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FRACTAL DIMENSION AS AN INDICATOR OF PROBABILITY FOR LANDSLIDES IN NORTH MATSUURA, JAPAN

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Fractal dimension as an indicator of similarity, density, complexity and frequency seems to be useful for analysing susceptibility assessment, distribution pattern. It can also be used as a comparable factor. To indicate the spatial distribution of the shallow landslide quantitatively, their fractal dimensions and probabilities were estimated in an landslide area north of Nagasaki in Japan. In order to calculate the fractal dimension, capacity and information dimensions were selected. Landslides were grouped on the basis of surface geometry analysis and geology of the study area. The probability of occurrence of landslides in an individual landslides group was calculated on the basis of the relationship between the ratio of the average landslide area and area of the landslide group and fractal dimension.

Key words: surface analysis, distribution, landslide, fractal dimension, probability

INTRODUCTION

The concept of fractals has found wide applicability, since its original introduction by Mandelbrot (1967). Fractals are easy to understand, but sometimes, they seem to be chaotic and very complex. "Fractal dimension" is based on a mathematical theory which describes the quality of complex shape or degree of

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irregularity (Mandelbrot 1967). A summary treatment of fractals from the application point of view has been given by Feder (1988). The fundametal principles of fractals, chaos, and aspects of dynamical systems in the context of geological and geophysical problems have been introduced by Turcotte (1992 and 1997) and Pelletier (1997).

In the last years, many authors have shown interest in the calculation of qualitative distribution of landslides based on fractals (Kubota 1994, Omura and Hicks 1994, Omura 1995, Tarutani, Majtan, Morita, Omura 2000). Fractal dimension as the indicator of similarity, density, complexity and frequency seems to be useful for analysing susceptibility assessment, distribution pattern and can also be used as a comparative factor.

The purpose of this paper is to use the method of fractal dimension with its relation to geometrical parameters of relief and geology as the basis for assessment of landslide susceptibility. The geometric parameters of relief were calculated as is described in the works of Krcho (1990), Mitašová and Hofierka (1993), Zlocha (1996).

FRACTAL DIMENSION ANALYSIS

In order to calculate the fractal dimension of the spatial distribution of landslides, capacity and information dimensions were selected. The general equation of fractal dimension can be expressed as follows:

$$N \approx S^D \tag{1}$$

where N is the total number of self-similar pieces, S is the magnification factor and D is the fractal dimension.

Fractal dimension depends on the number of self-similar pieces as well as on the magnification factor (equal to scale). The number of self-similar pieces means the number of scale units, which are occupied by landslides. Due to the limited number of landslides, fractal dimension was calculated with certain limitation of scale and iterations.

Limitation of the scale
- The magnitude of the scale ranges between minimal and maximal distances of individual landslides in this study.
- The maximun size of the scale is equal to half the maximum distance between landslides in this study.
- The other sizes of the scale are decreasing continuously by two in arithmetical order.
- The iteration is possible, if the regression coefficient of the magnification factor and the number of self-similar pieces is higher or equal to "0.99".

Landslides in a group have sufficient self-similarity, through their power relationship of the spatial distribution of the landslides with respect to the different magnitude, and can have a fractal dimension (Kubota 1996). Therefore, the landslides studied were grouped on the basis of geometrical analysis and the geology of the study area. The procedures result in six groups from the elevation

and slope points of view, in four groups from the geometric form and aspect points of view and in three groups from the geological point of view, as shown in Tab. 1.

Tab. 1. Range of categories choosen from different geomorphological points of view and geology

Categories	Elevation [m]	Slope [°]	Aspect	Geometric form	Geology
1	<= 100	<= 5	North	Fcc	Holocene
2	101-200	6-10	East	Fcx	Late Miocene
3	201-300	11-15	South	Fxc	Early Miocene
4	301-400	16-20	West	Fxx	-
5	401-500	21-25	-	-	-
6	> 500	> 25	-	-	-

Capacity dimension

The capacity dimension is also named the *box-counting dimension* (Voss 1986, Turcote 1997). By this method a mesh (equal to magnitude) of size ε is first placed on the distribution map of landslides, over the landslide group of which the capacity dimension D_C is to be calculated. The first mesh size is equal to the maximum size of scale. Then the number of meshes containing the sketch of the landslide group, $N_{(\varepsilon)}$ is counted. The process is repeated for different size of mesh up to limitation of scale as mentioned above.

After that, logarithmic values of scales and numbers are fitted by linear regression calculated by the least square method (from Ezekiel and Fox 1959). The absolute value of the slope of this fit is the capacity dimension of the landslide group and can be mathematically expressed in the following equation 2 (from Ezekiel and Fox 1959),

$$D_c = \frac{\sum(SN) - nM_S M_N}{\sum(S^2) - n(M_S)^2}, \tag{2}$$

where S is the scale, N is the sum of the occupied meshes, n is the number of iteration and M_S and M_N are the mean of scale and sum of the occupied meshes, respectively.

Information dimension

The centroids of the landslide group of which the information dimension is to be calculated, are covered by a set of N meshes of size ε. The mesh size and number of iteration has been limited by the same way as the previous method. To calculate the information dimension, we have to calculate the number of landslides as N_i in each of the N cells and determine the probability of finding a landslide in that cell P_i (eq. 3)

$$P_i = \frac{N_i}{N_0}, \sum_1^N P_i = 1, \qquad (3)$$

where N_0 is the total number of landslides in the landslide group.

The information entropy is defined by the expression (4) (Morse 1969).

$$I(\varepsilon) = -\sum_1^N P_i \log P_i. \qquad (4)$$

The values of the information entropy and logarithmic values of scales are fitted by linear regression calculated by the least square method. The absolute value of the slope of this fit is the information dimension of landslide group and can be mathematically expressed in equation 5 (from Ezekiel and Fox 1959).

$$D_I = \frac{\sum (SI) - nM_S M_I}{\sum (S^2) - n(M_S)^2}, \qquad (5)$$

where S is the scale, I is the sum of the information entropy of the scale S, n is the number of iteration and M_S and M_I are means of the scales and information entropy respectively.

APPLICATION OF FRACTAL DIMENSION

The fractal dimension is not only expressed in terms of similarity, complexity and density of the area, but also in terms of the probability information. Omura (1995) studied the relationship between landslide density and fractal dimension as follows. The number of landslides in the mesh has the relation with fractal dimension as given in equation 6

$$\rho = \frac{N}{S^2} = kS^{D-2}, \qquad (6)$$

where ρ is the density of landslides in an area S, D is the fractal dimension and k is the constant of proportionality. The area ratio R of landslides was selected as a basic parameter for the calculation of the probability of a landslide based on the fractal dimension. Using the following equation 7, the area ratio can be calculated.

$$R = \frac{\overline{a}N}{S^2}, \qquad (7)$$

where R is the area ratio of landslides in an area S, N is the number of landslides and $\overline{a}$ is the average area of the landslides. After substitution of equation 6 for equation 7, the ratio was calculated from equation 8

$$R = \overline{a}kS^{D-2}. \qquad (8)$$

If the area S is fixed at the constant value S_0 (equal to the average area of geomorphometric groups) we can get the relationship between the probability and fractal dimension as shown in Figure 1. If the regional tendency is kept for a short time into the near future, the probability of potential landslides can be suggested through the parameter R. Generally, the area of the higher value of fractal dimension also has a higher potentiality for development of landslides.

EXAMPLE OF APPLICATION

This approach to calculating probability from the fractal dimension is illustrated using an example from the distribution of landslides in North Matsuura, on Kyushu Island, Japan (Fig. 2). The study area lies between 33°10'N and 33°15'N latitude and 129°41'15"E and 129°49'15" E longitude. It occupies 128.12 km^2 areas.
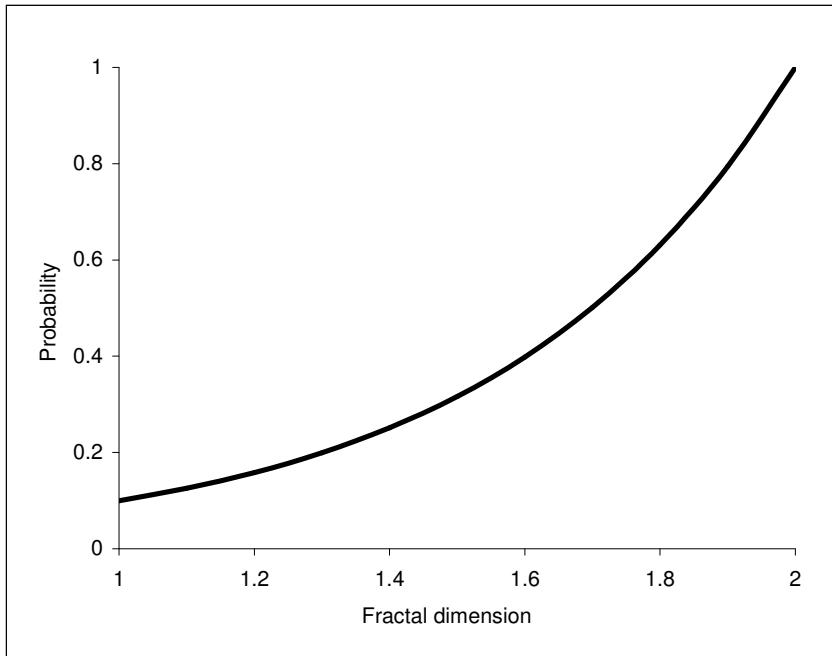

Fig. 1. Showing of the relationship between fractal dimension and probability at the given constant scale S_0 (10 m^2) and average landslide area (1 m^2)

The surveyed area is characterized by uplands with high steep slopes. The maximum elevation is slightly over 700 m and the average slope gradient around 20 degrees. The uplands are dissected by deep valleys.

Noticeable deposits are frequently found on gentle slopes. These deposits are called "fossil landslides" or "old landslides" (Ondrášik et al. 1996).

Fig. 2. Location of study area. Kita Matsuura on Kyushu island, Japan

Geologically, the area is mainly composed of the Sasebo Group and the Kita-Matsuura Basalt of Miocene age, but also partly of Holocene gravels, sands and clays. The bottom Early Miocene Sasebo Group consists of regular cyclic sediments from sandstone to mudstone of which the upper part is intercalated with coal seams sandwiching a clay layer of tuff origin. On the other hand, the upper Late Miocene Kita-Matsuura Basalt layers consist of alcalic, tholeiitic and high-alumina basalt. The thickness of these layers is several tens of meters. Both of them are covered by highly weathered rock, residual soil and colluvial deposits from several meters up to more than 10 meters in thickness.

Geomorphological analysis

The gradient of the slope and geometric forms of georelief correspond to the elevation. Generally, the inclination of the slope increases with the elevation. In the case of the geometric forms, they fluently pass from concave-concave through concave-convex, convex-concave to convex-convex forms with increasing elevation. The slopes toward the south are relatively equally distributed in the individual elevation categories. The frequency of north and west slopes slightly increases with increasing elevation, while slopes toward the east decrease with increasing elevation. Due to subordinate occurrence of the linear geometric forms of georelief, these were excluded from the evaluation. Higher values for the density of landslides were observed in the categories in which the slope inclination is higher, oriented toward the south and have the convex-concave geometric form of georelief. Generally, in the case of the slope layer, the area decreases with increasing of inclination. In the case of the aspect layer, east and west slopes have densities of landslides around 1.5 per square kilometer. North and south slopes have slightly over 2.0 per square kilometer. The

geometric forms layer of georelief has the minimal range for the landslide density value. That means landslides are rather uniformly distributed in them.

Fractal analysis

The location of the landslides, of which the fractal dimension is calculated, were taken from the series of the black and white aerial photographs at the scale 1:25 000. The landslide distribution map was corrected by reconnaissance in the field.

The fractal dimension of the whole study area was calculated from 243 data points, which represent the centroid of the landslides, by equation 2 and 5. The calculation results in two values of fractal dimension. The capacity dimension and the information dimension are estimated for the whole study area as 1.55 (Fig. 3). The landslides with fractal dimension close to 1 have the linear relationship with the scale. Therefore, if we want to forecast the susceptible area, we can consider an increasing number of landslides with increasing area along some natural lineament such as rivers, faults, ridges, gullies (Omura 1995). Whereas, the landslides with fractal dimension close to 2 have relatively homogenous distribution and should reflect specific tectonic structures such as two fault systems perpendicular to each other. The fractal dimension around 1.5 looks as the most dangerous, because the distribution is very chaotic and heterogeneous. A landslide can be developed in unexpected places. Thus, the landslide's distribution pattern in the study area as a whole seems very dangerous.
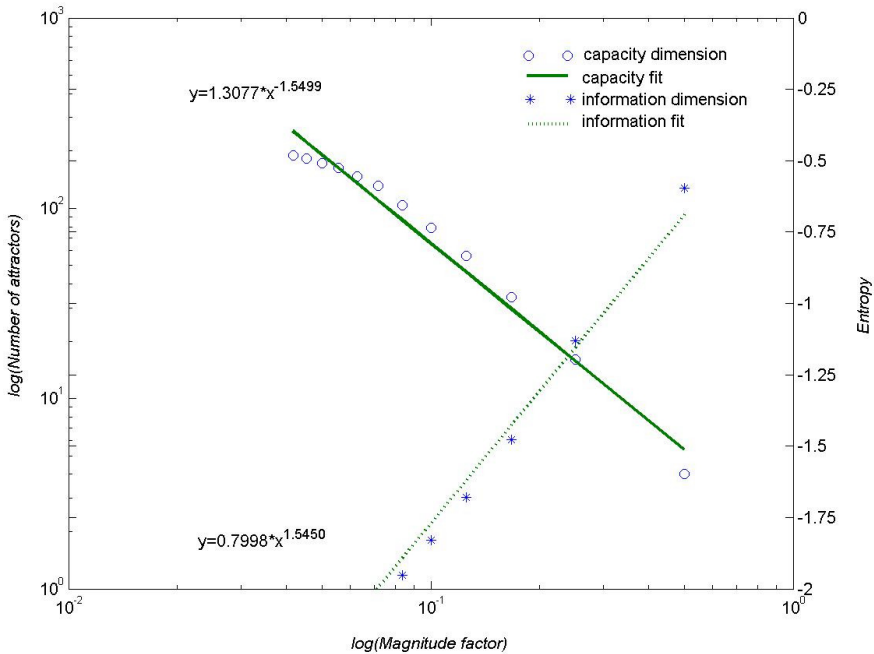

Fig. 3. Dependence of the number of self-similar pieces on the magnitude factor calculated by methods of box-counting and the entropy for all landslides in the study area

For the appropriate value of the fractal dimension the landslides were reclassificated from different geomorphological points of view and geology, as mentioned above (Tab. 1).

Fractal analysis of the elevation landslide groups

As shown in Table 1, landslides with respect to elevation were reclassified into six groups. For each landslide group the fractal dimension was calculated. The procedure results in two values of the fractal dimension in each landslide group (Tab. 2). The capacity dimensions range from 0.92 to 1.41, which correspond to the landslide group with the elevation of 401-500 m and the elevation of 201-300 m above sea level respectively. The minimum value of the information dimension was estimated as 0.90 and the maximum as 1.35 in the same landslide groups.

The average value of the capacity and information dimension of the individual landslide groups are estimated as 1.15 and 1.17. These values indicate a linear pattern of the distribution, which corresponds to the stripe pattern of the elevation ranges.

Fractal analysis of the slope landslide groups

Landslides with respect to slope were also reclassified into the six groups. The fractal dimension was calculated for each landslide group. Results are shown in Table 2. The capacity dimension ranks from 1.17 for a landslide group with inclination less than or equal to 5°, up to 1.48 which corresponds to a landslide group with an inclination over 25°. The minimum value of the information dimension is 1.21. It was calculated in the same landslide group as calculation by the capacity method. The maximum value of fractal dimension was calculated for landslides with inclinations between 6 and 10° as 1.46.

The average value of dimensions was calculated as 1.37 and 1.35 for capacity and information respectively. Compared to the elevation groups, the dimension of the slope groups indicates a more complex distribution. This reflects the slightly complex and chaotic distribution of inclination of the slope groups over the elevation groups.

Fractal dimension of the aspect landslide groups

The total number of landslides was reclassified into four landslide groups from the aspect point of view, which corresponds to the capital points. The results of the fractal dimension of the landslide groups from the aspect point of view are shown in Table 2. The minimum and the maximum value of capacity and information dimension were calculated in the same landslide groups. The minimum value was calculated in the landslide group oriented toward the east, while the maximum value was calculated for the landslides oriented toward the south. The landslides oriented to the north also show the maximum value of fractal dimension in the case of capacity dimension. The minimum values of the capacity and information dimension are 1.24 and 1.18 while the maximum values are 1.60 and 1.55 respectively.

Tab. 2. Capacity and information dimension with the ±2σ errors, corresponding to a 95% confidence interval in individual geometric and geological groups

Elevation group [m]	Capacity dimension	Information dimension
<= 100	1.13 ± 0.0776	1.29 ± 0.1031
101-200	1.28 ± 0.0591	1.26 ± 0.0539
201-300	1.41 ± 0.0815	1.35 ± 0.0676
301-400	1.04 ± 0.0558	1.17 ± 0.0639
401-500	0.92 ± 0.0801	0.90 ± 0.0902
> 500	1.11 ± 0.0939	1.05 ± 0.0777
Slope group [°]		
< 5	1.17 ± 0.0776	1.21 ± 0.0653
6-10	1.43 ± 0.0659	1.46 ± 0.0366
11-15	1.32 ± 0.0742	1.31 ± 0.0624
16-20	1.32 ± 0.0700	1.29 ± 0.0516
21-25	1.47 ± 0.0797	1.45 ± 0.0468
> 25	1.48 ± 0.1414	1.40 ± 0.1079
Aspect group		
North	1.60 ± 0.0807	1.47 ± 0.0682
West	1.50 ± 0.0832	1.36 ± 0.0541
South	1.60 ± 0.0867	1.55 ± 0.0478
East	1.24 ± 0.0928	1.18 ± 0.0718
Geoforms group		
Fcc	1.48 ± 0.0947	1.46 ± 0.0795
Fcx	1.53 ± 0.0720	1.51 ± 0.0506
Fxc	1.38 ± 0.0856	1.35 ± 0.0691
Fxx	1.52 ± 0.0714	1.45 ± 0.0571
Geology group		
Holocene	1.05 ± 0.0576	1.04 ± 0.0467
Late Miocene	1.29 ± 0.0630	1.38 ± 0.0482
Early Miocene	1.33 ± 0.0694	1.33 ± 0.0498

The average value is 1.49 for capacity and 1.39 for information dimension. These values for dimension reflect a complex distribution in space.

Fractal dimension of the geometric forms landslide groups

In order to get the value of fractal dimension from geometric forms of georelief point of view, the landslides were reclassified into four geometric groups, which represent combinations of the concave and convex forms in the vertical and horizontal directions, respectively (Tab. 2). The minimum and maximum values of dimension were calculated in the same landslide group for both types of dimension. The capacity dimension was estimated in the range between 1.38 and 1.53 for the landslide groups with georelief of convex-concave and concave-convex geometric forms respectively. From the information dimension point of view, the minimal dimension was calculated as 1.35 and the maximum dimension as 1.51 for the same landslide groups.

The average dimension is 1.48 for capacity and 1.44 for the information dimension. Likewise, as in the previous landslide group, the higher values of dimension indicate a complex, dense as well as chaotic distribution of the landslides in space.

Fractal dimensions of the geological landslide groups

For the calculation of the fractal dimension from the geological point of view, three landslide groups were classified: the Holocene, Early and Late Miocene landslide groups (Tab. 2). The minimum value for capacity as well as the information dimension was found in Holocene landslide group, while the maximum values for the capacity and information dimension were estimated in the Early Miocene and Late Miocene landslide group repectively. The values of the dimension are 1.05, 1.33 and 1.04, 1.38 in order of capacity and information dimension.

The average values for both dimensions are 1.22 and 1.25 respectively. The results show a relatively complex distribution. The close value of fractal dimesion in the Early and Late Miocene landslide group indicates that the landslides may have developed on the margin of these two stratigraphic units.

Probability analysis based on fractal dimension

In order to calculate probability from fractal dimension analysis, the average landslide area as well as average area of the groups S_o of individual morphometrical parameters and geology were calculated. After substitution, S_o and the corresponding value of fractal dimension into equation 8, the ratio R was calculated. The results show a ratio R of the average landslides area to the average area of the groups for each geomorphometric group with dependency to the fractal dimension. This calculation was caried out for all morphometric parameters. In order to get the effective value of ratio for the concrete geomorphometric group, the corresponding calculated value of the ratio R was weighted with the ratio of the average area S_o of the morphometric parameter to the area of the corresponding geomorphometric group S_i (eq. 9)

$$R_i = \frac{S_o}{S_i} R. \tag{9}$$

This means that the ratio of the geomorphometric group increases if the average area S_o of the morphometric parameter is bigger than the area of the geomorphometric group S and vice versa.

On the basis of this parameter, the probability from the individual morphological point of view was calculated using equation 10.

$$P_{Qi} = \frac{R_{Qi}}{\sum R_{Qi}}, \tag{10}$$

where P_{Qi} is probability and R_{Qi} is the ratio in i geomorphometric group of the Q morphometric parameter.

The procedures resulted in two values of the probabilities in each landslide group. The Fig. 4 shows the dimensions and probabilities in individual landslide group including $\pm 2\sigma$ errors, corresponding to a 95 % confidence interval. In the case of elevation the high potentiality of landslides was observed in the elevation range from 201 to 300 m above sea level and can be clearly distinguished. The higher values of the probabilities, in the case of the slope landslide groups, were observed between 21 and 25 degrees as well as on the slope with inclination over 25 degrees. From the aspect point of view, the higher values probabilities were observed on the slope toward the south and the north. From geometric forms and geology the highest values of the probability were observed in concave-convex and Early Miocene landslide groups.

The representative value of the landslide susceptibility assessment based on the fractal dimension in each grid cell was calculated as an average of individual probabilities in each grid cell. For this calculation the equation 10 was used. On the basis of these calculations, the potentiality map of landslide occurrence was prepared from the fractal analysis point of view.

$$P_i = \frac{\sum P_{Qi}}{n_s}, \tag{11}$$

where P_i is the landslide susceptibility assessment in "i" grid cell, is the sum of probabilities from elevation, slope, aspect, geometric forms and geological layers respectively in "i" grid cell, and n_S is number of layers.

The occurrence probability of landslides ranges from 0.05 to 0.46. In order to clearly distinguish the area with lower and higher values of probability, the occurrence of probabilities were divided into three equal categories based on percentual distribution. That means one third of the whole study area is occupied by each of the categories. These categories indicate relatively low, medium and high areas of potentiality respectively from the geomorphometric analysis point of view. This map is based on uniformity of area, which means that areas with similar values of probability have the same category. The result is shown in Fig. 5.

CONCLUSION

In order to get an appropriate value of the fractal dimension of the landslides, the capacity and the information methods were selected.
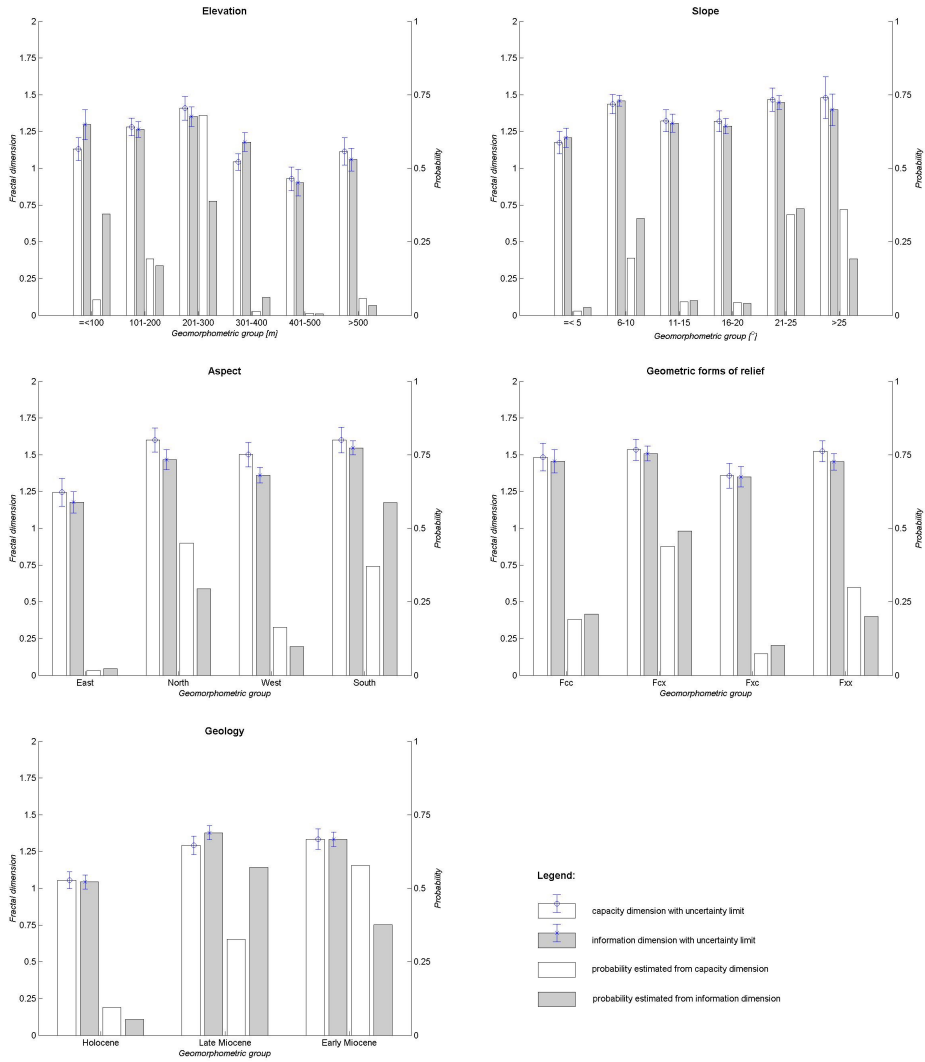
Fig. 4. Fractal dimensions marked with the ±2σ errors, corresponding to a 95 % confidence interval and the probabilities of the individual landslide groups based on equations 2, 5 and 10

The dimensions of the landslides were evaluated on the basis of their relationship to surface geometry analysis. This means, that a dimension was calculated in each geomorphometric group for all morphometric parameters as well as in geology groups as shown in Tab. 2 and in Fig. 4. In the case of the dimensions calculated based on the elevation, the higher values of the dimensions were observed in the middle parts of the slope. The toe of the slopes as well as the upper part indicates lower values. The average values of the capacity and

information dimension were estimated as 1.15 and 1.17 respectively. These values indicate a linear pattern of the distribution. It corresponds to the stripe pattern of the elevation groups. In the case of the slope, the results show a more complicated spatial distribution of landslide. The higher values of the probabilities were estimated on the slope over 20°. The average values of the dimension were calculated as 1.37 and 1.35 for capacity and information respectively. Compared with the elevation dimension, the slope dimension indicates a more complex distribution. In the case of the aspect, the higher values of fractal dimension can be observed in the north and the south landslide groups. From the geometric form point of view, the highest value of the dimension was calculated in the landslide group of the concave-convex form. From the geological point of view the higher values were observed in the Late and Early Miocene landslide group. This indicates that the landslides may have developed on the margin of these two stratigraphic units, where the hard Late Miocene basalts lie on the soft Early Miocene sands, clays and gravels.

The relationship between fractal dimension and probability is shown in Fig. 1. According to this, we were able to calculate the probability based on the value of the fractal dimension. Fig. 4 shows the results. The highest probability was calculated in the elevation landslide group of altitude ranges between 201 and 300 m above sea level.

It can be concluded, that for the north-western area of Kyushu island, where Kita Matsuura is located, the middle part of slopes having inclinations over 20°, characterized by joints of two stratigraphic units, oriented toward the south or the north, with concave-convex geometric forms have the highest potentiality for the development of landslides.
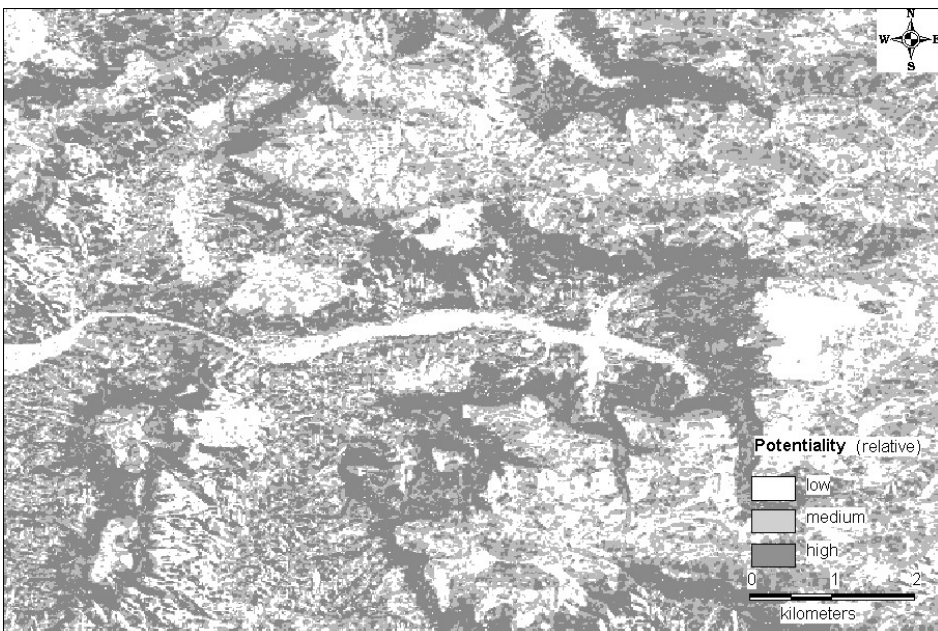

Fig. 5. Susceptibility assessment map based on fractal analysis

The susceptibility assessment map based on fractal analysis with respect to surface geometry analysis is shown in Fig. 5.

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FRAKTÁLNA DIMENZIA AKO INDIKÁTOR NÁCHYLNOSTI ÚZEMIA NA ZOSÚVANIE V SEVERNEJ MATSUURE V JAPONSKU

Cieľom štúdie bolo poukázať na možnosti aplikácie fraktálnej dimenzie pri zhotovení mapy náchylnosti územia na zosúvanie. Práca bola zameraný na sledovanie vzťahu fraktálnej dimenzie ku geomorfologickým parametrom reliéfu a geológii územia.

Na výpočet fraktálnej dimenzie zosuvov boli použité dve metódy, mriežková (box-counting) a informačná (information). Zosuvy boli zoskupené na základe výsledkov analýzy digitálneho modelu reliéfu a geológie. Výsledkom zoskupenia bolo šesť skupín zosuvov pri použití elevačného a sklonitostného parametra reliéfu, štyri skupiny pri použití orientácie sklonu svahu a geometrických foriem reliéfu a tri skupiny z hľadiska geológie. V každej skupine bola počítaná fraktálna dimenzia.

Vypočítaná fraktálna dimenzia kolísala v rozmedzí od 0,92 do 1,60 pri použití mriežkovej a od 0,90 do 1,55 pri použití informačnej metódy. Všeobecne môžeme povedať, že hodnota fraktálnej dimenzie odzrkadľuje podobnosť, hustotu, zložitosť a frekvenciu distribúcie zosuvov. Hodnota fraktálnej dimenzie 1 zodpovedá lineárnej a hodnota 2 homogénnej priestorovej distribúcii zosuvov. Fraktálna dimenzia blízko hodnoty 1,5 poukazuje na heterogénnu, chaotickú distribúciu zosuvov v priestore.

Na základe vzťahu priemernej plochy zosuvu k celkovej ploche danej skupiny zosuvov a fraktálnej dimenzie bola počítaná pravdepodobnosť P v zodpovedajúcom území. Ak by v krátkom období bol regionálny trend územia stály, potom by parameter P mohol odzrkadľovať pravdepodobnosť výskytu zosuvov na danom území. Najvyššia pravdepodobnosť výskytu zosuvov bola vypočítaná pre skupinu zosuvov reprezentujúcu územie s nadmorskou výškou od 201 do 300 m nad morom.

Záverom môžeme konštatovať, že fraktálna dimenzia sa dá použiť ako parameter na zhodnotenie náchylnosti územia na zosúvanie. Dôkazom môže byť praktický príklad zo severozápadnej časti Kyushu, kde stredná časť svahov s inklináciou nad 20 stupňov, charakterizovaná kontaktom dvoch stratigrafických jednotiek s orientáciou na sever alebo na juh, konkávno-konvexnou formou reliéfu má najväčšiu pravdepodobnosť pre rozvoj a výskyt zosuvov.