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Vibration serviceability of footbridges in crowded conditions: crowd dynamics simulations vs guidelines' predictions

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Abstract. Vibration serviceability assessment in crowded conditions requires a reliable human-induced loading model taking into account pedestrian interaction. Current guidelines provide simplified procedures to determine the maximum dynamic response based on very simplified loading models. The main objective of this paper is to assess the reliability of current guidelines for vibration serviceability assessment of footbridges. With this aim, an extensive campaign of numerical simulations of bidirectional pedestrian traffic is carried out through an agent-based model, considering variable pedestrian densities and deck widths. The results of numerical simulations are first compared against the experiments available in the literature in terms of fundamental diagram of the mean walking speed as a function of pedestrian density. Then, starting from numerical simulations, the dynamic response of a class of footbridges is estimated numerically and compared with guidelines' predictions in order to assess their reliability.

1. Introduction

Despite extensive research in the last twenty years, there is still lack of reliable models for human-induced excitation, especially with reference to crowded conditions. Guidelines (e.g., [1], [2]) provide simplified procedures to assess the maximum dynamic response of footbridges, such as, e.g., equivalent resonant uniformly-distributed loading with an increased loading amplitude for high density in order to account for the possible synchronization among pedestrians in very dense traffic conditions. This very simple loading condition does not take into account the variation of the walking velocity and step frequency with pedestrian density and may lead to unreliable predictions of the vibration level.

A reliable human-induced loading model on footbridges taking into account pedestrian interaction requires experimental tests on full scale structures, that are scarce in the literature and limited to low pedestrian densities [3]. In the literature, experimental tests in straight corridors have been carried out, both in the case of unidirectional and bidirectional traffic (e.g. [4], [5], [6]), providing fundamental diagrams of the mean walking speed as a function of pedestrian density. As an alternative to experimental characterization, numerical simulations based on suitable crowd dynamics models can be carried out. Pedestrian dynamics can be described through macroscopic or microscopic models. In the last decade, the latter have been employed with increasing frequency to calculate trajectories and velocities of pedestrians crossing footbridges (e.g., [7]-[10]). In most cases, pedestrian microscopic models are derived from the Social Force model, firstly proposed by Helbing and Molnar [11]. The main drawback of microscopic models is that they have a significant number of free parameters, which are

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very difficult to be tuned, especially due to the lack of empirical data. Despite some attempts made in the literature ([8], [10]), the calibration of the parameters to confidently apply this kind of models to pedestrian traffic on footbridges is still an open research issue.

The present paper studies vibration serviceability of footbridges in crowded conditions starting from numerical simulations of pedestrian flows with the aim of assessing the reliability of simplified methods suggested by guidelines. Numerical simulations of bidirectional pedestrian flow are carried out for different deck widths and pedestrian densities. After a comparison of results of numerical simulations against experiments available in the literature in terms of fundamental diagram of the mean walking speed as a function of pedestrian density, the dynamic response of a set of footbridges of varying natural frequency is estimated for different levels of pedestrian density and it is compared with guidelines' predictions in order to assess the reliability of the proposed simplified procedures.

2. Numerical simulations of pedestrian dynamics

Numerical simulations of pedestrian dynamics are carried out through the commercial software MassMotion 9.5 by Oasys Ltd [12]. MassMotion (MM) is a 3D agent-based simulation tool, which describes the crowd system as a collection of intelligent, autonomous, decision-making entities known as 'agents' (see [12] for a detailed description about the basic principles of MM). Even though MM has been originally conceived to address evacuation events, the data and theories upon which it relies on refer to normal human behavior: there is, actually, evidence that people in an emergency tend to behave normally and panic is very rare [13].

2.1. Description of the simulation setups

Simulations of both unidirectional and bidirectional traffic have been carried out on three ideal footbridges with the same length L = 60 m and three different widths B = [1.5, 2.7, 4.5] m (Figure 1). Results of unidirectional pedestrian traffic have been already presented and discussed in [14], therefore this paper focuses on bidirectional pedestrian traffic. In this case, pedestrians are initially randomly distributed in two starting areas before the footbridge entrances, ten times longer than the footbridge length. The same number of pedestrians is generated at both sides, and it is determined by trial and error to obtain the desired value of mean pedestrian density along the footbridge. Four values of pedestrian density, [0.3 0.7 1.1 1.3] ped/m^2, are considered. For each value of crowd density and footbridge width, 50 simulations are performed to obtain statistical reliability.

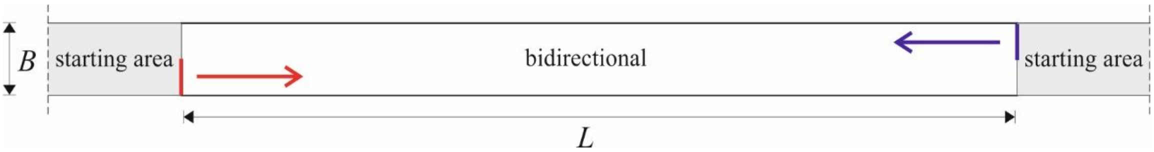

Figure 1: geometrical setup for bidirectional traffic.

2.2. Comparison with experiments

Results of the numerical simulations are compared against experiments available in the literature. The latter have been collected by Zhang et al. [4], who performed a comprehensive literature review on empirical data. The comparison is performed on the so-called fundamental diagram, that relates mean walking speed to mean pedestrian density.

For each simulation, mean values of the pedestrian density and velocity are calculated during the period of full occupancy $t \in [t_1 \; t_2]$. Specifically, for each simulation, the mean pedestrian density is calculated as:

$$\rho = \frac{1}{T_{full}} \frac{1}{BL} \int_{t_1}^{t_2} N(t) \mathrm{d}t \tag{1}$$

where, $N(t)$ is the number of pedestrians on the footbridge at time t, and $T_{full} = t_2 - t_1$ is the duration of the period of full occupancy. The mean speed v is calculated as:

$$v = \frac{1}{N_p}\sum_{i=1}^{N}\overline{v}_i \qquad \overline{v}_i = \frac{1}{T_{cross_i}}\int_{t_i}^{t_i+T_{cross_i}} v_i\left(t\right)\mathrm{d}t \tag{2}$$

Being t_i the time instant at which the i-th pedestrian enters the footbridge, $v_i(t)$ the instantaneous speed of the i-th pedestrian, $\overline{v}_i$ its time average during the crossing time T_{cross_i}, and N_p the total number of pedestrians in the simulation. The mean pedestrian density and velocity of the single simulations are then averaged over the total number of simulations.

Figure 2 plots the comparison between fundamental diagrams obtained through experimental and numerical tests. It is worth noting that the reported empirical data come from measurements performed in quite different conditions (e.g. in field or laboratory tests) and obtained through different methods, which strongly influence the resulting fundamental diagram [5]. This explains the high dispersion of data in Figure 2 and confirms the need for well-controlled experimental campaigns devoted to collect statistics of pedestrian dynamics. Despite this, a qualitative comparison between numerical and empirical data shows that the results of the numerical simulations fall in the range of empirical data, as already demonstrated for unidirectional traffic [14].

The results plotted in Figure 2 also show that the deck width influences the fundamental diagram especially for $B < 2.7$ m. In particular, the reduction of walking speed is significant when $B = 1.5$ m, when pedestrian free walking is highly conditioned by the repulsive effect of lateral boundaries. This outcome agrees with the numerical study in[10], relative to unidirectional traffic, where it was found an influence of the deck width on the fundamental diagram for width lower than 3 m.

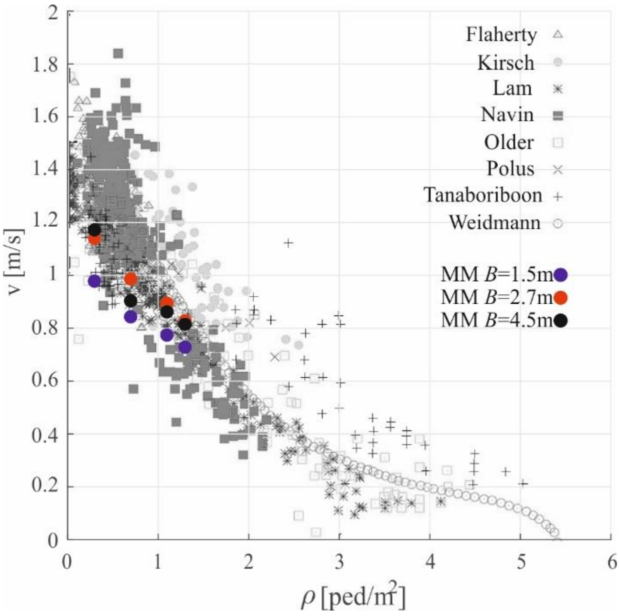

Figure 2: Comparison between numerical and experimental data (after [4]) for bidirectional traffic.

2.3. Statistical characterization of the mean step frequency

The instantaneous step frequency of the i-th pedestrian $n_i(t)$ is derived from the velocity according to the relationship [15]:

$$n_i\left(t\right) = 0.35v_i^3\left(t\right) - 1.59v_i^2\left(t\right) + 2.93v_i\left(t\right) \tag{3}$$

Then, the mean value of the step frequency of the i-th pedestrian during the crossing time is derived:

$$\overline{n}_i = \frac{1}{T_{cross_i}}\int_{t_i}^{t_i+T_{cross_i}} n_i\left(t\right)\mathrm{d}t \tag{4}$$

Figure 3 plots the mean value (Fig. 3a) and standard deviation (Fig. 3b) of the mean step frequency as functions of pedestrian density for the three deck widths considered in the simulations. Fig. 3(a) clearly shows that, for all the three widths considered in the simulations, the mean value of the step frequency tends to decrease on increasing pedestrian density. Furthermore, for B = 1.5 m the mean step frequency tends to be smaller than for higher widths. On the contrary, Fig. 3(b) doesn't show a uniform trend of the standard deviation of the step frequency on varying the pedestrian density and deck width.

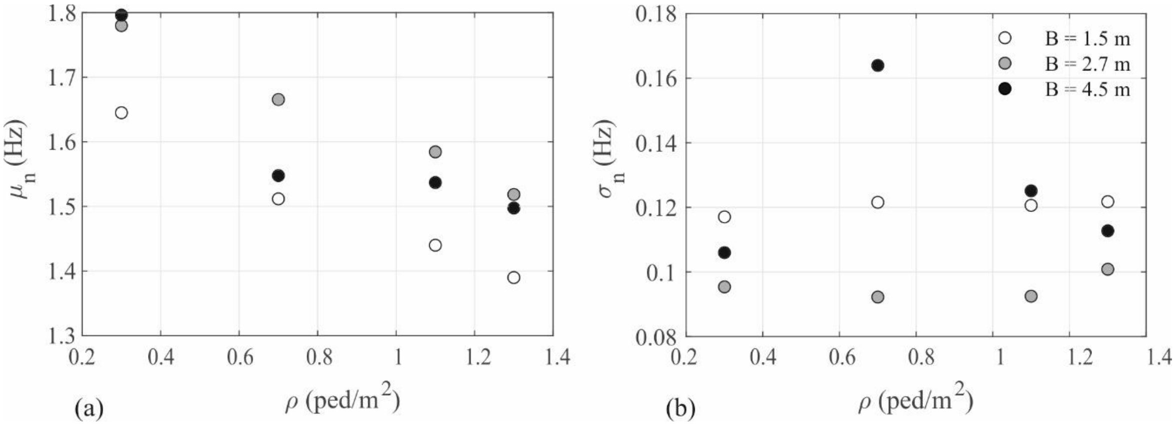

Figure 3: Mean value (a) and standard deviation (b) of the mean step frequency of pedestrians.

Figure 4 plots the probability density function (pdf) of the mean step frequency for the three widths considered, varying the pedestrian density. The pdfs follow quite well the normal distribution and, as already observed through the analysis of the mean value, they tend to move to the left on increasing pedestrian density. Since the harmonic content of the loading is proportional to the pdf of the step frequency [14], this observation has significant impact also on vibration serviceability assessment.

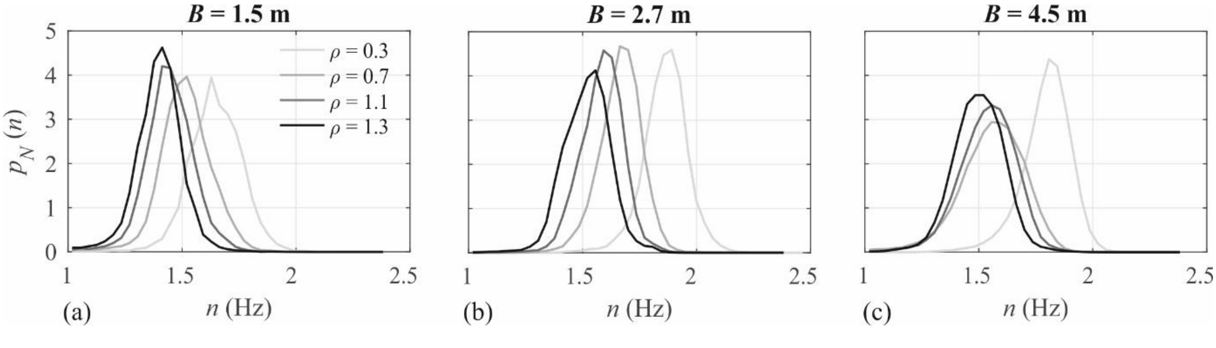

Figure 4: Pdfs of the mean step frequency of pedestrians for B=1.5 m (a), 2.7 m (b) and 4.5 m(c).

3. Maximum footbridge dynamic response

3.1. Numerical assessment

For vibration serviceability assessment, pedestrians are schematized as moving loads. The force per unit length exerted by N_p pedestrians is expressed as the sum of the forces exerted by each single pedestrian as follows:

$$f(x,t) = \sum_{i=1}^{N_p} f_i(t)\delta\left[x - x_i(t)\right] \quad (5)$$

where $x_i(t)$ and $f_i(t)$ are the instantaneous position and the force exerted by the i-th pedestrian, respectively, and $\delta(\bullet)$ is the Dirac delta function.

Since the pedestrian step frequency $n_i(t)$ is time variant during footbridge crossing, the force exerted by the i-th pedestrian can be modelled as a sinusoidal carrier signal, with a modulated base frequency $\bar{n}_i$, as follows:

$$f_i\left(t\right)=\alpha_i G_i \sin\left[2\pi\bar{n}_i t+2\pi\int_0^t\left(n_i\left(\tau\right)-\bar{n}_i\right)\mathrm{d}\tau\right] \tag{6}$$

where α_i and G_i are the dynamic load factor (DLF) and the weight of the i-th pedestrian, respectively.

The j-th modal load due to N_p pedestrians is then given by:

$$F_j\left(t\right)=\sum_{i=1}^{N_p} f_i\left(t\right)\varphi_j\left[x_i\left(t\right)\right] \tag{7}$$

where $\varphi_j\left(x\right)$ is the j-th mode shape. The dynamic response of the footbridge can then be estimated assuming that it is dominated by the j-th mode of vibration $q\left(x,t\right)=\varphi_j\left(x\right)p_j\left(t\right)$, where $p_j(t)$ is the j-th principal coordinate, provided by the solution of the following equation:

$$\ddot{p}_j(t)+2\xi_j\omega_j\dot{p}_j(t)+\omega_j^2 p_j(t)=\frac{1}{M_j}F_j(t) \tag{8}$$

being ξ_j, ω_j, M_j, the j-th modal damping ratio, circular frequency and mass, respectively.

3.2. *Simplified procedures: HiVoSS Guidelines*

The simplified procedures proposed by HiVoSS guideline are herein briefly recalled (the reader can refer to [1] for further details).

According to HiVoSS SDOF method, the following resonant uniformly distributed harmonic load is applied with the same sign as the one of the considered mode shape:

$$f\left(t\right)=\alpha_m G_m \cos\left(2\pi n_j t\right)N'\psi \qquad \alpha_m G_m=280\ \mathrm{N}$$

$$N'=\begin{cases}\dfrac{10.8\sqrt{\xi_j N_p}}{S} & \rho\le 1\ \mathrm{ped/m^2}\\ \dfrac{1.85\sqrt{N_p}}{S} & \rho>1\ \mathrm{ped/m^2}\end{cases} \qquad \psi=\begin{cases}0 & n_j<1.25 \text{ or } n_j>2.3\\ \dfrac{\left(n_j-1.25\right)}{0.45} & 1.25<n_j<1.7\\ 1 & 1.7<n_j<2.1\\ 1-\dfrac{\left(n_j-2.1\right)}{0.2} & 2.1<n_j<2.3\end{cases} \tag{9}$$

where n_j is the j-th natural frequency, S=BL. The peak acceleration is calculated as:

$$\ddot{q}_{\max_{SDOF}}=\frac{\alpha_m G_m N'\psi B\int_0^L \varphi_j\left(x\right)\mathrm{d}x}{2\xi_j M_j} \tag{10}$$

The HiVoSS Response Spectra (RS) method estimates the peak acceleration as follows:

$$\ddot{q}_{\max_{RS}}=g\sigma \tag{11}$$

$$\sigma^2=k_1\xi_j^{k_2}\frac{C_\sigma\sigma_F^2}{M_j^2}$$
$$k_1=a_1 n_j^2+a_2 n_j+a_3 \qquad k_2=b_1 n_j^2+b_2 n_j+b_3 \qquad \sigma_F^2=k_F N_p \tag{12}$$

where the peak factor g and the coefficients in Eq. (12) are functions of the pedestrian density [1].

4. Numerical application

The dynamic response of a set of footbridges is calculated adopting the numerical results of pedestrian traffic, as described in Section 3.1, and through the HiVoSS simplified procedures. The footbridges have the same geometry, i.e., L=60 m and B=2.7 m, same modal mass M_j=51000 kg and damping ratio ξ_j=0.005, sinusoidal mode shape, and natural frequencies varying in the range [1.4 - 2.2] Hz.

Figure 5 compares the maximum mid-span acceleration obtained from numerical simulations with the estimates provided by the HiVoSS simplified procedures defined by the SDOF method (Fig. 5a) and RS method (Fig. 5b). From Fig. 5, the following considerations can be derived:

- based on numerical simulations, the maximum dynamic response is provided by the maximum pedestrian density only for footbridges with low natural frequencies, since the harmonic content of the loading is concentrated around their natural frequency (Fig. 4). For footbridges with high natural frequency, the maximum dynamic response is provided by low-density traffic: this aspect cannot be captured by the simplified procedures provided by HiVoSS guideline, that tend to provide an increasing acceleration with increasing pedestrian density.
- The HiVoSS SDOF method (Fig. 5a) always overestimates the dynamic response for pedestrian densities higher than 1.7 ped/m^2, while it underestimates the response for lower densities and natural frequencies lower than 1.8 Hz. The method is not always conservative, and it is excessively conservative for high pedestrian density and natural frequencies higher than 1.8 Hz.
- For natural frequencies in the range [1.5 1.8] Hz, the HiVoSS RS method (Fig. 5b) provides maximum accelerations comparable with numerical estimates, even if not perfectly coincident, while it overestimates accelerations for higher natural frequencies. However, this approach is more reliable that HiVoSS SDOF method.

Even though the obtained results depend on the specific properties of the considered case studies, it is worth observing that the two simplified procedures recommended by HiVoSS guideline provide very different results, thus showing questionable reliability.

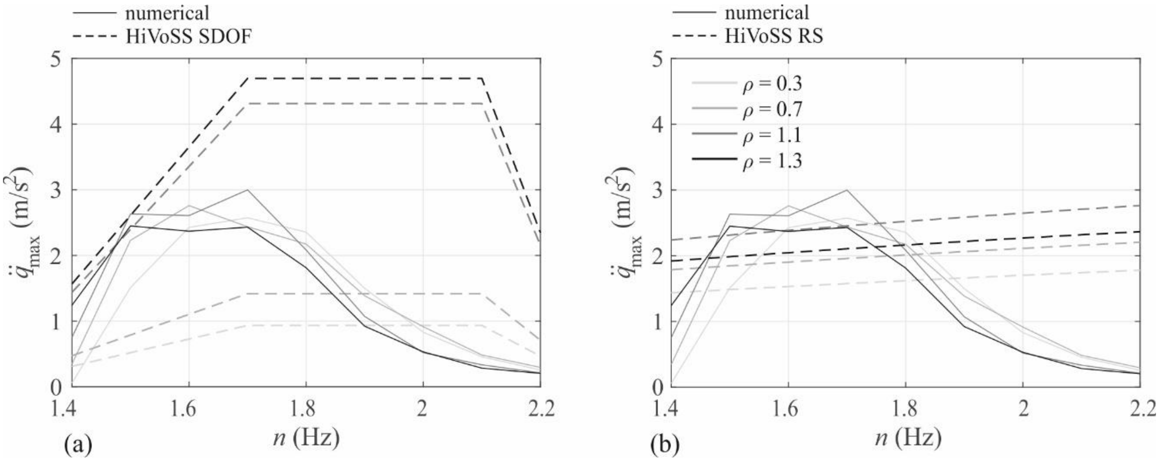

Figure 5: Comparison between accelerations obtained through numerical simulations and HiVoSS SDOF (a) and RS (b) methods.

5. Conclusions and prospects

In this study, the reliability of the simplified procedures recommended by HiVoSS guideline for vibration serviceability assessment of footbridges has been evaluated by means of a comparison with the dynamic response obtained from numerical simulations of bidirectional pedestrian traffic. First, the results of crowd dynamics simulations on footbridges of different widths are compared with the experiments available in the literature in terms of fundamental diagram of the mean walking speed as a function of pedestrian density. Then, pedestrian trajectories and walking frequencies obtained from the instantaneous walking speeds are adopted to generate the pedestrian moving loads and to calculate the resulting mean peak acceleration.

Comparison of the obtained peak responses shows that the two simplified procedures suggested by HiVoSS guideline provide quite different acceleration estimates, thus making questionable their reliability. RS method provides reliable estimates in a specific frequency range, while SDOF method is generally not reliable, overestimating the dynamic response for high pedestrian density and underestimating it for low pedestrian density.

The results of this study highlight the urgent need of a robust statistical characterization of pedestrian traffic in order to validate numerical models of crowd dynamics and develop reliable models of human-induced excitation. In particular, the pdf of the step frequency is a key element for the definition of the harmonic content of human-induced loading [16]: its experimental characterization in crowded conditions is an essential step for a thorough validation of the numerical results here presented.

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