Rockfall Damage in a Mountainous Area to the Single Column Pier of a Bridge

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ABSTRACT

In order to find out the damage caused by the impact of the falling stone on the bridge pier in the mountainous area of our country, the safety protection of the bridge pier of the mountain bridge in our country is provided with theoretical and practical technology. Using the finite element software that the nonlinear display power analysis tool LS–DYNA and damage constitutive model based on HJC, combined with the typical bridge pier on the highway line to study the damage of the single-column pier in the rockfall. The degree of damage to the pier column was analyzed by comparing the height, velocity, eccentricity, impact angle, impact surface and diameter and put forward protective recommendations.

KEYWORDS: Rockfall, Impact, Single column pier, Damage analysis.

INTRODUCTION

China's rock off the road along the impact of bridge accidents in the rainy season of the mountain valley has occurred, seriously reducing the normal life of the mountain bridge. At present, the impact of rock impact damage in mountain bridge design is the key consideration. According to the existing research, the impact of rockfall on the slope along the highway has a significant effect on the damage of the pier, which will cause serious damage and even collapse of the bridge[1]. The influences on the reinforced concrete structure under the impact load and its dynamic response law, domestic and foreign scholars to carry out related research. Schellenberg conducted an impact test on six reinforced concrete slabs consisting of a dense gravel cushion to test the crashworthiness of a special buffer system consisting of high strength steel mesh and porous glass[2]; Fujikake proposed a model and combined with the drop hammer impact test to study the impact of drop hammer height and longitudinal reinforcement on the failure of reinforced concrete beams[3]; Williams using a finite element model, through numerical simulation test data, described in the explosive load under the action of reinforced concrete peeling response mechanism[4]; Lu and Zhang were used to simulate the failure of bridge pier under rock impact, and the influence of impact load direction ,impact position and impact load on the performance of pier was studied[5]; Liu et al. introduced the modeling method of ship, anti-collision device and piers in nonlinear finite element collision analysis by means of oil tanker impact box type plastic energy absorption and collision avoidance device[6]; Wang R. used the drop hammer test to study the dynamic response of concrete components under the lateral impact energy, and numerical simulation test data can not be observed, analyzed and summarized its critical failure impact energy relationship between the ferrule and the coefficient[7]; Pei X.J. et al. using DDA method, simulation of the impact of strong earthquakes rocks piers dynamic response. Based on the quantitative analysis of the deformation of the slope and the piers, the paper puts forward the scheme of the prevention and control of the rocky slope of the rock slope based on the characteristics of the strong earthquake triggering collapse[8]. Lian Y.Q. took a bridge hollow piers as the object of study, and analyzes the dynamic process of the collision between the rolling stone and the pier and the main factors influencing the impact force. Design an anti roller rock impact device and verify its performance[9]. Wu C.K. analyzes the lateral forces of the double-column piers in a mountainous area, and puts forward the design of the pier-pillar protection system of the mountain bridge and improves the design strength of the piers to resist the impact of the rolling stones[10]. Gan W.C. based on the collision of non-navigable holes in a sea-crossing bridge, the impact path and deformation coordination mechanism in the impact process are simulated by numerical analysis. Through the scale test, the qualitative and quantitative pier damage[11]. Liu X.Y., et al. studied the impact force of the superstructure of the super high vehicle impact bridge based on the simulation model, and analyzed the magnitude and variation of the impact force under different vehicle weight and speed[12]. Gu X. based on the typical bridge pier on the Duwen highway, the damage of the rock-impact double-column pier is studied, and the damage, damage and damage of the pier degree[13].

MODEL ESTABLISHED

It is found that there are two main research methods: one is the model test, the method is intuitive and can simulate the impact of the real or impact, but costly, can not be carried out in large numbers, and the results obtained are limited. So it is difficult to carry out the model test for the ship, automobile and rockfall impact bridge or bridge, etc. Second, the numerical simulation analysis, the method can be a more comprehensive study of the impact or impact, but the need for the user's There is a correct understanding of the relationship. This paper is based on the second method of finite element model test analysis.

In this paper, the finite element model of HJC damage is established by means of nonlinear display dynamic analysis method. The damage rate and pier displacement of single column piers are analyzed by changing the height, velocity, eccentricity and diameter of rock fall. Which is the key factor to design the bridge pillar protection work.

Numerical calculation method

According to the basic concept of the central difference method, the acceleration can be expressed as the first-order central difference of velocity, and the velocity can represent the first-order central difference of the displacement. Thus, the following expression is obtained:

$$[\mathbf{v}(t_{n+\frac{1}{2}})-\mathbf{v}(t_{n-\frac{1}{2}})]/[\frac{1}{2}(\Delta t_{n-1}+\Delta t_n)]=\mathbf{a}(t_n)$$
$$\mathbf{u}(t_{n+1})\text{-}\mathbf{u}(t_n)/\Delta t_n=\mathbf{v}(t_{n+\frac{1}{2}}) \tag{2-1}$$

Δt ——Time Step

u——Displacement

v——Speed

a——Acceleration

The formula for defining the time step, the end point, and the time step is:

$$\Delta t_{n\text{-}1}=t_n-t_{n-1},\quad \Delta t=t_{n+1}\text{-t}_n$$
$$t_{n-\frac{1}{2}}=\frac{t_n+t_{n-1}}{2},\quad \text{t}_{n+\frac{1}{2}}=\frac{t_{n+1}+t_n}{2} \tag{2-2}$$

In this paper, the joint velocity difference vector can express the node velocity vector, and the joint velocity vector combined with the difference formula can express the node displacement vector,

$$v(t_{n+\frac{1}{2}}) = v(t_{n-\frac{1}{2}}) + \frac{1}{2}a(t_n)(\Delta t_{n-1} + \Delta t_n)$$
$$u(t_{n+1}) = u(t_n) + v(t_{n+\frac{1}{2}})\Delta t_n \quad (2\text{-}3)$$

u——Displacement increment

The new geometric configuration can be expressed as the initial configuration x0 plus the displacement increment u, ie:

$$x_{t+\Delta t} = x_0 + u_{t+\Delta t} \quad (2\text{-}4)$$

x——Displacement

Boundary conditions

The separate model is to build steel units and concrete units separately, and then coordinate them through boundary conditions so that they work together and constrain all degrees of freedom to simulate the actual working conditions. It is characterized by the full consideration of the bond between the steel and concrete sliding characteristics, but the configuration of a lot of steel, complex convergence time is slow, so the results more accurate. In the model, the load of the upper structure is transferred to the upper part of the pier, and the corresponding position is used to simulate the load with the mass unit. The global gravity and the top of the pile are applied by the dynamic relaxation algorithm before the start of the dynamic calculation.

The double - sided automatic contact algorithm is used to simulate the impact of stone and pier. There are three methods for handling contact surfaces in LS-DYNA: dynamic constraint method, distribution parameter method and basic algorithm of this paper-symmetric penalty function method. The method is simple, symmetrical, and it is not easy to cause the hourglass effect of the grid, and the momentum conservation is accurate. In each time step, the algorithm first checks whether each slave node penetrates the main surface and does not do any processing for the nodes that do not penetrate. If the penetration occurs, a larger interface force is introduced from the node and the main surface, and is proportional to the penetration depth and the contact stiffness, which is called the penalty function value. Its physical meaning is equivalent to placing a spring perpendicular to the contact surface between the slave and the main surface, thereby preventing the main surface from penetrating the node. Using the increase of the penalty function value and the reduction of the time step to control the occurrence of penetration, to ensure that the contact calculation can accurately simulate the actual situation. In addition, the use of erosion contact method to simulate the protective layer of concrete after the destruction of concrete and core area of the impact of concrete contact.

Model parameters and basic conditions

Single column piers model in accordance with the "line bridge construction map" in the small box girder column pillar column layout of the pillars according to Figure 1 established. The pier is modeled from above the pile height, with a diameter of D = 1.8m, a pier height of H = 10m, and a protective layer thickness of 40mm. The longitudinal reinforcement of the pier is 36C32, into the cover beam of 1.2m, the stirrup is 1B14, the spacing is 100mm, the spiral stirrup is 1B14, the encrypted area and the non-encrypted area stirrup spacing are 60mm and 120mm respectively, and the upper and lower pier For 1.8m and 3.6m. Falling stone and steel detailed parameters in Table 1.

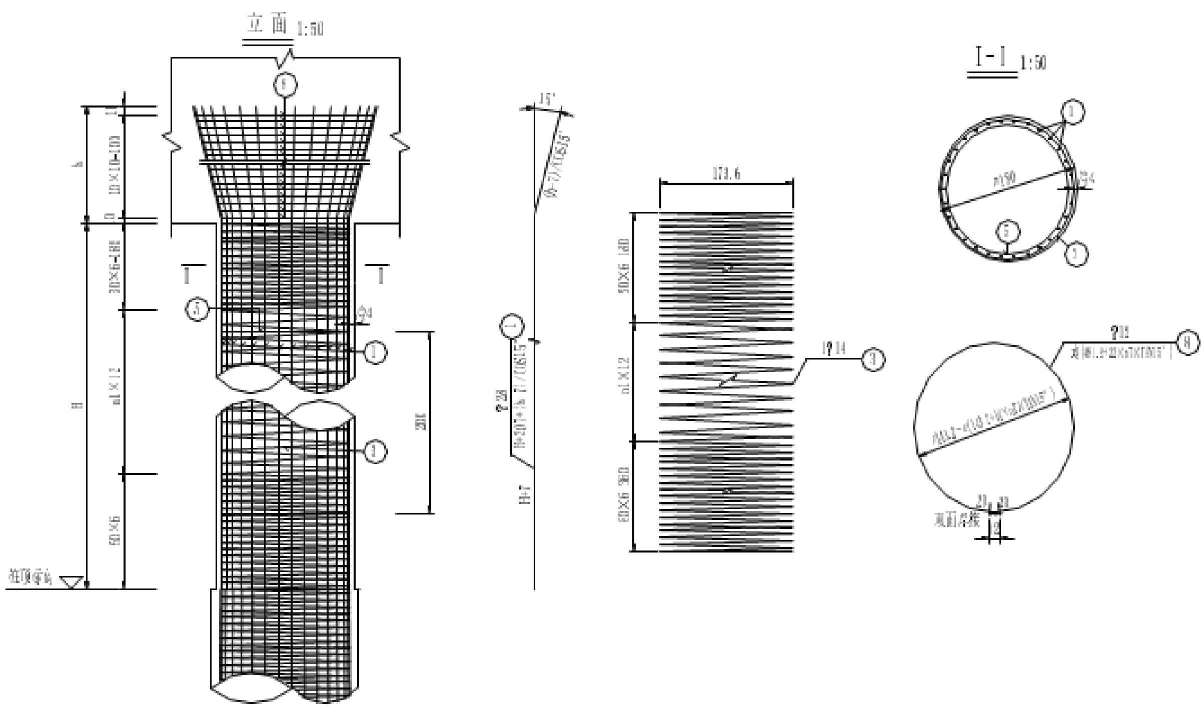


Figure 1: A line bridge construction drawings

Table 1: Rockfall and Reinforcement Parameters

Parameter	$\rho_0/(kg \cdot m^3)$	E_s/G	γ_0	σ/M	E_s'/G	ε_b
Falling stone	2660	8.95	0.16	—	—	—
Longitudinal reinforcement	7800	200	0.3	400	2	0.2
Stirrups	7800	200	0.3	400	2	0.2

The calculation parameters of the basic working condition of the single pillar pier are as follows: pier diameter D=1.8m, column height H=10m, stone diameter d =1m, impact surface is f1, impact height h=H/2, plane eccentricity e=0, the vertical impact angle α=0°, the impact velocity v=25m/s, as shown in Figure 2.

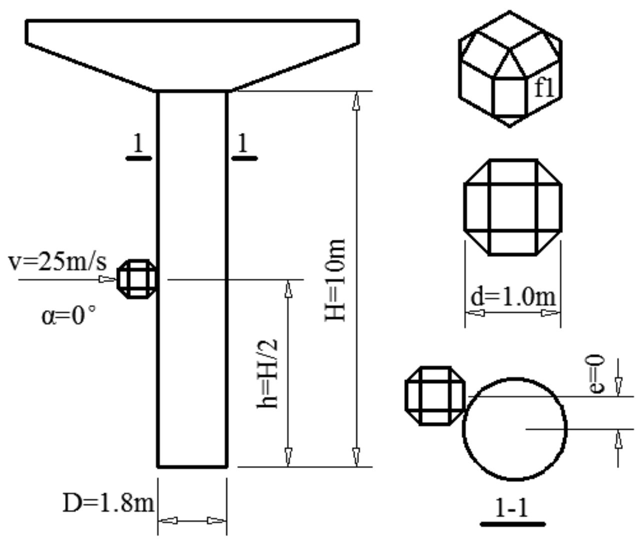


Figure 2: Sketch Map of Basic Working Condition

In the LS-DYNA software, a separate reinforced concrete model is established. The concrete is used to simulate the concrete in the model, and the steel bar is simulated with the truss element. The impact of the collision damage was analyzed by changing the diameter of the rock, the impact surface f, the impact height h, the plane eccentricity e, the elevation impact angle α and the velocity v, and the pier height H. In the calculation, the corresponding study parameters of the calculation, the remaining parameters in accordance with the basic conditions of the value, see Table 2 and Table 3.

Table 2: Parameter changes

Parameter	H/m	D/m	f	h	e	α/(°)	$v/(m\cdot s^{-1})$
1	4	0.25	f1	H/5	0	0	10
2	7	0.5	f2	2H/5	R/3	15°	15
3	10	0.75	f3	H/2	2R/3	30°	20
4		1.0	f4	3H/5	R	45°	25
5		1.25		4H/5		60°	30
6						75°	50

ANALYSIS,CALCULATION AND RESULT ANALYSIS OF EACH PARAMETER

Stone damage under the action of the concrete column as shown in Figure 3, the damage is more significant impact area of the concrete protective layer, the collision of the largest depth of about 40 mm, that is, the concrete protective layer completely destroyed, resulting in direct impact on the steel cage, The plastic deformation of the vertical reinforcement is significant, as shown in

Fig.4

According to Figure 4 analysis, the damage is more concentrated area for the pier concrete protective layer, reinforced concrete core area has not failed. The impact of the formation of the failure of the volume of 0.013m3, the basic conditions of the volume damage rate of 0.051%. While the upper structure (cover beam) along the direction of the maximum impact of the displacement of 2.65mm.

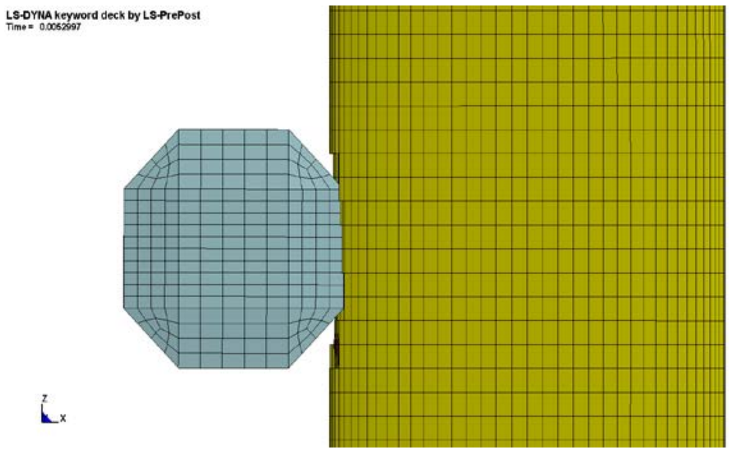


Figure 3: Concrete impact damage

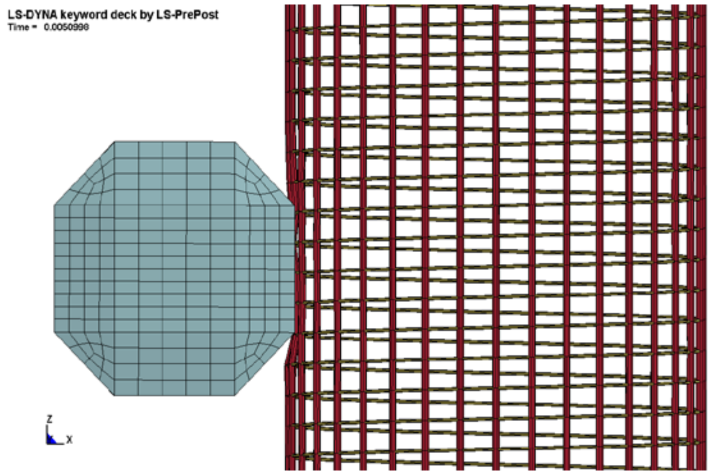
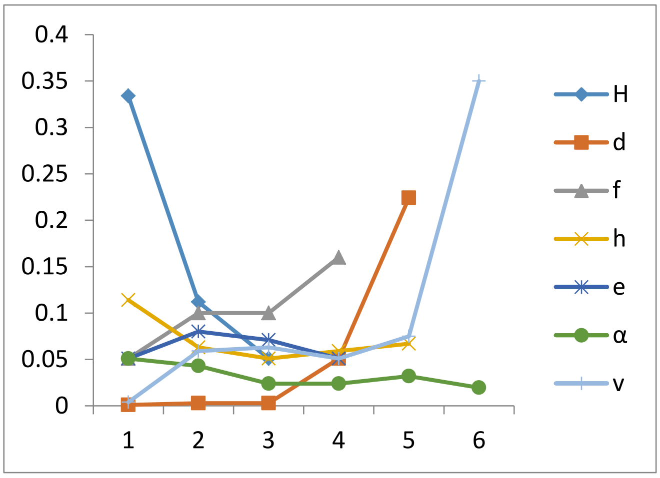


Figure 4: Dam damage deformation

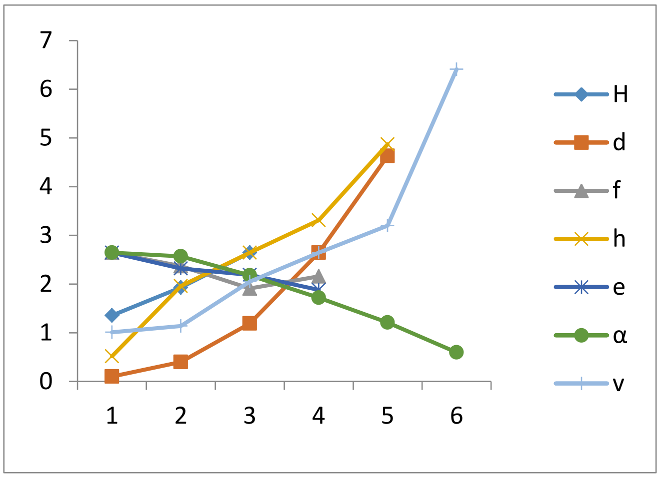
The volume damage rate ρf is the failure index of the column, ρf =Vf/V0, where Vf is the failure volume and V0 is the original volume of the concrete. Figure 5 shows the effect of the change of the parameters on the damage rate of the pier.



Damage rate ρf（%）

Figure 5: Effect of parameter change on damage of single column pier concrete

Similarly, Figure 6 shows the effect of parameter changes on the maximum displacement of the pier.



Pier top displacement (unit: mm)

Figure 6: Maximum displacement of the pier under parameter change

The influence of pier height H

The results of the three sets of models with high H=10m, H=7m and H=4m are shown in Table 4. With the decrease of the height of the pier H, the failure volume of the concrete under the impact is increasing, and the failure volume is about 2.6 times of the basic condition at H=4m. At the same time, the decrease of the pier height reduces the concrete volume of the pier The volume damage rate increases significantly with the decrease of H, and the maximum is about 6.5 times of the basic condition. The displacement of the pier increases with the increase of the height H of the pier. The main reason for the failure volume is the horizontal displacement of the pier after the impact, the larger it shows that the more the falling rock impact energy into the pillar potential energy, so the impact of rock erosion depth is smaller, the concrete damage failure volume The smaller. In addition, due to the provisions of the height of the spiral stirrups, H=4m model with high encryption, stone impact position for the stirrups encrypted area; H=7m model of the rock hit the location of the encrypted area and non-encrypted area ; The basic working model of the rock hit the location of non-encrypted area. Therefore, the spiral stirrup spacing on the concrete impact damage after the failure of the volume also has a certain impact.

Table 3: Calculation results of different pier height

Pier height H/m	4	7	10
Failure volume /m^3	0.034	0.02	0.013
Concrete volume /m^3	10.165	17.79	25.416
Volume damage rate /%	0.334	0.112	0.051
Pier top displacement /mm	1.355	1.929	2.646

The Effect of stone diameter d

The simulation results of different rock diameters are analyzed and compared, in which the diameter d is 0.25m, 0.5m, 0.75m, 1.0m and 1.25m respectively. When the diameter d from 0.25m to 0.75m, the impact of concrete under the impact of the volume is very small, only some of the unit of concrete protective layer damage; when d increased to 1.0m, although the damage volume increased significantly, but only The destruction of the protective layer; when d increased to 1.25m, concrete damage to expand significantly, and the core area of concrete failure volume is larger, 4.4 times the basic conditions. The maximum displacement in the direction of impact increases as the diameter d increases.

Table 4: Calculate the results of different diameters

Diameter d/m	0.25	0.5	0.75	1.0	1.25
Volume damage rate /%	0.001	0.003	0.003	0.051	0.224
Pier top displacement /mm	0.1	0.4	1.19	2.646	4.63

Impact of stone impact surface f

Compared with the calculation results of four groups of f1, f2, f3 and f4, the impact surface area of the latter three models is smaller than the basic working condition, so the concrete failure volume is larger than the basic working condition. At the same time, the maximum upper displacement along the impact direction is similar, and the distribution is about 2.2mm. When the energy of the stone remains constant, the minimum working condition is the maximum impact surface area. When the area of the impact surface decreases, the erosion depth increases obviously, and the damage volume of the concrete increases correspondingly.

Table 5: Different impact surface calculation model results

Impact height f	f_1	f_2	f_3	f_4
Volume damage rate /%	0.051	0.1	0.1	0.16
Pier top displacement /mm	2.646	2.37	1.91	2.16

Impact of rock impact height h

h=2H/5, h=3H/5 and h=4H/5. When h=2H/5~4H/5, h=H/5, the impact position of the stone is the non-encrypted area of the spiral stirrup. Only when h=H/5, the impact position is the encryption zone, and the damage capacity of the concrete is the largest. When the impact height h is increased, The displacement increases. Therefore, the change of the failure volume is related to the height of the rock impact, but the change law along the height direction is not obvious.

Table 6: Different impact height calculation model results

Impact height h	H/5	2H/5	H/2	3H/5	4H/5
Volume damage rate /%	0.114	0.063	0.051	0.059	0.067
Pier top displacement /mm	0.52	1.96	2.646	3.31	4.87

The impact of the plane eccentricity on the impact of the stone

Compared with the calculation results of the four groups of cavities with e= 0, e=R/3, e=2R/3 and e=R, the rock is still moving in the xz plane after the impact of the basic conditions ; And as the plane eccentricity e increases gradually, the angular velocity of the stone around the Z-axis occurs when the impact of the pier. When the e=R/3, the failure volume of the concrete is the largest. With the increase of the eccentricity e of the impact plane, the maximum displacement along the x direction decreases and the maximum displacement along the y direction increases. Therefore, the main factor affecting the failure volume is the contact surface shape and area when the collision, the smaller the collision area, the more serious damage to concrete.

Table 7: Calculation results for different plane eccentricity

Plane eccentricitye	0	R/3	2R/3	R
Volume damage rate /%	0.051	0.08	0.071	0.051
Pier top displacement /mm	2.646	2.32	2.19	1.88

The Impact of the frontal impact angle of the stone

The results of the analysis of the six groups of models are compared with the results of the analysis of the frontal impact angles α=0°, α=15°, α=30°, α=45°, α=60° and α=75° Up to 75 °, the angle of the collision increases, the speed of the horizontal direction of the stone, the volume of concrete failure correspondingly smaller, at the same time the top of the pier along the impact of the maximum displacement is also reduced, in addition to the basic conditions, only concrete protection layer failure. The reason of the failure volume change is mainly related to the horizontal impact velocity of the stone. The higher the horizontal speed, the greater the erosion depth, and the greater the damage capacity of the concrete.

Table 8: Calculate the model results for different impact angles

Impact angleα/ (°)	0	15	30	45	60	70
Volume damage rate /%	0.051	0.043	0.024	0.024	0.032	0.0197
Pier top displacement /mm	2.646	2.57	2.18	1.72	1.21	0.598

The impact of the impact velocity *v* on the stone

The calculation results of the six groups of models are compared with v=25m/ s, v=10m/s, v=15m/s, v=20m/s, v=30m/s and v=50m/s. When v=10m/s, the damage caused by the falling stone impact on the concrete pier is minimal. With the increase of the velocity, the corresponding increase of the concrete is not significant, but the increase is not significant, especially v=15m/s~30m/s, the failure of the pier is completely failure of the protective layer of the impact site, and the core area of the concrete slightly failed, the failure volume efficiency difference is not; when the impact speed increased to 50m/s, the pier of the core area concrete and steel are significant failure damage, damage is more serious, volumetric failure rate also increased to v=30m/s when 5 times. At the same time, the maximum displacement along the impact direction increases linearly with the increase of the impact velocity v. Therefore, the change of the failure volume is related to the impact velocity of the stone, which is generally increasing with the increase of the speed, but it is not linear. When the velocity is in a certain area, the failure volume change is not significant.

Table 9: Calculate the model results for different impact speeds

Impact speed v/ $(m \cdot s^{-1})$	10	15	20	25	30	50
Volume damage rate/%	0.004	0.059	0.063	0.051	0.075	0.35
Pier top displacement/mm	1.01	1.14	2.05	2.646	3.2	6.41

CONCLUSIONS

In the calculation and analysis of the pillar impact of the stone, all the parameters analyzed above have an impact on the impact damage of the pier concrete. Among them, within the scope of the study factors, the volume of the concrete failure rate of the smaller parameters of the following parameters:

(1) Pier height H: when the height of 10m, the volume failure rate of 0.051%, when the height of 4m, the volume failure rate of 0.334%, about 6 times the basic conditions;

(2) Impact surface f: in the four impact surface analysis, volumetric failure rate from 0.051% to 0.16%, about 3 basic conditions times;

(3) The impact height h: volumetric failure rate from H/2 when the minimum value of 0.051% to H/5 when the maximum 0.114%, about 2 times the basic conditions;

(4) The impact plane eccentricity e:

When not eccentric conversion to 0.9m eccentricity, the volumetric failure rate from 0.051% to 0.08%, about to expand to 1.5 times the basic conditions.

(5) Elevation impact angle α: From 0° gradually to 75°, the volumetric failure rate increased from 0.0197% to 0.051%, the rate of change is about 2.5 times.

In the above parameters analysis and calculation results, the change of concrete failure rate is basically 10 times, and the maximum damage rate is small, the concrete core damage is slight. In most cases, the destruction of the concrete protective layer is completely destroyed, while the local plastic deformation is caused by the impact of stone and steel. In addition, a little core area of concrete is slightly damaged.

Analysis of the comparative study of several factors, of which the impact of concrete volume failure rate of the larger parameters:

(1) The diameter of the impact of rock d: its change from 0.25m to 1.25m range, when the volume of the stone increased to about 125 times, with the corresponding volume failure rate increased by about 250 times;

(2) The impact speed v: its corresponding range of variation of 10m/s~50m/s, with the corresponding about 90 times the volume failure rate changes.

It can be seen that the volume and speed of rock fall on the pier damage greatly affected.

Based on the above analysis, it can be seen that the volume and speed of rockfall are the main factors that cause the damage of the single pillar bridge. Therefore, the protection of rock fall should be taken mainly to strengthen the mountain slope to prevent the formation of larger rock or rock , To reduce the rock fall speed, thereby reducing the column pier damage.

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