

Analysis of Human-induced Vibration and Stability Cable of Pedestrian Suspension Bridge on the Influence of Bridge Comfort

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Abstract: In the context of the booming and rapid expansion of the tourism industry, an increasing number of aerial glass landscape bridges with complete transparency have been built in various scenic areas, commonly adopting the structural form of suspension bridges. Of notable concern are incidents of human-induced bridge vibrations that have occurred both domestically and internationally, causing considerable distress among tourists. Therefore, it is of paramount importance to conduct further study into the comfort of pedestrian suspension bridges. Given the above circumstances, a finite element model of the pedestrian suspension bridge is constructed, with a primary objective of simulating and analyzing the responses of tourists engaged in stationary dance, walking and running at different positions and under diverse loading conditions, while additionally exploring the effects of installing various stable cables on bridge vibration and comfort. Subsequently, the relevant conclusions are further verified through physical model experiments.

Keywords: Pedestrian Suspension Bridge; Comfort; Stable Cable; Dynamic Response

In recent years, the tourism industry has experienced a significant surge in growth and development, leading to the construction of numerous completely transparent aerial glass landscape bridges in many scenic areas. These highly "Challenging" tourism projects commonly adopt the structural form of suspension bridges.

The popularity of pedestrian suspension bridges is on the rise and has been well received globally. However, the structural characteristics of such bridges often results in a fundamental frequency less than 3Hz. The normal walking frequency of humans is approximately 2Hz, which tends to decrease further when traversing a bridge. Consequently, when pedestrians walk on pedestrian suspension bridges, walking load can lead to the generation of a vibration response in the bridge structure. If the pedestrian walking frequency is close to the inherent frequency of the pedestrian bridge structure, it may cause significant vibration of the pedestrian bridge. This vibration caused by the pedestrian walking load is referred to as "Human-induced Vibration". The pedestrian suspension bridge, under the influence of pedestrian load, will be susceptible to vibration that can lead to structural damage or even collapse, as well as significantly affect pedestrian comfort while walking on the bridge.

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Fig. 1 Glass Bridge

For instance, on June 7, 2020, several elderly women were observed dancing on a glass bridge, resulting in severe vibration on the bridge deck. This particular bridge is a suspension bridge with a span of 260m, featuring a stabilizing cable set in the middle of the span. The aforementioned event serves as a typical instance of human-induced vibration, whereby the pedestrian-induced vibration response caused discomfort for tourists on the bridge, leading to considerable panic and screams. Similar incidents have also been reported on other bridges, including the Alexandra Bridge in Ontario, NEC Bridge in Birmingham, Millennium Bridge in England, Wuhan Yangtze River Bridge, and the pedestrian bridge in Shanghai Railway Station [2] [3] [4] [5].

Human-induced structural vibration not only causes damage to structural objects, but also has a significant impact on the comfort of pedestrians walking on such structures. This warrants the attention of civil engineering professionals. As a result, the study of human-induced vibration comfort of pedestrian suspension bridges holds great significance.

To address the aforementioned issues, a finite element model of the pedestrian suspension bridge has been developed. The model primarily focuses on simulating and analyzing the vibration responses of tourists dancing in place, walking, and running at various locations and under different load conditions on the bridge. In addition, the study delves into the impact of employing different stabilizing cables on bridge vibration and pedestrian comfort. Finally, the research aims to verify the related findings through experimentation on physical models.

1. Model Establishment and Analysis of Inherent Vibration Characteristics

1.1 Model Establishment

There is a bridge with a span of 108m, a width of 2.8m, a vertical-to-span ratio of 1/12, and a suspension rod spacing of 3m. The main cable and suspension rod are analogous to high-strength steel wire ropes with diameters of 85.448mm and 14.818mm, respectively. The bridge comprises 204 units, and a finite element model is established utilizing MIDAS/CIVIL software. The model incorporates the following details:

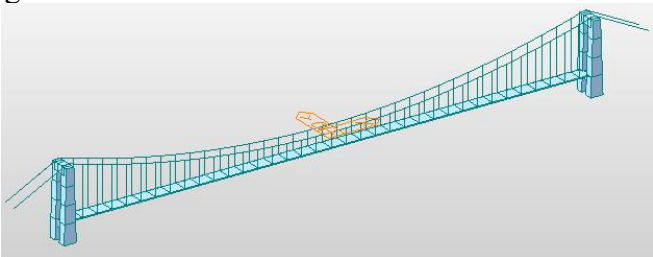


Fig. 2 Entire bridge finite element model diagram

1.2 Analysis of Inherent Vibration Characteristics

The inherent vibration properties of pedestrian bridges manifest in their vibration characteristics. The structure's modal analysis reveals a total of 80 vibration modes, with the Lanczos method being utilized for the overall vertical modal analysis. Table 1 presents the first 10 inherent frequencies and their modal mass participation coefficients for the pedestrian bridge, while Fig. 3 depicts the first four vibration modes. Finite element modal analysis is conducted using MIDAS. Table 1 presents the first 10 inherent frequencies and their vibration mode characteristics for the bridge, with corresponding vibration mode diagrams for the first four orders being shown in Fig. 3.

Table 1 Characteristics of the first 10 inherent frequencies and vibration modes of pedestrian bridges

Modal No.	Frequency (Hz)	Vibration Mode Description
1	0.484	First-order antisymmetric vertical bending

2	0.676	Symmetrical transverse vibration of the main cable
3	0.687	Anti-symmetric transverse vibration of main cable
4	0.724	Second-order symmetrical vertical bending
5	0.984	Symmetrical transverse vibration of main cable
6	0.984	Anti-symmetric transverse vibration of main cable
7	1.129	Third-order antisymmetric vertical bending
8	1.254	Fourth-order symmetrical vertical bending
9	1.334	First-order transverse bending and symmetrical transverse vibration of main cable
10	1.387	Anti-symmetric transverse vibration of main cable

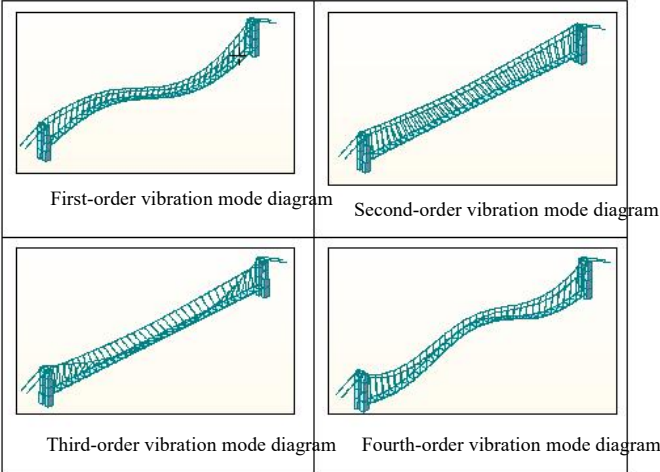


Fig. 3 Fourth-order vibration mode diagram of pedestrian bridge

2. Comfort Analysis of Different Parameter Models

2.1 Influence Parameters and Load Conditions

Vertical loads are generated by the walking of tourists, with crowd loads being categorized based on the number of tourists and their frequency. When fewer tourists are present on the bridge, they can walk freely without any hindrance. However, when there are numerous tourists on the bridge, their movement may slow down due to crowded conditions, or some tourists may pause to take photos, which can impede the flow of pedestrian traffic in certain areas. This may result in a decrease in walking frequency, while the collective pace may become more uniform due to enhanced synergy between tourists. Some tourists may also engage in activities such as taking photos simultaneously or dancing and capturing short videos on the bridge. During such activities, the jumping steps of the tourists may synchronize with the music. The aforementioned factors can result in a significant increase in vibration amplitude and acceleration of the pedestrian suspension bridge. This can cause panic among tourists on the bridge, and some may even run on the deck to evacuate. In accordance with the "Building Vibration Load Standard" GB/T 51228-2017, the vertical load generated by a single person walking is 280N [5]. The impact of pedestrians on the bridge deck adheres to the European standard "Design of Footbridge Guidelines" EN03-2007 [7], which specifies the following:

$$F(t) = nP\alpha_i \cos(2\pi f_s t)$$

Where: $F(t)$ -Vertical time history load generated by tourists walking, with unit of N;
 n - Number of tourists;
 P - The vertical force generated by a single pedestrian walking at f_s step frequency, taking value of 280N;
 α_i - Dynamic load factor, taking value of 1;
 f_s - Step frequency, with unit of Hz;

t - Time, with unit of seconds;

In the model, the impact of tourists on the bridge is incorporated using the aforementioned equation. Fig. 4 presents the simulated load time history of three tourists when their takeoff frequency aligns with the inherent frequency of the bridge. To simulate the corresponding load at a given node when tourists dance at a specific position on the bridge, the model applies the corresponding load. Approximate simulation is conducted when tourists move on the bridge using the following method: the corresponding loads are sequentially applied to the model nodes based on the movement speed of tourists. Moreover, the time when the load acts on the node must align with the time when tourists reach a specific position on the bridge. Specifically, the time that the load acts on the corresponding nodes equals the distance between the nodes divided by the travel speed of the tourists.

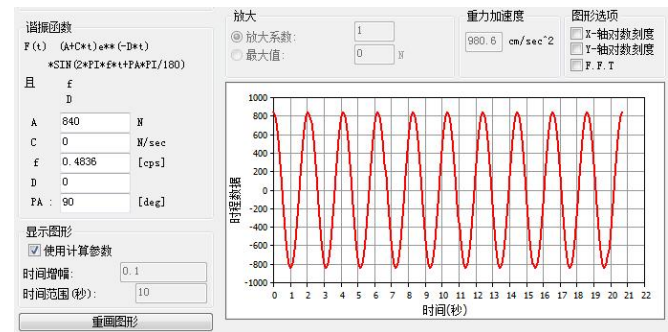


Fig. 4 Load time history of 3 tourists dancing according to the fundamental frequency of the bridge

To analyze the vibration characteristics of the bridge deck in various circumstances and in tandem with the bridge's inherent vibration characteristics, the design incorporates ten different working conditions, which are detailed in Table 2.

Table 2 Simulation of working conditions of pedestrian bridges

Bridge Deck Condition	Working Condition	Step Frequency	No. of People	Loading Situation
Dancing in the original place	1	0.363	3	1/4 span
	2	0.484	3	1/4 span
	3	0.605	3	1/4 span
Dancing in the original place with different numbers and positions	4	3.000	4	1/4 span
	5	3.000	4	1/2 span
	6	3.000	4	2 people 1/4 span, 2 people 3/4 span
	7	3.000	8	1/4 span
Tourists walk normally	8	2.000	10	Loading from 1/4 span to 1/2 span
	9	4.000	10	Loading from 1/4 span to 1/2 span
Tourists running in fear	10	4.000	8	4 people from 1/4 span to 1/2 span
				4 people from 3/4 span to 1/2 span

2.2 Comparison of comfort under different working conditions

2.2.1 Three Tourists Dancing on Bridge at Different Takeoff Frequencies

In accordance with the first-order inherent vibration characteristics of the bridge, the node dynamic load method is used to apply the position of three tourists at 1/4 span for a duration of 30 seconds. The resulting maximum acceleration at a specific location on the bridge at a given time is tabulated in Table 3 (Unit: cm/s²).

Table 3 Accelerometers for bridges at different frequencies and locations

Position (span)	1/8	1/4	3/8	1/2	5/8	3/4	7/8
Working condition 1	7.0	-24.4	6.5	3.3	-6.3	8.8	7.2
Working condition 2	-49.2	-62.2	-47.5	3.4	47.5	62.2	49.0
Working condition 3	7.7	-24.6	9.1	3.5	8.4	12.4	10.3

The aforementioned table reveals that the bridge's utmost acceleration occurs at 1/4 span or 3/4 span during three distinct operational circumstances. In the event of the dance step frequency of three tourists aligning with the bridge's fundamental frequency (working condition 2), the maximum acceleration is approximately 62.6cm/s², an escalation of roughly 2.5 times when compared to working condition 1 and working condition 3.

The acceleration time history curve at 1/4 span of the bridge during three working conditions is demonstrated in Fig. 5. It is observed that the acceleration peak of working conditions 1 and 3 did not display noteworthy oscillation; however, resonance occurred in working condition 2 within 30 seconds of loading. If the dancing tourists do not terminate their movements and intermittent jumping, the peak acceleration will continue to surge for a specific duration.

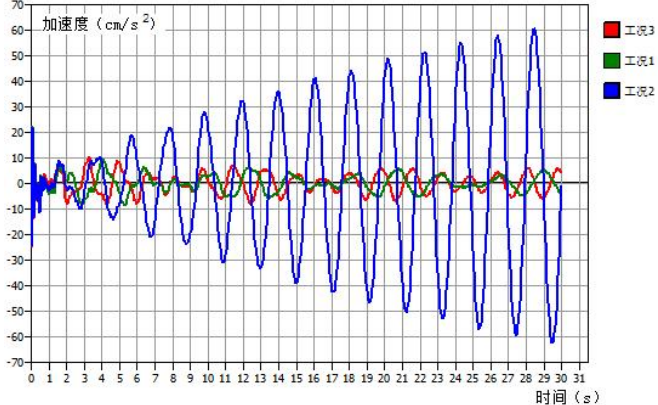


Fig. 5 Acceleration time history curve at 1/4 span of the bridge under asynchronous frequency
2.2.2 Dancing in Original Place with Different Numbers and Positions

By integrating the aforementioned research, we can comprehend that the acceleration response of the bridge deck varies when tourists dance at various frequencies on the bridge, and resonance arises when the frequency aligns with the bridge's fundamental frequency. Typically, the step frequency during dancing surpasses that of normal walking, with a frequency of 3Hz.

Working condition 4 comprises four tourists dancing at 1/4 span, while working condition 5 consists of four tourists dancing at the middle of the span. Working condition 6 entails two people dancing on 1/4 span and two people dancing on 3/4 span. Finally, working condition 7 encompasses eight people dancing on 1/4 span. Table 4 illustrates the maximum acceleration at a specific position on the bridge deck during a loading period of 10 seconds (Unit: cm/s²).

Table 4 Acceleration response table for dancing in the original place with different numbers and positions

Position (span)	1/8	1/4	3/8	1/2	5/8	3/4	7/8
Working condition 4	-14.9	-39.2	-18.2	17.0	19.2	-24.2	-21.1
Working condition 5	5.5	3.4	7.3	-24.5	7.3	3.4	5.5

Working condition 6	9.3	-19.6	-7.1	0.0	7.1	19.6	-9.3
Working condition 7	-29.7	-78.5	-36.3	33.9	38.5	-48.3	-42.1

In the table presented above, it is observed that, with the exception of working condition 5 where the maximum acceleration of the bridge deck is found at the middle span, the maximum acceleration of the bridge deck under all other conditions occurs at 1/4 span or 3/4 span. Notably, working condition 7 exhibits the highest peak acceleration of 78.5cm/s². While the number of tourists in working condition 6 is the same as in working condition 4, the peak acceleration is only half of that in working condition 4. Similarly, while the number of tourists in working condition 5 is the same as that in working condition 4, the peak acceleration is only 0.63 times that of working condition 4. These findings suggest that, even when other factors remain constant, the acceleration response of the bridge deck is influenced by the takeoff location, the distribution of the number of people taking off, and the number of people taking off.

Fig. 6 presents the acceleration time history curve at the point of maximum acceleration on the bridge deck for four working conditions. The curve indicates that the maximum acceleration response of the bridge deck tends to stabilize under all four working conditions after a certain period of loading.

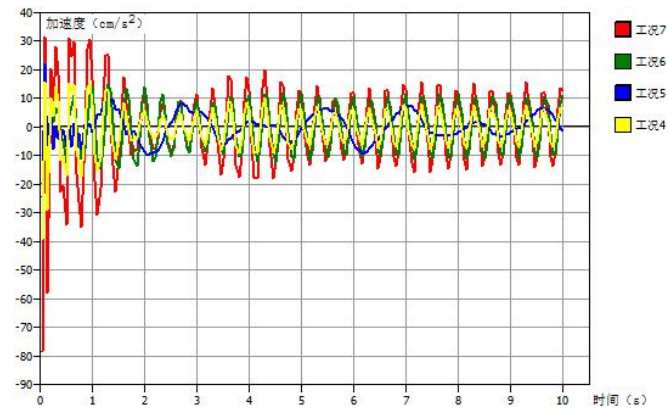


Fig. 6 Acceleration time history response curve at the maximum acceleration of the bridge deck under different numbers of people and positions

2.2.3 Tourists moving on the bridge deck

During normal walking, the typical walking frequency of pedestrians is approximately 2Hz. Working condition 8 involves a moving load of 8 pedestrians walking normally from 1/4 span to 1/2 span. On the other hand, working conditions 9 and 10 simulate the moving loads of tourists running on the bridge deck with a step frequency of 4Hz. Specifically, condition 9 involves 8 tourists running from 1/4 span to 1/2 span, while condition 10 involves 4 tourists running from 1/4 span to the middle of the span. Table 5 provides detailed information on the maximum acceleration that occurs at a specific location on the bridge deck during the 15-second loading period for each of these working conditions (in cm/s²).

Table 5 Acceleration Response Table under Different Moving Conditions

Position (span)	1/8	1/4	3/8	1/2	5/8	3/4	7/8
Working condition 8	-77.4	158	-42.7	66.5	-112	25.6	61.9
Working condition 9	-87.5	188	112	59.9	63.5	-51.0	30.8
Working condition 10	-87.3	201	160	0	-160	-201	87.3

Premised on the data presented in the aforementioned table, it can be deduced that the maximum acceleration of the bridge deck occurs at either 1/4 span or 3/4 span, depending on the working condition. Evidently, the bridge deck underwent substantial acceleration peaks across all working conditions, signifying that the synchronized movement of 8 individuals at the same cadence produced notable acceleration. Notably, the highest acceleration magnitude occurred during operating condition 10, reaching 201 cm/s².

The acceleration time history curve at the location where the maximum acceleration occurs on the bridge deck is presented in Fig. 7 for three distinct working conditions. The figure illustrates that the maximum acceleration response of the bridge deck appears to converge and stabilize after a certain period of loading under working conditions 9 and 10, while condition 8 continues to exhibit a steady increase.

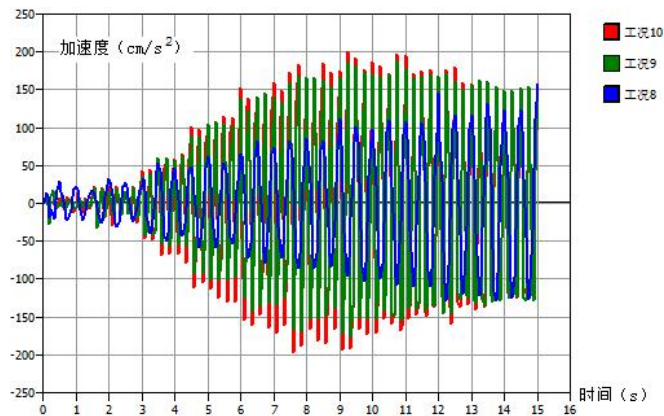


Fig. 7 The acceleration time history curve at the maximum acceleration point of the bridge deck when tourists move on the bridge

2.3 Summary

The data and figures presented in the preceding sections demonstrate that the acceleration response of the bridge deck is contingent upon several factors, including (1) the step frequency of dancing tourists, where the closer it is to the fundamental frequency, the higher the acceleration response; (2) the number, location, and dispersion of dancing tourists; and (3) the frequency and direction of the tourists' movement. According to the European standard “Design of Footbridge Guidelines” EN03-2007 regarding comfort levels (Table 6), discomfort is experienced by tourists under working conditions 8 to 10, while according to British regulation BS5400 [8], exceeding 0.5m/s² is deemed unacceptable. Given that working conditions 2, 7, and 8-10 of this bridge all exceed the limit, it is essential to study strategies to enhance the comfort of pedestrians using suspension bridges.

Table 6 Design guidelines for German pedestrian overbridges - pedestrian comfort indicators

Grade	Performances	Vertical Acceleration (m/s ²)
1	Highly comfortable	<0.5
2	Moderate comfort	0.50-1.00
3	Uncomfortable	1.0-2.5
4	Unbearable	>2.5

3. Establishment and Comfort Analysis of a Stable Cable Model

3.1 Setting up Stable Cables and Establishing Models

As mentioned in the previous section, the acceleration response of the bridge deck has surpassed the limits set by the relevant regulations, particularly under working conditions 2, 7, and 8-10. This section aims to address this issue by proposing the installation of stable cables below the existing

bridge main beam to enhance bridge comfort, as illustrated in Fig. 8. The stable cable suspension system comprises cables positioned at 1/4 span, 1/2 span, and 3/4 span of the bridge, respectively. The main and suspension cables of the stable cable system are made of high-strength steel wire ropes with diameters of 48.46mm and 14.82mm, respectively.

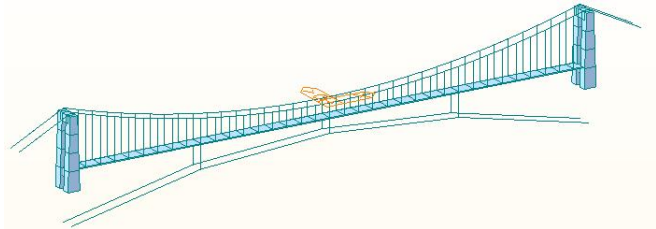


Figure 8. Model for Setting Stable Cables

3.2 Comparison of Comfort between Setting Stable Cable Bridges and the Original Bridge

When setting up a stable cable model, it is crucial to ensure the adherence of the applied conditions 2, 8, and 10 to the original bridge conditions. Subsequent to computation, the maximum acceleration encountered during the loading phase of the model with stable cables remains within either the 1/4 or 3/4 span of the bridge. Comparison of the maximum acceleration (in cm/s²) that emerges during the duration of load application is presented in the table below.

Table 7. Comparison of acceleration peaks between two models

Item	Original model	Model with stable cable	Improvement rate compared to the original model
Working condition 2	-62.25	-59.10	5.05%
Working condition 8	157.65	135.71	13.92%
Working condition 10	200.50	163.68	18.37%

As depicted in the aforementioned table, incorporating a certain number of stable cables can enhance the pedestrian bridge's comfort level, with the extent of improvement varying depending on the working conditions. To further scrutinize the acceleration time history curve at 1/4 span of the bridge deck under condition 10, Fig. 9 will be analyzed. The figure indicates an overall decrease in acceleration values during the loading phase.

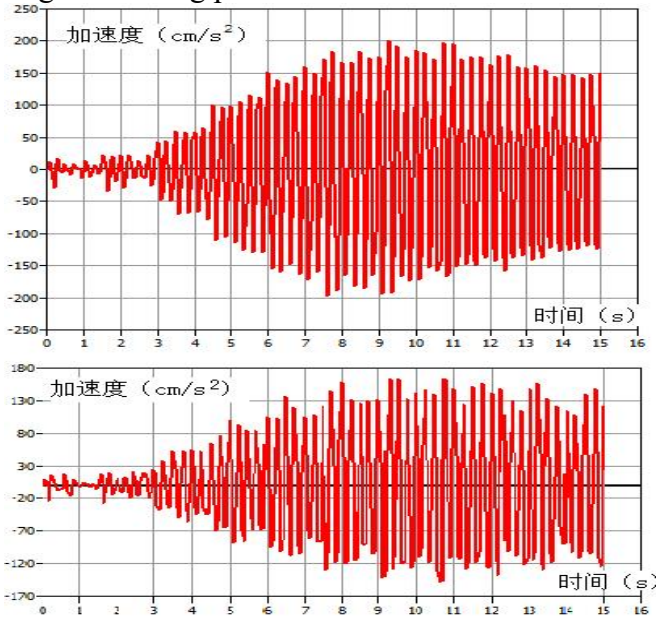


Fig. 9 Time history curves of acceleration values of two models at 1/4 span of the bridge under condition 10

3.3 Summary

The utilization of stable cables under the original bridge has led to a reduction in the peak acceleration of the bridge under the corresponding working conditions. Moreover, a corresponding decrease in the bridge's acceleration value during the loading phase has been observed, signifying the efficacy of this approach in enhancing the comfort of pedestrian suspension bridges to a certain extent.

4. Simulation of Physical Models

4.1 Introduction to Physical Models and Experimental Methods

4.1.1 Introduction to the Physical Model

In light of the aforementioned findings, a multitude of rigorous experiments were conducted to further substantiate the relevant conclusions. The physical model utilized in the experiment is depicted in Fig. 10, with a span of 8.25m, a vertical span ratio of the main cable at 1:11, and suspender spacing of 0.4mm. The main cable was constructed with high-strength steel wire measuring 6mm in diameter, while the suspender was comprised of a 10mm steel rod.

To simulate the impact of the proposed approach on enhancing bridge comfort, a stabilizing cable was installed beneath the original bridge, as depicted in Fig. 10. The slings were positioned at 1/4, 1/2, and 3/4 of the bridge. The stabilizing cable, composed of high-strength steel wire with a diameter of 6mm, was utilized alongside steel rods measuring 10mm in diameter as slings.

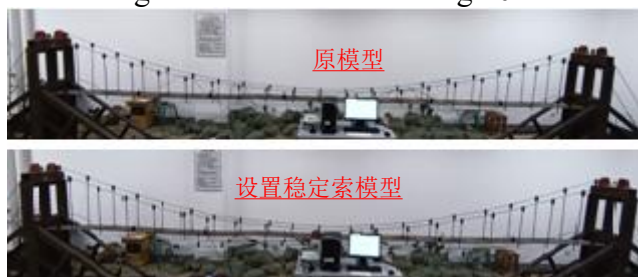


Fig. 10 Physical model of pedestrian suspension bridge

4.1.2 Simulation of dynamic loads and data collection

The dynamic load follows the simple harmonic dynamic load mentioned above, utilizing a simple harmonic dynamic load approach that utilizes an electric motor and a miniature vehicle to mimic the load that tourists would impose on a bridge, as depicted in Fig. 11. The small hammer is firmly attached to the transmission shaft of the electric motor with screws and nuts to simulate the dynamic load generated by the centrifugal force during motor operation. The walking frequency of pedestrians is simulated by regulating the speed of the electric motor, which models the pace of a tourist's stride per revolution. To simulate diverse walking frequencies, the speed of the electric motor can be adjusted accordingly. To ensure consistency in the applied centrifugal force, the nut is adjusted to vary the distance between the hammer and the transmission shaft at varying speeds.

Fix the electric motor on the trolley. When the electric motor is working, the trolley allows for free forward and backward movement, generating centrifugal force. This setup ensures that the longitudinal component of the centrifugal force exerted by the electric motor does not affect the bridge. The electric motor only produces vertical dynamic loads on the bridge to emulate tourists' stationary dancing on the bridge. Moreover, the negligible weight and static nature of the miniature vehicle negate any impact on the bridge's natural vibration characteristics.

The moving speed of the small vehicle, the speed of the electric motor, and the centrifugal force generated by the electric motor (adjusted by modifying the distance between the small hammer and

the rotating shaft through the nut) are all variable parameters. Thus, the movement of the vehicle can replicate pedestrian movement on the bridge.



Fig. 11 Simulation of dynamic load

4.1.3 Data Collection and Working Conditions

By utilizing the above-described method to apply the relevant dynamic load to the bridge, the acceleration response of the bridge is measured using acceleration sensors, as depicted in Fig. 12. The sensors are placed at the 8th equal portion of the bridge, with sensor bias numbers ranging from 1 to 8 employed to gather acceleration readings at the corresponding positions.



Fig. 12 Acceleration sensor

This experiment outlines four distinct operating scenarios for two models, which are illustrated in Table 8. Working conditions 1 and 2 replicate stationary dancing by tourists, whereas working conditions 3 and 4 simulate tourists' movement on the bridge.

Table 8 Working condition parameters table

Item	Frequency	Load amplitude	Position	Speed
Working condition 1	2	1.5N	1/4 span	0
Working condition 2	2	1.5N	1/2 span	0
Working condition 3	3	1.2N	Moved from1/2 span to 1/4	25cm/s
Working condition 4	3	1.2N	Moved from1/4 span to 1/2	25cm/s

4.2 Experimental Data Analysis

The described methodology was employed to conduct independent experiments on two models. For condition 1, the maximum acceleration value of the bridge deck over a 10-second period was recorded at measurement point 6, located near 1/4 span, at 4.21 m/s². Fig. 13 shows the acceleration time history curve for this scenario, while Fig. 14 depicts the time history curves of the 8 measurement points.

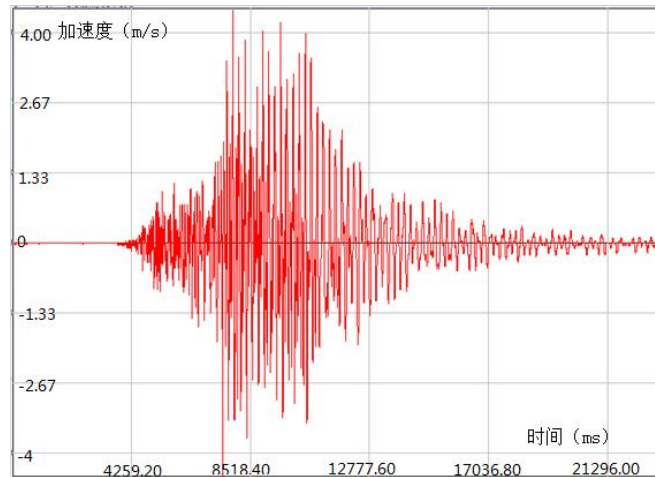


Fig. 13 Acceleration time history curve of measurement point 6 of the original model under working condition 1

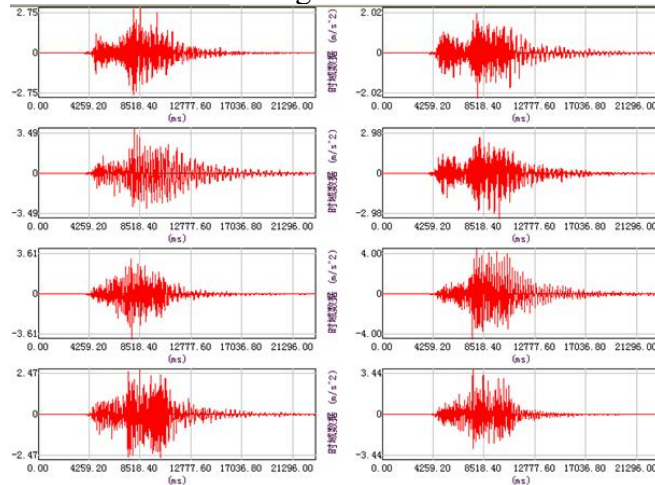


Fig. 14 Acceleration time history curves of 8 measurement points in original model under condition 1

Due to the limitation of the article length, this report solely presents the peak acceleration values of the two models under different working conditions during loading, as displayed in Table 9 Comparison table of acceleration peak values between two models under different working conditions.

Item	Speed (m/s ²)		Reduction rate compared to the original model
	Original model	Model with stable cable	
Working condition 1	4.21	3.62	14.01%
Working condition 2	3.16	2.87	9.18%
Working condition 3	3.48	3.25	6.61%
Working condition 4	2.84	2.51	11.62%

Upon comparison of several examples, it is apparent that the installation of a stable cable results in a variable decrease in the peak acceleration response of a bridge deck under identical working conditions.

4.3 Summary

The setting of stable cables in the original model has led to an improvement in the comfort of the bridge under diverse working conditions in this experiment. This suggests that the approach of enhancing bridge comfort by installing stable cables is indeed applicable.

5. Conclusion and Outlook

Premised on the finite element model and experiments conducted on a solid bridge model, the following conclusions can be drawn:

- 1) When tourists engage in dancing activities on the pedestrian suspension bridge, and the step frequency aligns with the basic frequency of the bridge, resonance can occur. The acceleration of the bridge deck will persistently increase for a certain duration, potentially resulting in discomfort for other tourists traversing the bridge.
- 2) The acceleration response of the bridge deck exhibits variation based on the number of tourists, the location of dancing on the bridge, and the distribution of dancing tourists on the bridge.
- 3) When tourists traverse the bridge at a particular step frequency, particularly while running, the acceleration response value of the bridge deck is comparatively elevated, potentially causing discomfort for other tourists on the bridge.
- 4) The implementation of stabilizing cables beneath the bridge can mitigate peak acceleration to a certain degree and enhance the comfort experienced on the bridge.

The current research presented in this article acknowledges that there is potential for further development in the investigation of certain subjects due to the influence of professional knowledge and expertise. Specifically, the following areas require additional attention and advancement:

- 1) When the distribution of tourists on the bridge diverges, what patterns will the acceleration response of the bridge deck show?
- 2) When the position, quantity, and cross-section of the stabilizing cables undergo alterations, what will the acceleration response of the bridge deck exhibit?
- 3) In addition to the implementation of stabilizing cables, it is also worthwhile to exploring the utilization of techniques such as tuned mass dampers [9], including the analysis of the efficiency and cost-effectiveness of various methods.

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