Impact characteristics of gustiness debris flow on check dam

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Abstract. The gustiness is a common motion form of debris flow, especially viscous debris flow. However, few researches have considered the gustiness into the impact characteristics of debris flow, which needs further research. In this study, the check dam was used as the load receptor to study the impact characteristics of gustiness debris flow. The results show that, under the same general flow depth, the dam stress considering the impact of gustiness debris flow is far less than that of disposable continuous debris flow. The impact force increases with the increase of the times of gustiness debris flow, and the impact torque increases linearly. Under the impact of gustiness debris flow, the displacement and stress of the dam vary in the same rule. The safety factors of anti-sliding and anti-overturning of the dam under the effect of gustiness debris flow are larger than those of disposable continuous debris flow, and the decrease rate of the safety factors increases with the increase of the times of gustiness debris flow. And under the condition of the same total flow depth, the increase of the debris flow depth can significantly decrease the stability of dam. The conclusions can provide reference for the design of blocking structures of gustiness and frequent debris flow.

1. Introduction
Debris flow is a common natural disaster all over the world, which occurs suddenly, fiercely and rapidly, and usually causes collapse, landslide and flood damage. Therefore, the damage degree of debris flow is more serious than a single collapse, landslide or flood. For example, in 1999, a massive mudslide in Venezuela killed more than 30,000 people and left 140,000 people homeless [1]. In 2010, debris flow occurred in the Zhouqu County, resulting in more than 1,600 deaths and about 300 homeless [2].

According to previous research data, debris flows, especially viscous debris flows, mostly moved in the form of gustiness flow [3-7], such as the gustiness debris flow in Jiangjia gully as shown in figure 1. According to years of observation and research about debris flow in Jiangjia Gully, it is known that the movement of viscous debris flow has thixotropy [8], which can affect the gustiness and bed-making process of debris flow [9]. Pierson [10] observed that debris flows moved in waves in the trench of mount Thomas, generating many standing waves in the process. Li et al [11] found that the movement of debris flows usually exists in the form of surge waves and consists of multiple waves that are temporally and spatially separated and have different patterns. Arai [12] found that surge intermittent is a common feature of viscous debris flow and muddy debris flow. According to on-site detection, Kean et al [13] found that debris flow has obvious surge characteristics.
The discharge of three gustiness debris flows [7]. The data is recorded in Jiangjia gully by Li [7]. The number 890623, 890803, and 940616 are the issue numbers of three gustiness debris flow.

In order to prevent and control debris flow, researchers have conducted a series of studies and designed kinds of blocking structures. Check dams are mostly used to prevent debris flow. When designing such structures, most of the designers considered the impact of debris flow slurry and coarse particles on such devices [14]. And the impact force addition of slurry and coarse particles are supposed as the design value of the debris flow impact force. Other researchers made coupling analysis between debris flow and its interception project to calculate the stress and deformation of retaining structure under impact of debris flow [15,16]. However, most of the above studies simplified the effect of debris flow into a single impact process, ignoring the impact of gustiness on the blocking device, which was often inconsistent with the actual situation. Therefore, considering the gustiness of debris flow is helpful to design more reasonable debris flow prevention engineering.

This study firstly obtained the real dynamic parameters of gustiness debris flow through field observation. Then, combined with the dynamic parameters of debris flow, the interaction between debris flow and interception structures under gustiness conditions was analyzed. Finally, the influence of the impact force of the debris flow on the different parameters of the check dam was analyzed. The conclusion of this study can provide some guidance and suggestions for structural design and theoretical research of prevention and control engineering of debris flow.

2. Methodology

In order to discuss the impact of gust impact characteristics in detail, the check dam was chosen as the load receptor. According to reference in “Handbook of debris-flow prevention” [17], the dam is set to a length of 10 m, a width of 7 m and a height of 10 m. The width of dam crest was 2 m, the bottom width of the dam was 7 m, the dam material was concrete with a per unit weight of 24 kN/m³. Midas/Gts Nx was used to simulate the impact influence of debris flow on check dam. Midas/Gts Nx is widely used in Gts Nx engineering field which could analyse dynamics process efficiently and accurately.

In the finite element model, the dimension was set the same as that of the check dam, and adopting tetrahedral meshes, there were 3,201,281 dividing units (figure 2). The bottom of the check dam was embedded in a trench bed, and both sides of the sediment storage dam were embedded in mountains, the bottom and both sides of the model were set as fixed boundary, as shown in figure 2. To reflect the gustiness of debris flow, it was assumed that the dam experienced five times of debris flow, each flow depth was 2 m (figure 3). The simulation experiments were designed in table 1. Each time the mudslide acted on the dam, and then the static earth pressure was generated, which combined with the next flow to act uniformly on the back of the dam.

Debris flow moves surging, the impact force of the mudslide on the check dam varies with different flow depths. Even for mudslide with the same depth, the impact force on the blocking...
structure is different. Therefore, this study selected the maximum impact forces at different flow depths from the actual measured debris flow impact data [18], as the impact force of the corresponding depth in numerical analysis. The details are as follows.

![Check dam simulated model](image1)

**Figure 2.** Check dam simulated model: the set of simulated model.

![Debris flow surges](image2)

**Figure 3.** The set of debris flow surges.

The impact force of the actual measured debris flow is divided into slurry and rock impact force, both of them are highly correlated with space. Therefore, the functions of the slurry impact force and rock impact force with position height are established respectively. Based on the above two functions, the impact load of slurry and rock can be simulated when the debris flow hits the sediment storage dam. At the same time, another function between static earth pressure and position height is built. When the second dynamic load is applied, the third function (function between static earth pressure and position height) will be added as the static soil pressure in the first dynamic load application region; when the third dynamic load is applied, the first and second dynamic load application region will add the third function as static earth pressure, and so on.

| Surge Name          | Flow Depth /m | Distance of between surge debris flow surface and ground |
|---------------------|---------------|--------------------------------------------------------|
| Flow a              | 2             | 2                                                      |
| Flow b              | 2             | 4                                                      |
| Flow c              | 2             | 6                                                      |
| Flow d              | 2             | 8                                                      |
| Flow e              | 2             | 10                                                     |
| Disposable continuous debris flow | 10           | 10                                                     |

**Table 1.** Design parameters.

3. **Results**

3.1. **Characteristics of stress in the check dam affected by gustiness debris flow**

Figure 4 shows the stress contour of the dam under the action of five gustiness debris flows and disposable (flow depth of 10 m) continuous debris flow. It can be seen from the figure that the stress distribution of the dam caused by five gustiness debris flows was similar, that was, the compressive stress was near the impact load action area, the tensile stress was in the other region, and the stress in the middle part of the impact zone was larger, while the stress on both sides gradually decreased. With the increase of the times of gustiness debris flow, the area of the compressive stress region increased gradually, the area of the tensile stress region decreased gradually, and the maximum stress value also increased. Compared with the disposable impact of debris flow depth of 10 m on the dam, it can be seen that the stress generated by the disposable continuous impact was larger than the maximum impact stress of gustiness debris flow. For example, the maximum compressive stress generated by the
disposable continuous impact was about 1.5 times of the other.

Figure 4. Stress contour of the dam: (a)-(e) effect of gustiness debris flow; (f) effect of disposable continuous debris flow.

Figure 5. The relationship between the impact force and the gustiness debris flow sequences of surges. The impact force in the figure is the resultant force along the debris flow direction, including the dynamic load and soil pressure generated by the gustiness debris flow.

Figure 6. The relationship between the impact moment of debris flow and the numbers of debris flow surges.

Figure 5 shows the change characteristics of impact force generated by five times of gustiness debris flow. We can see from the figure that the horizontal impact force increased in a nonlinear form with the increase of times of gustiness debris flow. Moreover, with an increase in times of gustiness debris flow, the difference of impact forces between two adjacent flows increased gradually. Figure 6
shows the relationship between the moment of the horizontal impact force to the ground and the number of flows. We can get the conclusion that the impact moment increased linearly with the number of flows. The difference of moments between two adjacent flows increased with the increase of the times of flow, but the difference was not big. According to calculation, the horizontal force and moment generated by the disposable continuous impact of debris flow at a depth of 10 m were about $1.1 \times 10^5$ kN and $5.4 \times 10^5$ kN·m, which were respectively 10 times and 6 times of the fifth (the last) flow impact.

3.2. Characteristics of displacement in the check dams affected by gustiness debris flow

Figure 7 shows the general displacement cloud diagram of the dam under the action of five gustiness debris flows and disposable continuous debris flow. We can see from the figure that the total displacement was larger in the impact load area of debris flow, and the further away from the impact load area of debris flow, the smaller the displacement was. Furthermore, the maximum total displacement occurred on the upper surface of the impact load (distributed load).

![Displacement nephogram of the check dam](image)

**Figure 7.** Displacement nephogram of the check dam: (a)-(e) effect of gustiness debris flow; (f) effect of disposable continuous debris flow.

The relationship between the maximum displacement of the check dam and the times of debris flow is shown in figure 8. It can be seen from the figure that the maximum displacement increased with the increase of the number of debris flows, that is, it increased with an increase in the height of debris flow. Furthermore, the difference of maximum displacement between two adjacent flows increased with the increase of the number of debris flows. For example, the maximum displacement difference generated by the first and second debris flows was $7.1397 \times 10^{-3}$ mm, and the maximum displacement difference generated by the fourth and fifth flows was $5.87401 \times 10^{-3}$ mm. In addition, from the comparison of the effect of gustiness debris flow and disposable continuous debris flow, it can be seen that the displacement generated by disposable continuous impact was larger than that
generated by gustiness impact under the same total flow depth condition.

![Figure 8. Relationship between the maximum displacement and the gustiness debris flow surges.](image1)

![Figure 9. The relationship between the anti-sliding safety factor and the gustiness debris flow surges.](image2)

3.3. The safety of check dam impacted by gustiness debris flow

The whole stability of the dam must be ensured during the normal operation. Under the action of design load or combination of dangerous load, the anti-sliding coefficient is a parameter to measure the anti-sliding stability of the dam. The anti-sliding coefficient of the dam is expressed in equation (1) [20].

$$k_{\sigma} = \frac{f \sum W}{\sum Q}$$  \hspace{1cm} (1)

Where $k_{\sigma}$ is the anti-sliding safety factor of the check dam, $f$ is the friction coefficient between masonry and foundation of the dam, $\sum W$ is the sum of the vertical forces acting on the unit length of the dam, $\sum Q$ is the sum of the horizontal forces acting on the unit length of the dam.

Considering the impact of debris flow, earth pressure, deadweight and friction of the dam, the anti-sliding coefficient of the dam is shown in figure 9. It can be seen from the graph that the anti-sliding safety factor decreased gradually with the increase of the number of debris flows, and the minimum value was about 1.2, larger than 1. While the safety factor of disposable continuous debris flow was about 0.1, which was much smaller. Therefore, when the total flow depth of debris flow was the same, the impact load of gustiness debris flow was much less dangerous than that of disposable continuous debris flow.

The anti-overturning coefficient is an index to measure the anti-overturning stability of the dam, which can be calculated in equation (2) [20].

$$k_{\gamma} = \frac{\sum M_{\gamma}}{\sum M_{\sigma}}$$ \hspace{1cm} (2)

Where $k_{\gamma}$ is the anti-overturning safety factor of the dam, $\sum M_{\gamma}$ is the anti-overturning moment of the dam, $\sum M_{\sigma}$ is the overturning moment of the dam.

The toe of the downstream slope of the dam was chosen as the rotation shaft, and the relationship between the calculated anti-overturning safety factor and the times of gustiness debris flow is shown in figure 10. It shows that the anti-overturning safety factor decreased with the increase number of debris flows, especially when debris flow accumulated to 2-4 meters, the anti-overturning safety factor decreased sharply, it might be the anti-overturning ability of the dam reached to a critical point due to
the accumulation of a certain height of debris flow. The anti-overturning safety factor of the dam under the impact of gustiness debris flow was larger than that of disposable continuous debris flow, indicating that under the same total flow depth condition, the impact of gustiness debris flow was less dangerous than that of disposable continuous flow.

![Figure 10](image1.png)  
**Figure 10.** The relationship between the anti-overturning safety factor and gustiness debris flow surges.

![Figure 11](image2.png)  
**Figure 11.** Influence of gustiness debris flow depth on: anti-overturning safety factor.

3.4. *The influence of gustiness debris flow depth to check dam*

Under the condition of the same general flow depth, shallower depth of a single gustiness debris flow means more times of the gustiness debris flows. The above analysis all depended on the situation of single flow depth of 2 m, in order to analyze the influence of flow depth on impact characteristics, five different flow depths (1 m, 2 m, 2.5 m, 5 m, 10 m) were selected in this study, it is worth mentioning that the flow depth of 10 m meant the gustiness of debris flow was not considered. The safety factors of anti-overturning under different flow depths were calculated as shown in figure 11.

As can be seen from figure 12, when the total flow depth of debris flow remained unchanged, shallower depth of single gustiness debris flow resulted in greater anti-sliding and anti-overturning safety factors. The results show that under the impact of a single flow, the low-depth debris flow had little influence on the safety of the dam, especially after considering the gustiness of debris flow, the anti-sliding and anti-overturning safety factors were obviously larger than those of disposable continuous debris flow.

![Figure 12](image3.png)  
**Figure 12.** Influence of gustiness debris flow depth on: anti-sliding safety factor.

![Figure 13](image4.png)  
**Figure 13.** Influence of gustiness debris flow depth on strain of the check dam.

The strain of the check dam under the effect of load is an intuitive parameter to evaluate the anti-safety performance of the check dam. Figure 13 shows the strain of gravity check dam when it was first impacted by debris flows with flow depth of 1 m, 2 m, 2.5 m, 4 m, 5 m, respectively. Conclusions
can be drawn from figure 13 that the growth rate of total strain increased with the increase of times of gustiness debris flow, and the greater the depth of a single debris flow, the faster the strain increased. Overall, keep the general depth of debris flow unchanged, the shallower the depth of a single debris flow, the smaller the final strain of the dam body would be.

4. Conclusions
Combined with the debris flow impact measurement data in Jiangjiagou gully, Yunnan and numerical analysis, the following conclusions were drawn.

- Under the condition of the same total flow depth, the impact force and moment of disposable continuous debris flow are far greater than those of gustiness debris flow. The impact force of gustiness debris flow has a nonlinear relationship with the times of gustiness debris flow, and the growth rate of impact force increases with the increase of the times of gustiness debris flow. While the impact moment has a linear relationship with the number of debris flows.
- Under the condition of the same general flow depth, the displacement of the dam under the impact of gustiness debris flow is smaller than that of continuous debris flow. Under the effect of gustiness debris flow, the displacement has a nonlinear relationship with times of gustiness debris flow, and the displacement growth rate increases with the increase of the times of flows.
- Under the condition of the same general flow depth, the anti-sliding safety factor and anti-overturning factor of continuous flow are much smaller than those of gustiness debris flow.
- As the total flow depth keeps the same, the stability of the dam gets worse with the increase of the gustiness debris flow depth.

In actual situation, the front of the dam is rarely filled by debris flow in one time, but by repeated debris flow. Therefore, multiple debris flow events can be simplified into gustiness flows of a long time series. The impact characteristics of gustiness debris flow discussed in this paper can provide a reference for the design of blocking structure in debris flow prone-to-occur area.

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