Study on transient dynamics of piers under the impact of debris flow

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Abstract. Because of the climate warming and the serious ecological damage of the valley slope, the frequency of debris flow in the valley is increasing frequently. The solid deposits in the debris flow are, transported at high speed under the action of water flow and self-gravity, have a great impact on the piers along the line, which greatly destroys the integrity and stability of the pier. Through the theoretical analysis and numerical simulation of debris flow, the transient dynamic response of the pier under the impact of debris flow is analyzed. It is concluded that the pier is subjected to the punching and shearing form load, and the impact damage of the coarse solid particles in the debris flow to the pier is more obvious. The pier displacement reaches the maximum at the second impact of the debris flow; the maximum displacement is 10.9mm, which appears at the 5m above the bottom of the pier. A tensile stress concentration zone appears at the bottom of the pier, and the maximum tensile stress is 1.84MPa, which exceeds the concrete strength of the pier and so we can take corresponding measures to guard against this problem so as to ensure the safety of bridge structure.

1. Introduction

Debris flow is a kind of geological disaster with great impact and destructive action under the action of special topography and landslide body. Highways often use bridges across river valleys. Under the constraints of geological conditions, in addition to the structure and construction problems of high piers in this area, the hazards of debris flow to the pier can not be underestimated for the areas where the terrain is dangerous, the surrounding rock is broken and the rainfall is concentrated. Once the pier is damaged by the debris flow, it is more difficult to repair. For example, in the afternoon of June 18, 2017, the maximum hourly rain intensity in the Mentougou Zhaitang area in Beijing reached about 100mm, and caused mudslides in the mountains. The debris flow carrying boulder destroyed the main road of the “V” type valley in the disaster area, causing 12 deaths and hindering the process of disaster relief. At present, most researches on the failure mechanism of piers under impact are focused on the response to earthquakes and ship impacts, and the research on the impact failure response of debris flow is relatively less. In order to ensure the safety and stability of the bridge in the valley area when the debris flow breaks out, it is of great engineering significance to study the transient dynamic characteristics of the pier under the impact of debris flow.
Huang Hexun [1] simulated the impact of different strength debris flow on different types of bridge piers, analyzed the impact pressure, displacement and stress at the top of the pier under the action of debris flow, and determined the failure stage of the bridge, and put forward the engineering prevention measures. Tan Yuezhang [2] used the ANSYS software transient analysis module to simulate the impact of the overall impact force and the impact of large rock in the debris flow on the stability of the pier; it is pointed out that when the pier is impacted by debris flow, the pier bears the load of the punching and shearing form; a large tensile stress zone will appear at the bottom, and the pier will be subjected to significant stress concentration due to the impact of the large rock. Wang Linfeng et al [3] optimized and corrected the calculation formula of the impact force of debris flow in the norm, and calculated the impact force of the two-phase flow of the debris flow by using the elastic collision theory and the Newton's second law respectively, and then superimposed it so as to get the total debris flow impact.

Debris flow fluids usually contain high-speed movement of gravel with different particle sizes and have considerable impact kinetic energy [4]. In order to study the transient dynamic response of the pier under the impact of debris flow, theoretical analysis and numerical simulation are used to study the stress-strain characteristics of the pier under the impact of debris flow, which has strong engineering guiding significance for the proposed and prevention of engineering measures.

2. Mechanism of Debris Flow Impact

An important direction in the study of debris flow dynamics is to study its impact on structures and the mechanical response of structures under impact. The influencing factors that contribute to the impact force of debris flow can be roughly classified into: solid particle gradation in debris flow, structure resists impact strength, debris flow velocity, and debris flow volume. When the bridge structure is impacted by the debris flow, the pier will bear the load in the form of punching and shearing. A large tensile stress zone will appear on the upstream surface of the pier, and a compressive stress zone will appear on the backflow surface of the pier. If the debris flow is accompanied by a large rock impact, the pier will have a significant stress concentration zone, resulting in a large displacement. If the pier is not strong enough, it will be unstable [5]. For the time being, the debris flow impact is a fluid-solid coupling effect, and the liquid and solid cross-react during the movement process, and the particle gradation distribution law in the fluid has great contingency. Therefore, the source of the impact force is irregular. It is necessary to determine the impact law by means of field site survey, indoor analysis and test, and the establishment of model numerical simulation. At present, the method of combining numerical simulation and theoretical analysis is more reasonable to study the impact of debris flow and the transient dynamic characteristics of the pier. The plastic stress and strain response of the pier under the impact of debris flow can be better analyzed by the analysis of the displacement stress cloud map.

3. Project Overview

The Daqing debris flow development zone is located on the right bank of the Dadan River in Lijiang, and the provincial highway S220 passes through the “V” type valley in the form of bridges. The provincial highway S220 is the main traffic line connecting Binchuan County and Yongsheng County. The traffic volume between the two is very large. Once the line is interrupted, it will directly affect the normal business travel between the two counties. The Daqing debris flow basin is high in the northeast and low in the southwest. The highest elevation is about 2520m, and the lowest elevation is about 1230m, and the relative height difference is about 1290m. The average longitudinal gradient of the ditch bed is about 350 per thousand, and the terrain gradient is more than 33 degrees, and the valley is severely cut, mostly “V” shaped gullies, with topographic conditions for the outbreak of debris flow. The overall appearance of the Daqing debris flow development zone is shown in Figure 1. The average annual rainfall of the basin is 619.5mm. The rainfall period is mostly concentrated in the summer. The rainfall is concentrated, the rainfall is large and the catchment area is wide. These provide sufficient hydrodynamic conditions for the generation of debris flow hazards. Most of the
gully deposits are mainly loose gravel soil, gravel silty clay, round gravel, pebbles and so on. The bedrock is exposed; joint cracks are developed; the degree of weathering is high; the stability of bank slopes and cliffs is poor. It has the material conditions for the outbreak of debris flow. The content of gravel with a particle size larger than 60mm in the solid material of Daqing debris flow is about 55.5%, which provides a powerful impact for the debris flow. The Daqing debris flow is currently in its prime. Once the debris flow is excited, it will pose a huge threat to the provincial highway S220 pier in the dangerous area. The location of the debris flow gully and the bridge is shown in Figure 2.

Figure 1. The development zone of the Daqing debris flow
Figure 2. The position diagram of gully and bridge

4. Transient Dynamic Response Analysis of Pier Under Impact Load of Debris Flow

4.1 Model establishment
Taking the Guge bridges in this basin as the research object, the abutment is simplified into the base support of the pier, combined with the calculation parameters of the previous survey and the physical and mechanical parameters in Table 1, the bridge model is established according to the ratio of 1:1. The model is shown in Figure 3. Because the bridge is heavily buried by heavy rain alluvial deposits, and during the migration of the debris flow, the large diameter solid particles are in a semi-suspended state [6,7]. Therefore, the overall impact load of debris flow is applied to the surface of the pier from the 4m of the bottom of the ditch, and the large rock impact load is applied in the form of point load on the upper side of the center of the upstream surface of the bridge pier 2.5 m away from the bottom of the trench. The specific loading position is shown in Figure 4.

Table 1. Physical and mechanical parameters of the Guge Bridge

| project name                  | parameter  |
|-------------------------------|------------|
| bridge length (m)             | 30         |
| bridge width (m)              | 12.5       |
| pier shape                    | round      |
| pier diameter (m)             | 1.5        |
| pier height (m)               | 8          |
| pier strength                 | C25        |
| elastic modulus E (Pa)        | $2.8 \times 10^{10}$ |
| poisson's ratio $\mu$         | 0.2        |
| debris flow impact force kPa  | 102.42     |
| large stone impact force kPa  | 480.77     |
Figure 3. The model of the Guge bridge  
Figure 4. Loading position diagram of impact load

4.2 Selection of impact load conditions for debris flow

According to the selected ANSYS transient dynamics analysis module [8], three working conditions as shown in Fig. 5 were selected to simulate the impact force of the debris flow on the bridge pier.

(a) Working condition 1 1-2s is affected by large rock (b) Working condition 2 1-2s, 3-4s are affected by large rocks

(c) Working condition 3 1-2s, 3-4s, 5-6s are affected by large rocks

Figure 5. Impact load condition

4.3 Pier body displacement analysis

The time-displacement curves of the Guge Bridge under the overall impact of the debris flow and the impact of the large rock are shown in Figures 6-8. Under the working condition 1, the displacement of the pier top increased rapidly before 0.9s, and the 0.9s began to receive the impact load from the large rock. The peak displacement of the pier reaches the peak value of 8.4mm at 1.2s, and the displacement begins to decrease rapidly to 5.8mm when it continues to 2S, and then oscillates back and forth near 6.0mm and finally returns to the initial state. When the large rock hits the pier for the first time under working condition 2, the maximum displacement of the pier top is 8.4mm, which appears at 1.1s; when the pier is impacted second times, the maximum displacement of pier top is 8.6mm, which appears at 3.16s. The second impact displacement is greater than the first time, and the superposition effect is more obvious. Under working condition 3, the displacement of the pier top caused by the first two impacts is similar to that of working condition 2, but the maximum displacement of the pier top of
The third impact is 8.1 mm, which is obviously smaller than the displacement of working condition 1 and working condition 2.

**Figure 6.** Time displacement curve of pier top under condition one

**Figure 7.** Time displacement curve of pier top under condition two

**Figure 8.** Time displacement curve of pier top under condition three
Comparing the displacement diagram of the pier, it can be concluded that the maximum displacement occurs in the working condition 2, and the maximum displacement is 10.9mm, and the action point is 5m above the bottom of the pier. The top of the pier has an oscillating displacement and is slightly smaller than the displacement of the point of action of the large rock. The displacement of the large rock impact and the maximum displacement of the pier are shown in table 2 and figure 9.

Table 2. Maximum displacement and action point displacement of large stone block

| displacement (mm) | working condition 1 | working condition 2 | working condition 3 |
|-------------------|---------------------|---------------------|---------------------|
| pier top displacement | 8.4                 | 8.6                 | 8.1                 |
| rock point displacement | 8.9                 | 9.3                 | 9.1                 |
| maximum displacement | 10                  | 10.9                | 10.6                |

Figure 9. Displacement curve of bridge pier under different working conditions

The above analysis shows that the overall impact force of the debris flow is the main cause of the deformation of the pier. Accidental large rock impacts exacerbate the deformation displacement of the pier. The maximum displacement of the pier after the continuous impact of the large rock block is no longer increased. In the process of bridge pier follow-up protection, early interception measures can be taken to reduce the proportion of large stones in debris flow, to prevent the accidental impact and erosion of the large rock blocks to destroy the concrete protective layer of the pier, and to take corresponding reinforcement measures according to the displacement of the pier in different parts.

4.4 Pier stress analysis
Because of the similarity of three loading conditions, the vertical stress distribution of the pier is not very different; only the vertical stress distribution characteristics of the pier under the condition of working condition 3 are selected for analysis. The tensile stress concentration zone at the bottom of the upstream surface of the pier is 1.84 MPa, which is much larger than the design value of the maximum tensile strength of the C25 concrete of the pier 1.23 MPa [9]. The structure at the bottom of the pier may have been partially cracked and the integrity of the pier has been damaged. The maximum compressive stress region is 13.42 MPa, which appears on the back flow surface of the pier,
and the compressive stress value of the impact part of the rock mass reaches 8.92 MPa. The vertical stress of the pier under three working conditions is shown in Table 3 and figure 10.

**Table 3.** The vertical stress value of pier under three working conditions

| position         | stress (MPa)                  | working condition 1 | working condition 2 | working condition 3 |
|------------------|-------------------------------|---------------------|---------------------|---------------------|
| pier bottom      | maximum tensile stress        | 1.76                | 1.84                | 1.84                |
|                  | maximum compressive stress    | -11.91              | -13.43              | -13.42              |
| large rock action| compressive stress            | -8.97               | -9.05               | -8.92               |

**Figure 10.** Stress curve of bridge pier under different working conditions

It can be seen from the above analysis that the impact of large rocks on the pier breaks the stress balance state, which makes the stress concentration zone appear at the bottom of the pier and exceeds the tensile strength of the pier material itself, and the concrete cracks at the impact point of the pier. The third impact of the big stone did not increase the stress of the pier, indicating that the multiple impacts of the short interval will not increase the stress on the pier, but it may cause cumulative damage and instability of the pier.

5. Conclusion

Through the analysis of the impact mechanism theory of specific debris flow and the stress displacement characteristics under the transient dynamic response of the pier, the following conclusions are drawn:

The overall impact of the debris flow is the main factor of the deformation of the pier. The impact of the large rock increases the displacement of the pier. The maximum displacement is 10.9mm, which appears 5m above the bottom of the pier. The tensile stress concentration zone appears at the bottom of the pier. The maximum tensile stress is 1.84MPa. Exceeding the strength of the concrete material, it is necessary to strengthen the bottom of the pier.

The shorter the impact time interval, the smaller the impact on the deformation of the pier. In the subsequent protection process of the pier, the early interception measures can be taken to prevent the
 accidental impact of the large stone, and the corresponding reinforcement measures can be taken according to the displacement of different parts of the pier.

The stress-strain value of the pier reaches the maximum at the second impact of the large rock, and does not increase with the increase of the number of impacts of the debris flow. It is more important to take measures to intercept the first two interceptions of the debris flow, and to prevent the phenomenon of stress superposition caused by the impact of large stones.

The impact force of debris flow is affected by the density of debris flow, and the bulk density of debris flow is affected by particle composition. By reducing the proportion of coarse particles in debris flow, the impact of coarse particles on piers can be prevented.

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