Study on the Failure Mechanism of Bridge Pier in the Active Debris Flow Regions

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Abstract. Highway bridges and culverts across debris flow gully are easy to be impacted by debris flow. When debris flow break out, the bridge pier foundation is scoured and undercutted by debris flow, which could lead to scour hole in a certain degree. Based on the model that mutant river scoured roadbed along the river in mountainous areas, putting the bridge pier that was scoured by debris flow as the research object, then we analyze the mechanism that the debris flow undercut bridge pier foundation, and study changes in the stability of bridge superstructure after the formation of the scour hole. Finally, the rationality of the failure mechanism is verified by the calculation of the relevant engineering examples.

Introduction

Debris flow is the block movement composed of loose material, water body and air under the action of gravity, which is a series of process between water flow and landslides¹. Washout of bridge and culvert structure means that the highway bridges and culvert structure crossing the debris flow gully are impacted and destroyed by mudslides and flash floods. The debris flow has the characteristics of big bulk density, high velocity, large flow, strong suddenness², its outbreak affects stability of highway bridge culvert structure along the river. So far, the domestic and foreign scholars have conducted a lot of research on the highway washout. D. Tibebe³ who used regular calibration of SWAT model simulated the process of Awash river basin surface erosion and soil erosion Awash river basin in Ethiopia. For bridge pier under the influence of different erosion degree, Kai Liang⁴ simulated the way that the bottom of foundation under different basal support modes was hollowed out by using the finite - element method, and explores foundation erosion area which leads to the failure of the abutment foundation. Based on the existing calculation formula of impact force of debris flow, Lin-feng Wang⁵ modified it and improved the calculation accuracy. Hong-kai Chen⁶,⁷ pointed out that debris flow produce the vortex flow at the end of abutment wall owing to the cavitation, and then scour the abutment foundation. According to scouring problem of the overbank river abutments.

Based on the model that mutant river scoured roadbed along river in mountainous areas, we analyze the mechanism that the debris flow undercut bridge pier foundation, and study changes in the stability of bridge superstructure after the formation of the scour hole.

The Failure Mechanism of Bridge Pier Washout

Basic Assumption

This article takes the highway bridges and culvert structure crossing the debris flow gully (Figure 1) as an example, and makes the following basic assumption: considering the debris flow as laminar flow, the velocity distribution is uniformly distributed on the cross section of the infinity of upper reaches and lower reaches on the river valley; the debris flow is considered as incompressible fluid.
The Formation Mechanism of the Scouring Hole

(1) The flow velocity of the point A: \( v_d \)

In the demarcation line of the vortex area and mixed area, energy is consumed in the vortex area and mixed area at the same time. The intersection of the streamline and ground is maximum scour point that debris flow scours the soil under bridge pier foundation. The flow section of narrow valley (width, height)\( = (b_1, h_1) \), the flow section of wide valley (width, height)\( = (b_2, h_2) \), the \( \frac{b_2}{2} \) is the flow velocity of the point A, \( v_s \) is the speed of point A in the x direction.

\[
L = \frac{b_0}{k}, \quad t = \frac{L}{v_x}
\]

The speed of point A in the y direction: \( v_y = 2v_s\sqrt{kb_0} \). The flow velocity of the point A is as follows.

\[
v_d = \sqrt{v_x^2 + v_y^2} = v_s\sqrt{1 + 4kb_0}
\]

(1)

According to Sri Bo Hei Bea formula

\[
v_s = \frac{6.5 \cdot 2^{\frac{1}{2}}}{a H^3 I^2}
\]

(2)

\[
a = \frac{\gamma_w - 1}{\sqrt{1 - S}}
\]

(3)

(2) The radius of scouring hole: R
The debris flow impact the soil under bridge pier at the angle of $\theta$, the speed is $v_A$, the scouring hole expands centered on one point A (Figure 3), and the radius of the scouring hole expands from the outside, the depth of each expansion is a fixed value $S$.

\[
R = \text{Int}\left(\frac{L}{t_2}\right) S
\]

(3) The failure time of the renegadelayer $S$: $t_1$

The process of particle starting is as follows: The large particles rotate under the action of shear stress, when rotating to the starting angle, and they were brought out under the action of shear stress in water flow. The whole process consists of rotating time as well as detachment time, but the time of departure is short and negligible.

We use median particle size $d$, the big particles start to detach when the angle between these particles and the flow direction is 45 degrees, then the thickness of departure is as follows,

\[
S = d\sin 45^\circ, \quad r = \frac{S}{\sin(\pi - \theta)} = \frac{S}{\sin \theta}. \quad f \text{ is frictionforce in the process of particle movement,}
\]

\[
f = 2u \gamma h ab. \quad p_i \text{ is the soil pressure of particle end in the process of rotation, } p_i = \gamma h 10^{\frac{\alpha - \theta}{C}}.
\]

Acceleration in ring direction of particle end

\[
a = \frac{2u \gamma h ab + \gamma h 10^{\frac{\alpha - \theta}{C}}}{\frac{4}{3} \pi abc \rho}
\]
\[
S \frac{(\theta - \theta_s)}{360^\circ} \cdot 2\pi = \int (v \cos \frac{0.5 \cdot at^2}{r} - at) dt
\]  

(6)

Through the simultaneous equation, we can get \( t = t_s \), then the radius of scouring hole can be solved.

**The Damage of Bridge Pier**

We should calculate the overturning destruction of bridge pier according to the Code for Design of Ground Base and Foundation of Highway Bridges and Culverts\(^9\).

The formula of overturning stability of the bridge pier

\[
k_a = \frac{s}{e_0}
\]  

(7)

The formula of stability against sliding of the bridge pier

\[
k_c = \frac{\mu \sum P_i + \sum H_p}{\sum H_k}
\]  

(8)

**Engineering Example**

In 2013, because of the "7.13" rainstorm disaster, Maojiawan Bridge was washed out (Fig.6).

The flow section of narrow valley is as follows: \( b_1 = 10m \), \( h_1 = 4.5m \); the flow section of wide valley is as follows: \( b_2 = 6m \), \( l_{ab} = 5m \), then the parabolic equation of arc OA: \( y = 0.08x^2 \). According to formula (2) and (3), \( S_s = 0.35 \), \( \gamma_s = 10kN/m^3 \), \( \gamma_c = 15.2kN/m^3 \), \( H_e = 5m \), \( I_e = 0.3 \), then \( a = 1.53 \), \( v_s = 9.20m/s^2 \), take these into formula (1), \( v_d = 11.78m/s \).
Because the lower part of soil is clay soil, according to the related regulations in the Soil Mechanics, we assume that the median grain size of soil particles is as follows: $d = 0.125\, mm$, $S = 0.088\, mm$, $r = 0.123\, mm$. And we assume that particles are ellipsoid: $a = 0.1\, mm$, $b = 0.06\, mm$, $c = 0.05\, mm$. According to formula above, $u_f = 0.4$, $\gamma = 21.6\, kN / m^3$, $h = 1.23\, m$, $\rho = 1.9 \times 10^3\, kg / m^3$. And then $f = 1.12 \times 10^{-4}\, N$, $p_1 = 3.8 \times 10^{-3}\, N$, $a = 1.64 \times 10^6\, m / s^2$. We take these into formula (6): $t_s = 7.08 \times 10^{-6}\, s$. Finally we obtain that $R = 2.53\, m$. The erosion of lower bridge foundation leads that the upper structure lose stability along a certain capsized shaft. According to the formula (7), $k_0 = 1.13 < 1.3$, so this moment the upper part of bridge loss stability, which cause damage of bridge pier.

**Conclusion**

When debrisflow break out, the bridge pier foundation is scoured and under cuted by debris flow, which results in scouringhole. We analyze the mechanism that the debris flow undercuts bridge pier foundation, and get the corresponding calculation formula of radius of scouring hole. According to the code for design of ground base and foundation of highway bridges and culverts, the effect of scouring hole on the stability of the upper structure is studied. According to analysis of the engineering example, the rationality of the scouring mechanism is verified.

**References**


