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A method for predicting the lateral girder response of footbridges induced by pedestrians

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ABSTRACT

A numerical method is proposed to predict the lateral girder response induced by pedestrians on footbridges. The method is based on the motion of equations including the coefficients of the rate of a pedestrian's lateral force, pedestrian density, rate of synchronized pedestrians, and pedestrians' attitude to large vibration amplitude. These coefficients were determined by the field measured data of two slender footbridges and the experimental data of pedestrian induced forces. The lateral girder responses were then predicted for these bridges with different pedestrian densities by the proposed numerical method. They agreed reasonably well with the field measured girder responses of these bridges, which verified the proposed prediction method.

1. Introduction

It was recently reported that the girder vibrated laterally on some slender footbridges when many people walked. This lateral vibration was first observed on the T-bridge (Fig. 1), a cable-stayed bridge, but the girder response was less than 15 mm and did not jeopardize its serviceability. However, as this kind of vibration had not been studied before, field measurements were conducted to clarify the mechanism of this lateral vibration [1–3]. It was found that the girder vibrated in the first lateral mode with a frequency of 0.90 Hz. The gravity center of the body moves laterally when a person walks with his right and left foot in turn, which induces a lateral dynamic force with a frequency of about 1.0 Hz. When the frequency of this lateral dynamic forces induced by pedestrians is close to the bridge lateral natural frequency, it can be a resonant force to excite the girder. The more pedestrians are synchronized to the girder vibration, the further the lateral girder responses increase. In this sense, the vibration has a self-excited nature. However, it is observed that, when pedestrians feel that the vibration is uncomfortably large, they reduce their walking speed or hold handrails, and therefore the girder amplitude remains in a steady state and does not become infinitely large thanks to this adaptive nature of human beings.

The same kind of vibration problem occurred on the London Millennium Bridge in the year 2000 [4,5], and the bridge was closed for 20 months until the vibration was suppressed by Taylor dampers and tuned mass dampers. A dynamic model was proposed by Dallard et al. to clarify this lateral vibration problem on the London Millennium Bridge [4,5]. Their model is based on the single degree dynamic equation, assuming that the external force induced by pedestrians is proportional to the girder velocity. However, the pedestrians' synchronization is much more complicated and there are many factors affecting the interaction between the girder and pedestrians walking; pedestrians modify their walking with the girder vibration amplitude, and the pedestrian density and the bridge mass affect the girder response.

The M-bridge (Maple Valley Great Suspension Bridge) is a suspension footbridge built in 1999, crossing a dam lake (Fig. 2). It has suffered from the lateral vibration since it was opened [6]. The girder vibration has been fairly large and some pedestrians feel unsafe. This vibration seems to be different from that on the T-bridge because the first lateral natural frequency of the bridge is about 0.3 Hz, which differs from the usual synchronous frequency. It was found from field measurements that the bridge vibrated in either the third asymmetric mode with a natural frequency of 0.88 Hz or the fourth symmetric mode with a natural frequency of 1.03 Hz, depending on the distribution of the pedestrians on the bridge [6].

Nakamura proposed a dynamic model including the non-linear dynamic forces induced by the pedestrians' synchronization [7]. The method is based on the motion of equations including coefficients of the rate of a pedestrian's lateral force, the pedestrian density, the rate of synchronized pedestrians, and the pedestrians' attitude to large vibration amplitude. In this paper these coefficients are determined by the field measured dynamic data of the T-bridge and the M-bridge and the experimental data

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Fig. 1. T-bridge.

Fig. 2. M-bridge.

of pedestrian induced forces. The lateral girder responses are then predicted by solving the proposed model numerically and compared with the measured responses with different pedestrian densities on the two bridges. These field data were collected by the authors themselves. This study is invaluable because only a few lateral vibration data are available on actual bridges in the world.

2. Proposed dynamic model

As the girder vibrates in a specific lateral mode, the lateral vibration induced by pedestrians can be modeled as a single degree of freedom dynamic model using the modal analysis of that specific mode.

$$M_B x_B''(t) + C_B x_B'(t) + K_B x_B(t) = F_P(t) \quad (1)$$

$$F_P(t) = k_1 k_2 H(x_B') G(f_B) M_P g \quad (2)$$

$$H(x_B') = \frac{x_B'(t)}{k_3 + \left|x_B'(t)\right|} \quad (3)$$

$$G(f_B) = 1.0. \quad (4)$$

Eq. (1) is the equation of motion; x_B is the modal displacement of the girder, x_B' the modal velocity of the girder, x_B'' the modal acceleration of the girder, M_B the modal mass, C_B the modal damping coefficient, and K_B the modal stiffness of the bridge. The right-hand side of Eq. (1), F_P, is the modal lateral dynamic force induced by pedestrians on the bridge deck. This is assumed to be proportional to the modal self-weight of pedestrians, $M_P g$, multiplied by the two coefficients, k_1 and k_2, and two functions, $H(x_B')$ and $G(f_B)$, as shown in Eq. (2).

The coefficient k_1 is the ratio of the lateral force to the pedestrian's weight. The coefficient k_2 is the percentage of pedestrians who synchronize with the girder vibration. $H(x_B')$ is the function to describe the pedestrians' synchronization nature. It is assumed that the pedestrians synchronize proportionally with the girder velocity x_B' at low velocities. When the girder velocity becomes large, the pedestrians feel uncomfortable or unsafe and they decrease their walking pace. Therefore, the girder response does not increase infinitely but is limited at a certain level. The denominator of Eq. (3) expresses this saturation phenomenon. The saturation rate depends on the coefficient k_3. The function $H(x_B')$ increases linearly at low velocities but its increase rate becomes smaller at higher velocities and it converges to 1.0. The value of k_3 (m/s) is decided by trial and error so that it corresponds to the measured data.

$G(f_B)$ is the function to describe how pedestrians synchronize with the bridge natural frequency. There have been many studies on the vertical behaviours of walking people. Many data suggest that the frequency range of people walking is between 1.5–2.5 Hz [8]. On the other hand there are few data available on the lateral load behaviours of walking people, and $G(f_B)$ cannot be decided. As the lateral force of pedestrians is 0.5 of the vertical force, it would be 0.75–1.25 Hz. Since the mechanism of the lateral vibration is the resonance of the bridge and the pedestrians, pedestrians are most likely to synchronize at the bridge frequency around 1.0 Hz. However, it is not known how much and how wide the bridge frequency range around 1.0 Hz affects the synchronization nature. There are not enough data available so far and future studies are required to clarify this. Since the natural frequency of the T-bridge and the M-bridge and the London Millennium Bridge is between 0.9–1.1 Hz, the function $G(f_B)$ is assumed to be 1.0 in this study.

The authors intend to establish a practical method instead of a pure mathematical method. There are other methods which contain harmonic terms in the loading function [9]. This may be more mathematically accurate than our method; however, even such a method usually contains a hypothetical equation. In our method the harmonic terms do not appear in the basic load equation but their effects are considered in Eq. (2).

3. Coefficients in the dynamic model

In this chapter the coefficients used in Eq. (1) to Eq. (4) are studied in detail.

Experiments were conducted to find the coefficient k_1, a ratio of the lateral force to the pedestrian's weight, and the pedestrians' dynamic forces on a laterally vibrating deck [10]. The testing was carried out using a shake table 1500 mm wide and 1000 mm long. A reaction plate 800 mm wide and 500 mm long was placed on the shake table deck. A pedestrian walked on spot of the reaction plate. The shake table was laterally vibrated by actuators with frequencies from 0.75 Hz to 1.25 Hz, with amplitudes from 10 mm to 70 mm. Five people were tested: two were female and three male. They were not bridge engineers and did not have any knowledge about this lateral vibration problem. They were not notified of the purpose and procedure of the test. Accelerometers were attached to the reaction plate and the waist belt of the pedestrian. The dominant frequency of the pedestrian movement was compared with that of the shake table to find the rate of synchronized people with the shaking frequency.

Fig. 3 shows the non-dimensional lateral forces induced by pedestrians, the lateral force divided by the pedestrian weight. The figure shows the non-dimensional lateral forces of five pedestrians at a shaking frequency of 1.0 Hz. The non-dimensional lateral forces increase with the shake table amplitude. The average of five pedestrians is about 8% of the pedestrian weight before the shake table moves, about 9% of the pedestrian weight at the shake table amplitude of 10 mm, and about 15% at the amplitude of 70 mm.