illustrated in table 3. Saaty & Vargas (2001), suggest that if inconsistency rate is above 0.1 the decision must be revised.

B. INFORMATION VALUE (IV)

The method was established by Yan and Yin on 1988. In this method landslide hazard zonation is conducted according to the relationship between each involving parameter in landslide occurrence and landslide concentration. Each parameter’s weight is calculated using equation 1. Greater weights show more influence on landslide occurrence. Eventually all parameters weights are added and a final weight is calculated for each pixel.

$$IV = \ln\left(\left(A/B\right)/\left(C/D\right)\right) \tag{1}$$

In above equation A is defined as number of pixels of occurred landslides in variable class, B is the number of pixels of variable class, C is the total pixels of occurred landslides, and D is the total number of pixels.

C. COMPREHENSIVE AERIAL MODEL OF EARTHQUAKE-INDUCED LANDSLIDES (CAMEL)

CAMEL is a regional landslide hazard interpretation model based on fuzzy logic (Miles & Keefer, 2007a)

Fuzzy logic system is a series of connected IF-THEN blocks which leads to output variables from input variables. In fuzzy logic each member has a degree of support which is defined in membership functions as number between 0 and 1. This is in opposite of boolean algebra (Roger Jang & Gulley, 1997).

CAMEL model is composed of two main parts: possibility part and hazard part. First part, determines the possibility of occurrence of landslide types. The output of this part goes to hazard part, if the possibility is zero then the hazard will zero too, and if there is a positive possibility the value of hazard will be calculated in hazard part.

In hazard part, the concentration of any kind of landslide type will be calculated in scale of landslide/square kilometers. (Miles & Keefer, 2007b)

CAMEL model categorizes landslides in three groups of I, II, III. Category I are falls and disrupted slides, category II consists of coherent landslides, and category III includes flows and lateral spreads. Category I and II may occur in both rock and soil, but category III occurs in soil only (Miles & Keefer, 2007a).

INPUT LAYERS PREPARATION

Input layers of AHP and IV models are the same; Slope angle, ground class, and earthquake intensity input variables of CAMEL model are the same as AHP, and IV models.

A DEM model with 45 meters pixels is used to create slope, aspect and height layers. DEM layer is created based on topographic documents with precision of 10 meters.

An inverse relationship exists between landslide concentration and distance to roads and rivers. For roads and rivers disturbance distance, a 6 class buffering is used (table 3) and the resulted concentrations are shown in table 3. For rivers landslide concentration reduces by increasing distance, but for roads the maximum landslide concentration occurs in buffering class of 400 to 600 meters which shows that there is a weak correlation between landslide concentration and distance from roads.

Precipitation is one of the triggering factors in landslide occurrence in the region. Equation 2 shows the relationship between elevation and precipitation based on a 15 years database in the study area, where y is precipitation in millimeters, and x is elevation above sea level. Precipitation of the region is calculated using DEM map and equation 2.

$$y = 0.3094x - 148.38 \tag{2}$$

Earthquake intensity is another triggering parameters for landslides in the study area. Zare et al. (1383) earthquake hazard map is used for generating earthquake intensity map of study area. This hazard map presents the acceleration in the scale of g as a result of main Mosha-Fasham fault, North of Tehran fault, Kahrizak fault and north and south faults of Rey.

Trifuance & brady (1975) equation (equation 3) is used to convert acceleration map (with return period of 475 years) to Mercalli intensity scale. In equation 3 x is earthquake intensity in Mercalli scale and y is earthquake acceleration in scale of Gal. Equation 4 is used to convert Zare et al. (1383) map to Gal scale

$$x = 1.4558 \ln 0.94849 y \tag{3}$$

$$1PGA = 981Gal \tag{4}$$

Ground class is a variable which is defined based on Hancox et al. (2002) and Keefer (2000) researches, and presents the strength of a specific lithology upon landsliding. For preparation of the ground class map for the study area, 1:100000 geological maps of East Tehran (Fasham), and Tehran were used. The lithology susceptibility to landsliding is determined by investigating landslide concentration in any of geologic formations (Miles and Keefer, 2007). A number between 1 and 5 is assigned to all formations of the study area. The strongest formations have value of 1 and the ground class increases with the strength reduction (Miles & Keefer, 2007b).

Landuse variable is used to show the effect of changing in landuse on landslide occurrence in downhill areas. Landuse layer is prepared based on existing maps of Forests, Range and Watershed Management Organization of Iran and is completed and verified investigating Satellite images.

Soil depth variable is defined based on Keefer (1984), and Bommer & Rodriguez (2000). As there is no accurate data to generate this input variable's map, a constant soil depth of 3.33 meters is assumed all over the region, which facilitates the occurrence of soil type landslides. The only landslide type which is affected by this input variable is soil coherent landslide.

For vegetation input variable generation, NDVI value is calculated using Landsat satellite images as shown in equation 5, where NDVI represents percent of vegetation cover, RED represents red band of the imagery, and NIR represents near infrared band.

$$NDVI = \frac{NIR(4) - RED(3)}{NIR(4) + RED(3)} \tag{5}$$

Disturbance distance is a variable which shows the effect of existence of roads, and rivers near slopes on slope instability. The threshold distance for considering this variable is 150 meters.

Slope height variable is an elevation layer like DEM but shows the relative height of any slope from the top to down. This variable is important for occurrence of rock avalanches and the threshold value is 150 meters.

Terrain roughness is defined as second derivative of height, Liao et al. (2002), demonstrated the effect of this variable on landslides occurrence, investigating 1999 Chi Chi earthquake in Taiwan. Terrain roughness values must be greater than 15(rough terrain) to facilitate occurrence of rock avalanches and falls. Terrain roughness is calculated using DEM .

Ground moisture is defined as depth of saturated layer to total layer thickness (Keefer, 1984). Fatemiaghda et al. (1391), used NDMI index to estimate soil moisture using equation 6 where NDMI represents moisture, NIR represents near infrared band, and SWIR represents shortwave infrared band.

$$NDMI = \frac{NIR(4) - SWIR(5)}{NIR(4) + SWIR(5)} \quad (6)$$

ASSESSMENT AND COMPARISON OF METHODS

Landslide hazard zonation maps of three methods is shown in figure 2, to present the best method a comparison between the results is conducted.

Two index of density ratio (DR) and quality sum (Qs) are used to evaluate and compare different methods ability to provide landslide hazard maps in the study area. These two indices where firstly introduced by Gee (1972). Density ratio index (equation 7) is used to compare different hazard grades of a hazard map individually, where DR is density ratio, %L is percent of pixels of region's landslides which locates in a specific hazard grade, and %A is the percent of regions pixels which is occupied by a specific hazard grade. Therefore if DR=1, it means that that specific hazard grade landslide concentration equals to mean landslide concentration of the region. And more or less values than 1, shows more or less landslide concentration comparing with mean landslide concentration of the region (DR values are shown in table 1).

$$DR = \frac{\%L}{\%A} \quad (7)$$

For comparing different models output landslide hazard zonation maps, quality sum (Qs) index is used. Quality sum (Qs) is calculated based on equation 8, where DRi and Ai are density ratio and pixels percent of each hazard grade, respectively, and n is the number of regions hazard grades.

$$Qs = \sum_{i=1}^{n} \left(DR_i - 1\right)^2 \times A_i \quad (8)$$

Table 1. DR value for different categories of landslide hazard zonation

	AHP	IV	CAMEL
Extremely Low	0.02	0.02	0.17
Very Low	0.12	0.05	6.65
Low	0.98	0.08	2.26
Medium	3.06	0.63	3.9
High	4.98	2.47	7.02
Very High	8.11	5.72	9.90

Quality sum (Qs) values are shown in table 2. AHP model have the biggest Qs in comparison with IV and CAMEL methods, so based on this research, AHP is the best method for landslide hazard zonation of this region.

Table 2. Qs values for different landslide hazard zonation methods

	AHP	IV	CAMEL
QS	3.41	3.35	3.15

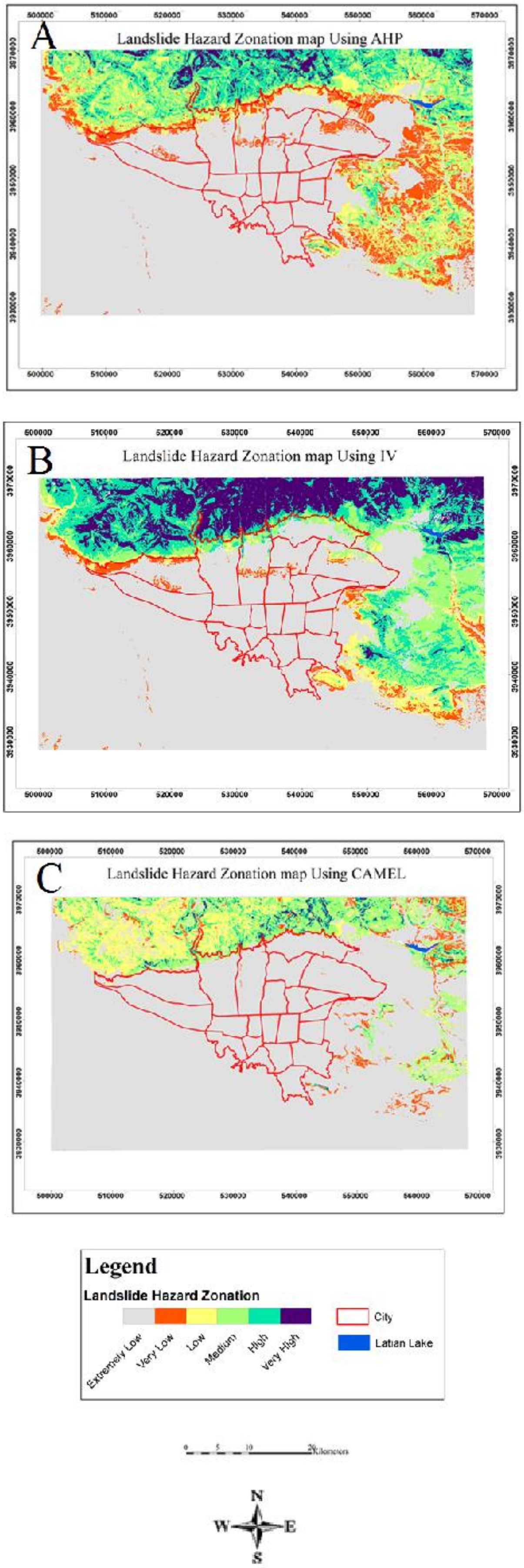

Figure 2. Landslide hazard zonation maps of A) AHP, B) IV and, C) CAMEL models

Table 3. Weight calculation for different classes in AHP and IV models

Parameter	Class	A	B	AHP		IV
Slope angle	5-15	2734	243982	0.062	0.316	-0.24
	15-25	7806	171109	0.160		1.17
	25-35	8965	118856	0.263		1.67
	35-45	1283	12540	0.419		1.97
	>45	1	82	0.097		-0.15
Ground class	1	356	154797	0.076	0.255	-1.18
	2	67	85196	0.040		-2.89
	3	2432	827162	0.137		-1.57
	4	16403	299711	0.297		1.35
	5	2062	28579	0.499		1.63
DEM	<1100	1	254997	0.022	0.157	-8.19
	1100-1500	176	867846	0.047		-4.25
	1500-2000	8871	352658	0.078		0.57
	2000-2500	8717	137845	0.183		1.49
	2500-3000	2661	44237	0.131		1.44
	3000-3500	665	9869	0.234		1.56
	>3500	131	963	0.305		2.26
Distance from river	0-100	6014	125198	0.386	0.109	1.22
	100-200	3941	110477	0.255		0.92
	200-400	5087	171232	0.165		0.74
	400-600	3022	120244	0.103		0.57
	600-800	1553	86432	0.064		0.24
	>800	1584	819444	0.027		-1.99
Slope aspect	N	2589	53379	0.233	0.027	1.23
	NE	2540	62900	0.159		1.05
	E	2211	84325	0.070		0.61
	SE	1625	244869	0.030		-0.76
	S	2412	541409	0.024		-1.16
	SW	2894	251422	0.044		-0.21
	W	3114	91217	0.107		0.88
	NW	3734	56312	0.333		1.54
Distance from road	0-100	2556	298418	0.040		-0.50
	100-200	1942	202453	0.057		-0.39
	200-400	3303	239572	0.089		-0.03
	400-600	2953	140168	0.263		0.39
	600-800	2423	97849	0.400		0.56
	>800	8125	473095	0.151		0.19
Land use	Out Crops	4846	74957	0.295	0.044	1.52
	Wet Land	75	1857	0.215		1.05
	Pasture	11723	367855	0.154		0.81
	Garden	1477	109292	0.097		-0.049
	Jungle	417	51303	0.071		-0.56
	Park	332	50739	0.061		-0.77
	Bushes	140	59638	0.040		-1.10
	Cultivated	862	262687	0.027		-1.46
	Built Up Area	1365	470050	0.025		-1.59
	River	4846	74957	0.015		-1.99
Mean annual precipitation	<200	1	364235	0.028	0.067	-8.55
	200-300	68	461914	0.043		-4.57
	300-400	3928	263547	0.100		0.05
	400-600	13125	254578	0.229		1.29
	600-800	3574	60761	0.233		1.42
	800-1025	657	8525	0.367		1.69
Earthquake acceleration	<8.47	1008	131849	0.105	0.035	-0.62
	8.47- 8.51	300	120660	0.041		-1.74
	8.51-8.59	422	167045	0.044		-1.73
	8.59-866	675	228723	0.070		-1.57
	8.66-8.73	2715	258078	0.157		-0.30
	8.73- 8.8	580	22194	0.231		0.61
	8.8- 8.86	8178	180719	0.332		1.16
	8.86-8.89	1	21701	0.021		-5.73

CONCLUSIONS

In this study it was aimed to analyze the slope stability and landslide hazard of Tehran metropolis and mountainous and downhill area in the vicinity of the city. Three models of AHP, IV, and CAMEL where used.

To evaluate the results, two indices of density ratio (DR), and Quality sum (Qs), where utilized. DR index was used to evaluate landslide concentration in any of hazard grades of the map. DR shows an increasing trend in all models' hazard grades despite CAMEL. This indicates that CAMEL cannot distinguish between the low and very low hazard grades precisely in the study area. Quality sum (Qs) is used to compare three different models of landslide hazard determination; as a result AHP is the best landslide hazard zonation model for the region. Input variables of slope angle, ground class, DEM, and distance to roads and rivers where determined to be the most important variables in landslide occurrence in AHP model. As shown in figure 2, IV model has put all of the northern parts of Tehran in very high hazard grade, which is a non-realistic overview of susceptibility degree of this part of the region to landsliding, and reveals that IV has overestimated landslide hazard in the region.

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