Dynamical Significance Indicated by Grain Size of Post-Dam Deposits in Jiajia Gully Debris Flow, Bailong River Basin

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Abstract: Through detailed field investigations in the Bailong River Basin, this study focused on Jiajia Gully in Wudu, Longnan, Gansu Province of China. Samples of post-dam deposits from Check Dams 1 to 3 were collected, and grain size data were obtained using the sieving method to conduct grain size analysis and explore the dynamic characteristics indicated by the grain size. The results show that: 1) The dominant components of each post-dam sample are coarse particles with a diameter greater than 10 mm; 2) The average particle size ranges from 20.72 to 31.83 mm, the sorting coefficient is between 19.30 and 21.97, the skewness ranges from -0.65 to 0.29, and the kurtosis is between 0.62 and 0.76; 3) The debris flow bulk density indicated by the post-dam deposits ranges from 2.18 to 2.23 t/m³, the average flow velocity is between 7.47 and 9.11 m/s, and the impact force of the slurry on the dam bodies during debris flow events ranges from 37.17 to 56.66 KN/m².From top to bottom along the gully (Dam.0~3) check dams, the content of coarse-grained components increases, the average particle size becomes larger, the sorting property deteriorates, the kurtosis value decreases, and the slurry bulk density, flow velocity, and impact force increase in sequence. It can be seen that the check dams are built in the gully sections where the dynamics of debris flow increase. Although they play a blocking role to a certain extent, it is insufficient to overcome the work done by the conversion of gravitational potential energy. Therefore, the design of the dam bodies, both in terms of site selection and strength, is very reasonable and can withstand the impact of debris flow slurry.

Keywords: Bailong River Basin; debris flow deposits; grain size; debris flow dynamics; Jiajia Gully

0 Introduction

As a common mountainous natural disaster, debris flow usually occurs in the process of sudden heavy rain, water converges in the gully and carries a large amount of loose particles to flow rapidly, forming a slurry with high-intensity destructive power. Due to its suddenness and huge impact destructive force, it seriously threatens the lives and property of residents along the gully and in the accumulation area at the gully mouth, and may even cause devastating disasters (Tang et al., 2011; Wang, 2013). During the occurrence of a debris flow, it carries a large amount of sediments and rocks of varying sizes, which form deposits in gullies where accumulation conditions are present. To reduce the massive losses caused by debris flows, check dams are often

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constructed in gullies prone to debris flows. When debris flow slurry flows through the check dams, the grain size characteristics of the deposits tend to change to a certain extent due to the interception and blocking effect of the dams (Liu et al., 2021). The grain size characteristics of post-dam deposits can serve as key physical indicators reflecting the dynamic processes of debris flows. They not only record dynamic information such as flow velocity, discharge, and energy during debris flow movement (Ruan et al., 2021; Saleh et al., 2025), but also directly affect the stability of the deposits and the risk of subsequent secondary disasters (Cui, 1999; Yang et al., 2024; Yu et al., 2023). Regarding research on the grain size of debris flow deposits, many scholars have conducted in-depth studies and found that the grain size distribution of debris flow deposits is significantly related to debris flow characteristics. However, research on the specific scenario of post-dam deposits still has the following limitations. For example, how do check dams change the relationship among the grain size of debris flows, their bulk weight, and impact force? How to verify the rationality of the site selection of check dams and the design to resist the impact force of debris flow slurry? Previous studies have mostly focused on the grain size characteristics of natural accumulation areas. However, there are few studies that use the grain size of post-dam sediments to quantitatively invert debris flow dynamics parameters and feedback to verify the rationality of engineering design. This study aims to make up for this deficiency.Therefore, this paper conducts research on the grain size and dynamic characteristics of post-dam deposits, which is of great significance for understanding the mechanism of debris flow disasters, optimizing the design of check dams, and carrying out disaster early warning.

1 Overview of the study area

Wudu District, Gansu Province, is located in the Bailong River Basin, a tributary of the Yangtze River, with geographical coordinates ranging from 104°10′ to 106°36′ east longitude and 32°35′ to 34°32′ north latitude. In terms of geological structure, it is traversed by the Central Qinling Variscan Fold Belt, South Qinling Indosinian Fold Belt, and Bikou Mesoproterozoic Fold Belt. Fold structures are widely developed in this area, with hard lithology and widespread crush fragmentation. In terms of geomorphic units, it is located in the eroded-denuded structural mountains in the western section of the West Qinling Mountains. Controlled by regional tectonics, the overall strike of the mountains is east-west. In terms of topography and landforms, it is characterized by high terrain in the northwest and low in the southeast, with obvious undulations. The highest altitude is about 3600 meters, and the lowest is about 660 meters. The terrain is mainly complex, consisting of high mountains and steep ridges alternating with canyons and basins. The overall topographic features include well-developed gullies, intense cutting, large surface undulations, steep mountain slopes, and large relative height differences. In terms of climatic and hydrological characteristics, the region spans subtropical, warm temperate, and mid-temperate zones from south to north in the horizontal direction. It receives relatively abundant but unevenly distributed precipitation, with annual precipitation ranging from 500 to 800 mm. The basin features a high drainage density (Fig.1) and a high vegetation coverage rate(Gansu Provincial Local Chronicles Compilation Committee, 2018).

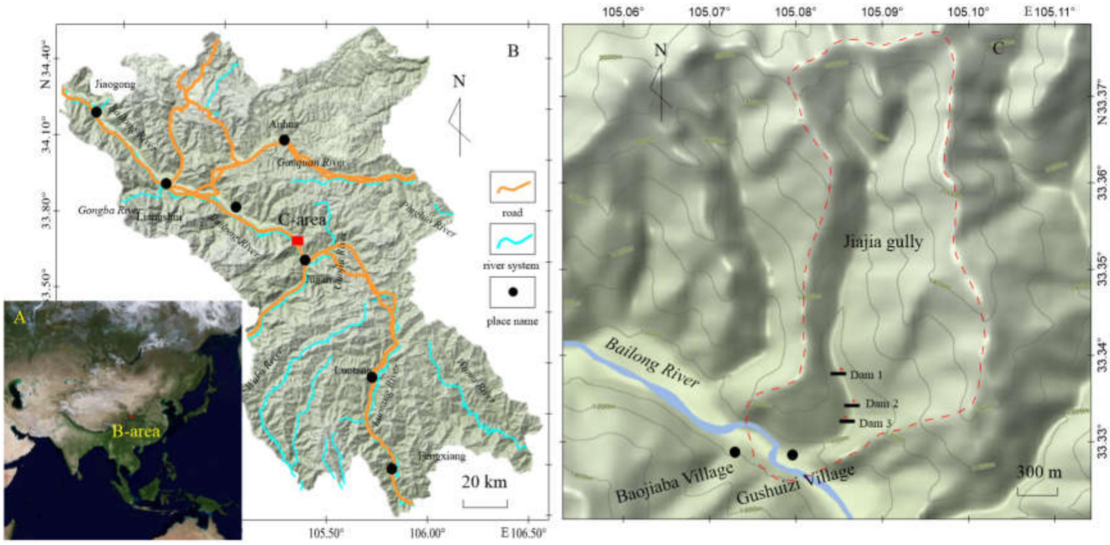

Fig.1 Geographical location map of Jiajia gully Wudu district in Gansu South

2 Basic characteristics of Jiajia gully debris flow

Jiajia Gully Basin is controlled by regional tectonics, with the gully roughly trending north-south, nearly orthogonal to the course of the Bailong River (Figs.1B,1C). The gully is strongly incised, resulting in an increased relative height difference from the surrounding mountains and steepened slopes. It has a long and narrow shape with a total area of 8.58 km^2 . The highest elevation in the basin is 2147 m, while the elevation at the gully outlet is 940 m, giving a relative height difference of 1207 m. The main gully is 5.78 km long, and both the main gully and its tributaries are “V”-shaped valleys. The debris flows occurring here are of the viscous type （Table1.）.

Table 1 Gully gradient at debris flow dam in Jiajia gully

Sample site	Elevation（m）	Gully length/m	Main gully gradient/‰
Dam.1	1132-1062	500	0.13
Dam.2	1065-1027	350	0.11
Dam.3	1027-1014	150	0.09

3 Materials and methods

3.1 Sample collection and data selection

Taking Jiajia Gully as a typical representative debris flow gully (Fig.1), 3 samples were collected from behind the debris flow check dams in the second half of 2024 (Table.2). During the sample collection process, multiple random samples were taken from the post-dam deposits, which were then mixed together, with each sample weighing approximately 8~10 kg. The collected samples were numbered and brought back to the laboratory for testing in accordance with the “Standard for Soil Test Methods” (GB/T 50123-2019) (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2019). In general, the debris flow sediments are characterized by a mixture of particles of various sizes, including muddy gravels and boulders, with poor roundness (Fig.2).

Fig. 2 Field photos of Jiajia gully in Wudu district, Gansu

Table 2 Locations of sampling points in Jiajia gully

Gully name	Sample site	Latitude	Longitude
Jiajia gully	Dam.1	33°20′18″	105°05′07″
Jiajia gully	Dam.2	33°20′05″	105°05′12″
Jiajia gully	Dam.3	33°19′58″	105°05′09″

3.2 Research methods

Grain size analysis is an important method for studying the sedimentological characteristics of sediments, containing rich information such as the source characteristics of loose particles, transport dynamics, and accumulation environment. By deeply exploring the information carried in sediment grain sizes, we can effectively reveal the characteristics of surface processes and sedimentary environments. There are various grain size analysis methods, including traditional direct measurement, sieving, sedimentation, and optical testing with laser grain size analyzers. Different sample types are suitable for different methods. Debris flow deposits are mixed accumulations, and their overall grain size is far larger than the range measurable by sedimentation and laser grain size analyzers. Therefore, for the grain size analysis of the samples in this study, in accordance with the “Standard for Soil Test Methods” (GB/T 50123-2019), the sieving method is adopted for the collected samples. The sample sieves are wire-woven test sieves, using a combination of coarse sieves and fine sieves.

Within the particle size index, the most commonly used are grain size parameters, which typically include mean grain size, sorting coefficient, skewness, and kurtosis. These parameters are effective indicators comprehensively reflecting the content composition of coarse and fine components in sediment particles. The commonly used calculation methods for grain size parameters include the graphic method and the moment method. The graphic method calculates grain size parameters based on the grain sizes corresponding to the representative percentage contents on the cumulative curve of grain size natural frequency (Folk and Ward, 1957). Considering that the grain size of samples in this paper is analyzed using the traditional sieving method, the traditional graphic method is adopted to calculate the grain size parameters.

Table. 3 The calculate formula of grain size parameters for graphical method

Grain size parameters	Folk and Ward formula（Folk and Ward，1957）
Mz	$\frac{d_{16}+d_{50}+d_{84}}{3}$
σ_i	$\frac{d_{84}-d_{16}}{4}+\frac{d_{95}-d_{5}}{6.6}$
Sk	$\frac{d_{16}+d_{84}-2d_{50}}{2(d_{84}-d_{16})}+\frac{d_{5}+d_{95}-2d_{50}}{2(d_{95}-d_{5})}$
Kg	$\frac{d_{95}-d_{5}}{2.44(d_{75}-d_{25})}$

Note: d5, d16, d25, d50, d75, d84, d95 represent the particle sizes corresponding to 5%, 16%, 25%, 50%, 75%, 84%, and 95% on the probability cumulative curve, respectively.

In this paper, the bulk weight and flow velocity of debris flow are calculated based on grain size data, and the bulk bulk weight is determined using the formula (Zhang, 2012):

$$r_{c}=1.65d_{cp}^{0.188} \quad (1)$$

The flow velocity is calculated using the formula (for viscous debris flow) (Zhang, 2012; Yu, 2016):

$$V=3.2\sqrt{gRi}\lg\frac{d_{50}}{d_{10}} \quad (2)$$

In formulas (1~2): r_c is the bulk weight; d_{cp} is derived from the average particle size of debris flow deposits, i.e., $d_{cp}=\log_2 Mz$, it should be noted that if the average grain size is directly calculated using *Mz* (mm), the resulting bulk weight value reaches 3 or above, which severely deviates from the actual bulk weight (generally 1.5~2.5 t/m^3); *V* is the flow velocity of viscous debris flow (m/s); *R* is the hydraulic radius of the debris flow (m), which is measured on-site, referring to the height of post-dam deposits; *i* is the gully bed gradient of the debris flow, measured on-site (Table1); *g* is the gravitational acceleration, taken as 9.8 m/s^2; d_{50} and d_{10} are the grain sizes corresponding to the 50% and 10% cumulative percentages in the grain size distribution curve, respectively, in mm.

The impact force of debris flow is a means to verify the rationality of check dam design. Its magnitude is related to the debris flow discharge, weight, and velocity, and directly determines various design parameters of the check dam. The design needs to go through multiple trial calculations to complete, and the specific impact force value is usually determined by the following formula (Ministry of Land and Resources of the People's Republic of China, 2006):

$$F=K\gamma_c V^2/g \quad (3)$$

In the formula: *F* is the impact force (KN/m^2); K is the conversion coefficient, generally ranging from 2.5 to 4.0, and 3.0 is adopted in this project; γ_c is the bulk weight of debris flow (t/m^3); *g* is the gravitational acceleration (9.8 m/s^2); *V* is the flow velocity of debris flow (m/s).

4 Results and discussion

4.1 Grain size characteristics of post-dam sediments in debris flow gully

Debris flow deposits are a type of mixed accumulations, so their formation process and grain size composition are extremely complex. Analyzing the frequency distribution characteristics of grain size intervals based on the characteristics of grain size components in debris flow deposits can directly reflect the mass percentage of each component in the total mass of the analyzed sample within each analyzed particle size range, which is a basic step in sedimentological grain size analysis. Based on the analysis results of 3 post-dam deposit samples from the post-dam deposits in Jiajia gully, Wudu District, Gansu Province, a natural frequency line chart was drawn (Fig.3a).

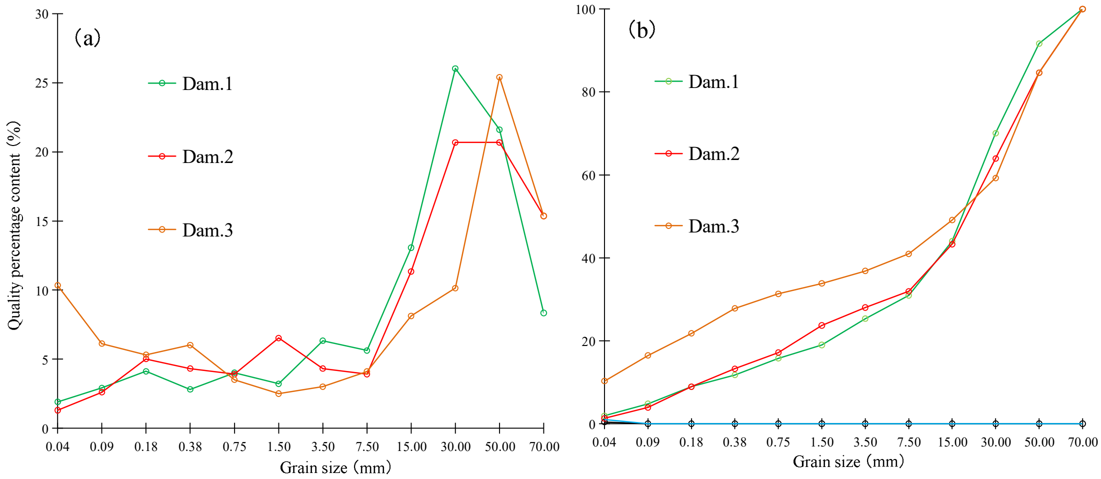

Fig.3 Frequency distribution and cumulative frequency distribution of grain size intervals in sediments of Jiajia gully

According to the analysis results, all samples exhibit a dominant grain size, which is mainly presented in the coarse-grained components, mainly 30~50 mm. Other grain size components change alternately and do not show an absolutely consistent regular grain size distribution (Fig. 3a, Table.4). From the cumulative frequency line chart (Fig.3a), the curves of each sample do not show a gently cumulative rising feature. They have a significant steepening characteristic around 15 mm, with a low degree of inhomogeneity and poor gradation. In terms of grain size intervals, particles smaller than 10 mm are grouped into one category, and those larger than 10 mm into another. The content of components smaller than 10 mm in Dam 1~3 shows a trend of increasing in sequence, while the content of coarse-grained components larger than 10 mm in Dam 1~3 shows a trend of decreasing in sequence (Fig.3b). It can be seen from this that debris flow check dams may play a certain role in the separation of coarse and fine particles in the deposits.

Table 4 Mass percentage of each grain size fraction in debris flow deposit samples of Jiajia gully

Grain size (mm)	0~0.075	0.075~0.10	0.10~0.25	0.25--0.5	0.5~1	1~2	2~5	5~10	10~20	20~40	40~60	60~80
Dam.1	1.9	2.9	4.1	2.8	4.0	3.2	6.3	5.6	13.1	26.0	21.6	8.3
Dam.2	1.3	2.6	5.0	4.3	3.9	6.5	4.3	3.9	11.3	20.7	20.7	15.4
Dam.3	10.3	6.1	5.3	6.0	3.5	2.5	3.0	4.1	8.1	10.1	25.4	15.4

Table 5 Grain size parameters and specific grain size component characteristics of post-dam sediment samples in Jiajia gully

Sample location	Mz（mm）	σ_i	*Sk*	*Kg*
Dam.1	20.72	19.3	0.26	0.76
Dam.2	23.3	21.79	0.29	0.67
Dam.3	31.83	21.97	-0.65	0.62

In this paper, the formula proposed by Fork and Ward is used to calculate the grain size parameters. According to the analysis results of grain size parameters (Table 5), the post-dam samples are generally relatively uniform with small differences: the average particle size ranges from 20.72 to 31.83 mm; the sorting coefficient is between 19.3 and 21.97; the skewness coefficient has a minimum negative skewness of -0.65 and a maximum positive skewness of 0.29; the kurtosis coefficient ranges from 0.62 to 0.76. From the analysis results, it can be preliminarily concluded that the check dams have a relatively obvious impact on the average particle size, and a regular influence on the sorting property and kurtosis coefficient (though the differences in values are small), but no obvious regular influence on the skewness.

4.2 Debris Flow Dynamic Characteristics

In this paper, for the dynamic characteristic indices of debris flows, common bulk weight and average flow velocity are calculated using grain size data, and the impact force on the dam body is also considered based on these indices. There are two methods for determining bulk weight: sampling and weighing, and parameter calculation. When direct measurement is not feasible, the parameter calculation method is undoubtedly a good approach (Formula1). There are many empirical formulas for calculating debris flow velocity; this paper selects the formula for viscous debris flows (Formula 2) which is based on grain size analysis and applicable to the Wudu area of Gansu Province. By obtaining the impact force of debris flow slurry based on debris flow deposits, the safety of the dam and the rationality of its design can often be verified (Formula3). Through calculations, the bulk weight, average flow velocity, and average impact force on the dam body represented by the debris flow deposits were obtained (Table5). The results show that the bulk weight of the Jiajia gully debris flow ranges from 2.18 to 2.23 t/m^3 , with significant differences in average flow velocity, varying from 7.47 m/s to 9.11 m/s. The post-dam flow velocity at Dam 3 is the highest, followed by that at Dam 2, and then at Dam 1, where the flow velocity is significantly lower. The corresponding impact force of the debris flow slurry on the check dam ranges from 37.17 to 56.66 KN/m^2，according to the engineering design report (Jin, 2009), the designed maximum impact forces for Dams 1 to 3 are all above 90 KN/m^2 (113.4 KN/m^2 , 99.1 KN/m^2 , and 90.1 KN/m^2 respectively). Therefore, the design of the check dams is reasonable (Table 6).

Table 6 Relationship between grain size of debris flow deposits and debris flow dynamics in Jiajia gully

Sample	$\log_2$（Mz）	d_{10}（mm）	d_{50}（mm）	m	i	R	Density（t/m^3）	V（m/s）	F (KN/m^2）
Dam.1	4.37	0.26	18.45	21.55	0.13	1.20	2.18	7.47	37.17
Dam.2	4.54	0.23	19.88	18.87	0.11	1.50	2.19	7.83	41.19
Dam.3	4.99	0.04	45.92	27.78	0.09	1.00	2.23	9.11	56.66

4.3 Discussion

Debris flow deposits are a type of mixed accumulations formed by the rapid transportation and deposition of loose materials in gullies under the condition of sudden heavy rain, which are significantly different from loess sediments, flood deposits and marine sediment layers (Wang et al.,2024；Shi et al.，2023；Andrews et al.，2023). Analyzing the dynamic significance of debris flows based on their grain size characteristics poses greater challenges. Although scholars have already carried out a series of studies, the calculated results derived from fitting debris flows in different locations and with different properties vary. Therefore, it is of great importance to appropriately apply the research results of previous studies in the process of conducting relevant work. In addition, during the process of conducting sedimentological analysis on debris flow deposits, the collection of grain size samples is also of great significance. For gullies with frequent debris flows, where consideration is often given to different episodes, it is necessary to find a complete profile of the debris flow deposits for layered sampling. However, this paper focuses specifically on debris flows that have occurred since the dam was built, with a short time scale, and does not take episodes into account. Therefore, during the sample collection process, samples should be taken as uniformly and representatively as possible within the 30 cm depth range on the deposits behind the dam.

According to the results of data analysis in this paper, the samples from different dams show a certain regularity from top to bottom, with changes in the composition of solid particles in the fluid. This is the result of the combined effect of fluid transportation and the blocking effect of the check dams. The reason why there are more particle components larger than 10 mm in the downstream dam bodies is that during their transportation, they carry greater energy and can better overcome frictional resistance, enabling them to flow a longer distance.In addition, from the perspectives of transport capacity and the selective deposition of check dams, downstream flows with higher energy can carry coarser particles. Meanwhile, the upstream check dams have preferentially trapped some fine-grained materials, resulting in debris flows reaching downstream dams with a higher proportion of coarse particles.The distribution characteristics of such grain size components also indicate that the area of check dams Dam0~3 belongs to the debris flow passing zone, rather than the debris flow transport zone or accumulation zone.

In this paper, the grain size of debris flow deposits is taken as an indicator, and empirical formulas are used to obtain the bulk density, average flow velocity, and impact force of debris flows indicated by the deposits. The calculation results are in line with objective reality: the differences in debris flow bulk density are small, while the differences in flow velocity are significant, which is related to the blocking effect of check dams on different gully sections. There are many empirical formulas for calculating the dynamic characteristics of debris flows, which are basically derived from fitting a large number of observations and cases, and are applicable to specific locations and conditions. Therefore, the appropriate application of these formulas requires in-depth discussion and comparison. However, due to considerations of space and research focus, this paper will not compare the calculation results of different formulas. Nevertheless, it is necessary to explain the reasons for choosing Formula (3) for calculation. After investigating the gullies studied in this paper and analyzing the sample data, it is concluded that the debris flows in question belong to viscous debris flows, which are closely related to grain size and fully conform to the characteristics of gully debris flows in Wudu District. Therefore, the results in this paper are obtained by calculation based on Formula (3), an empirical formula for viscous debris flows in Wudu District, Gansu Province. Comparing the calculation results with those from other scholars' research in the literature, it is confirmed that the results in this paper are reliable (Zhang, 2012; Yu, 2016;Huang et al.,2020).

In conclusion, debris flow deposits are formed in sudden environmental conditions where quantitative changes lead to qualitative changes in surface processes, resulting from the comprehensive action of multiple factors. Their grain size characteristics carry abundant information about surface processes, which are closely related to such elements as debris flow bulk density, debris flow dynamics, incubation time, transport distance, accumulation environment, geological background, and vegetation characteristics. Debris flow deposits are characterized by mixed accumulation with a very wide range of grain sizes, and some individual particles can even reach several meters in diameter. Particularly large particles need to be excluded in research. It is a long-term and arduous task to profoundly explore the surface process information carried in debris flow deposits.

5 Conclusions

Through the research, the following conclusions are obtained:

（1）The grain size characteristics of debris flow deposits formed in the same debris flow gully under different geographical location conditions are significantly different. The grain size characteristics of deposits are a comprehensive reflection of the surface activity process of the debris flow gully, which can serve as an important reference for debris flow control and soil and water conservation work.

（2）Among the representative samples selected from the gully, the average particle size of debris flow deposits ranges from 20.72~ to 31.83 mm, the sorting coefficient ranges from 19.30 to 21.97, the skewness ranges from -0.65 to 0.29, and the kurtosis ranges from 0.62 to 0.76.

（3）Based on the empirical formula of grain size characteristics, the debris flow bulk weight indicated by post-dam deposits is obtained to be between 2.18 and 2.23 t/m^3. The average flow velocity varies greatly, ranging from 7.47 m/s to 9.11 m/s, showing a strong impact force on post-dam deposits, ranging from 37.17 to 56.66 KN/m^2.

（4）From top to bottom along the gully check dams, the content of coarse-grained components increases, the average particle size becomes larger, the sorting property deteriorates, the kurtosis value decreases, and the skewness value shows no obvious trend. Meanwhile, the slurry bulk weight, flow velocity, and impact force increase in sequence. It can be seen that the check dams are set in the gully sections where the dynamics of debris flow increase. Although they play a blocking role to a certain extent, they are insufficient to counteract the work done by the conversion of gravitational potential energy. Therefore, the design of the dams, both in terms of site selection and strength, is very reasonable and can withstand the impact of debris flow slurry.

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