Landslide Hazard Zonation in Qeshm Island

Vahid Tajik[1*], Ebrahim Haghshenas[2], Mohammadreza Mahdavifar[2], and Massumeh Rakhshandeh[3]

1. M.Sc. Graduate, Researcher of Geotechnical Engineering Research Centre, IIEES, Tehran, Iran, * Corresponding Author; email: v.tajik@iiees.ac.ir
2. Associate Professor, Geotechnical Engineering Research Centre, IIEES, Tehran, Iran
3. Expert in Geotechnical Engineering Researcher Center, IIEES, Tehran, Iran

Received: 15/02/2015
Accepted: 16/12/2015

ABSTRACT

Persian Gulf's largest island, Qeshm is located in north-west of the Strait of Hormuz. Earthquakes of 27 November, 2005 (Mb=6) and 10 September, 2008 (Mb=6.2), causing 10 and 7 casualties respectively, destroying many villages and triggering numerous slope instabilities, revealed the need for a comprehensive study on development of safe construction more than ever. One of these studies could be on landslides, using its results could be considered for reducing damages and injuries during upcoming earthquakes. To achieve this goal, landslide hazard zonation of Qeshm has been studied. In this regard, the type of slope instability and its factors were identified, using the aerial photographs, satellite images and field surveys; showing that the most abundant type of landslide in the region is rock fall. In the next step, maps of landslide factors were prepared, and then by using and modifying Anbalagan methodology, landslide hazard zonation map was prepared. In addition to the above-mentioned method the fuzzy logic theory is also applied in order to achieve more accurate results and to investigate the effects of weighting method on the conducted zonation. Assessing and comparing the results of the zonations are carried out calculating the Quality Sum (QS) for each method. Comparing the results shows almost equal values. Concerning the equal situation and according to the obtained results (QS), it can be said that the appropriate selection of affecting factors on slope instability is more important than the simplicity or complexity of weighting methods.

Keywords:
Landslide hazard zonation; Fuzzy logic theory; Earthquake induced landslides; Fall; Slide; Geographic Information System (GIS); Qeshm Island; Density Ratio (DR), Quality Sum (QS)

1. Introduction

Qeshm Island is located in the Strait of Hormuz alongside the southeast part of Zagros mountain range between 55°, 15´ to 56°, 17.5´ east and 26°, 30' to 27°, 00' North, Figure (1). From the viewpoint of the tectonic structures, the area is the continuation of Zagros folding and a part of the southeastern edge of the Zagros folds, related to the subducted zone in frontal geological zone of Zagros [1]. Its outcropped stratigraphic sequence has been started by Miocene formation and continues to the current alluviums, except for salt dome of Namakdan Mountains in the southwestern part of the island, which caused the outcrop of Cambrian-aged gypsum and salt evaporation rocks (Hormuz Formation). Most of the rocky outcrops are located in the sand and marl deposits sequence of Aghajari formation that covers most of the island surface. From the morphologic and physiographic viewpoint, Qeshm island is formed of a series of heights based on anticline structures with the general Northeast-Southwest strike (except for the Northwest - Southeast strike of Gavarzin anticline), dune areas,

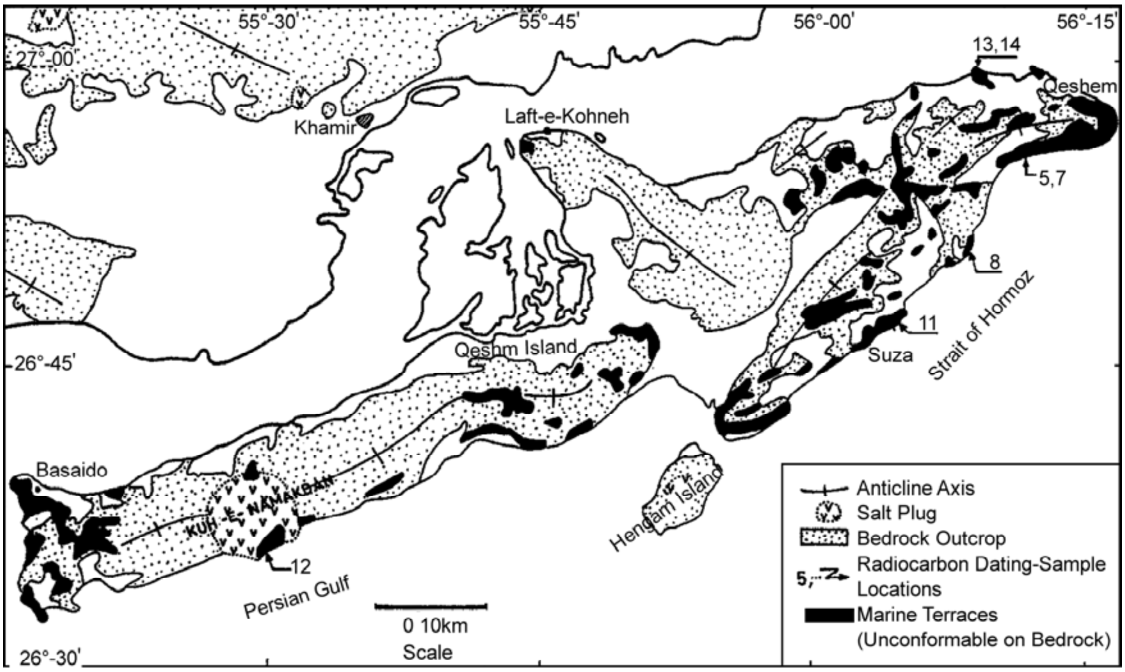


Figure 1. Study area and the location of the major axis of the anticlines in Qeshm Island [1].

calcareous marine terraces, plains and coasts. The anticline structures are formed mainly of marl, sandstone and mudstone formations. Their axial directions together with the syncline structures and their axial tilts and twists in them have a decisive role in the overall shape of the island, the coastline, climate and vegetation characteristics. The major anticlines of the island including the Gavarzin, Salakh, Holor, Suza-Zirang, and Kovehie are shown and introduced in Figure (1). Geomorphological features, especially the existence of cliff zones with alternation of hard and soft layers, and the condition of the geological unconformities relate to the slopes and slope dip direction have resulted in considerable potential of falls and topples in the area. Other types of slope instabilities such as translational slides of rock and soil are of lesser importance due to the lower impact of the factors in their occurrence [2]. Hence, with regard to the difference of slope instabilities mechanism in the area, the hazard zonation was provided for two separate types of landslides: fall hazard zonation (for falls and topples) and slide hazard zonation.

2. General and Geological Features of the Study Area in Terms of Landslide Factors

Haghshenas et al [3], divided the studied area into four regions in terms of the existence of the factors of landslides:

2.1. Highlands

According to the geological map of the area, Figure (2), the majority of the formations in the highlands are marl, sandstone or mudstone of Mishan and Aghajari formations, covered in some parts by Lomashel limestone layers belonging to Quaternary wave-built terraces. The only exception is Kuh-e-Namakdan salt dome in the western part of the island that is made of salt masses together with outcropped rocks. Inherent softness of the marls in Mishan and Aghajari formations along their rhythm and sequence with harder sandstone rocks caused the heights to be highly potential for slope instability. Furthermore, the impact of structural factors such as the relationship between structural discontinuities and slope has increased the instability potentialities in many zones of the region, Figure (3). The zones include:

- The zone surrounding the anticlines that is formed by hard Lomashel limestone and calcareous sandstone layers (Aghajari Formation), which acts as a protection for underlying layers in concordant slopes (in such areas, the slope instability is limited to the parts in which the protective layer has been removed by the natural and artificial factors).
- Band-shaped zone, consisting of marl and sandstone alternation (Aghajari Formation), which

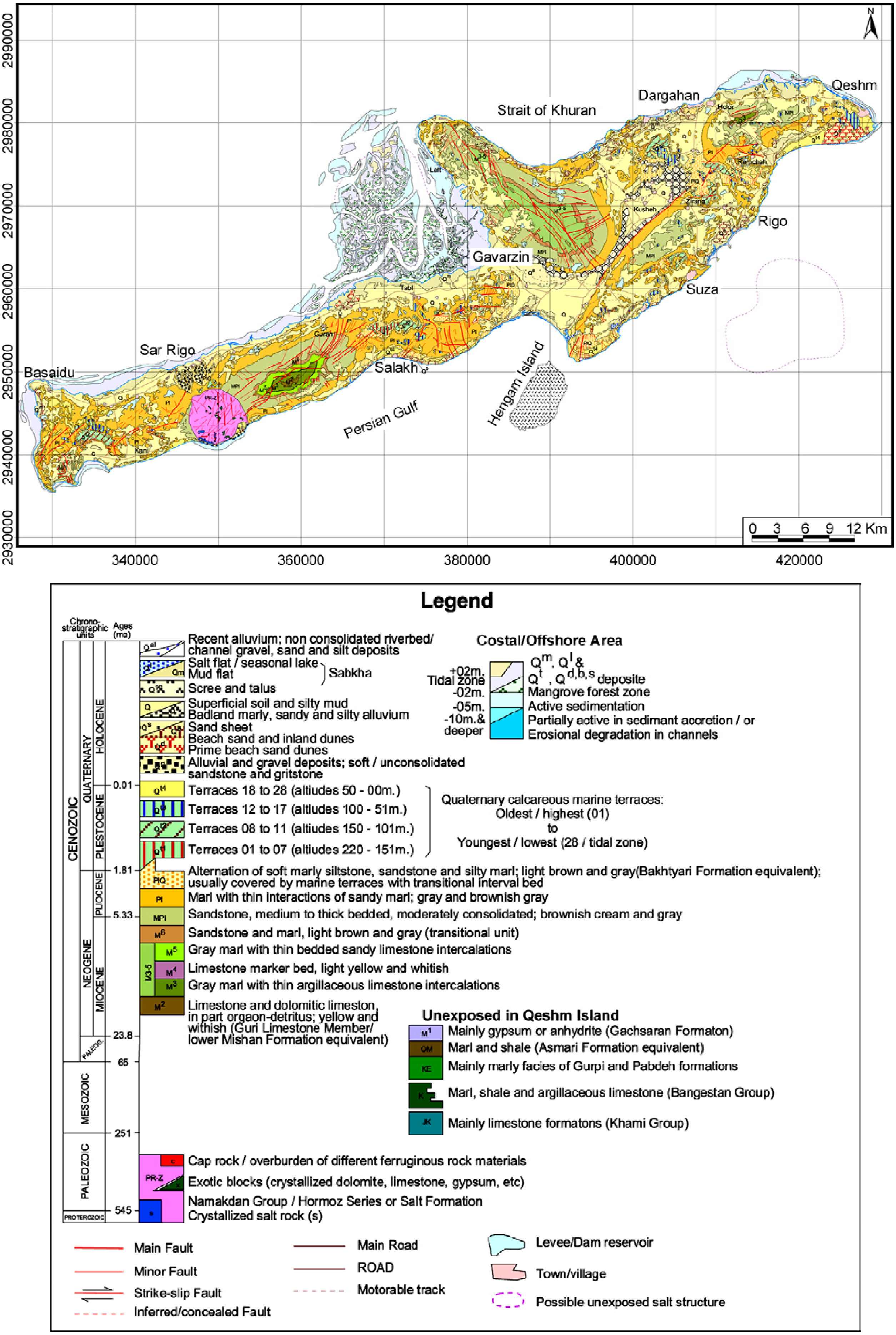


Figure 2. Geological map of Qeshm island (digitized by [3]), originated by Haghipour and Aghanabati 1:100000 map 2005) [6].

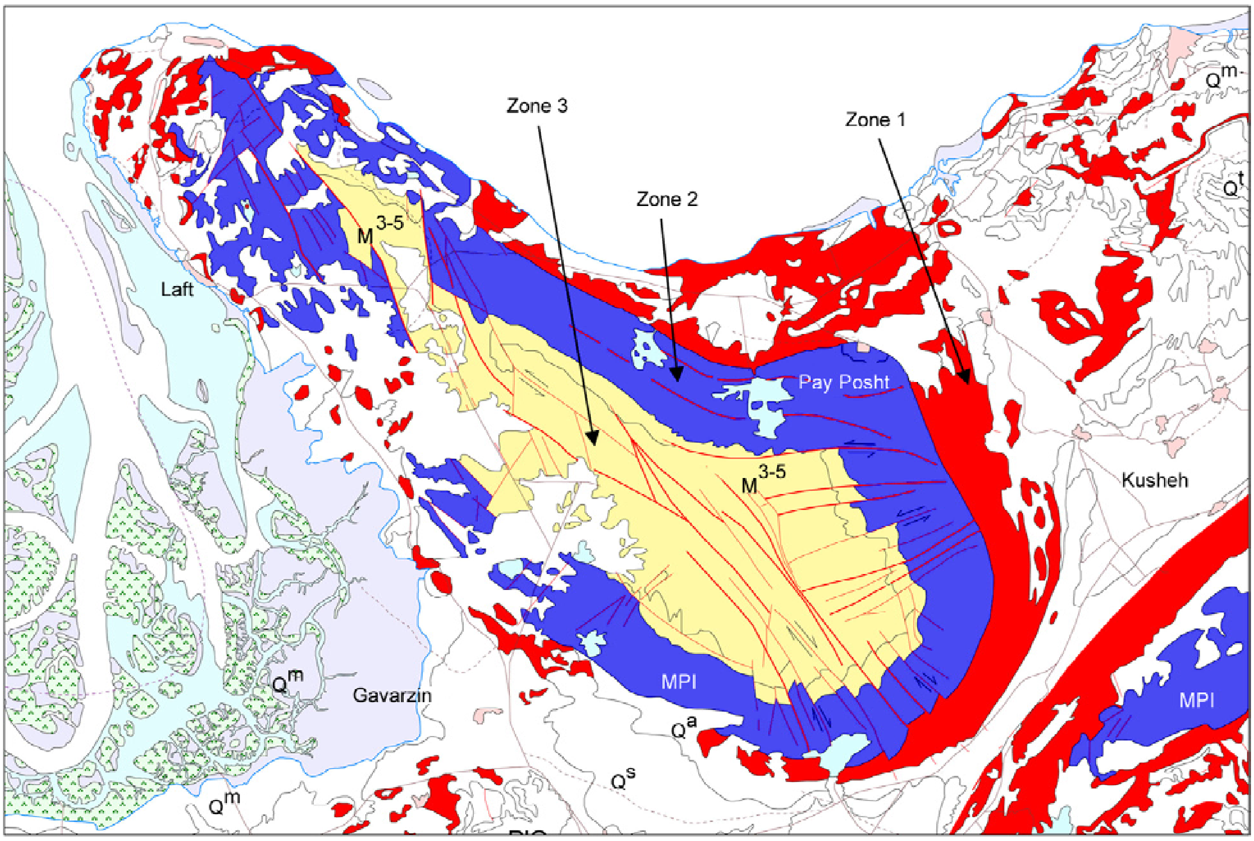


Figure 3. Different elevation zones in Gavarzin anticline [7].

surrounds Mishan formation in central parts, and in its outer limit ends in a sandstone layer or Lomashel limestone layers.

- The core of anticlines, in which the complete erosion of the younger formations caused the outcrop of thick marl layers of Mishan formation. The different erosion behavior of the formation caused to create morphology of bad-land type in these areas.

If the topography and bedding are concordant, the slope profile will be of the slope type in the first zone. However, if they are discordant or if the transverse valley walls are inclined, due to the erosion of the underlying layers and repeated fall of the upper parts, will be ranged from the steep slope type to cliff slopes and compound or sometimes concave profile. Differential erosion functions of these slopes result in the erosion of marl underlying layers and falling upper sandstone blocks. Figure (4) is an example of the falling in discordant slopes, and Figure (5) shows the instability of concordant

Figure 4. Fall in discordant slopes occurred by differential erosion of sensitive formation.

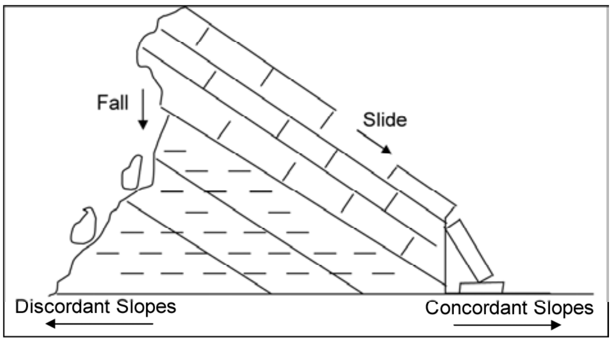


Figure 5. Potentiality of two types of landslide in both sides of highlands (fall occurrence in discordant levels and slide occurrence in concordant levels), upper and lower layers are formed by limestone and marl, respectively [4].

and discordant slopes [4].

2.2. Alluvium Terraces

Quaternary wave-built terraces at different height levels (the oldest one in 220 m elevation) with lithology of cemented Lomashel limestone, have covered the underlying deposits against erosion, acting as a protective layer. Forming of these wave-built terraces, simultaneous with the gradual uplift of the island, results from the gentle folding in the Neogene bedrock [1]. The forming process of these terraces are also currently visible in shallow coastal areas e.g. Salakh coast. One of the features of the areas covered by wave-built terraces is the steep or cliff margins overlooking the plains with low topography. The slopes have been created due to the lateral erosion of soft underlying materials. They are highly potential for rock falling occurrence. The evidences of instability in these regions include falling, Figure (6), and wide crack tensions along the edge of cliff in upper hard layer, Figure (7).

Figure 6. Wide crack tensions along the cliff edge of wave-built terraces formed in upper hard layer.

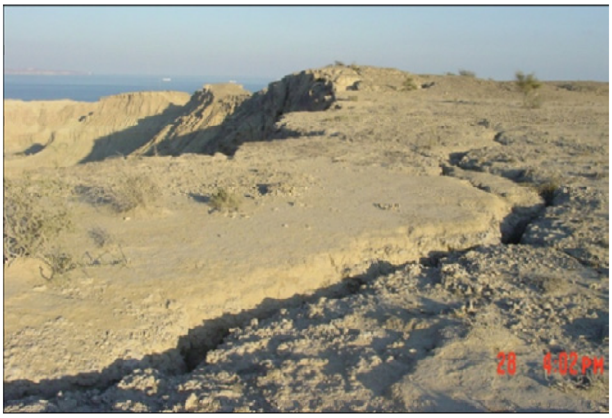


Figure 7. Wide crack tensions along the cliff edge of wave-built terraces formed in upper hard layer.

2.3. Dune Areas

In the island, many dune areas with two different origins can be seen. The first group is a result of severe erosion in marl formation of central parts of the anticlines, which are highly potential for landslide. For instance, seismic falls for the Qeshm earthquake of 2005 in Gavarzin anticline core can be mentioned. The second group is eolian sand dunes left by winds blowing from southwest in which the landslide phenomenon has not been observed.

2.4. Coasts

Generally, the island coasts are divided into two parts, southern coasts and northern coasts. With regard to the narrow width of the waterway between the island and coast of Bandar Abbas port, the northern coasts of the island are less struck by big waves, forming mud coasts in most parts despite of vast tidal zone and relatively shallow sea. Southern coasts are more susceptible to wave strikes [5]. This, in addition to concentration of Quaternary marine terraces with hard limestone lithology have caused frequent rock falling occurrences in wave-built terraces in some parts of the southern coasts due to the water erosion of underlying rocks, creating a cliff coast.

3. Falling and Sliding Hazard Zonation in the Island

As mentioned before, due to the various impacts of landslide factors in the study area, the zonation was prepared separately as two types of fall and slide.

3.1. Identification of Effective Factors

To identify the effective factors in the occurrence of slope instabilities, the assessment of the special situation and conditions prevailing in the area was done by background studies, field observations and identification of the landslides. The studies show that in addition to the weakness of the rocks forming the area formations, slope instabilities can be dependent on the sequence of soft and hard layers and the relationship between the bedding layers and the dip slope. Therefore, in the areas in which the hard layers are placed on the soft layers and the relationship between the dip slope and the bedding is of the discordant type; even at relatively low height slopes, the instability is expected for the fall and topples types. The reason is that there is a vast difference in the erosion of various layers when it is from different reasons such as the rain, wind and drainages. The function of the differential erosion by removing the support, leads to the conditions in which the fall of resistant limestone and sandstone layers occur due to the gravity and trigger factors such as earthquakes and heavy rainfall. Seismic activities showed to influence rock fall events, Bull et al [8] and Virdin et al [9]. The most common triggering factors are intense rainfall episodes, Andre [10], Ilinca [11], Berti et al [12] and meteorological factors, Delonca et al [13]; however, hot and dry climatic conditions of the region as well as the similarity between topographic slope and dip of bedding in concordant slopes caused the other types of movement to be occurred less. Since most of the region's rock falls occurred in steep and cliff areas, in addition to the direct impact of dip slope amount in slope instabilities, the cliff areas have a significant impact on the falling potential in the region.

3.2. Selecting an Appropriate Method for Zonation and Preparing Factor Maps

Considering the key role of the geological structures, the rock types forming the slopes, and the sequence of soft and hard layers in occurrence of landslides, as well as the existing technical literature in this field, the Anbalagan method [14-15] was considered as the base for preparing the landslide hazard map of the region. It is obvious that with regard to the differences in characteristics of the studied regions between Anbalagan's and of the Qeshm Island, some modifications and synchronizations have been made to the method. For this purpose, some parameters of Anbalagan method were used while some others were eliminated and replaced with some effective factors in the region. Besides, due to the dominance of the rock fall movements in the studied region, the two types of movements were investigated separately, and all factors were weighted differently for each movement (unlike Anbalagan who considered the movements of sliding type only). After selecting and preparing the work unit map in GIS environment, maps of landslide effective factors of this region were prepared and categorized.

In this study, slope units were used as base units. To prepare this map, first, the Digital Elevation Model (DEM) of the region was prepared by using topographic digital data. Then, the slope and aspect maps were extracted from DEM, Figures (8) and

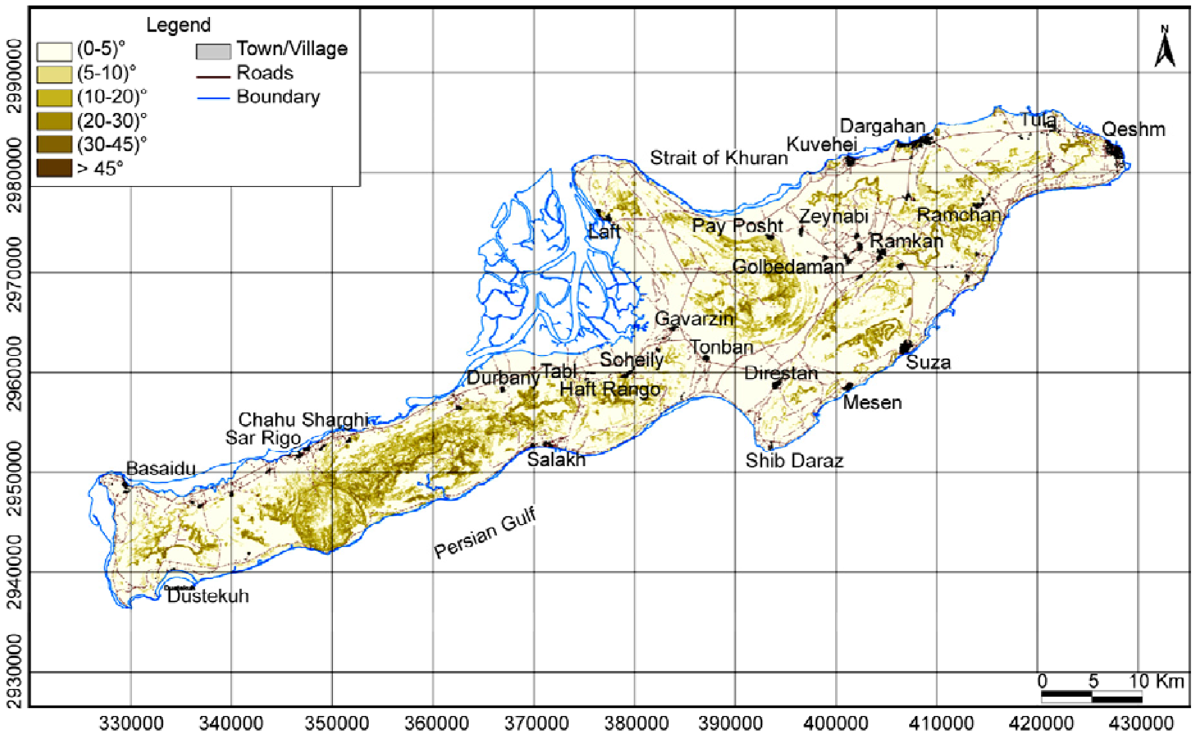


Figure 8. Slope map of the region.

(9). By overlaying the two maps, slope unit maps of the region consisting of 59797 slope units were obtained, Figure (10). As noted before, in this region, most of the rock falls have been occurred in steep and cliff areas. The cliff areas showed to be an important determining factor in the event of rock falls [16-17]. Therefore, in addition to using the slope map as an effective factor in the occurrence of landslides, the map of cliff was also prepared and considered as a separate factor map, Figure (11).

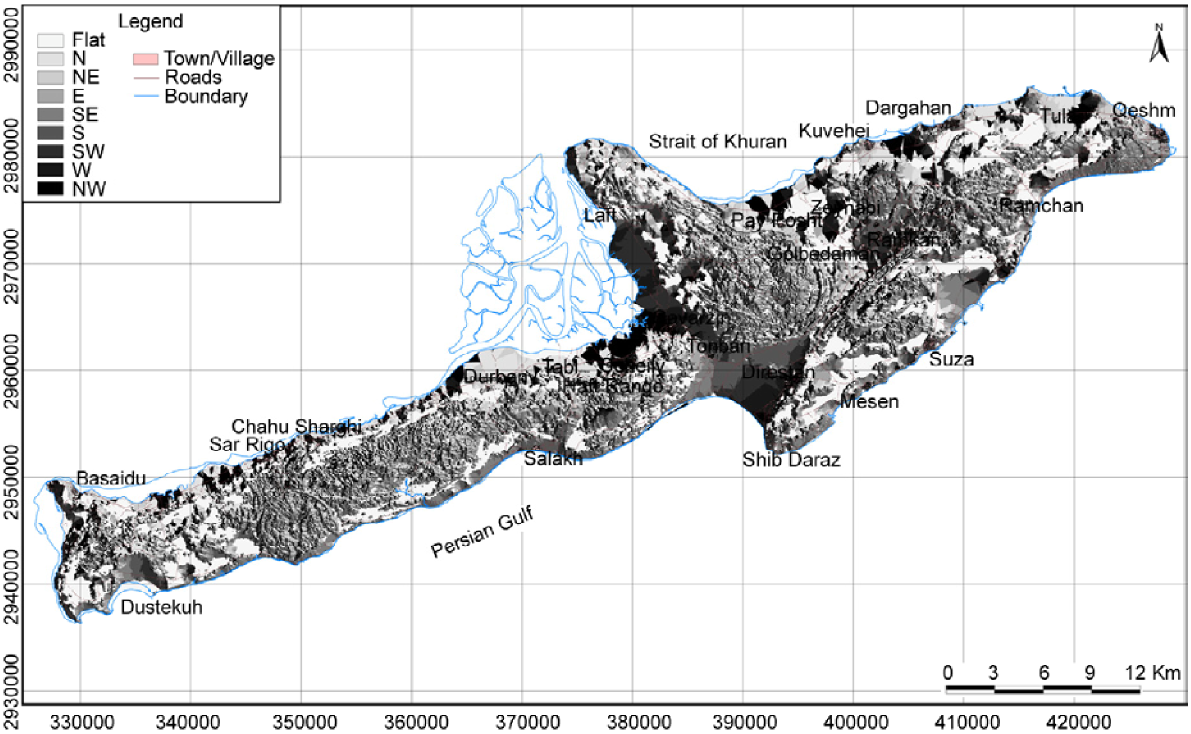


Figure 9. Slope aspect map of the region.

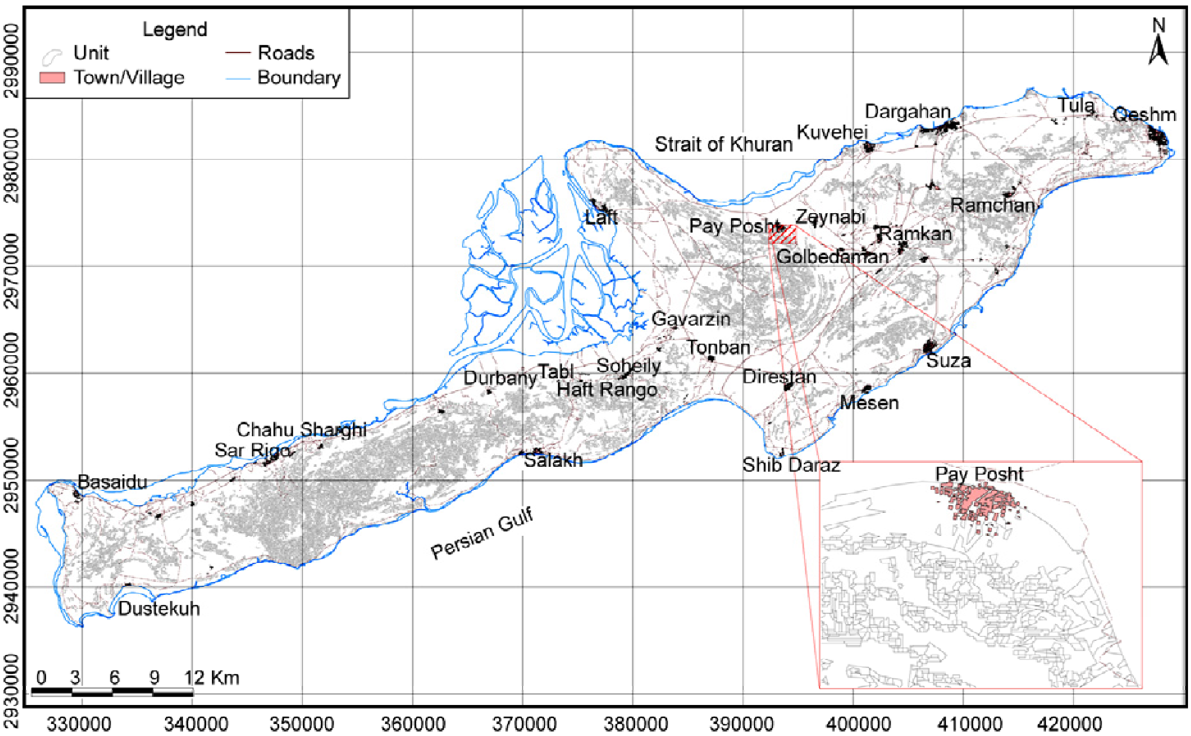


Figure 10. Slope map of the region.

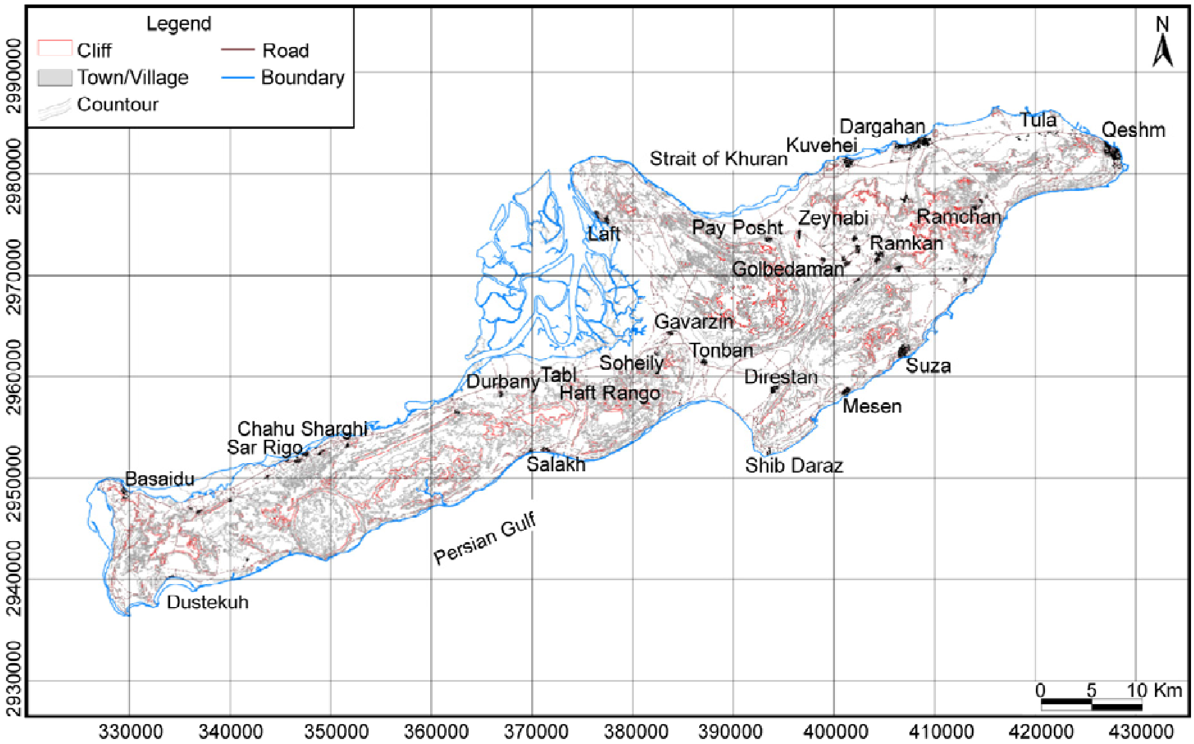


Figure 11. Map of the region's cliffs.

One of the most important factors controlling the risk of slope instabilities in the studied area is the relationship between the geological layers and the topographic slope direction. Most of the existing rock falls have been occurred on discordant slopes, hence, by overlaying the maps of topographic slope direction and bedding slope direction (from the geological map of the region), a map entitled structural unconformity map was prepared. The map represents the difference between slope dip direction and dip of bedding, separating the concordant and discordant slopes, Figure (12). Since the overall weakness of the region's rocks has significantly increased the potential of slope instabilities, the map of lithology factor was also prepared, Figure (2). Hard layers placement (Aghajari sandstone or quaternary limestone wave-built terraces) on soft and erodible layers (marl and mudstone) have caused the upper layers' support (especially in discordant slopes) to be removed and the rock fall potential to be increased. In order to consider the role of this factor, the map of soft and hard layer sequence was prepared, Figure (13). The height difference between the maximum and minimum heights in a slope unit could have a role in slope instability, but the role is small compared with the lithology and structural parameters [14-15]. The more the height difference in a slope unit is, the more the slope potential in landslide occurrence will be. For this purpose, the relative relief for all slope units of the area was calculated and categorized into three groups of under 100, between 100 to 300, and 300 and over; in the form of relative relief map, Figure (14). In this study, low rainfall and relative uniformity of rainfall throughout the region have caused the factor to have few changes in the whole region and to be ignored. On the other hand, seismicity of the region has caused the earthquakes to attract more importance, and the seismic hazard zonation map to be used as the triggering factor for slope instabilities. Based on the seismic studies done by Haghshenas et al [3], The Qeshm fault is the nearest seismic source to Qeshm, with maximum seismic potential of $Mw = 7.0$, and Peak Rock Acceleration (PRA) of 0.15 to 0.35 g for 475-year return period, and 0.25 g to 0.55 g for 2475-year return period in Qeshm Island bedrock. This can be a triggering factor for landslide occurrence, especially in the areas with high sensitivity to fall and slide, the evidence of which are numerous fall occurrences caused by 2006 and 2009 earthquakes in Qeshm. About 36 rock falls were occurred in earthquake

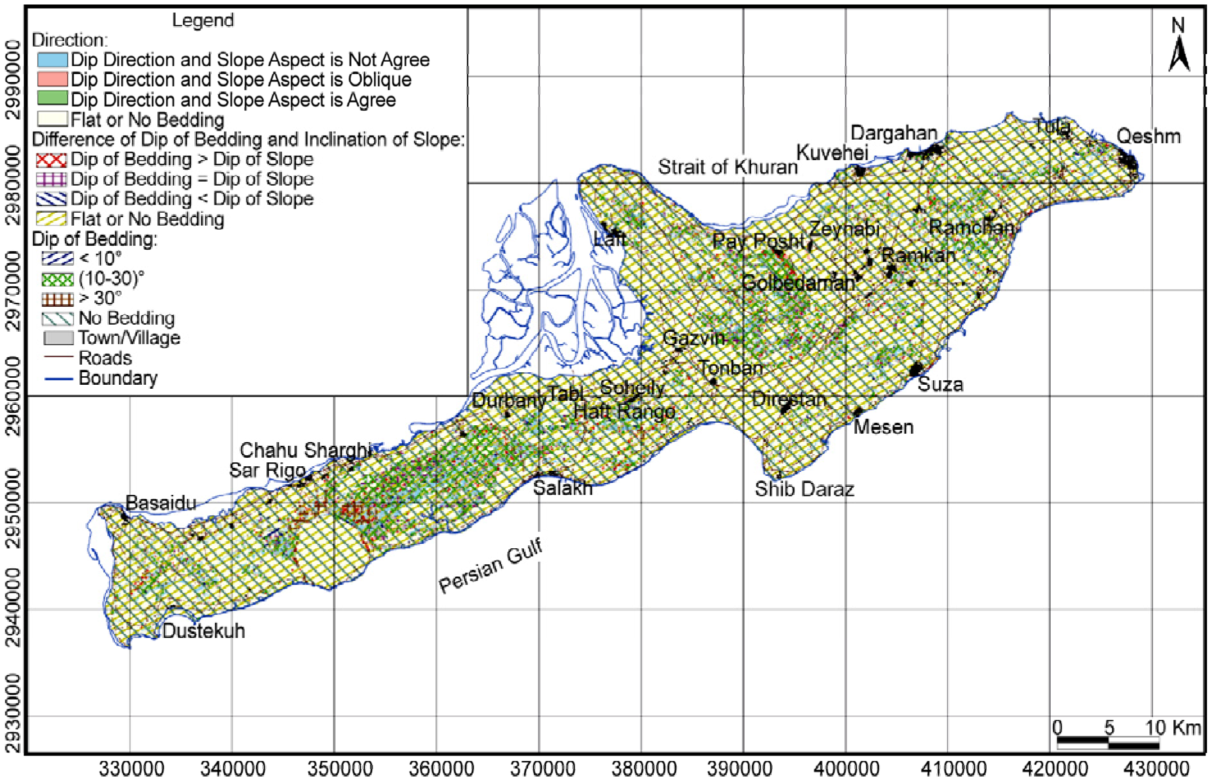


Figure 12. Map of the region's geological structure.

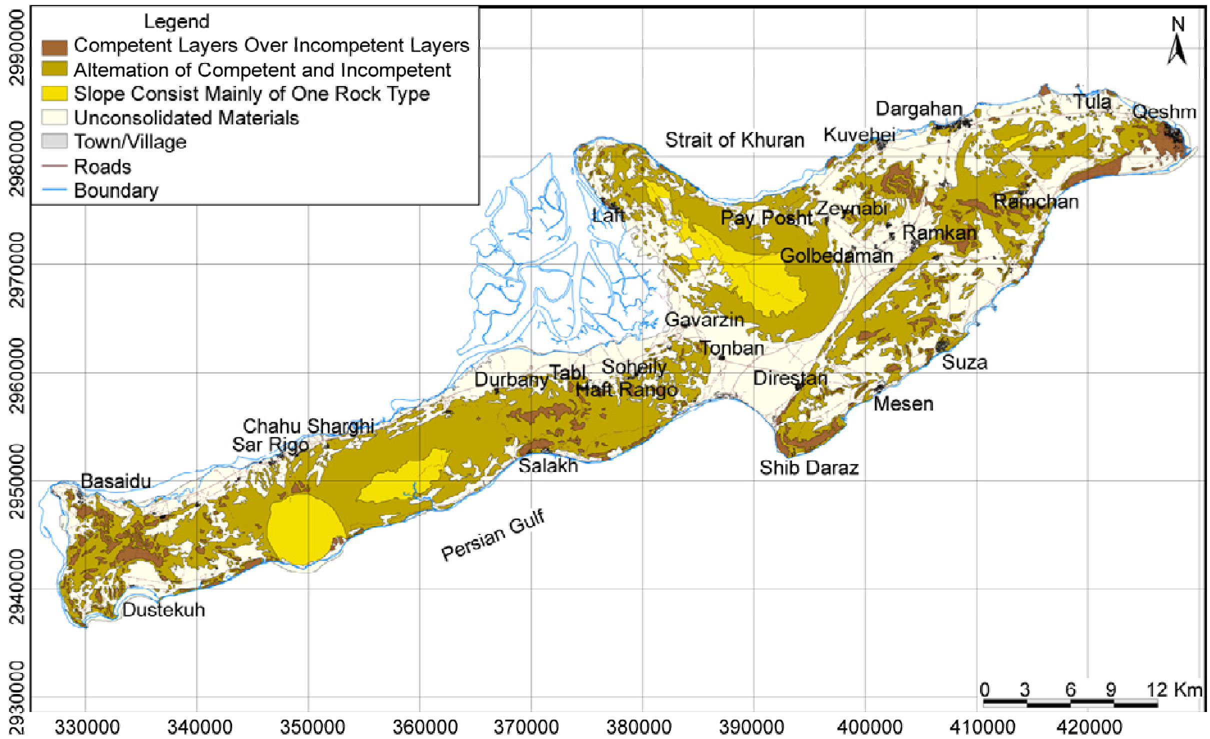


Figure 13. Map of soft and hard layer sequence in Qeshm Island.

of 2006, the position of which was detected and mapped by Haghshenas and Mahdavifar [18]. The Peak Ground Acceleration (PGA) zoning map calculated for return period of 2475 year [3] was used for preparing the earthquake factor map, Figure (15). With regard to the fact that the impact of some effective factors in occurring all kinds of slope instabilities in the area are different, some considerations were done for choosing the factor maps prepared for rock fall and slide hazard zonation. Accordingly, factor maps of lithology, dip slope, geological structures and seismic hazard were collectively considered as effective factors in fall and slide occurrences. Besides, maps of soft and hard layer sequence, cliffs (only for fall), and relative relief (only for slide), were considered as susceptibility factors. Subsequently, besides explaining how each factor map was weighted,

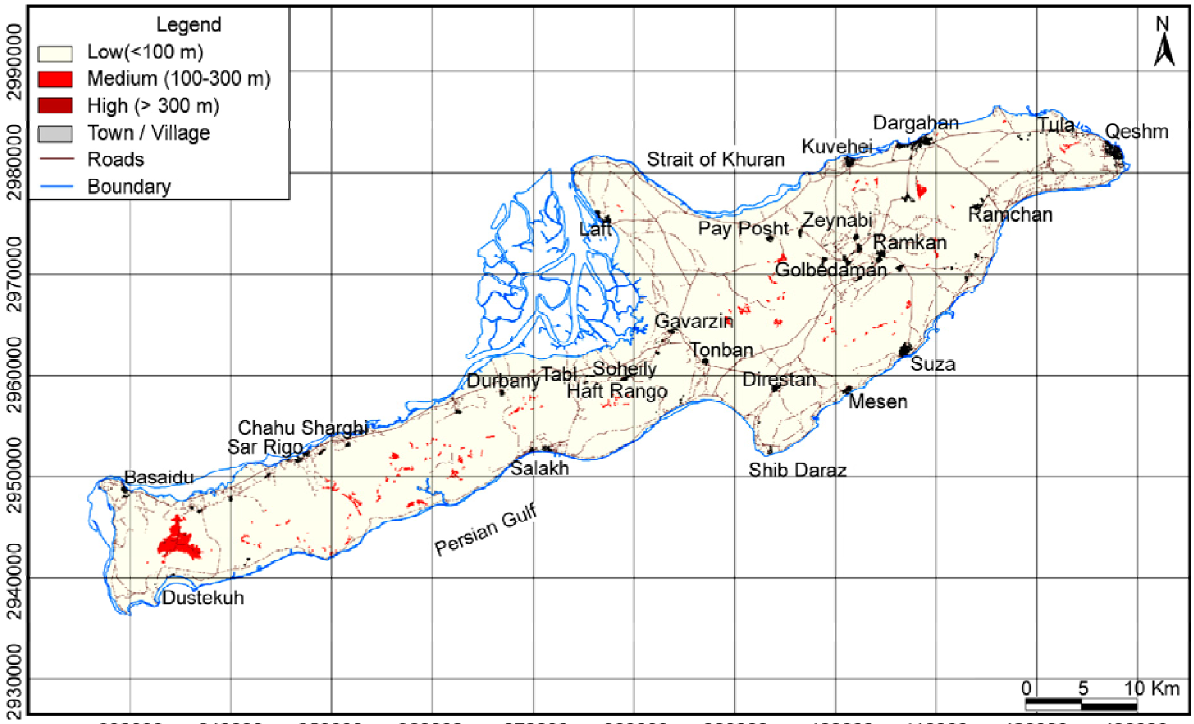


Figure 14. Relative relief map of the region.

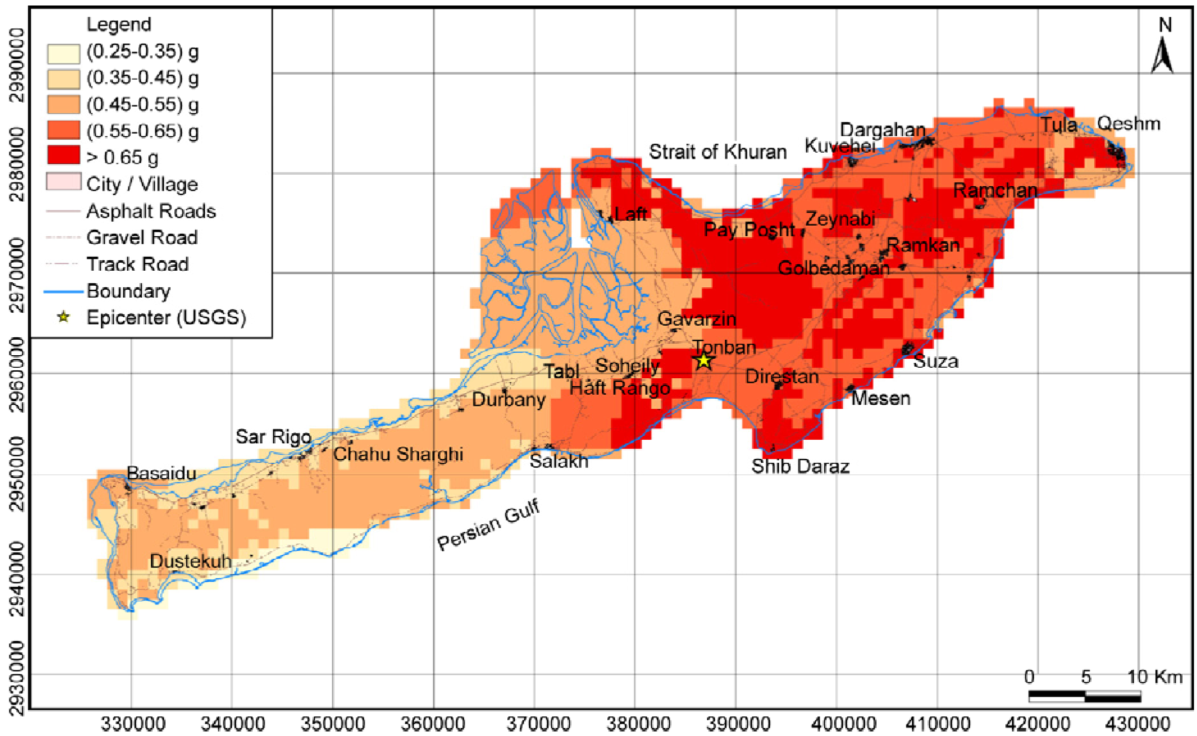


Figure 15. PGA distribution map of the study area for the return period of 2475 years [3].

fall and slide hazard zonation were described separately.

3.3. Fall Hazard Zonation in Qeshm Island Based on the Modified Anbalagan Method

To prepare the map of fall hazard zonation of the region, the factor maps were weighted based on Table (1). To categorize various hazard degrees from final scores, Table (2) was applied based on Anbalagan method [14-15]. As shown in Table (1), the sum of maximum weights given to the fall factors equals with 12, and to change the number into 10 (based on Anbalagan method), all other scores were normalized. Finally, by using the obtained results, the map of fall hazard zonation of Qeshm Island was prepared, Figure (16). By inspecting the map of fall hazard zonation as well as Table (2), it is observed that more than 17.9 % of the island surface contains the medium to very high hazard zones of rock fall.

3.4. Slide Hazard Zonation in Qeshm Island Based on the Modified Anbalagan Method

Among the effective factors mentioned in fall hazard zonation, two factors of cliffs and soft and hard layers sequence were omitted and replaced with factor map of relative relief. The preparation method of slide hazard zonation map is similar to fall hazard zonation map, and maximum weighting to the effective factors in slide was done and the final score was normalized, Table (3). The slide movements occurred in the region (except for some suspicious cases) have not been recognized due to dry weather conditions, low thickness of the soil covering the slopes, equality of dip of bedding and topographic slopes. Therefore, hazard groups in

Table 1. Maximum scoring for fall effective factors (adapted from Anbalagan method [14-15]).

The Effective Factors in the Occurrence of Slope Instabilities	Maximum Score Of Effective Factors	Final Score (Normalized; 12 to 10)
Lithology	2	1.66
Geological Structures	2	1.66
Dip Slope (Topography)	2	1.66
Relative relief	2	1.66
Cliff	2	1.66
Earthquake	2	1.66
Total	12	≃ 10

Table 2. Fall Hazard zonation based on the total estimated risk (adapted from Anbalagan method [14-15]).

Zone	Amount	Zone Description	Percent of Area Hazard Zone in Qeshm Island
I	3.5 <	Very Low Hazard (VLH)	79.81
II	3.5 to 5	Low Hazard (LH)	2.22
III	5.1 to 6	Medium Hazard (MH)	7.97
IV	6.1 to 7.5	High Hazard (HH)	4.96
V	7.5>	Very High Hazard (VHH)	5.05

Table 3. Maximum scoring for slide effective factors (adapted from Anbalagan method [14-15]).

The Effective Factors in the Occurrence of Slope Instabilities	Maximum Score of Effective Factors	Final Score (Normalized; 10 to 9)
Lithology	2	2.22
Geological Structures	2	2.22
Dip Slope (Topography)	2	2.22
Relative relief	2	2.22
Earthquake	1	1.11
Total	9	≃ 10

this map were categorized into four groups (rather than five groups in fall) including very low risk, low risk, medium risk, and high risk, Table (4), illustrated in the slide hazard zonation map, Figure (17). The results from slide hazard zonation show that about 10.3 % of the island surface contains the medium to high hazard zones of slide, Table (4).

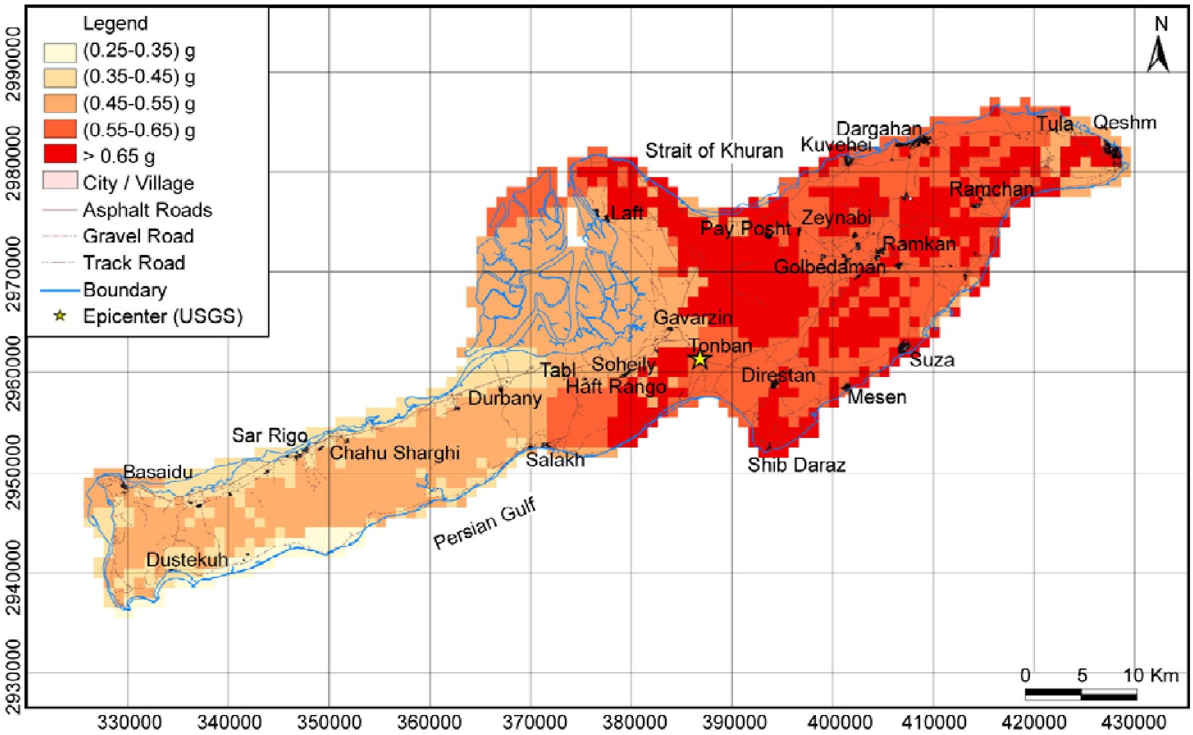


Figure 16. Map of fall hazard zonation of Qeshm based on the modified Anbalagan method.

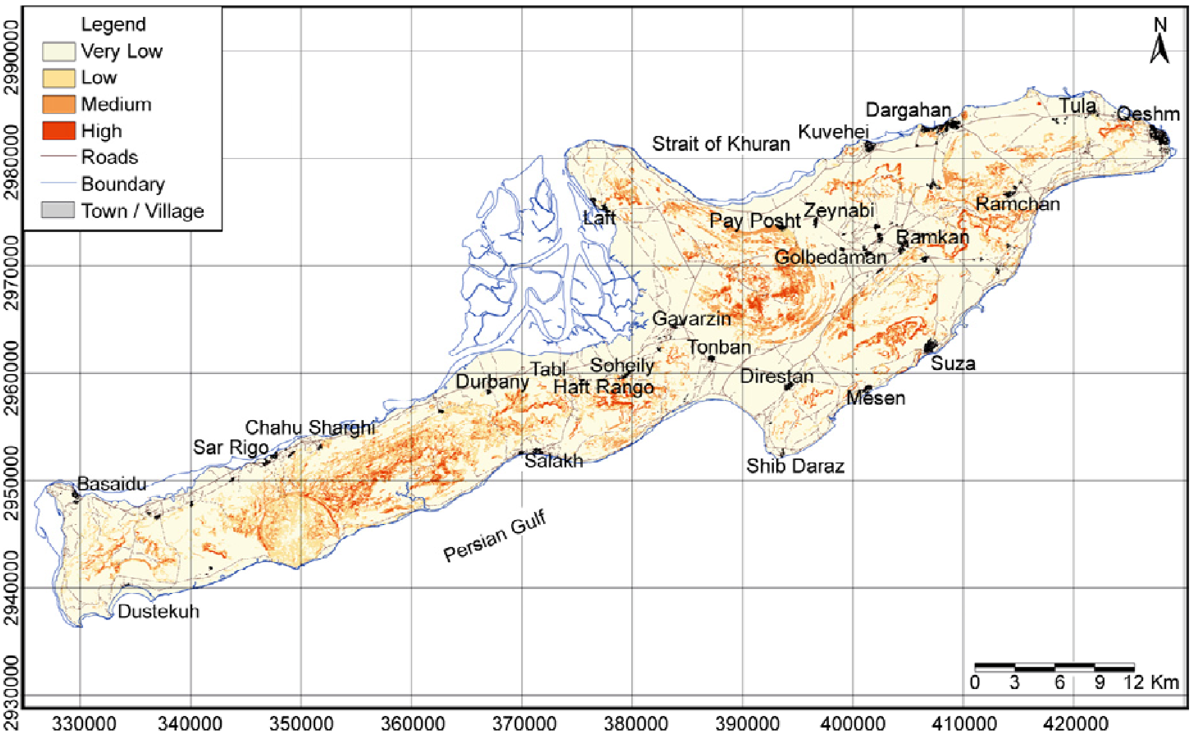


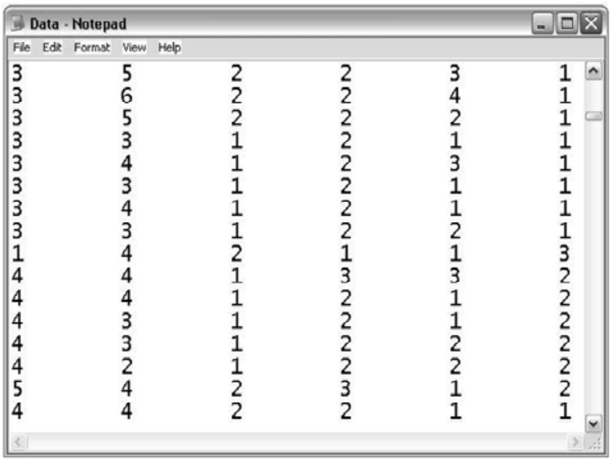
Figure 17. Map of slide hazard zonation of Qeshm based on the modified Anbalagan method.

Table 4. Slide Hazard zonation based on the total estimated risk (adapted from Anbalagan method [14-15]).

Zone	Amount	Zone Description	Percent of Area Hazard Zone in Qeshm Island
I	3.5 <	Very Low Hazard (VLH)	79.11
II	3.5 to 5	Low Hazard (LH)	10.60
III	5.1 to 6	Medium Hazard (MH)	7.91
V	6>	High Hazard (HH)	2.38

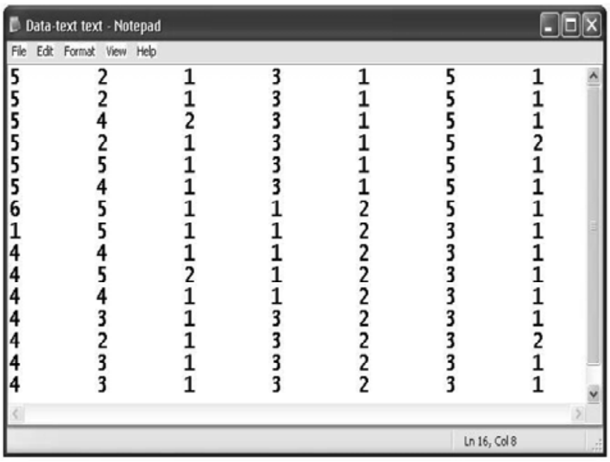
3.5. Fall and Slide Hazard Zonation in Qeshm Island by Using Fuzzy Logic Theory

In addition to the classical weighting method based on engineering judgment (Anbalagan method), in order to obtain more accurate results and to study the effect of weighting method for accuracy of the zonation is done carefully, the theory of fuzzy logic [19] was also benefited and the fuzzy sets in the landslide hazard zonation map was used, as done by Jang et al [20]. For this part of the study LHZ-FS Fuzzy Program (developed in MATLAB by Mahdavifar, 2000) [21] was used. For each weight category considered in the factor map, it constitutes a fuzzy set. For example, for the slope map of the region, with six weight categories (intended in Anbalagan modified method), six fuzzy sets are formed. In this program, the input data is in a form of a text file (Data.txt), consisting of a matrix the columns and rows of which represent the input data layers (each factor is classified) and slope unit, respectively. The input data images are shown in Figure (18). The program output will be the same matrix, only a new column is added to the end, containing fuzzy weights related to each slope unit. The numbers in this new column are resulted from the fuzzification factors, fuzzy sum of sets per slope unit, defuzzification, and converting the fuzzy numbers into classic numbers at the end. The numbers in this new column are resulted from the fuzzification factors, fuzzy sum of sets per slope unit, defuzzification, and converting the fuzzy numbers into classic numbers at the end. Therefore, the numbers in the new column were imported in GIS as a text file, and the fuzzy zonation was carried out separately for fall and slide, Figures (19) and (20).



3	5	2	2	3	1
3	6	2	2	4	1
3	5	2	2	2	1
3	3	1	2	1	1
3	4	1	2	3	1
3	3	1	2	1	1
3	4	1	2	1	1
3	3	1	2	2	1
1	4	2	1	1	3
4	4	1	3	3	2
4	4	1	2	1	2
4	3	1	2	1	2
4	3	1	2	2	2
4	2	1	2	2	2
5	4	2	3	1	2
4	4	2	2	1	1

(a)



5	2	1	3	1	5	1
5	2	1	3	1	5	1
5	4	2	3	1	5	1
5	2	1	3	1	5	2
5	5	1	3	1	5	1
5	4	1	3	1	5	1
6	5	1	1	2	5	1
1	5	1	1	2	3	1
4	4	1	1	2	3	1
4	5	2	1	2	3	1
4	4	1	1	2	3	1
4	3	1	3	2	3	1
4	2	1	3	2	3	2
4	3	1	3	2	3	1
4	3	1	3	2	3	1

(b)

Figure 18. Data.text file, including column of six effective factors in fall. The columns from left to right are: The lithology factor with 5 classes, the dip slope factor with 6 classes, the cliff factor with 2 classes, the soft and hard layer sequence factor with 3 classes, the geological structure factor with 4 classes and the PGA distribution (Earthquake) factor with 5 Classes (a). Data.text file, including column of seven effective factors in slide. The columns from left to right are: The lithology factor with 6 classes, the dip slope factor with 6 classes, the geological structure factor 1 (difference between slope dip direction and dip of bedding) with 4 classes, the geological structure factor 2 (difference between dip of bedding and dip of topographic) with 4 classes, the geological structure factor 3 (dip of bedding) with 3 classes, the PGA distribution (Earthquake) factor with 5 Classes and the Relative relief factor with 3 classes (b).

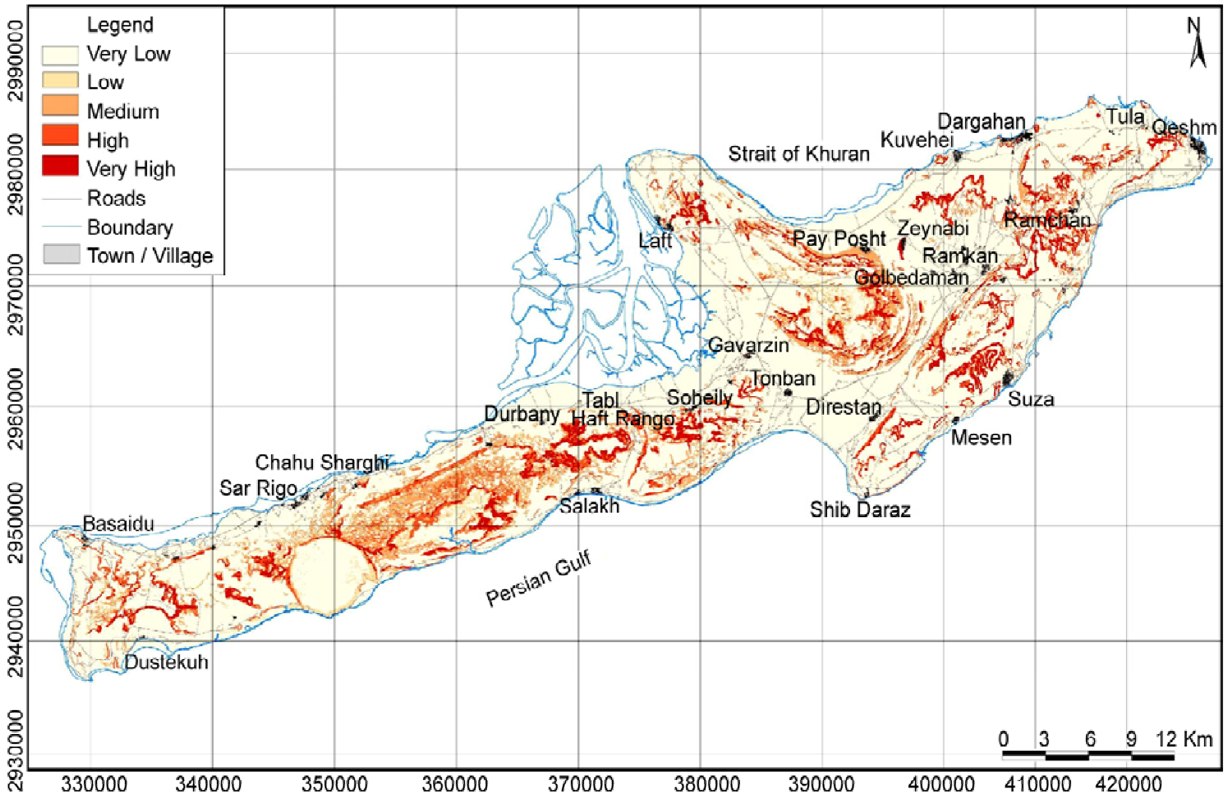


Figure 19. Fuzzy map of fall hazard zonation of Qeshm.

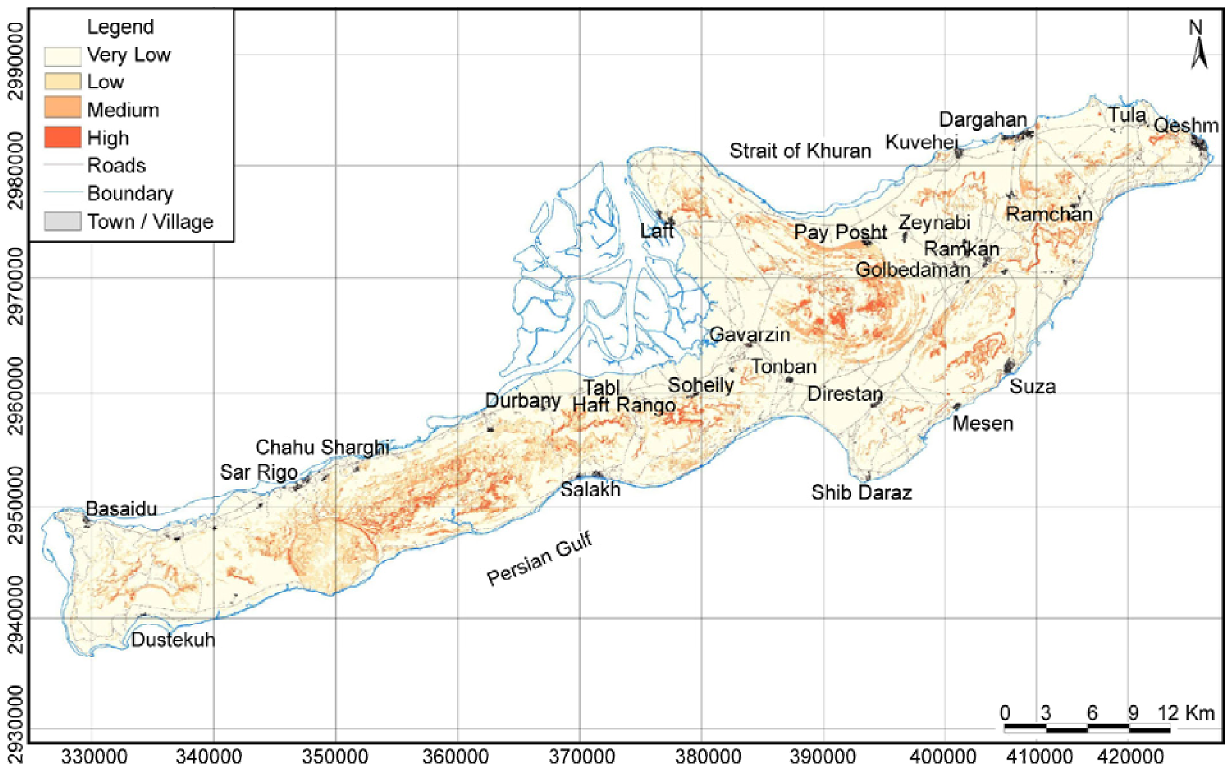


Figure 20. Fuzzy map of slide hazard zonation of Qeshm.

3.6. Assessing and Comparing the Results of the Zonations (Fuzzy Method with the Modified Anbalagan Method)

To compare landslide hazard maps produced by different assessment methods, two quantitative measures are defined. The first measure, termed the 'density ratio' (*DR*), is used to compare different hazard classes within a given hazard map. The second measure, termed the 'quality sum' (*QS*), is used to compare two or more hazard maps. To use these measures, landslides from a 'test' landsliding event within the study area are needed. Thus, density ratios are defined as [23]:

$$DR = \% \text{ Landslides} / \% \text{ Area} \quad (1)$$

where % Landslides is the number of test landslides within that hazard category expressed as a percentage of the total number of test landslides, and %Area is the areal extent of the hazard category expressed as a percentage of the total study area.

The Quality Sum is defined as [22]:

$$QS = \sum_{i=1}^{n} ((DR-1)^2 \times \% \, Area \quad (2)$$

where i is the hazard category rank and n is the number of hazard categories.

A good hazard map is considered to be one that provides the greatest separation into areas of high landslide density and areas of low landslide density. To compare several hazard maps, a *QS* is calculated for each hazard map. The *QS* measures the deviation of *DR* values for a given map from the mean value of 1.00 and sums the squares of these deviations after applying a weighting for area. The higher the *QS* value the better the separation into areas of different landslide densities and the better the hazard map. *QS* values will generally lie between 0 and 7, although theoretically there is no upper limit and differences between *QS* values of less than 0.1 are not considered to be significant [22].

In this study, in order to compare and evaluate the two types of zonation, *QS* and *DR* have been calculated by overlaying the data layer of fall inventory map in the area with each of the fall hazard zonation maps. *DR* and *QS* calculations for any fall hazard zonation maps are given in Tables (5) and (6).

In this assessment, the zonation maps of the region have almost the same amount of *QS* (with 0.13 difference) and is near to 0.1, which can be ignored according to Gee Studies [22]. Comparing the results shows almost equal values. Concerning the equal situation and according to the obtained results (*QS*), appropriate applying of the factors effective in instability is more important than the simplicity or complexity of weighting methods using in landslide hazard zonation. It means that reliable results can be obtained by recognizing and using the effective factors in slope instabilities, regardless of selected methods.

Table 5. DR and QS calculations for fall hazard zonation of Qeshm based on the modified Anbalagan method.

Relative Hazard Category	Area (Km^2)	% Area	% Landslides	DR	QS
V. Low	1133.91	78.47	0.01	0.00	
Low	29.09	2.01	3.97	1.97	
Moderate	105.98	7.33	6.95	0.95	
High	88.29	6.11	29.40	4.81	**6.43**
V. High	87.69	6.07	59.68	9.83	
Total	1444.95	100.00	100.00		

Table 6. DR and QS calculations for fall hazard fuzzy zonation of Qeshm (LHZ-FS program).

Relative Hazard Category	Area (Km^2)	% Area	% Landslides	DR	QS
V. Low	1131.80	78.33	0.01	0.00	
Low	35.61	2.46	4.68	1.90	
Moderate	119.19	8.25	6.96	0.84	**6.56**
High	85.37	5.91	38.67	6.55	
V. High	72.98	5.05	49.68	9.83	
Total	1444.95	100.00	100.00		

4. Conclusion

In this paper, the landslide hazard zonation of Qeshm Island in 1:50000 scale in two forms of slide and rock fall hazard zonation was studied. Field studies show that the major type of slope instability in the region is of rock fall type. Because the rock falls were happened in small masses and scattered blocks in vast zones, it was difficult to map them in the form of landslide inventory map and to use statistical methods for weighting the effective factors. Thus, based on the available data, the experts' judgment was used (modified Anbalagan method [14-15]). The study shows that:

- Dry weather conditions, type of geological materials (soft and hard layer rhythm), and the state of geological structures have imposed suitable conditions for the occurrence of fall and topple movements.
- Based on the map of fall hazard zonation, Qeshm heights especially the ones surrounding the anticlines in discordant slopes and quaternary wave-built terraces, have a medium to very high hazard due to the sensitive formations, soft and hard layers sequence, steep slope until cliff; therefore, construction should be avoided around them or done under special measures, a matter that has not been received enough attention currently, Figure (4).
- Based on the map of slide hazard zonation, if the slope supports are removed by excavation or natural erosion factors in the areas that are within low to medium hazard areas of slide, the hazard could be increased one or two grades. Low-height areas of Gavarzin anticline core are among the high-hazard areas because of a lithology sensitive to slide.
- The final maps show high hazard of slide for some parts of central heights of Kuh-e Namakdan salt dome, while field observations show further occurrence of rock falls. This is because of the high weight given to this lithology in slide hazard zonation. The study showed that despite the weakness of salt for its massive behavior and the impact of dissolution spaces, its potential for falling is more than its slide potential.
- The study showed that despite of using modified Anbalagan method (the experts' judgment) and fuzzy method, the same results were obtained, and it was due to the proper perception of effective factors and proper application of them in zonation.

Acknowledgment

We would like to give special thanks to Mr. Mohammad Siavoshan from IIEES for his sincere comments and helps with editing the paper.

References

1. Haghipour, A. and Fontugne, M. (1993) Quaternary uplift of Qeshm Island (Iran). *C.R. Acad. Sci., Série II*, **317**, 419-424, Paris.
2. Varnes, D.J. (1978) ‘Slope movement types and processes’. In: *Special Report 176: Landslides: Analysis and Control* (Eds: Schuster, R.L. and Krizek, R.J.), Transportation and Road Research Board, National Academy of Science, Washington D.C., 11-33.
3. Haghshenas, E. (2008) *Study of Seismic and Geotechnical Microzonation Hazard of Qeshm and Dargahan Cities*. Report of International Institute of Earthquake Engineering and Seismology (IIEES), **2**, Iran (in Persian).
4. Mahdavifar, M.R., Tajik, V., and Kamalpour, F. (2005) Landslide hazard zonation in Qom by using engineering judgment. *Proceeding of 4th Iranian Conference on Engineering Geology and the Environment*, **1**, 384-398, Tehran, Iran.
5. Haghipour, A. (1995) *Geological Researches and Mining Explorations in Qeshm Region.* Geolological Survey of Iran and Consulting Engineers Sakoo Co., p. 522, Iran.
6. Haghipour, A. and Aghanabati, A. (2005) *Geological Map of the Qeshm Area (1:100,000).* Report of Qeshm Free Area, Iran.
7. Tajik, V. (2009) *Landslide Hazard Zonation in Qeshm Island*. M.Sc. Thesis, Science and Research Branch, Islamic Azad University, Tehran, Iran.
8. Bull, W.B., King, J., Kong, F., Moutoux, T., and Phillips, W.M. (1994) Lichen dating of coseismic landslide hazards in alpine mountains. *Geomorphology*, **10**, 253-264.

9. Vidrih, R., Ribicic, M., and Suhadolc, P. (2001) Seismogeological effects on rocks during the 12 April 1998 upper Soica Territory earthquake (NW Slovenia). *Tectonophysics*, **330**, 153-175.

10. André, M.-F. (1997) Holocene rockwall retreat in Svalbard: a triple-rate evolution. *Earth Surf. Proc. Land.*, **22**, 423-440.

11. Ilinca, V. (2008) Rockfall hazard assessment. case study: Lotru Valley and Olt Gorge. Revista de geomorfologie, **11**, 101- 108.

12. Berti, M., Martina, M.L.V., Franceschini, S., Pignone, S., Simoni, A., and Pizziolo, M. (2012) Probabilistic rainfall thresholds for landslide occurrence using a Bayesian approach. *J. Geophys. Res.*, **117**, F04006, doi:10.1029/2012JF002367, 2012.

13. Delonca, A., Gunzburger, Y., and Verdel, T. (2014) Statistical correlation between meteorological and rockfall databases. *National Hazards and Earth System Sciences*, **14**, 1953-1964.

14. Anbalagan, R. (1992) Landslide hazard evaluation and zonation mapping in mountainous terrian. *Engineering Geology*, **32**, 269-277.

15. Anbalagan, R., Chakraborty, D., and Kohli, A. (2008)Landslide hazard zonation (LHZ) mapping on meso-scale for systematic town planning in mountainous terrain. *Journal of Scientific & Industrial Research*, **67**, 486-497.

16. Eisbacher, G.H. (1979) Cliff collapse and rock avalanches (sturzstroms) in the Mackenzie Mountains, northwestern Canada. *Canadian Geotechnical Journal*, **16**, 309-334.

17. Zimmer, V.L., Collins, B.D., Stock, G.M., and Sitar, N. (2012) Rock fall dynamics and deposition: an integrated analysis of the 2009 Ahwiyah Point rock fall, Yosemite National Park, USA. Earth Surf. Process. Landforms, **37**, 680-691. doi: 10.1002/esp.3206.

18. Haghshenas, E. and Mahdavifar, M.R. (2005) *Preliminary Report of Engineering Geology & Geotechnical Aspects of November 27, 2005 Qeshm*. Report of International Institute of Earthquake Engineering and Seismology (IIEES), Iran.

19. Zadeh, L.A. (1965) Fuzzy sets. *Information and Control,* **8**(3), 338-353.

20. Juang, C.H. Lee, D.H., and Sheu, C. (1992) Mapping slope failure potential using fuzzy sets. *Journal of Geotechnical Engineering,* ASCE, **118**(3), 475-493.

21. Mahdavifar, M.R. (2000) *Fuzzy Information Processing in Landslide Hazard Zonation and Preparing the Computer System*. Landslides in Research, Theory and Practice, 993-997.

22. Gee, M.D. (1992) Classification of landslide hazard zonation methods and a test of predictive capability. *Proc. 6th International Symposium on Landslides, Christchurch, New Zealand*, **2**, 947-952.