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ORIGINAL ARTICLE

Assessment of fractal dimension and geometrical characteristics of the landslides identified in North of Tehran, Iran

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Abstract The aim of the presented study is to assess the fractal dimension (*D*) and the geometrical characteristics (length and width) of the landslides identified in North of Tehran, Iran. At first, the landslide locations (528 landslides) were identified by interpretation of aerial photographs, satellite images and field surveys, and then to calculate the fractal dimension (*D*), we used the computer programming named as FRACEK. In the next step, geometrical characteristics of each landslide such as length (*L*) and width (*W*) were calculated by ArcGIS software. The landslide polygons were digitized from the mentioned landslide inventory map and rotated based on movement direction. The fractal dimension for all landslides varied between 1.665 and 1.968. Subsequently, the relationship between the length/width ratios and theirs fractal *D* values for 528 landslides was calculated. The results showed that correlation coefficients (*R*), which are different regression models such as exponential, linear, logarithmic, polynomial, and power, between *D* and *L*/*W* ratio are relatively high, respectively (0.75, 0.75, 0.76, 0.78, and 0.75). It can be concluded that the fractal dimension values and geometry characteristics of landslides would be useful indices for the management of hazardous areas, susceptible slopes, land use planning, and landslide hazard mitigation.

Keywords Landslide · Fractal theory · Landslide geometry · North of Tehran · Iran

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Introduction

Landslides are the most catastrophic natural hazards and the second most frequent natural catastrophic events, after hydro-meteorological events worldwide (Kouli et al. 2013). This phenomenon causes extensive damages to constructions and infrastructures as well as a thousand casualties annually (Saha et al. 2002; Akgun and Turk 2010; Kouli et al. 2013). In Iran, about 187 people have been killed by landslides and some infrastructure such as forest roads (3 km), railroads (6 km), main roads (252.67 km), and rural roads (46 km) have been damaged in a period of 25 years (between 1982 and 2007) (Iranian landslide working party 2007). The losses resulting from mass movements until the end of September 2007 have been estimated at 126,893 billion Iranian Rials (almost $12,700 million dollars) (Iranian landslide working party 2007; Pourghasemi et al. 2012a, b).

For landslide risk assessment and mitigation, it is significant to identify the moving directions and travel distances in susceptible areas with appropriate indices (Kubota et al. 2005). So, the fractal dimension is a statistical and mathematical good index to calculate landslide moving direction, size, and location of landslides (Yang and Lee 2006; Kubota et al. 2005). In other words, it is stating that landslide speed, shape, size, and location can all be characterized by a fractal dimension. Kubota et al. (2005) showed that the landslide moving directions decrease by the increase of fractal dimensions in high *D* regions. Also, the moving directions are similar in landslides that have high dimension (*D*) attributes. Yang and Lee (2006) observed that size distribution of landslides by earthquake is more uniform than rainfall, because *D* values for rainfall-type landslides are less than earthquake-type landslides. Usually, the larger box dimension implies that there are various sizes of landslides in a single event (Yang and Lee 2006).

The fractal theory was first introduced by Mandelbrot in 1967, and it is a simple and general method for solving complex problems and phenomena (Mandelbrot 1967). On the other hand, fractals are spatial objects whose geometric characteristics include scale dependence, irregularity, and self-similarity (Shen 2002). The mentioned theory was widely used in different researches and sciences such as extreme flood estimation (Turcotte 1994), geology (Turcotte 1990), rock mass characterization (Bagde et al. 2002), forest fires, earthquakes (Malamud and Turcotte 1999), urban morphology (Macadams 2006), river analyses (Butler et al. 2001), landform (Cai and You 2010), soil and tillage sciences (Perfect and Kay 1995; Ibanez et al. 2009; Bayat et al. 2013), and erosion (Chunxia et al. 2011).

In recent years, different methods and techniques have been used for landslide modeling (Kincal et al. 2010; Baeza et al. 2010; Ercanoglu and Temiz 2011; Pradhan 2011; Reis et al. 2012; Lepore et al. 2012; Erener and Duzgun 2012; Mohammady et al. 2012; Pourghasemi et al. 2012c; Zare et al. 2012; Devkota et al. 2013; Park et al. 2013; Regmi et al. 2013; Pourghasemi et al. 2013c). Also, several studies have been applied to assess landslide susceptibility/hazard using fractal theory in different parts of the world.

Hiura and Fukuoka (1993) computed a fractal dimension of 11,000 landslides in Hokkaido Island (Japan). Their results showed that fractal dimensions ranged between 1.42 and 1.6 depending on the method used and, also, they found dimension values of 1.44 and 1.77 for shallow landslides. Tarutani et al. (2002) used fractal dimension to identify the spatial distribution of rapid shallow landslides in the case study in Amakusa Island (Japan). In their study, the values of fractal *D* ranged between 0.81 and 1.16, which shows the linear pattern due to parallel distribution of the strata (sedimentary rocks and faults).

Majtán et al. (2002) used fractal dimension as an indicator of landslide occurrences in north Matsuura, Japan. The results of this research indicated that higher and lower values of fractal dimension were observed in the middle and toe of the slopes. Also, average values of capacity and information dimension were calculated as 1.15 and 1.17. Based on these values, they revealed some linear pattern of the distribution of landslides. Fan and Qiao (2006) evaluated equality, Poisson, and fractal distributions to model time distribution of the landslides that occurred in Three Gorges region, China. They indicated similarity and hierarchy of landslide occurrence in the fractal, as scale spectrums for whole landslides were 2.4–4.2 and for size ranks 1.98–5.84. Yang and Lee (2006) tried to explain the fractal properties of landslides that occurred due to rainfall and earthquakes, as well as landslide distributions in scale and location at central Taiwan. Their finding indicated that size distributions of the landslides that occurred due to earthquakes were more uniform than those due to rainfall; the degree of clustering for rainfall type is more serious than the earthquake type and the fractal *D* for rainfall and earthquake-type landslides is 0.53 and 0.9, respectively. Wu et al. (2009) used fractal dimensions to assess slope instability for landslide boundary trace. Their results showed that landslides with larger fractal *D* did not have a stable state in view of the boundary trace. Sezer (2010) presented a computer program (FRACEK) to calculate the fractal dimension with the application to various mass movements. According to the results of Sezer (2010), a clear difference exists between 116 mass movement events such as debris flow, and rotational and translational failure. Hu et al. (2011) stated that fractal theory has an important role in landslide monitoring data, re-organization of evolving stage, and calculation of deformation trend of landsides. Li et al. (2012) used spatial fractal clustering distribution of landslides, and landslide susceptibility mapping was implemented by using fractal theory in the Zhejiang Province, China.

The main goals of the current research are to present a detailed landslide inventory mapping in the North of Tehran and evaluation of their fractal dimension and geometric attributes. The main difference between the present study and the approaches described in the aforementioned publications is that it assesses the relationship between length/width ratio and their fractal *D* for 528 landslides in the study area and offers a regression model to calculate *D* value for all of the landslide occurrences in Tehran metropolitan. Landslide is a very common phenomenon in the study area due to its climate condition, lithological formation, and earthquake occurrence (Pourghasemi et al. 2013b). On the other hand, population density and high price of lands of these areas are the original reasons for the current research.

Study area

The study area is located in the North of Tehran metropolitan, Iran, between longitudes 35°45′50″N and

35°59′16″N, and latitudes 51°05′26″E and 51°50′30″E (Fig. 1). It covers an area of about 900 km^2 (Pourghasemi et al. 2013a). A total of 528 landslides were mapped at 1:25,000-scale, using aerial photograph, satellite images, and field survey (Fig. 1). The smallest landslide had an extent of 685 m^2, while the largest one had 280,804 m^2. The altitude of the area ranges from 1,349.5 to 3,952.9 a.m.s.l, and the slope angles of the area range from 0° to as much as 83°. The major land use of the study area consists of rangeland and covers almost 90.5 % of the whole area. Based on the Geological Survey of Iran (GSI 1997), the lithology of the study area is covered 33.97 % by group 5 (Table 1) and 27.54 % by group 4 (Table 1). The major thrusts and faults in the study area include Mosha-Fasham, Purkan-Vardij, North of Tehran thrusts, and Shirpala and Emamzadeh Davud faults (GSI 1997).

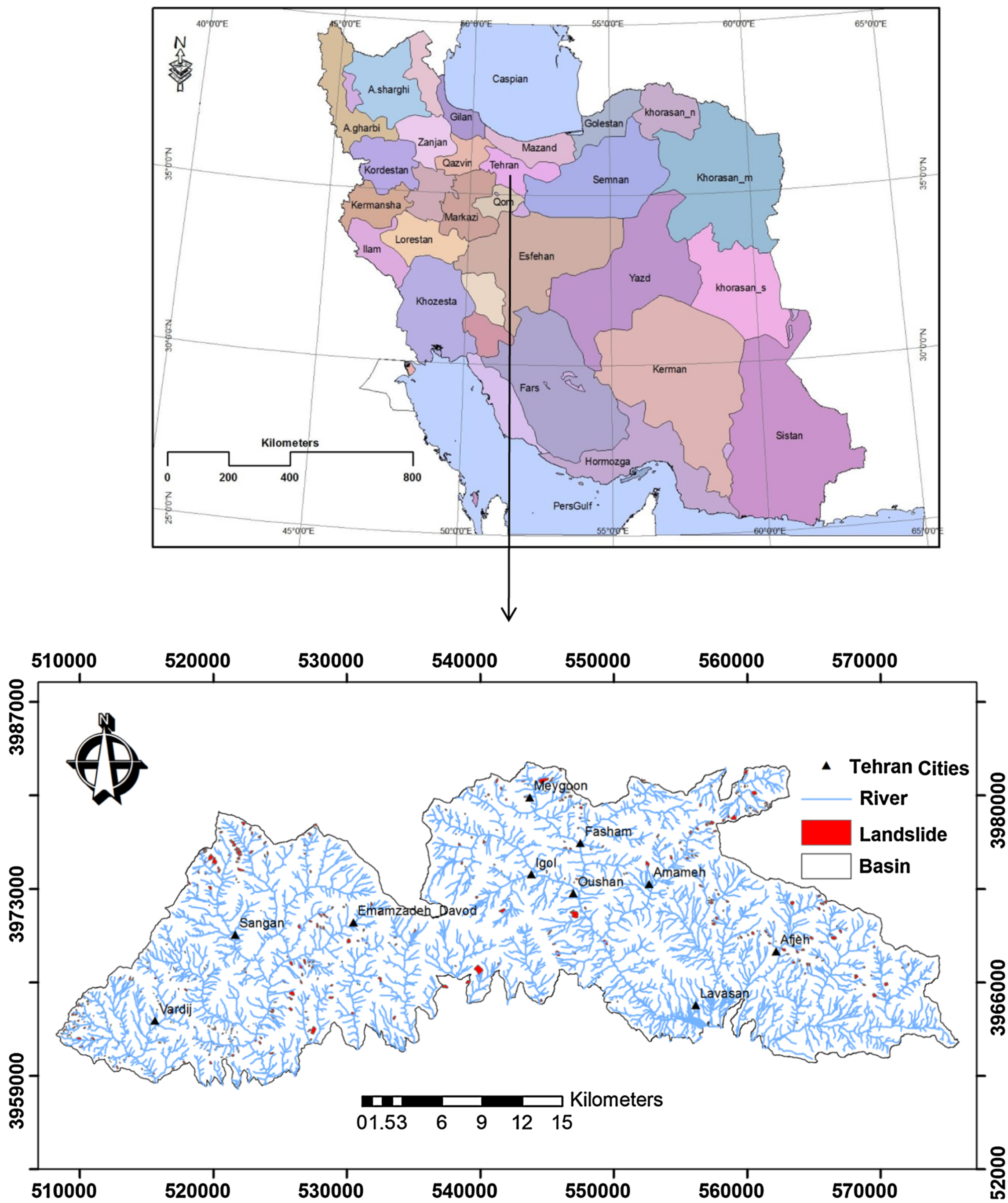


Fig. 1 Landslide location map of the study area

Table 1 Lithology of the study area (GSI 1997)

Code	Group	Formation	Lithology	Geological age
Q^2		Sub-recent Tehran alluvium—unit C	Young alluvia fans and terraces	Quaternary
Q^l		Kahrizak—unit B	Old alluvial fans and terraces	Quaternary
Q^s		–	Young and old scree, talus deposits	Quaternary
Q^f		–	Young and old alluvial fans, agglomerate	Quaternary
Q_U	1	–	Undifferentiated young and old alluvial fans and terraces, alluvium, residual soils	Quaternary
Q^{al}		–	Loose alluvium (including recent alluvium—unit D)	Quaternary
Q		–	Conglomeratic terraces and fans	Quaternary
Q^m		–	Morain	Quaternary
Q^{sc}		–	Scree	Quaternary
Q_2^t		–	Young terraces	Quaternary
Q_1^t		–	Old terraces	Quaternary
Q^{tr}	2	–	Spongy porous travertine	Quaternary
PlQ_c^s		Hezardarreh—unit A	Conglomerate, sandstone, mudstone intercalations	Pleistocene
M		Upper red	Undivided Miocene deposits including sandy marl, siltstone, conglomerate, gypsum, Miliolidus limestone	Miocene
M_u^2		Upper red	Sandstone, silty marl, mudstone, siltstone	Miocene
E_{Kn}		Kond	Sandstone, conglomerate, gypsum, Nummuliti marly limestone	Eocene
E_4^{sc}		–	Sandstone, conglomerate, green tuff	Eocene
E_4^{st}		Turbiditic sediments	Light color sandstone, greenish tuffite, conglomerate	Eocene
E_3^{sc}		–	Tuffaceous sandstone, micro-conglomerate with intercalations of tuffite	Eocene
E_3^{tc}	3	Turbiditic sediments	Tuffite sandstone, conglomerate	Eocene
E_3^{sh}		–	Shale with intercalations of tuffaceous sandstone and siltstone	Eocene
E_f^{sl}		–	Red conglomerate and sandstone with intercalations of limestone	Eocene
E_f^c		–	Red conglomerate, sandstone and shale	Eocene
E_f^{st}		–	Shale, sandstone and tuffite with intercalations of limestone	Eocene
E_m		Mila	Medium-thin-bedded limestone with intercalations of shales	Eocene
E_z		Zagun	Red, green micaceous shales and sandstones	Eocene
PE_z		Ziarat	Alveolina–Nummuliti limestone, conglomerate, gypsum	Paleocene
E_K^m		Karaj	Light green-gray laminated calcareous mudstone, shale, tuff, gypsum, tuffite	Eocene
E_K^t		Karaj	Green thick-bedded tuff, tuffaceous shale, minor lava, pyroclastic, tuff, breccia (mainly consisting of mid. Tuff member)	Eocene
E_K^{sh}		Karaj	Calcareous and siliceous dark color shale, tuffite, pyroclastic	Eocene
E^{dg}	4	–	Micro-dioritic micro-gabbro as sill and dikes	Post lower Eocene
E_5^{sh}		–	Shale with intercalations of tuffite and tuffaceous sandstone	Eocene
E_5^{tb}		–	Green tuff, tuff breccia, tuffite with intercalations of tuffaceous siltstone	Eocene
E_5^{td}		–	Hyalotrachyandesite, trachte–dacite, tuff breccia	Eocene
E_3^b		–	White-green tuff breccia, ash tuff	
E_3^{ss}		–	Alternation of shale and tuffaceous siltstone	Eocene
E_2^t		–	Green crystal, lithic and ash tuff, tuff breccia, and partly with intercalations of limestone	Eocene
E_2^{ts}		–	Alternation of shale and tuffaceous siltstone	Eocene
E_2^r		–	Rhyolitic tuff with some intercalations of shale	Eocene
E_1^{tsv}		–	Massive green tuff, shale with dacitic and andesitic–basaltic lava flows	Eocene
E_1^{sht}		–	Dark gray shale with alternation of green tuff, and partly with sandstone, shale, conglomerate and limestone	Eocene
E_1^{tsh}		–	Alternation of green tuff and shale	Eocene
E_1^b		–	Andesitic–basaltic lava breccia and lava flows	Eocene

Table 1 continued

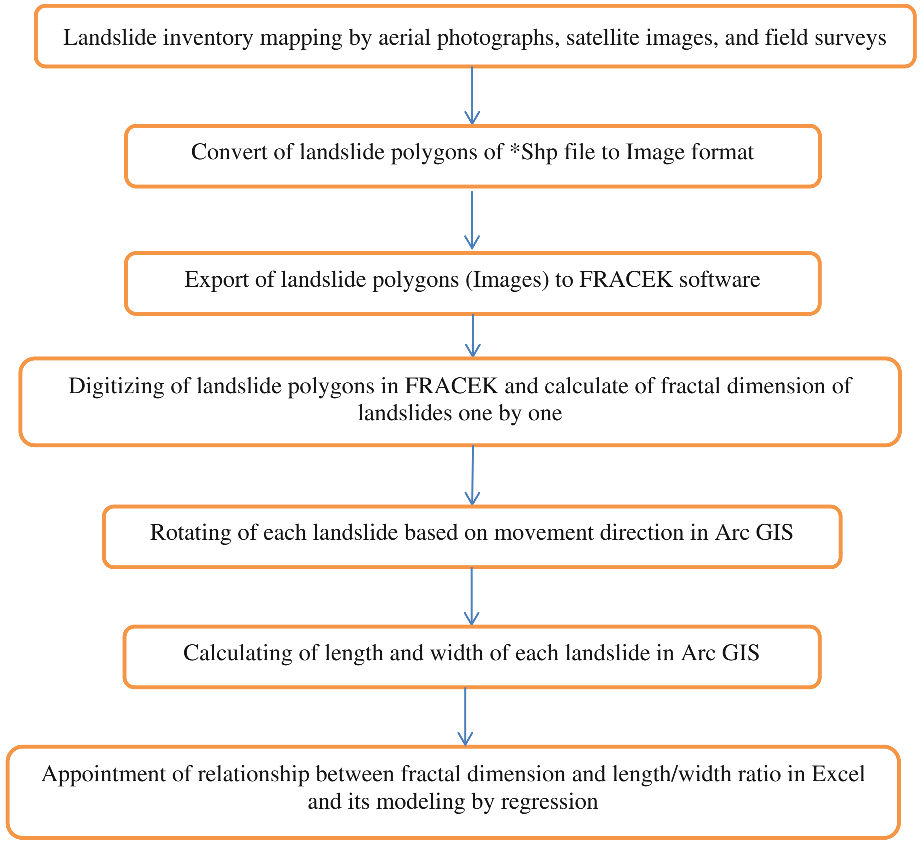
Code	Group	Formation	Lithology	Geological age
E_1^r	5	–	Rhyolitic tuff and lava flows	Eocene
E_1^{da}		–	Dacitic to andesitic lava flows and rhyodacitic pyroclastic	Eocene
E_1^{ss}		–	Bituminous siltstone and shale, calcareous tuffite	Eocene
E_1^{st}		–	Tuffaceous sandstone, green tuff	Eocene
E_1^{sl}		–	Shales and siltstone	Eocene
E_1^{tl}		–	Green tuffs and limestone	Eocene
Gy		–	Gypsum	Paleocene
$PE^{m,s,c}{}_f$		Fajan	Marl, sandstone, conglomerate, gypsum	Paleocene
PE_f^c	6	Fajan	Thick-bedded to massive polygenetic conglomerate, sandstone, locally limestone beds	Paleocene
PE^v		–	Andesitic–dacitic rocks, red–purple agglomerate, pyroclastic, tuffs	Paleocene
K_u^b		–	Thin-bedded limestone	Turonian-early Senonian
J_l		Lar	Thin-bedded to massive limestone, in some plates may include undivided Dalihai formation	Jurassic
J_d		Dalihai	Thin-bedded marly limestone, marl, Ammonite bearing	Jurassic
TR_3J_s		Shemshak	Shale, sandstone, siltstone, clay stone, locally limestone intercalations, coal bearing	Triassic
TR_e^d		Elika	Thick-bedded-massive dolomites and dolomitic limestone	Triassic
TR_e^l		Elika	Thick-bedded to massive limestone	Triassic
$TR_e^{m,l}$		Elika	Platy marly limestone, oolitic limestone	Triassic
P_n	7	Nesen	Marly limestone	Triassic
P_r		Ruteh	Medium-bedded limestone	Permian
C		Mobarak limestone	Dark gray medium-bedded limestone with intercalations of marly limestone	Carbonifer
C_j^c		Jeirud	Light gray massive dolomitic limestone	Carbonifer
C_j^b		Jeirud	Black limestone, clayey marl intercalations	Carbonifer
C_j^d		Jeirud	Black oolitic and intraclastic limestone	Carbonifer
m		Mobarak	Black oolitic, dolomitic limestone, marl intercalations	Miocene
D_j^a		Jeirud	Sandstone, shale, limestone, marl, phosphatic layers	Devonian
E_m		Mila	Trilobite-bearing limestone, marl, dolomite and shale	Eocene
E^q		–	White quartzite, quartzitic sandstone (formerly top quartzite)	Eocene
E_l		Lalun	Red arkosic sandstone	Eocene
E_{bt}		Barut	Miaous variegated siltstone and shale, cherty dolomite intercalations	Eocene
E_{bt}^d		Barut	Black massive dolomite, green-black shale intercalations	Eocene
T^b	8	–	Basic and intermediate sills	Tertiary, mostly Oligocene
T^s		–	Mostly syenite and some leuosyenite porphyry	Tertiary, mostly Oligocene
E^d		–	Dacitic dikes	Lower Eocene
E_6^s		–	Gray-brown shale, siltstone and sandstone	Eocene

Methodology

This research was conducted to investigate *D*, *L*, and *W* parameters of the recorded landslides in the North of Tehran metropolitan, Iran. Figure 2 shows the analysis of fractal dimension and the methodology used in this study with a flowchart.

Preparation of landslide inventory is one of the most important stages in landslide susceptibility and hazard mitigation (Ercanoglu and Gokceoglu 2004). This map portrays the spatial distribution of a single landslide event (a single trigger) or multiple landslide events over time (Malamud et al. 2004). At first, to produce a detailed and reliable landslide inventory map, extensive field surveys

Fig. 2 Flowchart of the methodology



and observations were performed. A total of 528 landslides were mapped at 1:25,000 scale, using aerial photograph, satellite images, and field survey. In the next step, for calculating D values, each landslide polygon was converted from shape file (*.shp) to image format and was exported to FRACEK software.

In this step, landslide polygons were digitized in the above computer program and the D value was calculated for each of the landslides. Due to the relationship between dimension, linear scale, and size, changes were computed from the following equation (Davis 2002):

$$N = r^D \tag{1}$$

where N, r, and D are size changes, linear scaling, and dimension, respectively.

According to the available literature, several methods are proposed to calculate the fractal dimension such as Box Counting, Minkowski Dilation, or Fourier Analysis (Ahammer 2011). In this study, we used FRACEK software that analyses images in two dimensions. The mentioned program was developed by Sezer (2010) using Java Script and an object-oriented approach to calculate fractal dimension according to grid-cell method. This tool requires the image, while it has the landslide polygon whose fractal dimension will be calculated. Also, it produces primary parameters such as: N (edge length of squares), $F(N)$ (number of squares), $N \times F(N)$ (perimeter), and the secondary attributes including log $(1/N)$, log $F(N)$, and log $[N \times F(N)]$ (Sezer 2010). The details of the algorithm of the mentioned tool (FRACEK) can be found in Sezer (2010).

After calculating the fractal dimension for each landslide polygon, we computed the length and width of landslides in ArcGIS. According to IAEG Commission on Landslides (1990) and Sezer (2010) “width is the maximum breadth of displaced mass perpendicular to the length (perpendicular to the movement direction), whereas length is the minimum distance from the toe of landslide to crown (parallel to the movement direction)” (Fig. 3). At first, we calculated the centroid of each landslide polygon. Then, using high-resolution satellite imagery (GeoEye satellite imagery with resolution of 0.5 m) and slope aspect map, the direction of movement of each landslide was calculated. In the next step, each landslide polygon was rotated in one of the aspects such as 0, 90, 270, and 360 angles and the minimum and maximum coordinates computed for x and y axes. Finally, the width (W) and length (L) can be defined as Eqs. 2 and 3, respectively:

$$W = X_{\max} - X_{\min} \tag{2}$$

$$L = Y_{\max} - Y_{\min} \tag{3}$$

or

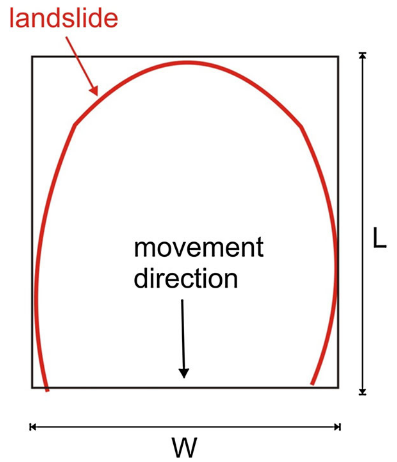


Fig. 3 Calculating the *W* and *L* parameters based on movement direction

W is obtained on subtracting the eastern most point from the western most point of the polygon and *L* by subtracting the northern most point from the southern most point of the polygon.

Results and discussion

A total of 528 landslide polygons were applied in the current research. Achieved *D* values range between 1.660 and 1.968. The results of the percentage of the fractal *D* values based on the equal interval classification method are given in Table 2. It can be seen that 0.38, 9.81, 69.62, and 20.19 % of *D* values correspond to the classes of <1.7, 1.7–1.8, 1.8–1.9, and >1.9, respectively. Some typical values of fractal dimension are shown in Fig. 4.

Based on the hypothesis of Wu et al. (2009), which asserts that a landslide has stable state if the fractal dimension values are 1 and between 1.1 and 1.3, some small slope failures in ranges of 1.1–1.3 may have happened. On the contrary, a landslide has potential for reactivation when its fractal dimension value is between 1.4 and 1.5. According to *D* values and the observed field surveys, a total of 528 landslides in our study area (North of Tehran) have unstable or active conditions. Also, a high value of fractal dimension corresponded to a complex

Table 2 Descriptions of the four classes for *D* values based on equal interval classification method

Class of *D* value	% of class
<1.7 (Class 1)	0.38
1.7–1.8 (Class 2)	9.81
1.8–1.9 (Class 3)	69.62
>1.9 (Class 4)	20.19

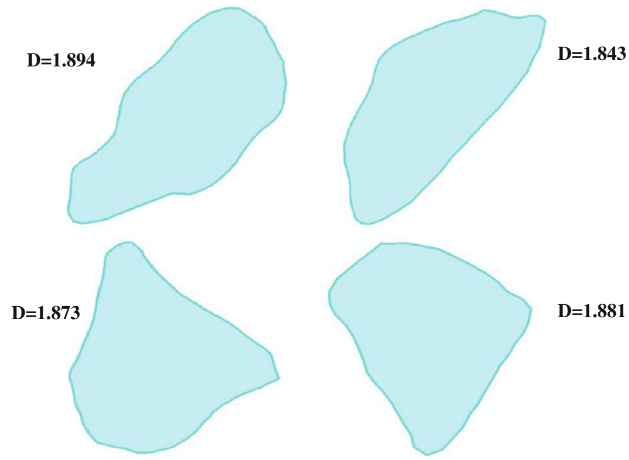


Fig. 4 Fractal dimension value for some landslides in the study area

dendroid pattern. This result was confirmed by the results of Omura (2009). Omura (1995) stated that landslides with *D* value of about 1 have a linear correlation with scale and reflect the linear pattern of landslide distribution (Aleotti and Polloni 2000). However, Tehran study area does not have any fractal dimension with value of 1. Based on the calculated fractal dimensions and checking the landslides that occurred in the study area (spatial relationship between each landslide and conditioning factors), it may be observed that there is a good correlation between increasing number of landslides occurrence with areas close to the rivers, faults, ridges, and gullies. On the other hand, if *D* values are close to 2, then landslides have a relatively homogenous distribution (Majtán et al. 2002). According to the fractal values in the Tehran area (1.660–1.968), it can be said that these results confirm those of Omura (1995) and Majtán et al. (2002). Majtán et al. (2002) believed that a *D* value of about 1.5 is very dangerous, because landslide distribution is the most heterogeneous and chaotic. In other words, a bigger *D* means bigger complexity, and so it should be assessed as more susceptible in the study area.

Similarly, the values of *L* and *W* of each landslide were calculated. Minimum and maximum of *L* and *W* of landslides are 62.96, 880.22, 19.53, and 618.62 m, respectively, whereas the length/width ratio was between 1.001 and 6.084. In general, the *L*/*W* is less than 5 in the studied area and only two landslides have higher value than 5 (6.084 and 5.905).

In this research, we tried to model a relation between fractal dimension and length/width ratio of 528 landslides. Different regression models such as exponential, linear, logarithmic, polynomial, and power were employed to compute relationship between two variables (Fig. 5). The results of Fig. 5 showed that there was a good correlation coefficient (*R*) between *D* values and *L*/*W* ratio. Also, the results revealed that the polynomial regression model

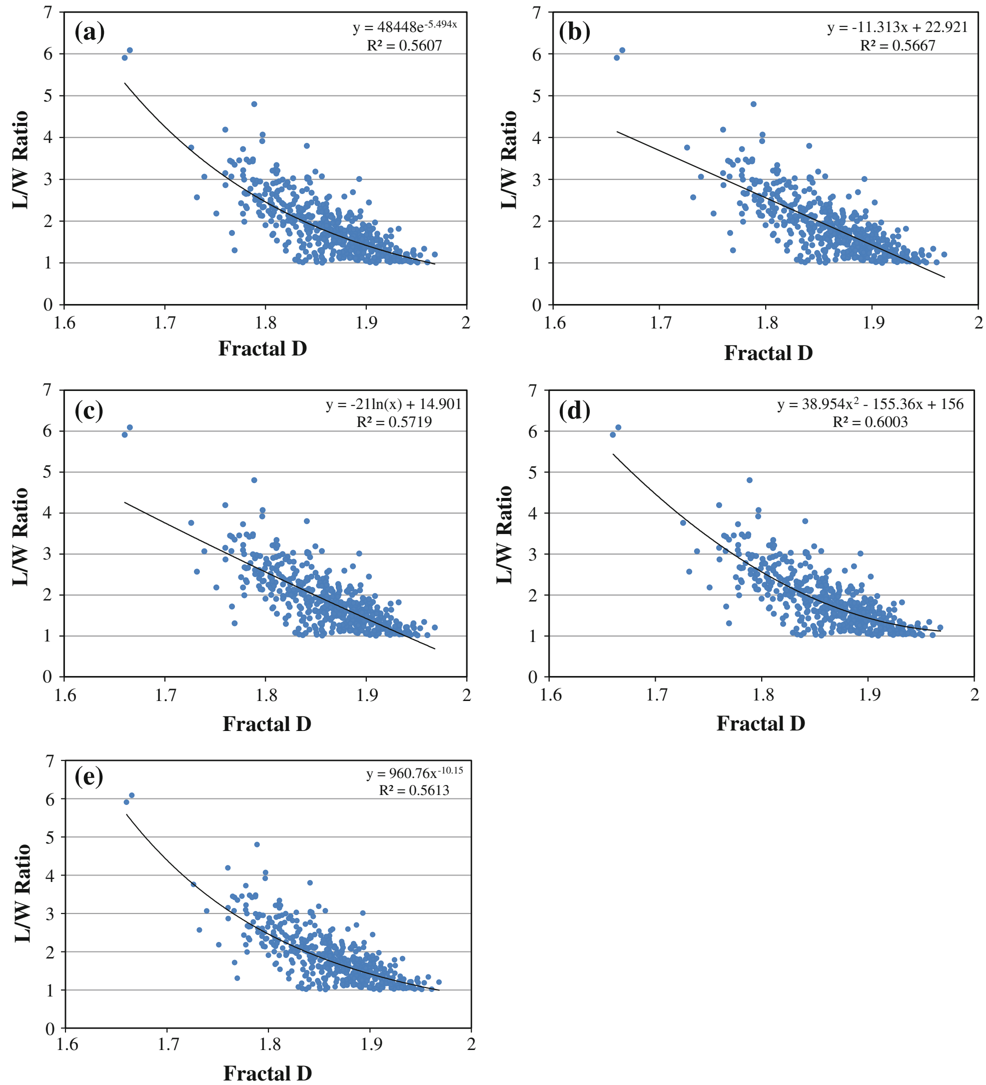


Fig. 5 Correlation coefficient (*R*) between *L*/*W* ratio and *D* values with different regression models. **a** Exponential, **b** linear, **c** logarithmic, **d** polynomial, **e** power

achieved slightly better performance than the other models with $R^2 = 0.6003$ ($R = 0.78$). According to the results of Sezer (2010), a power regression model has the higher correlation coefficient ($R = 0.85$) between *D* and *W*/*L* ratio of debris flow. Whereas in rotational and translational failure, two models, i.e. power and exponential had the highest *R* value (Sezer 2010). Based on Fig. 5, we observed an inverse trend, which indicates that the fractal dimension values increase with respect to the decrease of the *L*/*W* value.

Conclusion

Fractals are spatial and temporal model systems generated using iterative algorithms with simple scaling rules. In the first stage of the study, a landslide inventory map was prepared and their fractal dimension was calculated. In the next step, two parameters of landslides geometry attribute, namely *L* and *W*, was calculated for each landslide in ArcGIS 9.3. Finally, the relationship between length/width ratio and theirs fractal *D* for 528 landslides in the study area was calculated. In general, the findings showed that the *L*/*W* was <5 and *D* value ranged between 1.66 and 1.97 for the study area, respectively.

Also, the results indicated that the correlation coefficient (*R*) between *D* and *L*/*W* ratio with different regression models such as exponential (0.75), linear (0.75), logarithmic (0.76), polynomial (0.78), and power (0.75) is relatively good and reliable. As a conclusion, the fractal theory could be considered as an efficient tool in the analysis of landslide susceptibility/hazard mapping and stability/instability condition by calculating the landslide movement direction, size, and its location. Also, it is possible to conclude that the fractal dimension is useful as quantitative index of the complexity of the two-dimensional landslide spatial distribution. We believe that the results obtained from our study provide a considerable contribution to the landslide literature.

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