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Mechanical Study on Blasting Demolition and Collapse Process of Single Tower Cable-Stayed Bridge

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Abstract. During the demolition of a single-tower cable-stayed bridge, the initiation delay time of each blasting incision is determined by the deflection angle of the main tower, and the steel cable of the cable-stayed bridge directly affects the instability and dumping of the main tower due to the complex stress. In this paper, the fixed-axis rotation of the rigid body is combined with the kinetic energy theorem to obtain the functional relationship between the deflection angle of the main tower and the time. Under the condition of satisfying the model similarity theory, the time required for the main tower to deflect each angle is measured by using a high-speed camera. Studies have shown that the deflection of the main tower at 3° takes 3.52 seconds, and the force of the bridge deck acting on the main tower through the steel cable does not exceed 42.15% of its own weight. This conclusion can provide a reference for other projects in the industry.

Keywords. Demolition blasting, model experiment, cable-stayed bridge, blasting cut, blasting delay time

1. Introduction

With the rapid development and progress of society, many structures are no longer adapted to the needs of today's society and have a greater impact on the economic benefits of society, such as the old buildings in cities, abandoned water tower chimneys, Bridges with low traffic efficiency, these buildings have a certain hindering effect on the economic development of society, and these structures are usually demolished by blasting.

Blasting demolition emerged in the 1950s, and a lot of research and practice has been carried out [1]. For example, Shi Xiuzhi et al. [2] applied the theory of eccentric compression of the cylinder to obtain the calculation formula of blasting design such as the delay time of the upper and lower folded cylinder in the blasting demolition process for the chimney and other barrel structures. The delay time of the blasting network is very important and will affect the final blasting effect, and only the appropriate delay time can make the project reach the expectation. Demolition blasting started earlier in some foreign countries [3]. Conny Sjoberg of Sweden used high-speed cameras to study the collapse process of demolition blasting of buildings and used a digitizing instrument

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to input the position information of landmark points into a computer. Through computer analysis, time-position and time-velocity maps were drawn. It is possible to calculate the potential energy, kinetic energy, total energy of the structure, reaction on the upper part of the building incision and collapse load [4]. Cui Xiaorong of China also studied the process of demolition and collapse of buildings by using a close-range photogrammetry analysis system and deeply analyzed the movement attitude, energy transformation analysis, and explosion pattern of buildings (structures) in the air [5].

At this stage, with the rapid development of China's economy and construction, many buildings of the last century and the beginning of this century can no longer meet the needs of social production and life, and it is necessary to dismantle them and build new structures to meet the requirements. At present, the demolition of buildings is mainly carried out by blasting demolition [6-10], and the demolition technology of Bridges has become the research focus of Chinese engineers and technicians and academia [11]. However, most of the research is based on the blasting demolition design, and the mechanical analysis of the bridge itself and the mechanical behavior in the blasting process is rarely analyzed. Therefore, this paper simulated the demolition collapse process of the single-tower prestressed cable-stayed bridge from the perspective of mechanical analysis, so as to provide more theoretical analysis for the blasting demolition of the cable-stayed bridge in the future, so that the process and effect of directional blasting can be more in line with expectations.

2. Single-tower Prestressed Cable-stayed Bridge

Jinwu Bridge is located in Jinhua City, Zhejiang Province, across the Wuyi River, connecting Jinhua Economic Development Zone in the west and the Duohu area in the east. It is an important part of the Binhong Road East Extension project. Started in 1996, the bridge was completed and opened to traffic in December 1997. The bridge structure is damaged to different degrees and there are hidden dangers. Although it has been repaired and reinforced many times, it still can not meet the needs of the rapid growth of traffic flow, so it is urgent to blast demolition.

The cable-stayed bridge is a complex body generally composed of a main pier, cable tower, main beam, and cable. Its characteristic is that the main beam is suspended on the cable tower by the cable cable. The force of its main beam is only different from that of the main beam of an ordinary bridge by bending moment [12]. According to the number of cable towers, it can be divided into multi-pylon cable-stayed Bridges, double-pylon cable-stayed Bridges and single-pylon cable-stayed Bridges. A cable-stayed bridge with only one cable tower is a single-pylon cable-stayed bridge. Jinwu Bridge is a typical single-pylon cable-stayed bridge structure, as shown in figure 1.

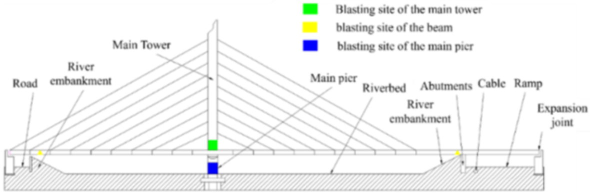


Figure 1. Schematic diagram of Jinwu Bridge structural model.

3. Rotation Angle and Time Relationship

There is only one cable tower of a single-tower prestressed cable-stayed bridge, and the condition for blasting demolition and collapse is that the only cable tower (main tower) is unstable, so the main tower can be simplified into a rigid cubic column model. As shown in figure 2, the constraint generated by the cable can be regarded as exerting part of the mass of the main beam on the main tower, that is, the weight becomes the sum of part of the weight of the main tower and main beam. The cable is simplified as an intermediate for transmitting the force.

According to the design specification for the blasting demolition of Jinwu Bridge, the remaining section width of the blasting incision is calculated by 0.7 m in the engineering design scheme, and the blasting incision is stable, which will not cause forward thrust, backseat, crushing and breaking, and the mass distribution of the main tower is uniform. After simplification, the length a=5 m, width b=2.7 m, height l=59.5 m, weight m=1.856×10^6 kg of the main tower, the volume and mass of the cut part are far less than the mass and volume of the whole main tower, and the mass lost by the blasting cut is m_{loss} =130.5 t.

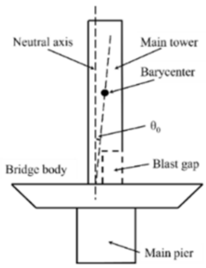


Figure 2. Simplified schematic diagram of the main tower.

3.1. Moment of Inertia and Time Equation around Blasting Incision

According to the moment of inertia of the rigid body against the axis in theoretical mechanics [13]: set the mass per unit length as r, take a micro-segment dx on the main tower, and take the mass as $m = rdx$, then the moment of inertia of the main tower against the X-axis is $J_x = \int_0^l \left(rdx \cdot x^2\right) = r \cdot l^3 / 3$, the mass $m = r \cdot l$, the height of the main tower is l , and the mass of the main tower is $m = r \cdot l$. That is:

$$J_x = \frac{1}{3} m l^2 \tag{1}$$

The moment of inertia of the main tower to the neutral axis of the blasting incision is:

$$J = J_x + m\left(\frac{b-d}{2}\right)^2 \tag{2}$$

From the kinetic energy theorem of fixed axis rotation of a rigid body:

$$\int_{\theta_1}^{\theta_2} M d\theta = \frac{1}{2} J \omega_2^2 - \frac{1}{2} J \omega_1^2 \tag{3}$$

In the elastic deformation stage, the small deflection process of the main tower can be approximated as a uniform angular velocity movement, and if the force exerted by the main beam on the main tower through the steel cable does not change, the angular velocity of the main tower is deflected arbitrarily $\omega = \frac{\theta - \theta_0}{t}$.

By synthesizing formulas (1), (2), and (3), we can obtain the (F_1 is the horizontal component force generated by the cable on the main tower):

$$mg \cdot \frac{l \cdot \cos\theta_0}{2} - mg \cdot \frac{l \cdot \cos\theta}{2} + F_1 \frac{l \cdot \sin\theta_0}{2} - F_1 \frac{l \cdot \sin\theta}{2} = \frac{1}{2} J\omega^2 \tag{4}$$

Solved:

$$t = \sqrt{\frac{J(\theta - \theta_0)^2}{mgl(\cos\theta_0 - \cos\theta) + F_1 l(\sin\theta_0 - \sin\theta)}}, 0 < \theta_0 < \theta \le \frac{\pi}{2}, \tag{5}$$

θ_0 *and* θ *satisfy small deflection*

3.2. The Action of the Bridge on the Main Tower Through the Steel Cables

During the main tower's tipping process, the steel cable's stress state is difficult to judge and calculate. However, according to formula (5), the tipping time of the main tower is in a functional relationship with the horizontal component force F_1 of the steel cable, and the magnitude of F_1 at the tipping Angle can be determined by determining the tipping Angle and the tipping time, that is, the force of the bridge on the main tower through the steel cable.

In equation (5), the initial condition is $t_0=0$; And g, l, J are known, after the formation of the blasting incision, the neutral axis of the remaining section is not in the same vertical line with the center of gravity of the upper part of the main tower, the deflection Angle is: $\tan\theta_0=1/32$, $\theta_0=1.79°$, the magnitude of the tensile force in the cable can be obtained, and the percentage of the force in the weight of the main beam can also be calculated accordingly.

4. Model Experiment

The experiment takes the Jinwu Bridge in Jinhua City, Zhejiang Province as the model, which is a single-tower cable-stayed bridge. Figure 3 depicts the experimental model, with a geometric scale ratio of 40:1 used to design and generate a simple supporting bridge model. The blasting support part of the main tower is pre-formed by combined treatment. The blasting demolition mechanism of a single-tower single-cable prestressed cable-stayed bridge is studied experimentally.

Figure 3. Actual model drawing.

Figure 4. High-speed camera appearance map.

In the test, the deflection Angle data of the main tower were collected by high-speed camera, as shown in figure 4, GX-8 digital ultra-high sensitivity high-speed camera of

NAC Company of Japan was adopted, and the maximum shooting speed was 600,000 frames /s. In this test, the shooting frame rate was set at 2000fps, and the image width was 852×384 pixels. The test system is connected by a camera to a computer equipped with HX-LINK control software, and data is manually triggered by a hand-held remote control J-Pad3.

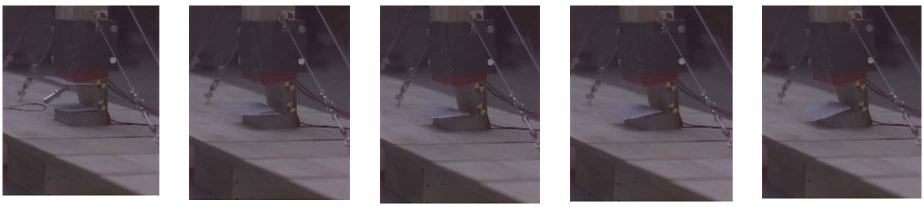
4.1. Experimental Data

During the experiment, the high-speed camera aimed at the incision and captured pictures of the incision changes (frame rate 2000 photos /s). The experiment site is shown in figure 5.

The moment when the snap of the blasting notch (the metal rod in figure 6a) is taken as the 0 moment of the timing, the effect is equivalent to the detonation of the charge, the blasting notch is formed, and the main tower is deflected under the action of overturning torque.

Figure 5. Experimental field diagram.

Instantaneous deflection of the main tower at 0°- 4° is shown in figure 6:



a) 0° b) 1° c) 2° d) 3° e) 4°

Figure 6. Plot of blasting incision changes under high-speed camera.

According to the image data captured by the high-speed camera, the notch feature points can be extracted to determine the relationship between the tower deflection Angle and time, as shown in table 1. With the increase of deflection Angle, the time used for each deflection of 1° is gradually shortened, that is, the tipping speed of the main tower is gradually accelerated.

Table 1. Model main tower deflection Angle and time relationship table.

Deflection Angle (°)	0	1	2	3	4
Time (s)	0	0.1565	0.2340	0.2770	0.3065

4.2. Model Similarity Coefficient

The main tower structure is a concrete structure, and concrete is a brittle material with high compressive strength and low tensile strength. Therefore, before the tensile area of the remaining part is broken, it can be approximated that the part is still in the range of elastic deformation. The basic form of the vibration equation of the elastic structure is as follows [14]:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F\} \tag{6}$$

The meanings of symbols in formula (6) are shown in table 2:

Table 2. The meaning table of each symbol.

Mass matrix	Damped array	Stiffness matrix	Structural displacement	External force
$[M]$	$[C]$	$[K]$	$\{u\}$	$\{F\}$

It mainly keeps the elastic restoring force and inertial force similar, and the Equation (7) is the similarity coefficient of the time of introduction according to Equation (6):

$$\lambda_t = \lambda \cdot \sqrt{\frac{\lambda_p}{\lambda_E}} \tag{7}$$

The scale factor between the entity and the model is described in table 3.

Table 3. Similarity coefficient and numerical table.

Physical quantity	Symbol	Entity	Model	Similarity coefficient
Mass density	λ_p	2400 kg/m^3	1500 kg/m^3	1.6
Geometric length	λ	260 m	6.5 m	40
Modulus of elasticity	λ_E	3.5×10^10 pa	2.2×10^9 pa	15.9
Time	λ_t			

In demolition blasting, it is generally believed that a stable tipping trend can be formed after a deflection of about 3° occurs in the main tower, and detonators at other positions of the bridge main beam and main pier can complete excitation at this time. However, when the main tower is deflected about 3°, the cut site does not undergo obvious deformation and is still in the stage of elastic deformation. Therefore, the time similarity coefficient λ_t=12.71 is calculated by equation (7), and the time $t_{prediction}$ of solid deflection 3° is 3.52s according to the model experiment.

4.3. Deflection Time and Cable Tension

According to the initial conditions and equation (5), the horizontal component force of the steel cable at different times can be calculated. Combined with the relationship between the deflection Angle and time obtained by the model experiment, the pressure exerted by the main beam on the main tower through the steel cable can be obtained, as shown in table 4.

Table 4. 0-4 ° deflection time and cable tension meter.

Deflection Angle(°)	model deflect time(s)	model similar time(s)	F_1(N)	F(N)	Gravity load ratio(%)
0	0	0			
1	0.1565	1.989	579689.32	33240719.59	42.15%
2	0.234	2.97	758654.40	21760745.21	27.59%
3	0.277	3.52	911098.82	17431423.20	22.10%
4	0.3065	3.89	1059282.71	15209451.68	19.29%

Notes: The time used for model similarity (s) is the product of the measured time $t_{experiment}$ and time similarity coefficient

As can be seen from table 4, the horizontal component force of the steel cable gradually increases during the toppling of the main tower, that is, the steel cable acts as an obstacle to the toppling of the main tower, and the obstacle effect will also increase with the increase of the deflection amplitude of the main tower. The resultant force on the steel cable gradually decreases with the deflection of the main tower, but the decreasing trend and amplitude are weakening. All the force generated by the cable on the main tower comes from the dead weight of the main beam, so the resultant force inside the cable is the force exerted on the main tower by the dead weight of the main beam, and it can be seen from table 4 that the percentage of this force in the dead weight of the main beam does not exceed 42.15%. According to the change trend of the resultant force in table 4, the force reaches the maximum at the beginning of the deflection of the main tower, and then gradually weakens. According to the blasting demolition design, after the main tower reaches its stable tipping trend, the pier column explodes immediately, and the main beam also becomes unstable and topples. How to choose the blasting delay time of the blasting incision at the pier column has a very important influence on the overall blasting effect.

5. Field Blasting Effect and Analysis

At 6:45 am on November 30, 2019, the Jinwu Bridge was successfully demolished by blasting. The vertical bridge of the main tower faces the lower reaches of the Wuyi River within 200 meters, and the main pier and bridge floor collapse in place. The blasting sequence is the main tower, beam block, and main pier, and the detonation time is 4.5 seconds. According to the analysis of the mark points recorded by the UAV image, the deflection of 4° after the main tower's detonation was 4.1s, and a stable tipping trend was formed. The error between the predicted tipping time of the main tower and the actual blasting tipping time is 5.12%. Within the allowable error range, the model experiment based on dimensional analysis can accurately predict the actual blasting demolition tipping time of the bridge.

The post-explosion inspection shows that the collapse of the bridge body is complete, the collapsed posture is stable, there is no backseat of the tower body, and the bridge floor is completely disintegrated. All kinds of pipelines operate normally during blasting, all the inspection after blasting is normal, the surrounding buildings (structures) are safe and sound, and the blasting is a complete success. The blasting process and effect are shown in figure 7.

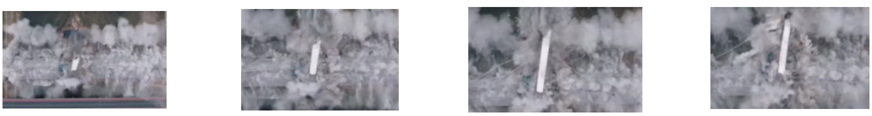


Figure 7. On-site blasting renderings.

6. Conclusion

In this paper, a theoretical analysis of the initial process of directional tipping of the main tower of a single-tower cable-stayed bridge was carried out by applying theoretical mechanics of rigid body rotation and kinetic energy theorem, and a solid similarity model was made. Experimental data were collected by high-speed camera and other test equipment, and the following conclusions were obtained by combining the physical and geometric parameters of a certain bridge:

1. Under this model, the research shows that the main tower takes 3.89s to deflect 4°, and the error with the actual tipping time is 5.12%.

2. In this paper, a formula for the time of instability deflection of the main tower in the process of demolition by blasting demolition with the presence of cable-stayed bridge cables is proposed. The formula involves physical quantities such as the deflection time of the main tower, the deflection Angle, and the force exerted by the cable on the main tower. Between the deflection of the main tower of the cable-stayed bridge and the Angle that can form a stable tipping trend, the process is relatively slow and the angular velocity is small. It is feasible to treat the process as a uniform angular velocity motion.

3. Taking a bridge as an example, in the process of blasting demolition of a single-tower prestressed cable-stayed bridge, the force acting on the main beam through the steel cable does not exceed 42.15% of its own weight.

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