Landslide displacement analysis based on fractal theory, in Wanzhou District, Three Gorges Reservoir, China

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\textbf{ABSTRACT}
Slow moving landslide is a major disaster in the Three Gorges Reservoir area. It is difficult to compare the deformation among different parts of this kind of landslide through GPS measurements when the displacement of different monitoring points is similar in values. So far, studies have been seldom carried out to find out the information hidden behind those GPS monitoring data to solve this problem. Therefore, in this study, three landslides were chosen to perform landslide displacement analysis based on fractal theory. The major advantage of this study is that it has not only considered the values of the displacement of those GPS monitoring points, but also considered the moving traces of them. This allows to reveal more information from GPS measurements and to obtain a broader understanding of the deformation history on different parts of a unique landslide, especially for slow moving landslides. The results proved that using the fractal dimension as an indicator is reliable to estimate the deformation of each landslide and to represent landslide deformation on both spatial and temporal scales. The results of this study could make sense to those working on landslide hazard and risk assessment and land use planning.

\textbf{1. Introduction}
Because the geologic environments and climate conditions in the Three Gorges Reservoir area (TGRA) (Wang & Li 2009) are prone to the formation of landslides, landslides have become the most serious geo-hazard in this region, causing major property losses and casualties. For example, on 7 August 1998, the Baijiechun landslide located in Fengdu County occurred and 309 people became homeless. On 1 May 2001, the Wulong landslide located in Wulong County caused 79 casualties (Wu et al. 2004). Thereafter, significant environmental changes have been made in this region because of the construction of the Three Gorges Dam and Reservoir, especially after the impoundment of the reservoir. Some landslides were reactivated and some slopes began to deform due to changes in their hydrologic conditions. For example, the Qianjiangping landslide occurred after the first impoundment of the Three Gorges Reservoir on 14 July 2003, and destroyed 346 houses and 70 Ha of fields and caused 24 deaths (Wang et al. 2004). Another, the Shuping landslide, which is a large ancient landslide, was also reactivated by the initial impoundment in June 2003 (Wang et al. 2008). Therefore, the large financial losses borne by society from the movement of reactivated landslides (Mansour et al. 2010; Massey et al. 2013) highlight the importance of research on this type of...
landslide. Numerous Chinese scientists and geological experts have contributed to different aspects of this study, such as investigating landslides distribution (Wu et al. 2001; Liu et al. 2004; Bai et al. 2010) and exploring the mechanisms of the landslides in the TGRA (Deng et al. 2000; Jian et al. 2009). However, the behavior of landslides is always complicated, and the details of the moving processes of landslides are difficult to analyze.

There is no doubt that monitoring is crucial to build an understanding of the kinematic aspects of landslide movement (Angeli et al. 2000) and the mechanisms of landslide deformation (Thiebes 2012; Massey et al. 2013), especially when landslide displacement monitoring combines with monitoring of the triggering factors. In the last two decades, a range of techniques have been used in landslide displacement monitoring. These techniques can be subdivided in two main groups: geodetic and remote-sensing techniques (Travelletti et al. 2012). The main purpose of geodetic surveying is to directly measure the changes in landslide topography, referring to differences in angles, distances or elevation. For example, wire extensometers can be used to detect the movement of the landslide surface (Angeli et al. 2000) in addition to a GPS network (Wang 2012; Dogan et al. 2013), and measurements from an inclinometer provide a way to evaluate the movement of a landslide versus its depth (Calcaterra et al. 2012). In addition to the conventional techniques, remote-sensing offers a synoptic view that obtains spatially distributed information on landslide topography, which makes it possible to discriminate and map landslides temporally over different time scales. The main techniques applied in landslide monitoring are Synthetic Aperture Radar Interferometry (InSAR) (Tarchi et al. 2003; Antonello et al. 2004; Strozzi et al. 2005; Liu et al. 2013), Permanent Scatterers (PS) (Colesanti et al. 2003; Tofani et al. 2013) and Terrestrial Optical Photogrammetry (TOP) (Travelletti et al. 2012).

GPS was conceived in the early 1970s, and Gili et al. (2000) explained the basic principles, equipment and working procedures of GPS. GPS allows the coverage of a large area and has acceptable accuracy; the observations are independent of the weather conditions and can be divided between stations (Mora et al. 2003). Because of the wide use of GPS, some studies were conducted to improve the use of this technique in landslide displacement monitoring, such as by optimizing the monitoring equipment and system in order to reduce the monitoring cost (Chen et al. 2000; Benoit et al. 2015) and by analyzing the methodology and observations to increase the accuracy of the GPS monitoring system (Ifadis 2000; Malet et al. 2002; Hastaoglu & Sanli 2011). The reliable observations of the GPS monitoring system make it possible to analyze the deformation and mechanism of landslides (Cencetti et al. 2000; Rizzo 2002; Coe et al. 2003; Squarzoni et al. 2005; Brückl et al. 2006; Peyret et al. 2008; Nordvik & Nyrnes 2009; Zabuski et al. 2015). In the TGRA, to prevent and mitigate the damage caused by reactivated landslides, since 2003, a demonstration station for the real-time monitoring of landslides and an early warning system have been established at the relocated Wushan town. Thereafter, the monitoring methodology and technology have spread through the TGRA (Yin et al. 2010). Because of the local conditions in the TGRA, GPS is commonly adopted as one of the major techniques to monitor landslide surface displacement. Those observations have been interpreted to assess the deformation of landslides, to detect the mechanism of landslides and to forecast the movement of landslides (Yin et al. 2010; Du et al. 2012; Wang et al. 2012; Lian et al. 2014; Hu et al. 2015).

In recent years, fractal geometry has been widely considered as a tool in scientific studies in different fields. Sivakumar (2000) proved the suitability of using a multi-fractal framework to characterize the behavior of rainfall observed in different climatic regions. Kotowski (2006) proposed a complete method to measure the fractal dimension of fracture surfaces of ferrous alloys and confirmed that fractal dimension of the fracture surface do not depend on the investigated material. Zhang et al. (2008) utilized fractal theory in city geography by reflecting and simulating urban morphology. Kincal et al. (2010) demonstrated a fractal dimension approach that could be effectively applied to determine the weathering grade. In addition, fractal theory has also been adopted in landslide research field. For example, it has been used to analyze the frequency–magnitude relationship on a large number of landslides using power law statistics (Guzzetti et al. 2002; Iwahashi et al. 2003;
Malamud et al. 2004; Liucci et al. 2014), to identify fractal structures and scale invariance in numerous subaerial environments based on topographic data (Pelletier 1999; Southgate & Möller 2000; Micallef et al. 2008; Pourghasemi et al. 2014), and to extrapolate and explain the fractal behaviour in the deformation and mechanisms of landslides (Katz & Aharonov 2006; Li et al. 2011; Hu et al. 2011; Ma et al. 2014).

In the TGRA, slow moving landslides occupies the major proportion of geological hazard and they are always large in size, sometimes it is not easy to compare the deformation among different parts of the landslide using only the values from the surface displacement monitoring data. And studies on the comparison among the deformation of different parts of the landslide are seldom carried out, let alone based on fractal theory. Therefore, in this text, three landslides with totally different shapes and deformation situations were chosen to perform landslide displacement analysis. The data are from the landslide GPS monitoring work carried out by the staff of the Wanzhou Environmental Monitoring Agency. The main purpose of this study is to estimate the deformation of each landslide on both the spatial and the temporal scales using fractal theory. The fractal features of landslide movement will be explored through the moving traces of landslide GPS monitoring points. The results shown in this text could be useful in understanding the deformation history of different parts of each landslide, and this will make sense to those working on landslide hazard and risk assessment and land use planning.

2. Methodologies

A fractal object is self-similar at a variety of scales, whereby the object contains scaled copies of itself and has an infinite length and is infinitely complex when the scale decreases (Micallef et al. 2008). The fractal or the similarity dimension \((D)\) exhibits the fundamental property of a fractal object and represents the relationship between the apparent length and measurement scale. Normally, fractal geometry includes a shape characterized by irregularities that cannot be explained by Euclidean structures. For ordinary Euclidian shapes, \(D\) is always an integer, for example, the \(D\) value of points is 0, of lines is 1 and of area is 2. Whereas, to measure the characteristic size of a fractal object by linear scaling, usually the result of \(D\) is not an integer and exceeds the Euclidian dimension (Sezer 2010), for example, the \(D\) of the Koch snowflake is 1.26, of the Cantor set is 0.63 and of the Sierpinski triangle is 2.73. Because the natural objects are not strictly self-similar, the definition produced by Mandelbrot (1983) is more subtle. He defined a fractal as a set whose Hausdorff–Besicovich dimension strictly exceeds its topological dimension. This broad definition not only allows the use of fractal analysis to address mathematical fractals, but also to measure natural objects through statistical means.

In this study, fractal theory is adopted to analyze the deformation of three landslides in Wanzhou District, TGRA, China. The details of these landslides will be given in the next section. The framework of this study is illustrated in figure 1. The main process is to calculate the annual fractal dimension of the horizontal moving traces of different GPS monitoring points on each landslide. Herein, a

![Figure 1](image_url)

*Figure 1.* This flow chart illustrates the framework of this paper. The main part is to calculate the annual fractal dimension of the horizontal moving traces of different GPS monitoring points on each landslide. Thereafter, the spatial temporal stability of each landslide is analyzed.
GPS can offer the coordinates of monitoring points in geographic directions. The ‘horizontal moving traces’ defined here means that only the moving traces on the plane of GPS monitoring points have been considered; the vertical displacement of monitoring points have not been considered in this study. The main process uses three steps: first, the GPS monitoring data of the three landslides is collected and the annual horizontal moving trace of each monitoring point on each landslide is represented separately. The annual horizontal moving traces were represented by calculating the Euclidean distance and marking the direction of the movement between two consecutive monthly recorded GPS coordinates of each specific monitoring point in a specific year. Second, the two-dimensional (2D) image of the horizontal moving trace for the following calculation is prepared. In this step, image processing software was used to transform the graph into a grey image and set the image resolution. Finally, the fractal dimension of each moving trace image is estimated. The main method used in this estimation is box-counting method. Because the box-counting method is easy to automatically perform with programming, it is one of the most popular ways to measure the fractal dimension of fractal objects (Buczkowski et al. 1998; Foroutan-Pour et al. 1999; Jiménez and Ruiz de Miras 2012). The regression equation (Conci & Proença 1998) used to calculate the fractal dimension is given by

$$D = \lim_{r \to 0} \frac{\log(N_r)}{\log(1/r)}$$

where $D$ is the fractal dimension, $N_r$ is the number of the boxes with length $r$, and with which the moving trace has at least one intersection. $r$ can be simplified as $r = 1/2^n$ (Hu et al. 2011).

The core process of the box-counting method used to calculate the fractal dimension of the moving traces of the GPS points is demonstrated in figure 2. Before starting this process, the moving traces have been transformed into grey images and the image size is defined by $2^n \times 2^n$ in pixels. In

![Figure 2](image-url)
the final step, the regression graph is obtained and the fractal dimension can be obtained by equation (1).

After calculating the fractal dimension of the moving traces of the GPS monitoring points on the landslides, a fractal dimension map will be created. The Inverse Distance Weighting (IDW) interpolation method is used to prepare this map. This map allows the representation of the deformation of each landslide according to the fractal dimension of each GPS point in both the spatial and the temporal scales.

3. Case studies

The TGRA crosses 20 communities (cities, districts and counties). Wanzhou District is one of these communities and is located approximately 281.3 km from the Three Gorges Dam. According to a reconnaissance survey by the local geological agency in 2011, there are more than 700 landslides that now exist in this area. Figure 3 illustrates the damage caused by landslides in this area and figure 4 shows the mitigation protection measures that have been taken in this area. In this study, three landslides have been chosen to perform the analysis. The locations of these landslides are illustrated in figure 5.

3.1 Huayuanyangjichang landslide

The Huayuanyangjichang (HY) landslide is an active landslide. Since 1992, visualized deformations have been observed on this landslide, and after 2003, when the impoundment of the Three Gorges Reservoir began, the rate of landslide deformation increased. Figure 6(a) demonstrates the plan shape of the HY landslide. Table 1 shows the basic information of this landslide. Since 2003, the toe of the landslide has been submerged by the water of the Yangtze River, and since 2009, approximately half of the surface area of the landslide has been influenced by the annual changes of the water of the Three Gorges Reservoir, which changes circularly and annually between 145 m and 175 m a.s.l (Water information acquisition system for China Three Gorges Corporation).

![Figure 3. Damage caused by landslides in Wanzhou District. (a) Road damage from the Miaoba landslide; (b) subsidence from the Laojialin landslide; (c) cracks on a building from the Fujiayan landslide; (d) ground cracking from the Jinjinzi landslide; (e) ground cracking from the Rangduchangbei landslide; and (f) cracks on a building from the Sharentian landslide. These photos were taken in November 2010 when we carried out the field survey.](image-url)
Figure 4. These photos illustrate the mitigation protection measures in this area. (a) Friction piles at the Laojiaolin landslide; (b) bolting with wire mesh at the Huangnibao landslide; and (c) slope protection at the Laotangfang landslide. (d–f) The basic landslide displacement monitoring methods. (d) Ground settlement monitoring point; (e) Monitoring mark on buildings to measure the changes in the cracks; and (f) the GPS monitoring point.

Figure 5. This map illustrates the boundary of Wanzhou District. The area of Wanzhou district is approximately 3459 km² and is located approximately 281.3 km from the Three Gorges Dam. The location of three landslides has been marked on the map. The terrain in this map refers to the Google map (Google 2013).
The material of the landslide is structured loosely and composed of silty clay with some gravelly, which was formed from Quaternary talus and eluvia. The major material of the slip surface is clay, and it consists of a small amount of sandstone and mudstone debris. The average slope angle of the slip surface is approximately 21°. The landslide rock bed is made of sandy mudstone and is from the Middle Jurassic.

3.2 Jinjinzi landslide

The Jinjinzi (JJ) landslide is relatively stable, except for some parts of the landslide where deformations are developing, according to the report in 2009. In July 1996, heavy rainfall induced deformation on the upper part of the landslide which caused cracks on the walls of several houses. The plan shape of the JJ landslide is illustrated in figure 9(a). The terrain of this landslide forms steps in combination with platforms and scarps. Table 1 shows the basic information of this landslide. This landslide toe has also been submerged by the water of the Yangtze River since 2003. After 2009, the annual changes to the water level of the Three Gorges Reservoir influences more than half of the surface area of this landslide.

Table 1. Basic information of three landslides in this study.

| Landslide | Length (m) | Width (m) | Depth (m) | Area $10^2$ (m$^2$) | Volume $10^2$ (m$^3$) | Slope angle | Toe (m a.s.l) | Crown (m a.s.l) |
|-----------|------------|-----------|-----------|---------------------|----------------------|-------------|--------------|--------------|
| HY        | 380        | 360       | 18        | 137                 | 2470                 | 10 to 30    | 125          | 230          |
| JJ        | 450        | 1500      | 20        | 675                 | 13500                | 10 to 30    | 110          | 225          |
| YJ        | 740        | 190       | 15        | 140.6               | 2100                 | 7 to 20     | 110          | 295          |

Note: Length is the maximum length from the toe to the crown of landslide. Width is the average width. Depth is the average depth. These data are from Wanzhou District GPS monitoring report 2009, offered by the Wanzhou Environmental Monitoring Agency.
The material of this landslide is similar to the HY landslide and is composed of silty clay with gravel interlayer, but it is formed from Quaternary colluvial and slumping. The average angle of the relatively flat and smooth sliding surface is approximately 15°, and the major material of the slip surface is clay and a small amount of sandstone and mudstone debris. The landslide rock bed is from the Middle Jurassic and is composed of intervals of sandstone and mudstone.

### 3.3 Yangjiaba landslide

The Yangjiaba (YJ) landslide is rather stable. According to the records, in August 1999, this landslide had observed deformation. On some parts of the landslide, houses showed cracks on the walls, and farmland sank on the lower part of the landslide. Whereas, based on the reports in 2009, the landslide was almost stable and there was no obvious deformation. The plan shape of the landslide is illustrated in figure 11(a). The length of the landslide is almost four times its width and it is flat on the lower part of the landslide and steep on the upper part of the landslide. Table 1 shows the basic information of this landslide. The toe of this landslide has also been submerged by the water of the Yangtze River since 2003, and after 2009, the annual changes in the water level of the Three Gorges Reservoir influenced the lower part of the landslide.

The material of this landslide is also composed of silty clay with gravel interlayer formed from Quaternary deposits. The average angle of the relatively flat and smooth sliding surface, which is steeper on the upper part and flatter on the lower part, is between 7° and 20°. The major material of the slip surface is also clay with a small amount of sandstone and mudstone debris. The landslide rock bed is from the Middle Jurassic and is composed of thick mudstone interbedded with sandstone.

These three landslides were chosen for two main reasons. The first reason is that these landslides have totally different dimensions. The ratio of the maximum length of the landslide with the average width of the HY landslide is 1.06, while that of the JJ landslide is 0.30, and that of the YJ landslide is 3.89. The second reason is that all of them have suffered episodes of deformation in the past and are influenced by the water of the Three Gorges Reservoir, but they are in different stages of deformation. The HY landslide is the most active while the JJ landslide is relatively stable and the YJ landslide is rather stable. The purpose of the next section is to analyze and compare the spatial and temporal deformation of each landslide based on the fractal characteristics of their displacement monitoring data.

### 4. Results

In 2007, the water level of the Three Gorges Reservoir was first impounded to 156 m a.s.l, and then in 2009, it reached 172 m a.s.l (Water information acquisition system for China Three Gorges Corporation). To strengthen the monitoring and early warning system in Wanzhou District, 16 landslides, which were submerged or partial submerged by the water of Yangtze River, have been chosen to receive monitoring since 2007. The landslides in this study are three of these 16 landslides. The available period of the monitoring data in this study is from 2007 to 2009 with monthly records, which includes three annual circular changes of the water level in the Three Gorges Reservoir: from 156 m to 145 m to 156 m in 2007, from 156 m to 145 m to 170 m in 2008 and from 170 m to 145m to 172 m in 2009 (Water information acquisition system for China Three Gorges Corporation). In the following sections, each landslide will be analyzed.

#### 4.1 HY landslide

The moving traces of the six GPS monitoring points on the HY landslide over the period from 2007 to 2009 are shown in figure 6(b). Besides it, Figure 6(a) illustrates the total displacement vectors of these points in these three years. According to the monitoring data, from 2007 to 2009, the maximum displacement was 701 mm at point WZ03 and the minimum displacement was 30 mm at
point WZ02. The right side of the landslide deformed more seriously than the left side. For example, the displacement of the GPS monitoring points on the right side, points WZ03 and WZ04, is 701 mm and 260 mm, respectively, whereas that of the points on the left side, points WZ01 and WZ02 is 42 mm and 30 mm, respectively. Additionally, it is interesting to detect that the deformation of points WZ03, WZ05 and WZ01, which are closer to the Yangtze River, are, respectively, larger than that of points WZ04, WZ06 and WZ02. As shown in figure 6, the directions of the displacement of these six points are different. For the right side of the landslide, the direction of movement is towards the north-west, while for the middle and left sides of the landslide, the direction of movement is towards the south-west. This is due to the various heterogeneous and anisotropic topographical and geo-environmental conditions on different parts of the landslide.

Following the flow chart in figure 1, the fractal dimension of the annual moving traces of these six GPS monitoring points has been calculated separately. As an example, the calculation process of point WZ03 is demonstrated in figure 7. First, the horizontal moving traces from 2007 to 2009 were represented by calculating the Euclidean distance and marking the direction of movement between two consecutive monthly recorded GPS coordinates of each specific monitoring point. The axis of each moving trace is defined at the same scale to keep the results comparable. Second, the represented horizontal moving traces were separated annually and the axis and marked points were hidden. At this time, 3 years of annual horizontal moving trace curves have been produced. These trace curves were exported into 2D grey images by image processing software and the size of each image has been defined as 256 pixels × 256 pixels. Third, according to the process exhibited in figure 2,
computer programming was used to calculate the fractal dimension of each moving trace on an annual basis.

The results are presented in Table 2. Comparing the calculated fractal dimension (\(D\)) with the total displacement of the GPS monitoring point, for point WZ03, both the \(D\) value and its total displacement are the largest of those six monitoring points, while they are the smallest for point WZ02. According to the box-counting method, in Figure 2, the fractal dimension (\(D\)) is equal to the slope of the regression line, which expresses the relationship between the number of boxes (\(N_r\)) and the lengths of the boxes (\(r\)). \(N_r\) and \(r\) are directly proportional to each other. When the lengths of boxes decrease (increase), there will be an increase (decrease) in the number of boxes in the specific square area, and the moving trace can cross more (less) number of boxes, which causes an increase (decrease) in \(N_r\). Therefore, when \(r\) changes in the same way, the more number of boxes (\(N_r\)) the moving trace can cross, and the steeper the slope of the regression line will be. In this study, every time \(r\) has been set to a specific value, \(N_r\) depends on the length of the moving trace: the longer the moving trace, the more number of boxes (\(N_r\)) can be counted, which leads to a bigger fractal dimension \(D\) that can be obtained. In addition, the length of the moving trace can indicate the degree of deformation. Thus, it can be inferred that the degree of deformation and the fractal dimension of the moving trace are directly proportional to each other. Furthermore, as it is widely accepted, the more obvious deformation the landslide has, the less stable situation the landslide is. Therefore, based on this point of view, according to Table 2, by analyzing the value of \(D\), the right side of landslide is less stable than the left side because the \(D\) value of points WZ03 and WZ04 is larger than that of points WZ01 and WZ02. In addition, the places that are closer to the Yangtze River might be less stable than the places farther away from the Yangtze River, because the \(D\) value of point WZ03 is larger than that of point WZ04, while the \(D\) value of point WZ01 is also larger than that of point WZ02. However, this is not the case for points WZ05 and WZ06. This might because point WZ05 is at a flatter location, and is not as close to the Yangtze River as points WZ01 and WZ03. In addition, by comparing the \(D\) values between different years, it is not easy to judge in which year the whole landslide is the most active because the \(D\) values of different points vary. For example, at points WZ01, WZ02 and WZ03, the maximum value of \(D\) is found in 2009, which means, in 2009, these locations are the least stable when compared with 2007 and 2008. However, at points WZ04, WZ05 and WZ06, the maximum value of \(D\) is found in 2007. This result shows that the deformation of this landslide varies not only in time but also in different locations. This insight cannot be gained from traditional method of calculating landslide safety factors using only a given profile.

Subsequently, after the calculation and analysis, the annual fractal dimension map of this landslide is made. The objective of this map is to differentiate the relatively active and stable parts of the HY landslide and to represent the annual changes in deformation. The annual fractal dimension of each landslide GPS point will be used as an indicator. The map, created by ArcGIS based on Inverse Distance Weighting (IDW) interpolation, is demonstrated in Figure 8.

As explained earlier, with the box-counting method, the size of the fractal dimension reflects the amount of deformation and the amount of deformation reflects the stability situation of landslide.
According to the annual fractal dimension map (figure 8), there are some observations as follows: first, the right side of landslide is less stable than the left side. Second, locations approximately 175 m a.s.l, which are closer to the Yangtze River, are less stable than the upper part of landslide, and this is in agreement with the displacement in the monitoring data. Third, the landslide is more stable in 2008 than in 2007 and 2009, which might because in 2007, it is the first time the water level of Three Gorges Reservoir increased to 156 m a.s.l, and in 2009, it is the first time that increased to 172 m a.s.l. Finally, by comparing the stability of different parts of the HY landslide in 2007 and 2009, it seems that the unstable places had a tendency changing to the lower right side of the landslide.

4.2 JJ landslide

The total displacement vectors and the moving traces of the GPS monitoring points on the JJ landslide in the period from 2007 to 2009 are illustrated in figure 9. This landslide is relatively stable and
the maximum horizontal cumulative displacement is only 58 mm over these three years. It is not easy to compare the deformation situation between different parts of this landslide only through the total displacement of GPS points. For example, it is not easy to compare the deformation on the right side of the landslide based solely on the values of surface displacement between points WZ 02 and WZ04, WZ05 and WZ06. Thus, the same analysis was carried out on the moving traces of each GPS point on this landslide, and the fractal behaviour was detected to use as an indicator of the deformation of this landslide.

In this case, the axis of the moving traces of the JJ landslide is defined as the same scale as the HY landslide. Because the displacement of the JJ landslide is much smaller than the HY landslide, the size of the trace curve images was defined by 512 pixels × 512 pixels in order to increase the image resolution. The calculated fractal dimension is demonstrated in Table 3. By comparing the results, point WZ01 with the maximum average D value was less stable than the other points, and conversely, point WZ03 was the most stable with the minimum average D value. This agrees well with the total displacement; point WZ01 has the largest displacement of 58 mm, while point WZ03 has the lowest of 20 mm. Meanwhile, using the average D values it can also be observed that the locations on steeper slopes, such as point WZ01, WZ02, WZ05 and WZ06, are more active than flat locations, such as points WZ03 and WZ04. Subsequently, by comparing the D values in different years, the most stable year of this landslide can be determined to be 2007 because all the points have their lowest D value during this year. Consequently, the fractal behaviour of the JJ landslide agrees well with what was demonstrated in the HY landslide.

**Table 3. Fractal dimension of annually moving traces of JJ landslide GPS monitoring points.**

| GPS monitoring points | 2007  | 2008  | 2009  | Average |
|-----------------------|-------|-------|-------|---------|
| WZ01                  | 0.6990| 0.7405| 0.8456| 0.7617  |
| WZ02                  | 0.7068| 0.7748| 0.7913| 0.7576  |
| WZ03                  | 0.5587| 0.6737| 0.6455| 0.6260  |
| WZ04                  | 0.5510| 0.6896| 0.7764| 0.6723  |
| WZ05                  | 0.7156| 0.7388| 0.7689| 0.7411  |
| WZ06                  | 0.5301| 0.7908| 0.7239| 0.6816  |

Figure 9. (a) The plan of the JJ landslide. The green arrow stands for the total displacement vector of each GPS point from 2007 to 2009. The length of the vector is not in the real scale but the number in pink represents the real value with unit millimetre. (b) The moving traces of the six GPS monitoring points on the JJ landslide in the period from 2007 to 2009. To view this figure in colour, please see the online version of the journal.
Therefore, for the JJ landslide, an annual fractal dimension map has also been created based on the fractal dimension of the moving traces of its GPS points. This map is illustrated in Figure 10.

According to this map, the deformation of different parts of the JJ landslide can be compared. This landslide is relatively more stable in 2007 than in the other two years. In 2007 and 2009, the left side is less stable than the right side, whereas in 2008, the opposite can be observed. Point WZ03 is always more stable than the other points, possibly because it is located in a flatter area, where is more stable than the others. In addition, this map does not show any correlation between the distance to the Yangtze River and the stability of the landslide. This might due to topographic patterns. The lower parts of this landslide which can be submerged by the river are flatter than the upper parts of the landslide. Flat locations always have higher stability. Therefore, in this case, it is not easy to judge whether the water level is an influence factor of stability or not.

By comparing the fractal dimension map of the JJ landslide with the HY landslide, the D value of JJ landslide is lower. This result reflects that the JJ landslide is more stable than the HY landslide, which agrees well with reality deformation observations.

4.3 YJ landslide

For the YJ landslide, the displacement vectors and the moving traces of the GPS monitoring points, from 2007 to 2009, are illustrated in Figure 11. This landslide is rather stable. The maximum
displacement was only 19 mm between 2007 and 2009. The differences in deformation between each GPS point are very small. To differentiate the relative stability between different parts of this landslide, the same steps were followed, and the fractal behaviour of the moving traces of each GPS point on this landslide was detected.

As the JJ landslide, in order to increase the image resolution, the image size of the moving trace curves of the GPS points are set as 512 pixels × 512 pixels. The fractal dimension is demonstrated in Table 4. The average fractal dimension value of point WZ03 is the largest. This is correlated with the largest total displacement which is found at point WZ03. Coincidentally, point WZ03 locates closest to the Yangtze River. Point WZ01 is less stable than point WZ02 through the comparison of the average D values. This might be because the location of point WZ01 is steeper than point WZ02 and steeper places always make the slope less stable. In addition, by comparing the D values through different years, the most active year of each point is different.

Based on the fractal dimension of the moving traces of the GPS points of the landslide, the annual fractal dimension map of the YJ landslide is illustrated in Figure 12. The fractal behaviour of the YJ landslide exhibits an advantage in the use of the annually fractal dimension map to represent the slightly differences in the stability between different parts of the YJ landslide.

According to the map given in Figure 12, in 2007, this landslide was relatively less stable than in the other two years. By comparing the upper, middle and lower parts of this landslide, in 2007 and 2009, the upper part and the lower part are less stable than the middle part, whereas in 2008, the upper part is more stable than the middle part. In general, through these three years, the lower part of landslide was always relatively active. This might be correlated with the annual changes of the water level in the Three Gorges Reservoir. Overall, the fractal dimension of the YJ landslide is smaller than the JJ landslide and the HY landslide. This agrees with the fact that this landslide is more stable than the other two landslides.

Table 4. Fractal dimension of annually moving traces of YJ landslide GPS monitoring points.

| GPS monitoring points | 2007  | 2008  | 2009  | Average |
|-----------------------|-------|-------|-------|---------|
| WZ01                  | 0.5771| 0.0000| 0.6659| 0.4143  |
| WZ02                  | 0.6647| 0.0000| 0.0000| 0.2216  |
| WZ03                  | 0.5688| 0.6442| 0.5854| 0.5994  |
5. Discussions

Nowadays, GPS measurements are commonly used in landslide surface displacement monitoring. As GPS measurements are only measurements of single points, and they cannot cover the study area completely like other remote-sensing techniques, for instance, InSAR, GPS monitoring data are always treated as point cumulative displacement curves for the researchers to analyze the mechanism of landslide (Hu et al. 2015) and to predict landslide movement (Du et al. 2012; Lian et al. 2014). The periodical moving traces of these GPS monitoring points are seldom considered. In addition, fractal theory provides an efficient way to explore the characteristics behind the data, but in landslide research field, this theory are always popularly used in landslide frequency analysis and size characteristic analysis (Malamud et al. 2004; Liucci et al. 2014; Ma et al. 2014; Pourghasemi et al. 2014). The study on exploring the fractal characteristic behind landslide deformation data is rare. Therefore, the study in this text provides an effective way to analyze landslide deformation based on fractal theory, and more information can be obtained from GPS monitoring data in order to compare the relative deformation and stability among different parts of slow moving landslide.

Figure 12. This figure is the annual fractal dimension map, which illustrates the relative active and stable part of the YJ landslide and to represent the annual changes in the situation of its stability. The map is based on the fractal dimension calculated using the box-counting method. The value of fractal dimension is correlated with the stability of landslide, which has been explained in Section 4.1.1 that the larger the value is, the less stable the place is. (Note: The intervals in blue box between 0.5 and 0.8 has been changed from 0.1 to 0.05 for better display.) To view this figure in colour, please see the online version of the journal.
From the results of these three landslides, the fractal dimension is able to estimate the stage of deformation of each landslide and to detect the annual changes in the landslide deformation. Besides, as deformation is a macro-performance of landslide, it can be used to reflect landslide stable situation. Thus, the fractal dimension is also able to reflect the stability of landslide. In this study, when the stability of the landslide decreases, the fractal dimension of the moving traces of its monitoring point would increase.

In addition, it should be highlighted that the greatest advantage of this study is that the fractal analysis method can reveal more information from the GPS monitoring data. It not only considers the values of the displacement of the GPS monitoring points, but also considers the moving traces of them. Therefore, this study makes it possible to compare the deformation on two points even if they are slow moving and have slight differences in cumulative displacement.

There are still some uncertainties in the calculation and representation of the distribution of the fractal dimension of a landslide. For example, there are uncertainties in the collection of the GPS monitoring data, in the choice of the axes scale when prepare the moving traces of the GPS points, in the resolution of the 2D grey images, in the reliability of the fractal dimension interpolation of those points farther away from the control points, and in the applied dimension where only 2D displacement are used for the analysis because of the low accuracy in vertical displacement measurement by GPS monitoring, etc.

6. Conclusions
After extracting and detecting the fractal behaviour behind the horizontal moving traces of the GPS monitoring points on the three landslides in Wanzhou District, Three Gorges Reservoir, China, the conclusions of this work are summarized as follows.

First, the fractal characteristics of the horizontal moving traces of the GPS monitoring points agree well with their deformation behaviour. Second, using this fractal dimension as an indicator provides a way to represent the deformation history of a landslide on both the spatial and temporal scales. Third, the method presented in this study can excavate more information from the GPS monitoring data and makes sense especially for the slow moving landslides, which have small deformation and similar total displacement among their own GPS monitoring points. Finally, the fractal dimension map makes this method more visual when doing further landslide partial failure probability calculations and risk assessment. Overall, the study could be useful in understanding the deformation history of different parts of a landslide, and this is useful to those working on landslide hazard and risk assessment and land use planning, especially for the analysis and assessment of slow moving landslides.

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