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Fractal-statistical analysis of grain-size distributions of debris-flow deposits and its geological implications

Abstract Breakage models and particle analyses have been widely used as tools for describing and interpreting various deposits and providing parameters for assessing the particle-size distribution of the deposits. Debris flows can be seen as a two-phase rheological fluid with a clay-fluid composition, and debris-flow deposits comprise mud, silt, sand, and boulders, with grain sizes ranging from less than one μm to more than several meters. As a consequence, according to fractal theory, the particles in debris-flow deposits have self-similarity in geometrical shape and scale invariance in size. In this paper, the fractal dimensions of particles in various debris-flow deposits are calculated and corresponding fractal features are determined based on fractal-statistical theory. The aims of the study are: to provide a quantitative grain parameter that reflects both the grain composition and grain-size distribution in debris-flow deposits; to compare the fractal dimensions of grains in different types of debris-flow deposits and the degree of self-organization of debris flows; as well as to discuss the geological implications of fractal dimensions and fractal features of particles in debris-flow deposits.

Keywords Debris-flow deposits · Grain-size distribution · Fractal dimension · Fractal-statistical analysis

Introduction

Debris flows are a type of gravity-driven flow with highly concentrated mixtures of sediment, and debris-flow deposits are complex in structure, with some implications for debris-flow behavior and characteristics (Wu et al. 1990; Zhou et al. 1991). Researchers and engineers have been trying to obtain information on the mechanisms producing debris flows through various methods of analysis of debris-flow deposits, especially the grain-size distribution of debris-flow deposits (Cui 1996; Oguchi and Oguchi 2003; May and Gresswell 2004). Carpinteri carried out an experiment to evaluate the influence of particle-size distribution on energy density dissipation and related size effects (Carpinteri et al. 2004). Sohn (2000) described some dimensionless parameters, such as Bagnold number, Savage number, friction number, and Darcy number, to assess the roles of various momentum-transportation processes by applying a scaling-analysis method to debris-flow deposits in Miocene fan deltas in southeast Korea.

In addition, the non-linear and fractal feature of grains in debris-flow deposits, based on fractal geometry, have been discussed (Yi 1994; Yi and Sun 1997; Wei et al. 2000; Bai and Wang 2003; Ni and Liu 2005; Li et al. 2005; Ni and Liu 2006; Li et al. 2007). Thus fractal theory has been gradually applied to research on the grain composition and grain-size distribution of debris-flow deposits, in addition to statistical and graphical methods (such as cumulative curves, frequency curves, and distribution diagrams) widely used before (Wu et al. 1990; Zhou et al. 1991).

In this study, based on fractal theory and fractal-statistical-analysis methods, the fractal dimensions of solid grains in debris-flow deposits on fans accumulated from different debris-flow gullies in the Xiaojiang River basin were first calculated, then the corresponding fractal features of different types of debris-flow deposits were determined. We then discuss the geological implications of the fractal dimensions of different types of debris-flow deposits.

Study area

The debris-flow deposits studied come from the Xiaojiang River basin in the northeast of Yunnan province, SW China (Fig. 1). Xiaojiang River has a drainage area of 3,040 km^2 and a length of 144 km. A total of 107 gully-type debris flows and numerous small-scale slope-type debris flows are distributed in a reach of less than 90 km of Xiaojiang River near Dongchuan city (Fig. 2). Regional-scale destruction with long-term socio-economic and life-safety consequences, as well as environmental deterioration, have been caused by debris flows from gullies in the past years (Du et al. 1987; Zhou et al. 1991; He et al. 2003). As debris flows in this region occur frequently and they include various types and characteristics, the Xiaojiang River basin is therefore called a natural laboratory for debris flows in China.

Tens-of-years research on debris-flow hazards have shown that the occurrence and development of debris flows are closely linked to mountain-evolution processes and mountain-environment deterioration. Based on the former research (Du et al. 1987) and field investigations in recent years, it is believed that the formation and development of debris flows in the Xiaojiang River basin is predominately controlled by the special environmental and geological conditions such as the Great Xiaojiang fault, active neotectonic movements, frequent seismic activity, mountain landform with substantial relief and deeply dissected gullies, as well as the monsoon climate characterized by sharply different dry and wet seasons with concentrated and intense rainstorms in summer. In addition, it cannot be denied that activities of the local people accelerated the development of debris flows in this region. Consequently, we concluded that the special mountain environment, in conjunction with the increasing human disturbance, has resulted in favorable conditions for debris-flow occurrence, and caused this area to be highly vulnerable to debris-flow activity. As a result, there are a series of aggrading fans, rich in debris flow deposits (Fig. 3).

Methods

Fractal theory and fractal dimensions

Fractal theory was originally proposed by Mandelbrot in 1977 (Chen and Chen 1998); it has been found to be a useful tool for describing and interpreting the sophisticated problems existing in nature were it is helpful in finding whether complicated phenomena are consistent in behavior across large variations in scale. For example, fractal theory has been used in examining the size distributions of particles in many kinds of deposits (Bai and Wang 2003; Cheng et al. 2002; Millán et al. 2003; Lavigne and Suwa 2004; Yong et al. 2004). However, to use fractal theory, two preconditions, including self-similarity and scale invariance,

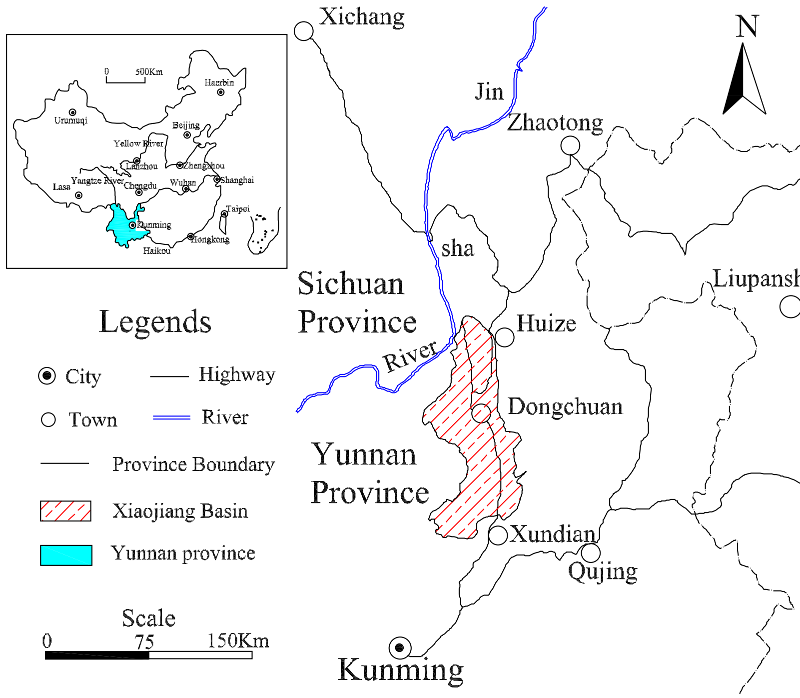

Fig. 1 Location of Xiaojiang River basin, Yunnan, China

should be fully considered (Chen and Chen 1998). Self-similarity means that when part of an object is enlarged or diminished, both part and integrity in shape, function and information are still similar, in other words, their integral structure is not changed. Scale invariance usually means that the research object has many measurable scales, and even if measured at different scales, the basic characteristics of the research object are not altered.

In fractal theory, the fractal dimension is a measurement of the research object that has fractal features and it can be seen as a parameter to make fractal feature quantifiable. In contrast to the traditional size dimensions that must be integers, fractal dimensions in most cases are fractions (hence the term "fractal").

Calculation methods of fractal dimension

Calculation of the fractal dimensions for particles in debris-flow deposits is based on a breakage model and granularity analysis method (Yi 1994; Chen and Chen 1998; Yi and Sun 1997; Wei et al. 2000; Bai and Wang 2003). Supposing r represents the size of the particles in debris-flow deposits, and $N(r)$ the corresponding cumulative number of particles with size smaller than r. If the grain-size distribution fits a power-law distribution (as is

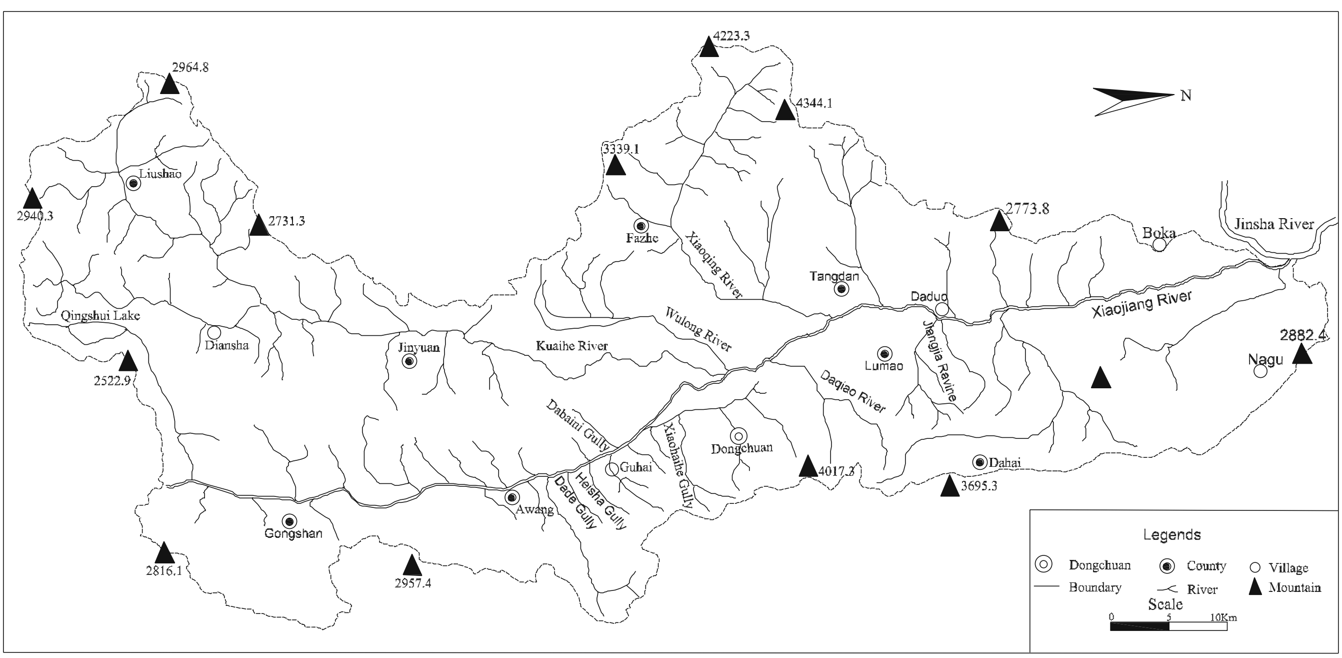

Fig. 2 Distribution of debris-flow gullies in Xiaojiang River basin, Yunnan, China

Fig. 3 View of debris-flow deposits (Jiangjia ravine at the left of Xiaojiang River)

commonly the case), the relation between r and $N(r)$ can be given in the following form according to fractal theory:

$$N(r) \sim r^{-D} \tag{1}$$

Where, ~ means the linear relation between these two quantities, D is the fractal dimension; r is the size of solid grains in debris-flow deposits; and $N(r)$ is the cumulative amount of grains with a size smaller than r.

To adopt a differential operation to Eq. 1, the corresponding formula can be expressed as:

$$dN(r) = r^{-D-1}dr \tag{2}$$

Based on a breakage model, when it is broken, a rock will break into small fragments which are distributed under a type of Weibull distribution (Chen and Chen 1998):

$$\frac{M(<r)}{M_o} = 1 - \exp\left[-\left(\frac{r}{r_o}\right)^b\right] \tag{3}$$

where $M(<r)$ is the volume of all the fragments whose size is smaller than r; M_o is the volume of all the fragments (the volume of the original grain before breakage); r_o is the average size of the fragment formed during the breakage; and b is a constant.

If a Taylor progression is applied to Eq. 3, and then a more succinct equation may be expressed as:

$$\frac{M(<r)}{M_o} = \left(\frac{r}{r_o}\right)^b \tag{4}$$

If another differential operation is applied to Eq. 4, a simple power equation is obtained in the following form:

$$dM(<r) = r^{b-1}dr \tag{5}$$

Further, supposing that each grain in a debris-flow deposit can be represented as an equivalent sphere, then the volume of grains in debris-flow deposits and the grain size may take on an exponential relation with the exponent of 3. Therefore, the relationship between the volume of certain solid grains with size smaller than r and corresponding amount of solid grains can be expressed as:

$$dM = r^3 dN(r) \tag{6}$$

Based on the above equations, the fractal dimension of particles in debris-flow deposits can calculated from the following equation:

$$D = 3 - b \tag{7}$$

Equation 7 is the most common relationship that is used to calculate the fractal dimension of grains and it can be easily carried out in a bi-logarithmic coordinate diagram with the x axis indicating the proxy of logarithm of grain size and y axis indicating the logarithm of cumulative percentage content of grains whose size are smaller than r. If grain-size r and cumulative proportion of grains $M(<r)/M_o$ plot as a line on a bi-logarithmic coordinate diagram, then it can be concluded that the grains in the deposits have obvious scale invariance and are fractal in nature. The slope of the fitted line in the bi-logarithmic coordinate diagram is equal to the constant b in Eq. 7. Therefore, the fractal dimension of solid grains in debris-flow deposits can easily be obtained from the gradient of the fitted line.

Fractal feature and fractal dimension results

On the depositional fans where large debris flows occur frequently, including Jiangjia ravine, Dade gully, Xiaohaihe gully and Heisha gully (Fig. 2), deposit samples were collected and tested in laboratory (Du et al. 1987; Wu et al. 1990). The grain-size distribution data of the debris-flow deposits are shown respectively in Table 1 (Du et al. 1987) and Table 2 (Wu et al. 1990).

It can be seen from the data listed in Tables 1 and 2 that the debris-flow deposits consist of grains varying in size by six orders of magnitude, with a wide-ranging grain distribution from clay (diameter in mm) to boulders (diameter in m). Although their size distributions are different, numerous samples from the debris-flow deposits in various valleys have properties in common, including their physical properties. To a certain degree, it can be said that smaller debris-flow grains have much the same features as do larger grains. In other words, in debris-flow deposits, small grains can be seen as the reduction of large ones and large grains can be seen as the magnification of small ones. Consequently, the grains in debris-flow deposits have an obvious feature of self-similarity in geometrical shape, which is the essence of fractal theory, and it is feasible to apply fractal theory to debris-flow deposits and to calculate fractal dimensions using the fractal-statistical method, so as to further analyze the corresponding geological aspects.

Another remarkable feature of the grain-size distribution of debris-flow deposits is their scaling property. Considering the cumulative proportion of grains larger than a given diameter and plotting the grain-size r and cumulative percentage content $M(<r)/M_o$ of the debris-flow deposit samples shown in Tables 1 and 2 in a bi-logarithmic coordinate diagram, a significant linear relation between $\ln r$ and corresponding $\ln M(<r)/M_o$ is shown (Figs. 4 and 5), all with correlation coefficients $R>0.965$. In order

Table 1 Grain-size distribution and corresponding grain-size fractal dimension of the selected debris-flow deposits (units in% except D and R)

Gully	Type	Grain-size distribution in debris flow deposits									D*	R**
		<0.005	<0.05	<0.1	<0.5	<2	<10	<40	<100	>100		
Heisha	Viscous	2.3	6.2	3.1	5.2	11.7	26.2	20.6	6.8	17.9	2.65	0.993
	Watery	1.7	6.8	1.2	1.6	4.8	18.0	32.6	20.3	13.0	2.64	0.989
Jiangjia	Viscous	4.1	4.1	0.9	4.6	1.3	31.6	37.6	15.9	0	2.67	0.979
	Watery	1.4	2.6	10.3	8.2	3.2	40.3	30.1	3.9	0	2.57	0.968
Xiaohaihe	Viscous	12.2	9.2	15.1	8.3	7.0	22.0	26.2	0	0	2.78	0.989
	Watery	1.5	2.5	1.4	3.0	1.0	14.1	41.0	35.8	0	2.6	0.991
Dade	Viscous	8.0	7.1	15.5	0	0	19.7	30.7	19.3	0	2.75	0.995
	Watery	2.9	1.1	12.5	0	0	44.5	32.8	6.2	0	2.63	0.98

*D** fractal dimensions, *R*** correlation coefficient

Table 2 Grain composition, grain-size distribution and corresponding grain-size fractal dimension of debris-flow deposits along Jiangjia ravine (units in% except D and R)

<0.1	<0.25	<0.5	<1	<2	<5	<10	<25	<45	>45	D*	R**	Deposited times
23.5	9.8	8.5	7.6	3.1	17.7	14.6	14.2	1	0	2.76	0.988	
23.2	11.8	9.7	10.1	5.9	13.1	11.6	11.6	3	0	2.77	0.985	Ancient deposits
20.7	9.6	8.8	8.7	4.5	22.4	15.4	8.9	1	0	2.74	0.982	
17.7	7.1	9.9	9.3	0.1	18.7	16.7	13.2	3.3	4.0	2.71	0.986	
14.6	6.4	9.9	8.8	3.1	10.8	10.5	23.2	6.3	6.4	2.71	0.987	Aged deposits
7.7	3	2	2	1	9.1	22.8	8.5	12.3	31.6	2.63	0.98	Modern deposits

*D** fractal dimensions, *R*** correlation coefficient

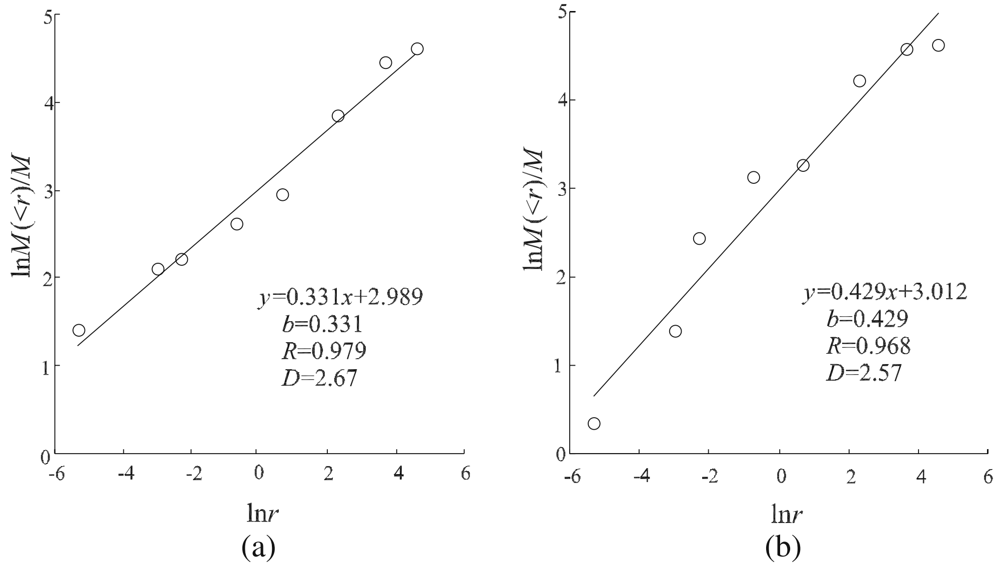

Fig. 4 Fitted lines of grain-size distribution in debris-flow deposits of different types along Jiangjia ravine and corresponding fractal dimensions. **a** Viscous debris-flow deposits; **b** watery debris-flow deposits

to further demonstrate the correlation between ln*r* and corresponding ln$M(<r)/M_0$, all the regressive functions were tested by a statistical method of bivariate correlation analysis, carried out with the statistical software SPSS 15.0. Tested results indicate that all the correlation is significant at the 0.01 level (2-tailed) with all Pearson coefficients more than 0.909. Such significant linear relationship at logarithmic scale demonstrates scale invariance over the range of measured grain sizes, from several microns to several centimeters. Because of the limitation in sampling and statistical analysis, the larger grains with grain sizes of more than 10 cm were ignored.

Consequently, it can be concluded that obvious fractal features are shown by the grains of debris-flow deposits, which have self-similarity in geometrical shape and scale invariance in size magnitude. The fractal dimensions of grains in different debris-flow deposits have been calculated according to Eq. 7, and fractal dimensions and associated correlation coefficients are shown in Tables 1 and 2. Results indicate that fractal dimensions of grains in debris-flow deposits range from 2.5 to 2.8 and vary with different debris-flow gullies and different debris-flow types. According to earlier studies on the fractal dimensions of grain-size distributions (Bai and Wang 2003), fractal dimension can be seen as a new grain-size index which can reflect both grain composition and environmental background and fractal features are found in many deposition types, such as debris flows and landslides. However, in terms of different kinds of deposits, grain-size fractal dimensions are usually different because of the different grain compositions and geological conditions. Fractal dimensions with a correspondingly small range of between 2.5 and 2.8 indicate the similar conditions to those forming the debris flows along the Xiaojiang River basin.

Geological implications

It is easy to calculate the fractal dimensions of debris-flow deposits using the previously discussed fractal-statistical-analysis method. However, it is more important to determine the corresponding geological implications and their application. Debris-flow researchers have undertaken some work and reached some conclusions in this area (Yi and Sun 1997; Wei et al. 2000; Bai and Wang 2003). According to the fractal dimension values listed in Tables 1 and 2, some useful geological implications are revealed as follows:

1. Fractal dimensions of solid grains in debris-flow deposits reflect the grain-size distribution. As debris-flow deposits comprise solid materials with different sizes and the relative proportions of these sizes also vary, it is difficult to use a specific index to point out the inner structure. However, both

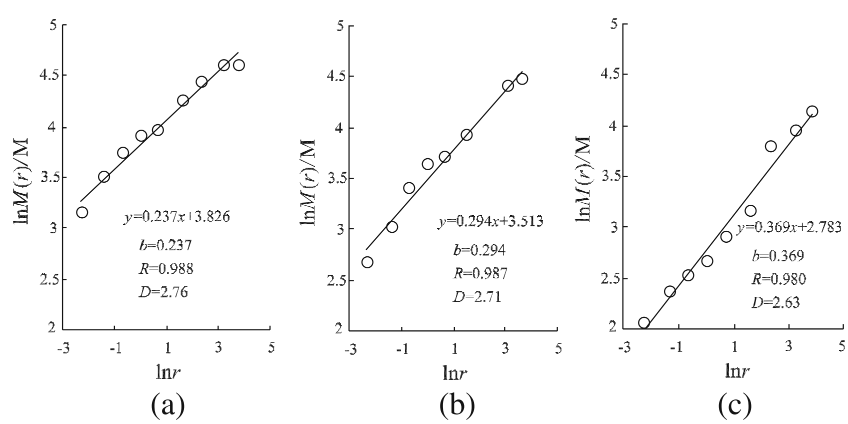

Fig. 5 Fitted lines of grain-size distribution in debris-flow deposits occurring at different times along Jiangjia ravine and corresponding fractal dimensions. **a** Ancient debris-flow deposits; **b** aged debris-flow deposits; **c** modern debris-flow deposits

grain size and grain-size distribution are fully taken into account in the fractal dimension. Therefore, compared with other grain-size parameters such as mean value, deviation degree, variance, and kurtosis, the fractal dimension can be considered as a parameter which reflects the uniformity and inner structure of debris-flow deposits. According to the calculated fractal dimensions, an obvious geological rule is that the more uniformly the solid grains in debris-flow deposits are distributed, the larger the corresponding fractal dimension is.

2. The fractal dimension of grains in debris-flow deposits varies with the viscosity of the debris flow. Within a single debris-flow gully, Jiangjia ravine for example, both viscous and watery debris flows occur. Their deposits have different characteristics including both grain composition and size distribution. The fractal dimension can be seen as a measurement to distinguish the difference. From the data in Table 1, it can be concluded that viscous debris-flow deposits have larger fractal dimensions than those of watery debris-flow deposits. As viscous debris flows can carry large boulders, they consequently result in an unsorted deposit with a wide size range and a corresponding larger fractal dimension. Therefore, the fractal dimension of debris-flow grains can reflect both the viscosity and sediment capacity of debris flows to a certain degree.
3. The fractal dimensions of grain sizes in debris-flow deposits vary over time. Debris-flow deposits are commonly regarded as a self-organized system within special environments with related geographical, geological and climatic backgrounds, and grain composition or grain-size distribution is depicted as a fractal structure under such systems, which has some degree of freedom to control their evolution (Liao and He 2006). Therefore the fractal dimension of solid grains in deposits can also be regarded as a measure of the degree of self-organization in debris flows. Using the estimated fractal dimensions in Table 2, a plot of age on the horizontal axis and fractal dimension D on the vertical axis was made, and it can be seen that fractal dimensions of debris-flow grains in ancient or aged deposits in Jiangjia ravine is larger than those of modern deposits (Fig. 6). In fact, because of additional factors such as weathering and erosion of the ancient or aged debris-flow deposits, some larger-size grains have been reduced to smaller ones. As a result, compared with modern debris-flow deposits, even with similar environmental conditions and grain structure or grain-size distributions, the proportions of finer grains increase and coarser grains decrease over time. Therefore, the self-organization degree of ancient or aged debris-flow deposits become progressively higher than modern debris-flow deposits and the complexity of the debris-flow deposits are reduced. From the aspect of grain fractal dimension in debris-flow deposits, the larger the grain fractal dimension is, the higher the degree of self-organization of the deposits is, and the older the time of occurrence of the debris flow is. This can be seen in Table 2, which shows that the grain fractal dimensions from ancient deposits are obviously larger than those from modern deposits. In order to validate the relation between occurrence sequence of debris flows and fractal dimensions, more samples were collected from Peilong gully and their corresponding fractal dimensions were calculated. The calculations likewise suggest that the fractal dimensions (>2.63) of solid grains from old debris-flow deposits are larger than those for grains from more recent debris-flow deposits, whose fractal dimensions are smaller than 2.62.

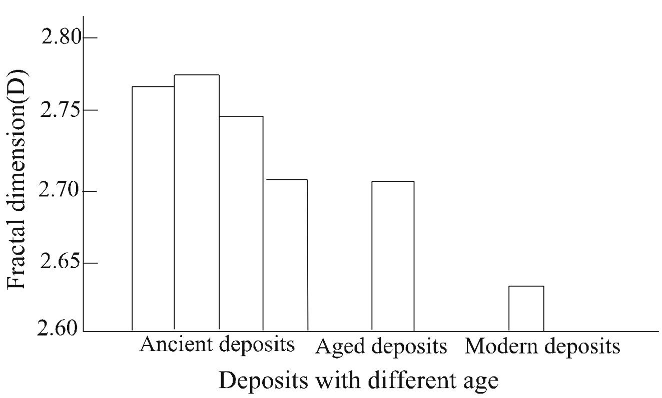

Fig. 6 Bar graph showing fractal dimensions of debris-flow deposits of different age along Jiangjia ravine

Discussion and conclusions

From analysis of debris-flow deposits in the Xiaojiang River basin, using fractal theory and the fractal-statistical-analysis method based on the grain-size distribution of the debris-flow deposits, some useful conclusions may be drawn.

(1) On the basis of a grain-breakage model and fractal theory, a fractal-statistical analysis based on grain-size distribution of debris-flow deposits was introduced. On a bi-logarithmic coordinate diagram, there is an obvious linear relationship between grain size and cumulative proportion of grains smaller than a specified size, which shows that grains in debris-flow deposits have evident fractal features and fractal dimensions ranging between 2.5 and 2.8.
(2) Geological indications of fractal dimension were investigated by taking into account both the types and age of debris flows. There is a positive correlation between grain fractal dimensions in debris-flow deposits and their degree of self-organization.
(3) Fractal dimension can be seen as a parameter that reflects the inner structure of debris-flow deposits. At the same time, the fractal dimension may be used to differentiate debris-flow gullies, and to roughly distinguish the type and sequence of occurrence of the flows, based on the grain fractal dimensions within the deposits.

Grain size is commonly analyzed using statistical and graphical methods. Statistical methods usually adopt grain-size parameters such as mean value, standard deviation, variance and kurtosis to represent the grain-size distribution in debris-flow deposits (Wu et al. 1990). Graphical methods generally show the grain composition and grain-size distribution of debris-flow deposits in diagrams such as cumulative curves, frequency curves, and distribution diagrams (Wu et al. 1990). It is obvious that statistical methods easily quantify in several parameters and graphical methods are more intuitive. In contrast to these two methods, the fractal-statistical-analysis method used in this paper adopts only one parameter, grain-size fractal dimension, to express both the grain composition and the grain-size distribution in debris-flow deposits, making it simpler to construct a quantifiable relationship between the characteristics of debris flows. Fractal-statistical analyses based on grain-size distributions of debris-flow deposits have some advantages in research on debris-flow deposits as compared with the statistical and graphical methods.

However, one deficiency in using fractal-statistical analysis and fractal dimension parameters for debris-flow deposits must be pointed out. The roles played by gravel and boulder grain sizes in debris flows are difficult to take into account due to the limitation of both sampling and grain-size testing measures. In addition, the variance of fractal dimensions from debris-flow deposits in different regions with different environmental conditions needs further study.

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