Chapter 11
Comparative Study of Floor Serviceability Methodologies

C. Chen, P. Duffour, and A. Margnelli

Abstract With the advent of lighter floor systems and the drive to lower the embodied energy in structures, meeting vibration serviceability requirements for floor systems can be a challenge. A number of guidelines have been published in the UK over the past 15 years (e.g. SCI P345, CCIP-016) that have been helpful in providing a consistent methodology. Although these can differ slightly in the detail, they are essentially based around the concept of response factor. Other methodologies have been proposed in continental Europe. The better documented one is the One-Step RMS90 (OS-RMS90) developed as part of the Technical Steel Research of the European Commission (e.g. EUR 24084 EN). Although similar in spirit, OS-RMS90 differs from the UK methodologies in key aspects which can be categorized along three strands (1) Footfall force definition, (2) Floor modelling and estimation of the dynamic response of the floor; (3) Acceptability criteria. This paper proposes a detailed comparison between these methodologies in each of these aspects and concludes by applying the methods on a composite floor case study. Based on this comparison, the merits of various quick assessments are evaluated.

Keywords Floor vibration · Serviceability · Design methodologies

11.1 Introduction

Floor serviceability limit state (SLS) criteria play a key role in the design of lighter floor structures. The assessment of floor serviceability starts from the modelling of the dynamic forces applied to the floor which are usually associated with human walking. According to previous research [1–3], the frequency range of the excitation is in the range from 1.5 to 2.5 Hz with different root-mean-square (RMS) values. Expressions for the average values of the peaks in the force were given by [4] using Fourier components. Measurements were also carried out to statistically characterise the walking excitations [5]. Formulae have been proposed to determine approximately the modal properties of the floor structures. For example, the modal masses can be calculated by multiplying the total mass of the slab with some effective lengths and widths. The calculation of effective lengths and widths is dependent on the particular floor system (SCI, Canadian guide, and AISC). Alternatively a detailed finite element (FE) model can be used to determine the modal properties. The modal damping ratio is the sum of contributions from different components within the system which are distinguished according to the construction materials, the use of the floor and the potential presence of supplemental damping.

Several methods are currently available to calculate the floor dynamic response at the design stage. SCI P354 [6] considers the steady-state or impulse response of floors at different natural frequencies and uses modal superposition to determine the total dynamic response. The peak root mean square (RMS) values of the acceleration are then determined to obtain the R-factors. CCIP-016 [7] and CSTR43 App G are similar to the SCI method. The OS-RMS90 method (also called HiVoSS) developed by the Research Fund for Coal and Steel (RFCS) has been presented in varying degrees of detail in a number of publications [6, 8, 9]. In this method a more statistical response metrics is computed also using a frequency domain approach, in which the floor system is assumed to be composed of individual single degree of freedom (SDOF) systems. A useful overall comparison of serviceability assessments was carried out in [10]. This paper compares systematically and in more detail the SCI and the OS-RMS90 methods only as the other methods mentioned above are fairly similar to SCI.

C. Chen · P. Duffour (✉)
Department of Civil, Environmental and Geomatic Engineering, University College London, London, UK
e-mail: p.duffour@ucl.ac.uk

A. Margnelli
AKT II, White Collar Factory, London, UK

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11.2 Background: Description of the Two Methods

Both methods assume that the modal properties of the floor to be assessed have been determined from the material and geometrical properties of the floor. This can be done using either approximate formulae or by running a modal analysis on an FE model. More detail on this can be found from the references mentioned in the introduction section.

Both methods also follow essentially the same three-stage process:

1. Definition of the force excitation;
2. Estimation of the dynamic response of the system;
3. Comparison of the response level against thresholds of acceptability.

11.2.1 OS-RMS90

Excitation A person walking normally produces a vertical contact force with each foot. This contact force has two peaks corresponding to the heel drop and uplift of the feet. The detailed shape of the one-step force varies moderately but noticeably with the step frequency. OS-RMS90 defines this force through an 8-order polynomial function of time t as follows:

$$F(t) = M_b g \cdot \left(K_1 t + K_2 t^2 \cdots K_8 t^8 \right), \tag{11.1}$$

where M_b is the body mass, g is the acceleration of gravity and $K_1 - K_8$ are coefficients dependent on the step frequency and fitted from experimental data. From this, a walking load time history can be obtained by superposing a series of single contact forces at a $1/f_s$ time interval, where f_s is the step frequency. The statistics on the force step frequency and the walker body mass are provided in the form of empirical cumulative distributions. Assuming the two variables are independent, the joint distribution, whose probability density is illustrated in Fig. 11.1 can easily be calculated by multiplication.

Response As presented in the existing literature this method only considers one mode of the floor system at time. This assumes, either that the system is dominated by this mode and its behavior is well described by the corresponding single degree of freedom system or that a multimodal response can be obtained by some form of modal combination such as SRSS

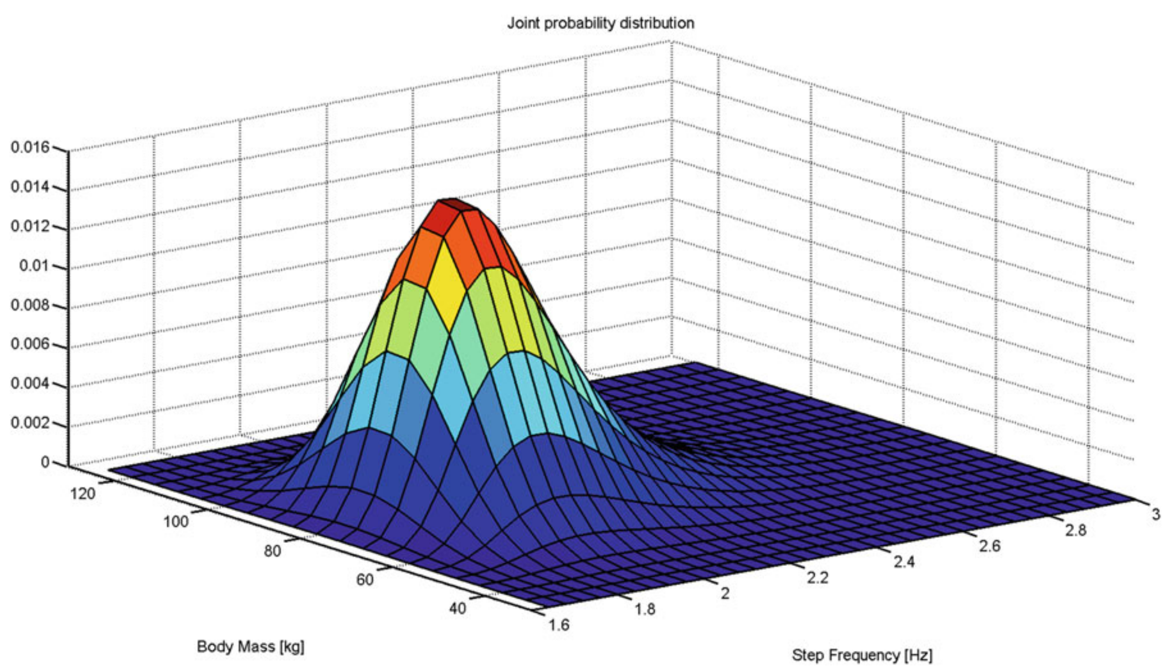


Fig. 11.1 Body mass and step frequency joint probability distribution used as a statistical input for the OS-RMS method. This gives an expected frequency of 2.0 Hz and a body mass of 78.2 kg

or CQC. The next step consists in calculating the response of this single degree of freedom to the walking load history just described. Little detail is provided on this particular step (although frequency domain is mentioned in [9]) but this can be done either in frequency domain or in the time domain using any direct integration technique (e.g. Newmark or any alpha-method). From this a raw velocity response time history, denoted $\dot{X}(t)$ is obtained. A frequency weighting function is applied to this velocity signal to account for the dependence of human perception of vibration with the frequency content of the disturbance. The frequency weighting function used is that recommended in [11]. The weighting is implemented in frequency domain following a Fourier transform of the velocity:

$$\dot{X}_H(f) = \dot{X}(f)H_v(f), \tag{11.2}$$

where $\dot{X}(f)$ is the Fourier transform of the velocity and $H_v(f)$ is the filter transfer function. $H_v(f)$ is defined by:

$$\left| H_v(f) = \frac{1}{v_0} 1 \Big/ \sqrt{1 + \left(\frac{f_0}{f}\right)^2} \right|, \tag{11.3}$$

where $v_0 = 1$ mm/s and $f_o = 5.6$ Hz. The weighted time domain response $\dot{X}_H(t)$ is then obtained by inverse Fourier transform. The calculation of the OS-RMS for a specific step frequency $f_{s,m}$ and modal mass M_n is done by finding the RMS value of response over a time window $[t\ t + T_s]$ starting at arbitrary time but after any initial transient that may have been caused by an artificially sudden onset of the force. This calculation is based on the following equation:

$$\mathrm{OS-RMS}n, m = \sqrt{\frac{1}{T_s}\int_t^{t+T_s} \dot{X}_H^2(t)dt}. \tag{11.4}$$

The value of OS-RMS90 requires the introduction of the probability distribution of the step frequency f_s and the body mass M_b shown in Fig. 11.1 and provided in tabulated format. OS-RMS90 is the value 90% percentile of the OS-RMSn,m values weighted by the corresponding value of the $f_{s,m}$ and modal mass M_n joint-probability distribution. OS-RMS90 can be plotted for varying slab natural frequencies and modal masses (and damping as a parameter). Two-dimensional maps (with constant damping) have been published. They allow rapid assessment of a floor serviceability performance which is useful in early design stages.

R-factor Based Assessment (SCI P354)

This method [6] describes the walking force as a periodic continuous function of time that is represented by a finite number of Fourier components at the walking fundamental frequencies and its harmonics. This set of frequencies excite the floor eigenmodes to varying degree depending on their relative proximity in frequency and the harmonic amplitudes. The method distinguishes between two types of responses: the modal response of a floor at an eigenfrequency much higher than the harmonic frequency considered is deemed to be impulsive while the modal response of the floor is considered to be in steady state when the floor eigenfrequency is lower than the force component frequency. The amplitude F_h of the h^{th} harmonics is expressed by:

$$F_h = \alpha_h Q, \tag{11.5}$$

where α_h is the step frequency-dependent coefficient of the h^{th} harmonic and Q is the static force of an "average person" (normally 746N). Equivalent force for impulse excitation is calculated by

$$F_I = 60 \frac{f_s^{1.43}}{f_n^{1.30}} \frac{Q}{700}, \tag{11.6}$$

where f_n is the structure eigenfrequency of the n^{th} mode under consideration. For the steady-state response, the RMS value of the acceleration for n^{th} single mode and force of h^{th} harmonics is

Table 11.1 Frequency weighting curve (Z – axis)

Z – axis vibrations weighting (W_h)	
$W = 0.4$	For $1Hz < f_s < 2Hz$
$W = f_s/5$	For $2Hz \leq f_s < 5Hz$
$W = 1.0$	For $5Hz \leq f_s \leq 16Hz$
$W = 16/f_s$	For $f_s > 16Hz$

$$a_{w,rms,e,r,n,h} = \mu_{e,n}\mu_{r,n}\frac{F_h}{M_n}D_{n,h}W_h, \tag{11.7}$$

where $\mu_{e,\,n}$ and $\mu_{r,\,n}$ are the mode shape amplitudes respectively at the excited point (subscript e) and the response point (subscript r), M_n is the modal mass, W_h is the frequency weighted factor defined according to [12]. $D_{n,\,h}$ is the dynamic magnification factor and expressed by

$$D_{n,h} = \frac{h^2\beta_n^2}{\sqrt{\left(1-h^2\beta_n^2\right)^2+\left(2h\zeta_n\beta_n\right)^2}}, \tag{11.8}$$

where $\beta_n = f_s/f_n$, ζ_n is the modal damping ratio. For impulse response, the RMS value has a similar expression and can be calculated by:

$$a_{w,peak,e,r,n,h} = 2\pi f_n\mu_{e,n}\mu_{r,n}\frac{F_I}{M_n}W_n\sqrt{1-\zeta^2}. \tag{11.9}$$

The total response is then obtained by summing up the components for all modes considered and force harmonics. This can be done either using full time history or by SRSS combination. Using SRSS, the RMS of the steady-state response and the total acceleration is calculated by:

$$a_{w,rms,\mathrm{e},r} = \frac{\sqrt{2}}{2}\sqrt{\sum_{h=1}^{H}\left(\sum_{n=1}^{H}a_{w,rms,e,r,n,h}\right)^2}. \tag{11.10}$$

The RMS of the impulse response is calculated in the time domain by the following equation:

$$a_{w,rms,e,r} = \sqrt{\frac{1}{T}\int_0^T\sum_{n=1}^{N}a_{w,peak,e,r,n,h}\sin\left(2\pi f_n\sqrt{1-\zeta^2}\right)e^{-2\pi\zeta f_n t}dt}. \tag{11.11}$$

The RMS values calculated here also needs to be weighed using Table 11.1. According to [13], the R factor for z axis vibration can be finally determined by

$$R = \frac{a_{w,rms}}{0.005}. \tag{11.12}$$

11.3 Comparison of the Methods

- Force definition

SCI-P354 methods and OS-RMS90 use somewhat different force definitions. Both are parametrized, in time by the step frequency and in amplitude by the weight of a single walking person. The R-factor methods capture the footfall force using the first four Fourier components of the force as fitted from experimental data. OS-RMS90 stores the time profile of the force in terms of polynomial coefficients (although a Fourier decomposition is suggested an approximation in [8]). As a result, the

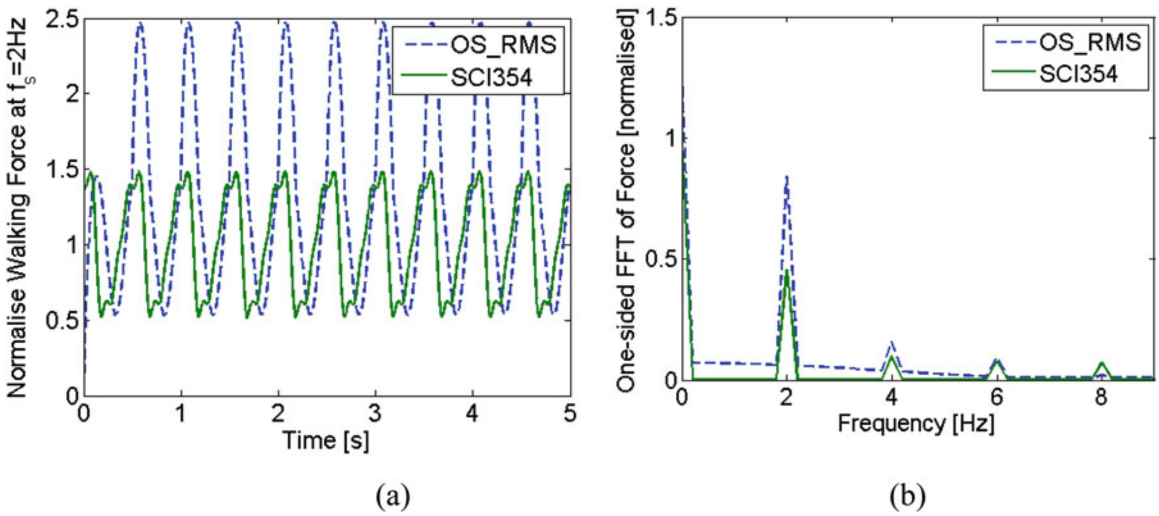


Fig. 11.2 Comparison of walking force time histories (**a**) and spectra (**b**). The body mass was taken as unity and the step frequency as 2 Hz

latter does not bring out explicitly the significance of harmonics content of the force signal. R-factor methods use a single average person walking weight and a narrow range of frequencies with uniform probability of occurrence. The OS-RMS method offers a more developed statistical framework, providing a first step towards a firmer reliability basis.

Figure 11.2 compares walking forces in the time domain (a), and the frequency domain (b) for a footfall frequency of 2 Hz. From the time histories, it can be seen that the OS-RMS profile looks quite different and is significantly larger. This has been noted before in the literature [10]. The frequency spectra show that both the static components and the first harmonic are significantly higher (almost by a factor of 2) for the OS-RMS force. This difference increases further as the footfall frequency increases.

It should be noted that the range of walking frequencies given in the OS-RMS probably distribution goes up to 3 Hz. As the bell curve in Fig. 11.1 already hinted, walking at this pace is unlikely but in terms of calculation, care should be taken that the values of the coefficients K_i have been obtained by fitting experimental data over the range 2–2.25 Hz. Extrapolating linearly for higher frequencies (up to 3 Hz as suggested by the table defining the Ks in [5]) produces forces time histories which are clearly wrong. We tried to estimate better these Ks but a secondary fitting. This gave a walking forced with a plausible profile but their normalized amplitude reaches 6–7 which is clearly unrealistic.

- Calculation of the response

Both approaches are based on modal decomposition. With R-Factor methods the response for each mode to the various force harmonics is obtained separately and superimposed. OS-RMS90 only considers the response of one mode force by the footstep time history. For multimodal response an SRSS combination is recommended.

R-factor methods make a distinction between impulsive and steady state response of the floor. This distinction is not clearly made in OS-RMS90 but this distinction is not necessary if the equation of motion is directly integrated but this comes at a higher computational cost.

Although both methods assume that the walking person is effectively stationary (usually at the antinode of the mode shape considered to be conservative) R-Factor methods include an attenuation coefficient that accounts for the fact that a person walking over a typical slab dimension is unlikely to cause the system to reach a full steady-state amplitude. This coefficient depends on the damping, the walking speed and the characteristics length of the slab (its definition in SCI354 contains a typo as reported by [4]). No such coefficient is mentioned in OS-RMS90 methodology although the particular one-step interval chosen to compute the RMS value could be selected with this effect in mind. The criteria for selecting this interval currently remain vague.

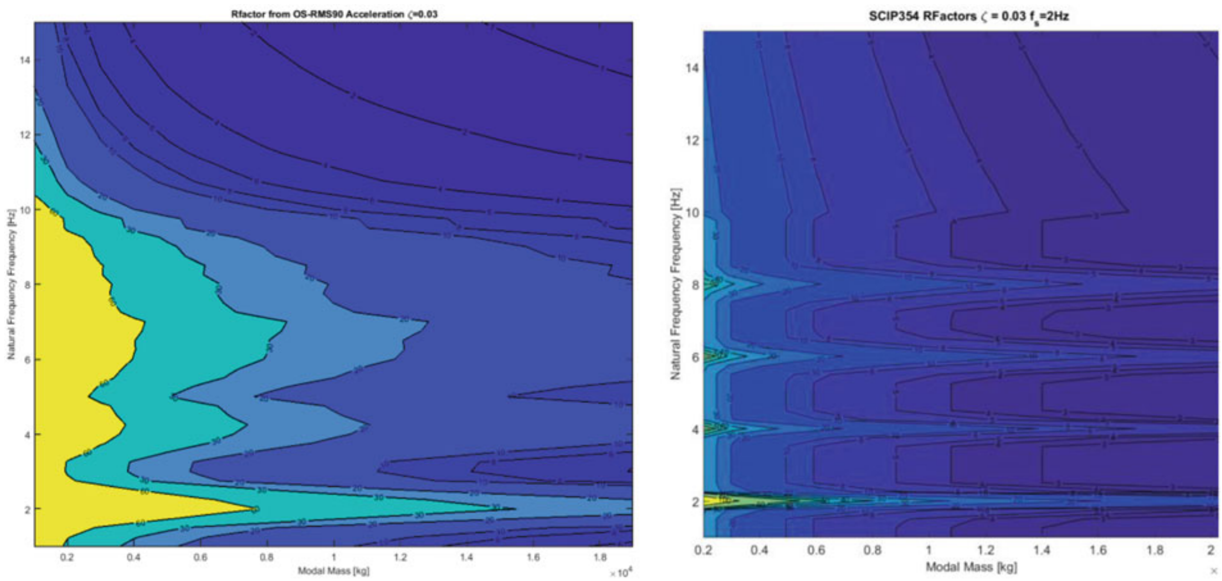
- Thresholds of acceptability

OS-RMS90 eventually produced results in terms of velocity whereas R-Factor methods work with acceleration. In principle both contain the same information but this means the direct comparison of the two methods is not straightforward. Different criteria of acceptability are provided in terms of floor usage. However Feldmann et al. [5] offer some elements of comparison which we have attempted to summarize in Table 11.2.

Table 11.2 Main thresholds of acceptability for the two metrics considered

	Hospitals	Residential day	Residential night	Office
R-Factor	1	2–4	1.4	4
OS-RMS90	0.1	0.8–3.2		

Note that the R-factor and OS-RMS90 values quoted in this table cannot be directly compared



(a) (b)

Fig. 11.3 Contour maps of response factors in terms of floor modal masses and natural frequencies. Both maps were obtained with a constant damping ratio $\zeta = 0.03$. (**a**) R-Factor based on OS-RMS90 Accelerations. (**b**) Acceleration R-Factor following SCIP354

11.4 Single Degree of Freedom Contour Maps

To provide a quantitative comparison between the two methods, they were both adapted to produce results that can be related. The OS-RMS90 processed as described earlier was followed except that the force time histories were generated using the harmonics defined in SCI-P354. It was judged that the forced originally defined with the OSRM90 method were too high for fs >2.2 Hz. Also the results were expressed in terms of acceleration rather than velocity. This acceleration was not filtered according to Eq. (11.3) as it is not clear what the equivalent transfer function for accelerations is. Instead the W_b filter [12] was applied in the frequency domain to the acceleration time series. The final acceleration levels obtained for each walking frequency and body mass pair were multiplied by the corresponding probability density value and the 90% percentile of the resulting sample values was calculated then divided by 5 mm/s^2. The process was repeated for a range of SDOF systems of varying modal mass and frequency. Newmark ($\beta = 1/4$ and $\gamma = 1/2$) with a time step of 1 ms was used for time integration. The results are plotted as a contour map in Fig. 11.3a.

The standard R-Factor method (SCI-P354) was applied to the same array of single degree of freedom systems with the same level of damping ($\zeta = 0.03$). The walking frequency and body mass were kept constant at 2 Hz and 76 kg resp. The results, also presented as a contour map are shown in Fig. 11.3b.

The two contour plots show a number of similarities. The R-factor is fairly low for heavy floors and natural frequencies above 10 Hz. The two maps show horizontal ridges of high responses for light floors. These represent resonant responses at multiples of the walking frequency (harmonics of the force). These ridges are more clearly defined in the SCI-P354 map presumably because a single step frequency is used to define the force whereas a whole distribution comes into the OS-RMS90 calculation. Clear resonant ridges no longer feature for natural frequencies above 10 Hz for either method. In the case of SCI P354 this is because the response of the system is then governed by an impulsive behaviour (threshold of 10 Hz).

In terms of process the main remaining differences between the two methods are (1) the range of body masses and walking frequency for OSRMS90 vs one single mass and frequency in SCI P354, and (2) in OSRMS90 the response is obtained by direct integration. It is reassuring that the 10 Hz frequency threshold is also clearly visible in the OSRMS90 map even though the method makes no distinction between impulsive and resonant response.

The detail of the contours can differ slightly, but more importantly, the OSRMS levels are consistently higher by almost about 50%. Two reasons explain this difference: (1) the wider range of walking frequencies is likely to broaden the ridges in all directions; (2) by definition the OS-RMS90 metric returns a value at the higher end of the distribution. In fact, a map showing the weighted average of the all the values obtained for the $\boldsymbol{M_b}$ and $\boldsymbol{f_s}$ range is closer in value to those of the SCI P354 map.

It should be noted that implemented with a time integration, the OSRM90 map takes a lot longer to generate than the SCI P354 one.

11.5 Case Study: Serviceability of a Composite Office Floor

This section compares the two methods on an office floor. The flooring system is a concrete slab supported by steel beams (with shear transfer) represented by blue lines, which are themselves supported by columns (yellow squares) and the side of a shear wall (green strip) as shown in Fig. 11.4.

The basic properties of the floor are described in Table 11.3. To obtain the modal properties of the floor system, the slab was first modelled in Robot Structural. Columns were modelled as pin supports. The slab was modelled with shell elements. A modal analysis was then carried out, producing the modal properties shown in Table 11.4. The low-to-high frequency

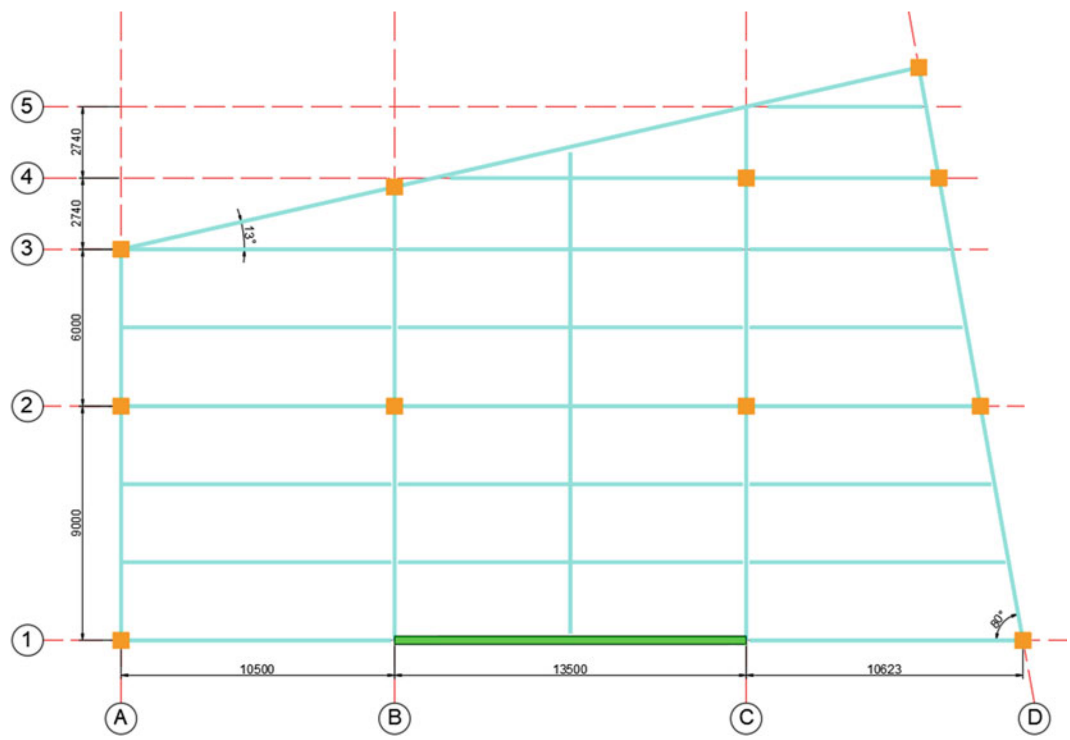


Fig. 11.4 Schematic of the office floor plane

Table 11.3 Basic information about the floor system

Design code	EN 1992-1-1:2004 Eurocode 2
Strength grade of concrete	C30
Slab thickness (mm)	130
Young's modulus (N/mm^2)	26000
Poisson's ratio	0.17
Density of slab (t/m^3)	2.453
Beams	UB533x165x85

Table 11.4 Modal properties and R-Factors values from each mode and each method as read from the contour maps

Mode numbers	Frequency (Hz)	Modal mass (t)	SCI P354	OS RMS90
1	4.51	19.64	2.0	2.7
2	5.50	17.11	3.0	4.1
3	5.91	24.23	5.8	3.4
4	6.30	11.92	4.2	6.2
5	7.01	8.80	4.3	7.2

Table 11.5 Modal combination results from various methodologies

	SCI-P354 chart	OS-RMS90 chart	SCI-P354 Matlab (mode shapes all 1)	SCI-P354 Matlab (mode shapes from Robot)	Robot footfall analysis
SRSS	9.6	11.2	15.7	7.7	9.1

cut-off for general floor (open offices *etc.*) is 10 Hz. This floor can be regarded as low-frequency floor. The damping ratio of the floor slab is selected as 3% based on the usage of the floor and the recommendation from [14].

Based on these modal properties, several calculations of the response factors can be attempted. First, using the SCI P354 contour map, values of each modes can be read off the chart and combined. The same process can be followed using the OS-RMS90 map. These two values were compared to results from a Matlab program that calculates the R-Factor according to the SCI P354 method first assuming that all the mode shapes have their maximum at the same location which is also the position of the walker and second taking into account the mode shape (as read from the Robot modal analysis results). The results are shown in Table 11.5.

It can be seen that a good estimate of the Matlab result can be obtained by combining the graph corresponding readings. The OS-RMS90 values are a little higher, reflecting the issues with the metrics highlighted earlier with the calculation of the force embedded in the method. The robot value is lower than the other two as expected since the program takes into account the fact that the mode shapes have maximum values at different locations. From this it is clear that combining values read-off the charts lead to reasonable estimates on this example. From the two Matlab results, it is also clear that including the mode shape in the calculation makes a significant difference and using 1 for all in the absence of better information can lead to a significant over estimate of the R-factor.

11.6 Conclusion

This paper carried out a systematic comparison of two available method to assess the vibration of floor system. OS-RMS90 has a more robust statistical framework but its force definition seems to be problematic. SCI P354 is simpler and quicker but it relies on the distinction between impulsive and resonant response which has been shown not to be so clear. OS-RMS90 could prove a better solution if it was based with a more reliable definition of the force.

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Dr Philippe Duffour is an Associate Professor in structural dynamics at UCL. He has extensive experience in vibration modeling and measurements in the areas of wind turbines, earthquake engineering and floor serviceability.