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VIBRATION SERVICEABILITY OF FOOTBRIDGES: CROWD EVACUATION IN EARTHQUAKE

X. Wei(1), B. Fu(2), J. Chen(3)

(1) *Wissenschaftliche Mitarbeiter, Ruhr-Universität Bochum, Germany, wei_xinxin@hotmail.com*
(2) *Associate Professor, School of Civil Engineering, Chang'an University, China, 90_bofu@chd.edu.cn*
(3) *Assistant Professor, School of Civil Engineering, Chang'an University, China, jinchen2019@chd.edu.cn*

Abstract

Footbridges are important infrastructures allowing the passing of pedestrians. They are often used to avoid the conflicts of people flow and traffic flow, increase the safety of pedestrians, and reduce the occurrence rate of traffic accidents. There is a general trend that the footbridges become lighter and slenderer with larger span, and thus the vibration issue turns out to be increasingly prominent. When designing a footbridge, it is crucial to satisfy the vibration comfort levels of the users. The comfort levels are generally ensured by limiting peak acceleration of the structure. Most of the current design guidelines and codes for the footbridges comply with the above requirements.

For most situations, the crowds can successfully pass on a well-designed footbridge as its vibration levels are within the acceptable comfort levels of human beings. When some accidental events such as earthquakes occur, however, it remains uncertain that whether the crowds are still able to evacuate or not. Most of the previous studies focused on the dynamic behaviour of footbridges under the crowd loads even simpler load cases, i.e., single pedestrian induced loads. There are quite limited research concerning the vibration performance of footbridges subjected to both the crowd loads and earthquake loads.

In this study, a typical steel footbridge is considered. The behaviour of crowd evacuation in earthquake is realistically simulated with a widely applied social force model by Helbing et al. By combining with a walking force model, crowd loads are considered. A series of earthquakes with different frequency characteristics are used as the seismic inputs.

The footbridge subjected to only the crowd loads is firstly simulated. It is found that the vibration levels of the footbridge are within the acceleration limits as specified in the frequently applied European guideline HiVoSS. The numerical simulation of the footbridge under the earthquake loads are then conducted. Although the structural responses are larger than the comfort limits, the crowds are still able to evacuate for most earthquake cases. Finally, the vibration serviceability of the footbridge is analysed by combining both the crowd loads and earthquake loads. The results indicate that under the dual excitations of crowd loads and earthquake loads, the acceleration level of the footbridge could be even close to 2.0 m/s^2 (unacceptable discomfort in according to HiVoSS), which will render that the extreme uncomfortableness of crowds. As a result, the crowds are possibly unable to successfully evacuate, which could cause great casualties. The findings in this study demonstrates that it is critical and urgent to consider the dual excitations of the crowd loads and earthquake loads as a load case in the design process of footbridges.

Keywords: footbridges, vibration serviceability, crowd evacuation, crowd load, earthquake

1. Introduction

Footbridges are important infrastructures, which are often used to avoid the conflicts of people flow and traffic flow, increase the safety of pedestrians, and reduce the occurrence rate of traffic accidents. There is a general trend that the footbridges become lighter and slenderer with larger span [1]. As a result, the vibration issue turns out to be increasingly prominent [2]. When designing a footbridge according to the current design guidelines and codes [3-5], it is critical to ensure that it meets the requirement of vibration comfort, which is generally quantified by the peak acceleration of the structure.

The crowds are able to successfully pass on a well-designed footbridge as its vibration levels in both vertical and lateral directions are within the acceptable comfort levels of human beings for general situations. However, when some accidental events such as earthquakes occur, it remains uncertain that whether the crowds are still able to evacuate or not. It should be noted that most of the previous studies focused on the dynamic behavior of footbridges under the crowd loads even simpler load cases, e.g., single pedestrian induced loads. To the authors' best knowledge, there are quite limited research regarding whether the crowds are able to evacuate the footbridge or not when earthquakes occur.

In this paper, the basic information of a well-designed footbridge is firstly presented. The modelling of crowd loads and the seismic inputs are then provided. The structural responses of the footbridge subjected to the crowd loads, the earthquake loads and the combination of them are calculated thereafter. By comparing the structural responses and the comfort limits proposed by the renowned design guideline HiVoSS as well as the observations from the London Millennium Bridge, the vibration serviceability of the footbridge is finally assessed.

2. Basic information of footbridge

A typical steel footbridge designed according to the French guide Sétra [3] and the European guideline HiVoss [4] is adopted as the target structure, which is idealized as a simply supported beam both in the vertical (Z) and lateral (Y) directions. The width and span are 5 m and 50 m, respectively; the inertial moments I_z and I_y are 0.08 m^4 and 0.02 m^4, respectively; the mass per unit length is 1.6×10^3 kg/m; and the elastic modulus of material is 2×10^5 MPa.

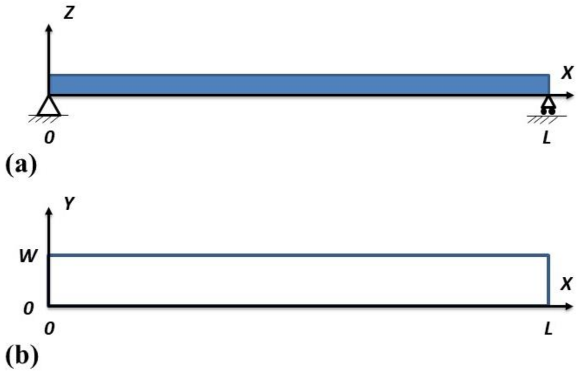


Fig. 1 –Schematic diagram of the idealized target structure

Based on the modal analysis of the structure, the fundamental natural frequencies of the vertical and lateral modes are 2 Hz and 1 Hz, respectively, which fall into the sensitive frequency ranges of the footbridges [3-4].

3. Crowd loads and seismic inputs

3.1 Crowd loads

In this study, the crowd induced loads are applied by considering a pedestrian crowd with a representative high pedestrian density of 1.0 pedestrians/m^2 as defined in the European guideline HiVoSS [4]. Correspondingly, during the relevant time, there are 250 pedestrians passing on the bridge from one end (x=0) to another end (x=L) (Fig. 1).

To simulate the crowd evacuation behavior on the structure in earthquakes, the social force model proposed by Helbing and Molnar [6] and Helbing et al. [7] is applied. Both psychological and physical forces determine persons' evacuation behavior. Psychological forces include three aspects:

(a) A force (acceleration) term to retain the pedestrian moving to the desired direction $\vec{e}_\alpha(t)$ is $\vec{F}_\alpha^0(\vec{v}_\alpha, v_\alpha^0(t)\vec{e}_\alpha(t)) = [\, v_\alpha^0(t)\vec{e}_\alpha(t) - \vec{v}_\alpha(t)\,]/\tau_\alpha$, where $\vec{v}_\alpha(t)$ is the actual velocity. $\vec{v}_\alpha^0(t) = v_\alpha^0(t)\vec{e}_\alpha(t)$ is the desired velocity. The scalar $v_\alpha^0(t)$ is the desired speed, which follows a Gaussian distribution with a mean of 1.34 m/s and a standard deviation of 0.26 m/s [6]. $\tau_\alpha = 0.5$ s [6] is the relaxation time to adjust walking speed.

(b) A repulsive force (acceleration) term to keep from others, which is represented by a random pedestrian β with walking velocity $\vec{v}_\beta(t)$ at the location of $\vec{r}_\beta(t)$, with a certain distance: $\vec{F}_{\alpha\beta}(\vec{r}_{\alpha\beta}) = -\nabla_{\vec{r}_{\alpha\beta}} V_{\alpha\beta}\left(b(\vec{r}_{\alpha\beta})\right)$. In which, $V_{\alpha\beta}\left(b(\vec{r}_{\alpha\beta})\right) = V_{\alpha\beta}^0 \exp(-b(\vec{r}_{\alpha\beta})/\sigma)$ is the repulsive potential, which is a monotonic decreasing function of $b(\vec{r}_{\alpha\beta})$ with equipotential lines having the form of an ellipse directed into motion direction. The parameter values are $V_{\alpha\beta}^0 = 2.1$ m^{2}s^{-2} and $\sigma = 0.3$ m [6]. $\vec{r}_{\alpha\beta} = \vec{r}_\alpha(t) - \vec{r}_\beta(t)$ is the relative location of the two pedestrians. $b(\vec{r}_{\alpha\beta})$ is the semiminor axis of the ellipse as determined by $b(\vec{r}_{\alpha\beta}) = \frac{1}{2}\sqrt{(\| \vec{r}_{\alpha\beta} \| + \| \vec{r}_{\alpha\beta} - v_\beta \Delta t \vec{e}_\beta \|)^2 - (v_\beta \Delta t)^2}$, where Δt can be assigned as 2 s in [6] or other values.

(c) A repulsive force term to prevent the pedestrian from borders B such as walls and obstacles: $\vec{F}_{\alpha B}(\vec{r}_{\alpha B}) = -\nabla_{\vec{r}_{\alpha B}} U_{\alpha B}(\| \vec{r}_{\alpha B} \|)$, where $U_{\alpha B}(\| \vec{r}_{\alpha B} \|) = U_{\alpha B}^0 \exp(-\| \vec{r}_{\alpha B} \|/R)$ is the monotonic decreasing potential with $U_{\alpha B}^0 = 10$ m^{2}s^{-2} and $R = 0.2$ m [6]. $\vec{r}_{\alpha B} = \vec{r}_\alpha(t) - \vec{r}_B(t)$ the relative location between the pedestrian α and the nearest border B.

Physical forces are resulted from inter-personal pushing and physical interactions as:

(d) The force (acceleration) resulted by other pedestrians' pushing and physical interactions is $\frac{1}{m_\alpha} kg(r_{\alpha\beta} - d_{\alpha\beta})\vec{n}_{\alpha\beta} + \frac{1}{m_\alpha} \kappa g(r_{\alpha\beta} - d_{\alpha\beta})\Delta\, v_{\beta\alpha}^t \vec{t}_{\alpha\beta}$, where $kg(r_{\alpha\beta} - d_{\alpha\beta})\vec{n}_{\alpha\beta}$ is the body force to counteract body compression; $\kappa g(r_{\alpha\beta} - d_{\alpha\beta})\Delta\, v_{\beta\alpha}^t \vec{t}_{\alpha\beta}$ is the sliding friction force to impede relative tangential motion, when the pedestrian α approaches to pedestrian β.

(e) The force (acceleration) resulted by pushing and physical interactions with borders is $\frac{1}{m_\alpha} kg(r_\alpha - d_{\alpha B})\vec{n}_{\alpha B} - \frac{1}{m_\alpha} \kappa g(r_\alpha - d_{\alpha B})(\vec{v}_\alpha \cdot \vec{t}_{\alpha B})\vec{t}_{\alpha B}$, where $d_{\alpha B}$ is the distance from the pedestrian center to the nearest point of the border. $\vec{n}_{\alpha B}$ is the normalized vector directing from pedestrians α to the border and $\vec{t}_{\alpha B}$ the tangential vector.

Totally, the social force (acceleration) $\vec{F}_\alpha(t)$ acting on the pedestrian α is the sum of the five contributions as defined in from (a) to (e). The motion of the random pedestrian α, which is characterized by time-variant location $\vec{r}_\alpha(t)$ and velocity $\vec{v}_\alpha(t)$, is determined by the following nonlinearly coupled Langevin equations:

$$\frac{\mathrm{d}\vec{r}_\alpha(t)}{\mathrm{d}t} = \vec{v}_\alpha(t) \tag{1}$$

$$\frac{\mathrm{d}\vec{v}_\alpha(t)}{\mathrm{d}t} = \vec{F}_\alpha(t) \tag{2}$$

By solving the above governing equations of motion of the pedestrian α, the time-variant locations $\vec{r}_\alpha(t)$ and velocities $\vec{v}_\alpha(t)$ are determined. The simulated behavior of each random pedestrian in the crowd is time-variant and subject-dependent. By combing the simulated evacuation behaviour with the stochastic walking force model as presented below, the crowd induced loads are considered in this study.

The pedestrian-induced walking forces by a random pedestrian α are considered as follows:

$$F_{walk,z,\alpha}(t)/G_{ped,\alpha} = 1 + DLF_{z,\alpha} \cdot \sin\left(2\pi \cdot f_{ped,\alpha} \cdot t + \varphi_{z,\alpha}\right) \tag{3}$$

$$F_{walk,y,\alpha}(t)/G_{ped,\alpha} = DLF_{y,\alpha} \cdot \sin\left(\pi \cdot f_{ped,\alpha} \cdot t + \varphi_{y,\alpha}\right) \tag{4}$$

In which, $F_{walk,z,\alpha}(t)$ and $F_{walk,y,\alpha}(t)$ are the pedestrian induced walking forces in the vertical (Z) and lateral (Y) direction of the bridge deck (Fig. 1), respectively. $G_{ped,\alpha}$ is the pedestrian's weight. $DLF_{z,\alpha}$ and $DLF_{y,\alpha}$ are the corresponding dynamic load factors (DLFs) in the vertical (Z) and lateral (Y) directions, respectively. $f_{ped,\alpha}$ is the walking step frequency. $\varphi_{z,\alpha}$ and $\varphi_{y,\alpha}$ are the phase angles in the vertical (Z) and lateral (Y) directions, respectively. All these parameters can be variant for different individuals due to inter-subject variabilities and are not always the same, e.g., time-variant, even for a same person because of intra-subject variabilities. Thus,

(1) To consider the variabilities of walking forces, the pedestrian weight $G_{ped,\alpha}$ is regarded as a normal distribution with a mean value of 800 N and a variation coefficient of 10%.

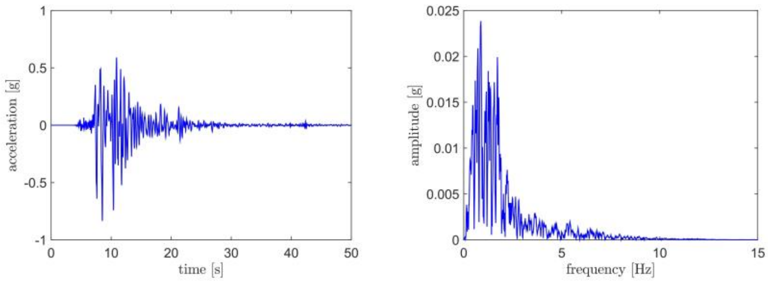
(2) By using a widely-applied frequency-speed relation [8], the step frequency $f_{ped,\alpha}$ is derived based on time-variant movements, i.e., locations and velocities, of the pedestrian α, as simulated by the social force model.

(3) According to [9], the dynamic load factors in the vertical direction depends on step frequency as: $DLF_{z,\alpha} = 0.41(f_{ped,\alpha} - 0.95)$ with $f_{ped,\alpha}$ in [1, 2.8] Hz. In this study, $DLF_{y,\alpha}$ is assumed to follow a normal distribution with 0.05 as the mean and a variation coefficient of 10%.

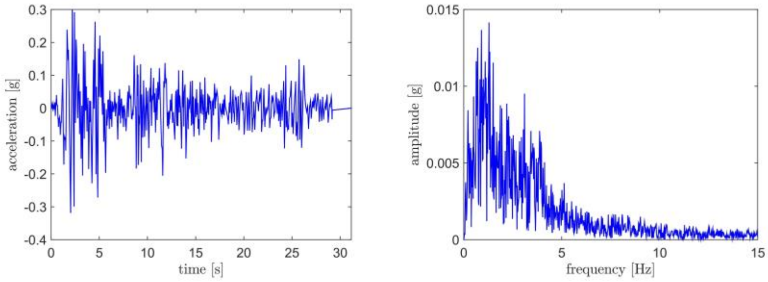
(4) Due to lack of reliable experimental data and precise physical meaning, phase angles are kept as $\varphi_{z,\alpha} = \varphi_{y,\alpha} = 0$.

3.2 Seismic inputs

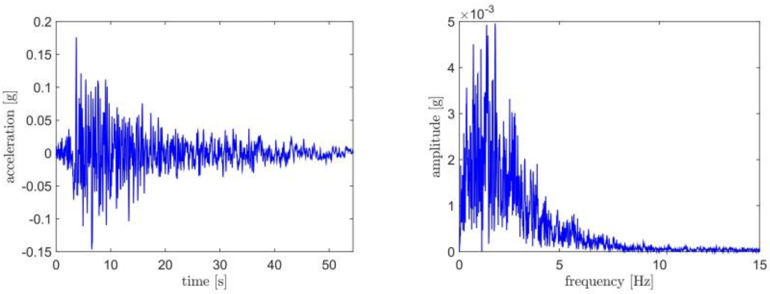
Three well-known ground motions, namely Kobe, El Centro, and Taft, are selected as the seismic inputs (Fig. 2). We assume that the target structure is located in the district with the peak ground acceleration (PGA) of 0.035 g.



(a) Kobe



(b) El Centro



(c) Taft

Fig. 2 –Time history curves and frequency characteristics of the seismic inputs

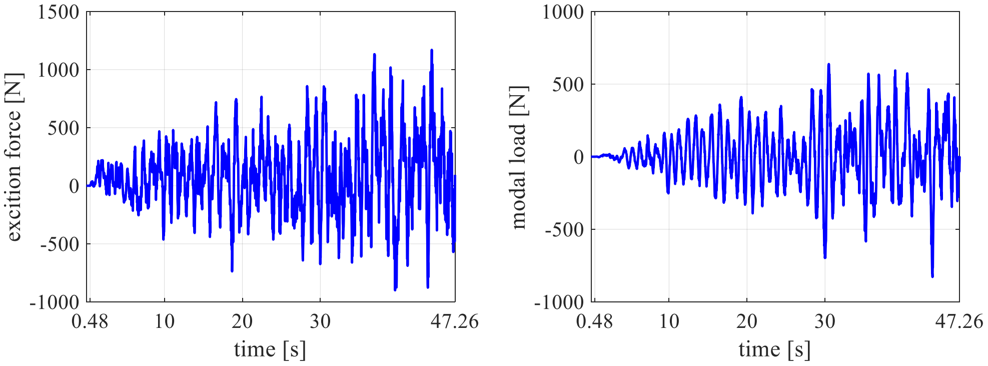
4. Structural responses

The earthquakes are assumed to happen at a random time instant t_{eq}. The arrival time on the bridge of the pedestrians are supposed to follow the Poisson's distribution [10] from 0.48 s to 47.10 s. The desired speeds of the crowd follow a Gaussian distribution with a mean v_α of 1.34 m/s and a standard deviation of 0.26 m/s [6]. The time step in simulating the crowd loads is selected as 0.02 s, which is in consistent with the time step of the seismic inputs.

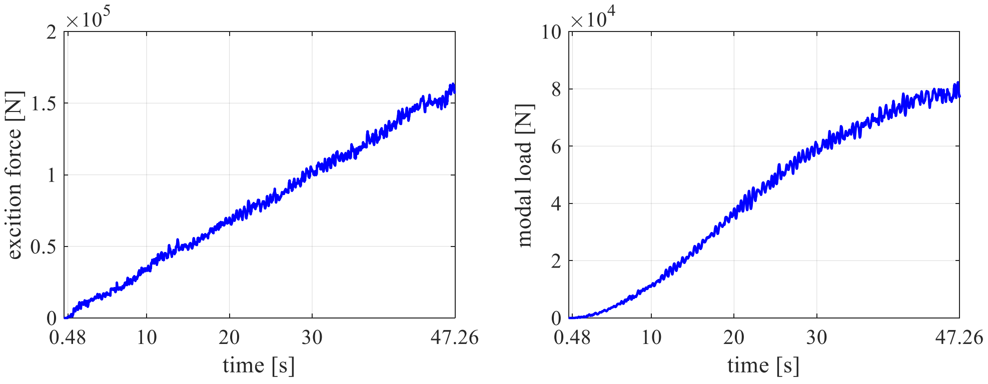
4.1 Structural responses due to crowd loads

Fig. 3 shows the time history of the crowd-induced loads. In the lateral direction, the crowd-induced load fluctuates around the zero line. The increasing trend of the force amplitudes results from the increasing number of pedestrians. In the vertical direction, the load fluctuates and increases with time due to the increasing number of pedestrians as well. The fluctuations are caused by the adjustments of walking parameters of pedestrians in the crowd.

Fig. 4 shows the time history of the crowd-induced structural vibrations. The acceleration response amplitudes are 0.28 m/s^2 and 1.76 m/s^2 in the lateral and vertical directions, respectively.

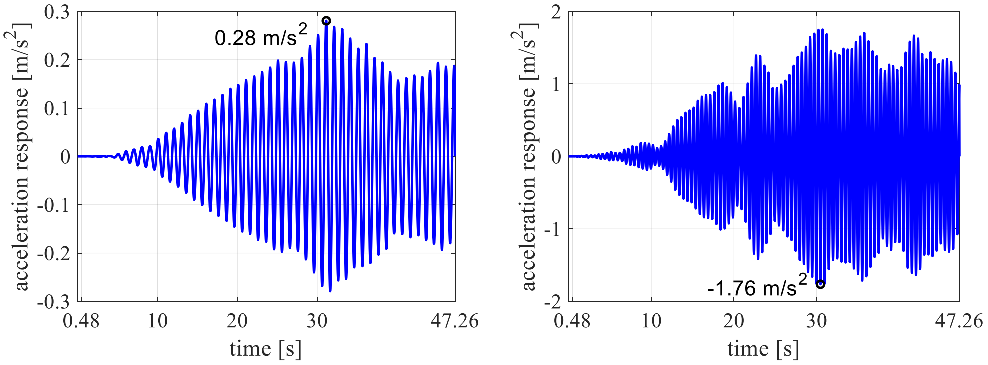


(a) Lateral direction



(b) Vertical direction

Fig. 3 –The time history of the crowd-induced loads



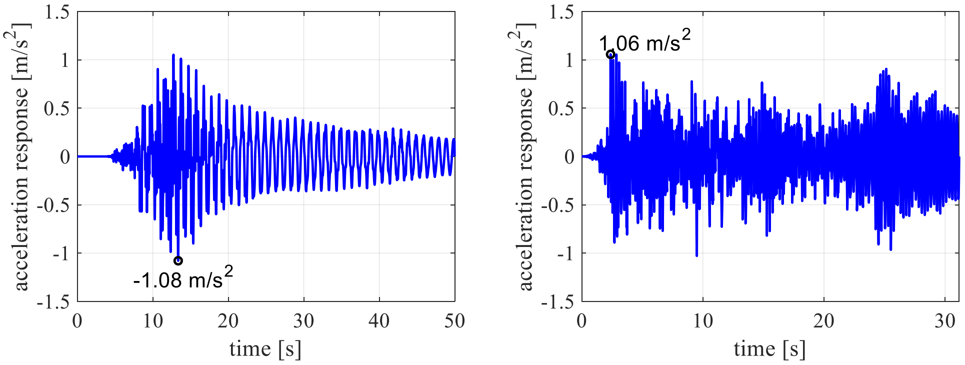
(a) Lateral direction (b) Vertical direction

Fig. 4 –The time history of the crowd-induced vibrations at the midspan of the structure

4.2 Structural responses due to earthquake loads

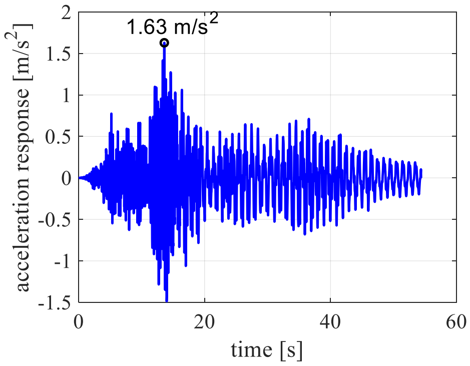
In calculating the structural responses due to earthquake loads, the contributions from the first five vertical and first five lateral modes are considered. The earthquakes are assumed to happen at the time instant t_{eq}=0 s as an illustrative example. Fig. 5 presents the time history of the structural acceleration responses in the lateral direction subjected to the three different ground accelerations which happens at the time instant t_{eq}=0

s. The maximum acceleration amplitudes of the Kobe, El Centro and Taft earthquakes are 1.08 m/s^2, 1.06 m/s^2 and 1.63 m/s^2, respectively.



(a) Kobe wave

(b) El Centro wave



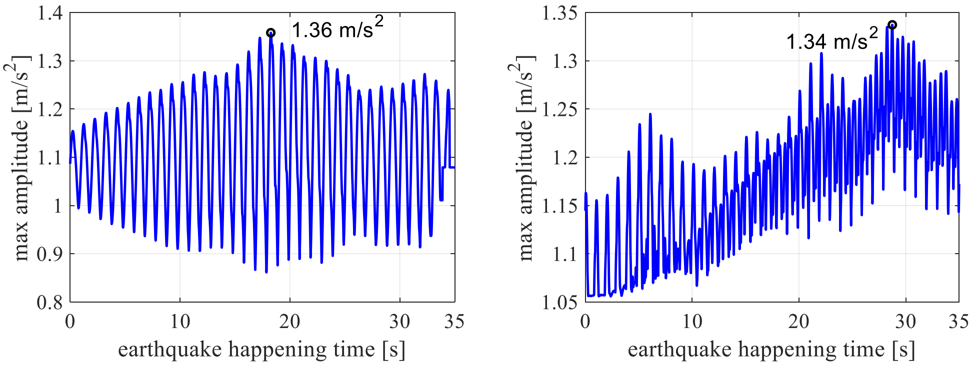
(c) Taft wave

Fig. 5 –The time history of the structural acceleration responses in lateral direction to ground accelerations

4.3 Structural responses due to crowd and earthquake loads

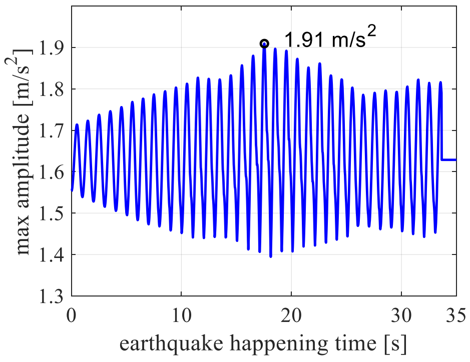
It is assumed that the induced structural responses caused by the crowd and earthquake loads are decoupled for the vertical and lateral directions. Specifically, the resulting total response in the vertical direction is only caused by the crowd loads, while the induced total response in the lateral direction is a combination of the vibrations due to the crowd and earthquake loads. To consider the randomness of the earthquake happening time instant t_{eq}, the time range from 0 s to 35 s with the time shift of 0.02 s is adopted.

Fig. 6 depicts the maximum amplitudes in the time history of the total structural acceleration responses in the lateral direction subjected to the crowd loads and the three different ground motions that happen at different time instant t_{eq}. The combined structural responses are significantly affected by the time instant t_{eq}. The largest maximum amplitudes are 1.36, 1.34 and 1.91 m/s^2, respectively.



(a) Kobe wave

(b) El Centro wave



(c) Taft wave

Fig. 6 –The maximum amplitudes of the acceleration responses in lateral direction due to the crowd and earthquake loads

5. Assessment of vibration serviceability

The vibration comfort criteria of structures are often quantified as limiting accelerations a_{limit}. According to HiVoSS [4], the human comfort limits of vibration serviceability in the vertical and lateral directions are 2.5 m/s^2 and 0.80 m/s^2, respectively. More strictly, lateral lock-in starts to be triggered when the lateral acceleration amplitude exceeds 0.1 (or 0.15) m/s^2. It is rather risky when the pedestrian crowd is fully synchronized with the lateral vibrations of the structure. As observed in the London Millennium Bridge [11], extensive vibrations with the maximum acceleration around 1.96 m/s^2 to 2.45 m/s^2 are induced by lateral crowd-structure synchronization and thus pedestrians can hardly walk or pass the bridge. These observations are in accordance with the research findings by Nakamura [12] from field measurements of lateral vibrations of a footbridge. Venuti and Bruno [8] reported the threshold acceleration above which people stop walking, namely 2.1 m/s^2.

In the lateral direction, when the vibrations are only induced by crowd loads, the maximum vibration levels are within the comfort limits (0.8 m/s^2). When the structure is only subjected to earthquake loads, some vibration amplitudes exceed the comfort limits.

If both the earthquake and crowd loads are taken into consideration, all maximum vibration amplitudes in the lateral direction are significantly higher than the comfort limits. The maximum acceleration amplitude occur with the Taft earthquake, it reaches to 1.91 m/s^2. This may result in that the pedestrians are unable to evacuate because they are subjected to continuous vibrations exceeding the comfort limits.

The structural responses in the vertical direction is 1.76 m/s^2, which is lower than the corresponding comfort limits (2.5 m/s^2) of vibration serviceability. Furthermore, as pointed in HiVoSS, 'Pedestrian streams synchronising with vertical vibrations have not been observed on footbridges'. In other words, whether the pedestrians can evacuate in earthquake from the bridge or not mainly depends on the lateral vibrations of the structure. Specifically, it mainly lies on the combinations of the crowd and earthquake loads.

6. Conclusions

This paper studies the vibration serviceability of footbridge subjected to crowd loads and earthquakes. A footbridge with typical characteristics is used as the target structure. The crowd loads are simulated by integrating the social force model and walking force model. Three commonly used earthquakes with different frequency characteristics are adopted as the seismic inputs. The structural responses under three load cases, i.e., the crowd loads only, the earthquake loads only, and the combination of crowd loads and earthquake loads, are investigated. The vibration serviceability of the footbridge is assessed by comparing the structural responses and the requirements specified in HiVoSS and the observations from the London Millennium Bridge. Several conclusions can be drawn as follows:

If only the crowd loads are considered, the vibrations in both lateral and vertical directions are within the comfort limits of vibration serviceability provided by HiVoSS. It means that the crowds are able to evacuate the footbridge.

If only the earthquake loads are considered, the maximum acceleration of the lateral vibrations for the three earthquakes exceed the comfort limits, but the crowds are still able to evacuate the footbridge.

If both the crowd loads and earthquake loads are considered, the resulted lateral vibrations are probably larger than the comfort limits. This may even result in that the pedestrians are unable to evacuate the footbridge.

7. Acknowledgements

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