Serviceability of buildings subjected to seismic excitations

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Serviceability of Buildings Subjected to Sesmic Excitations

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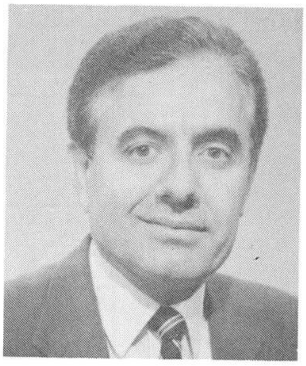

Anis Farah , born 1943, received his B.SC (Queen's, Belfast 1966), M.A.Sc (Toronto, 1967) and Ph.D (Waterloo, 1977) all degrees in civil engineering. He was Director of the School of Eng. at Laurentian Univ., and served on two committees of SCI, Deflection and Safety, and chaired the Computer Applications Committee of the Civil Eng. Div. of ASEE. He is currently a member of the ASCE Lifelines Earthquake Investigation Committee.

Summary

The response of a vibrating building, due to earthquake or wind, is greatly influenced by the soil-structure interaction. This interaction modifies the building resonant frequencies and affects its serviceability relative to the human occupant. In this paper, the serviceability is measured in terms of "human comfort" which is expressed as absorbed power(rate of energy dissipation) through a biomechanical model placed at a given floor in the building. This single value encompasses the characteristics of the structure, the soil, the human, and the dynamic excitation. The latter is represented by its power spectrum whose parameters were evaluated by using nonlinear regression on available earthquake spectra.. The results indicate that absorbed power differentiates between comfort levels at different floors, and that the damping in the structure as well as the soil foundation and power spectrum characteristics have significant impact on building serviceability.

1. Serviceability of buildings to vibration

In addition to being functional, a building must have structural integrity and be serviceable relative to the human user. The serviceability of a building in a vibrational environment has been the subject of numerous studies and recommendations, Chang and Robertson(3), and Chen(4). The recommended criteria have tended to specify acceleration, velocity or displacement limits. For example, it is generally accepted that accelerations of the order of 0.5%g-1%g are perceptible, 1%g-5%g are annoying, and >15%g are disturbing and may be intolerable. Some recommendations for residential buildings, Chang(3) also couple the amplitude of vibration with a corresponding frequency thus leading to human comfort limit curves which are a function of frequency. However, it has been shown by Farah (7) that human comfort levels can be evaluated in terms of the absorbed power through a biomechanical model. This single value incorporates the characteristics of the human, soil-structure system and the seismic excitation.

Earthquake excitation characteristics coupled with suitable site conditions can lead to a large amplification of the structural response of a building. Such a situation arose with the 1985 Mexico earthquake where resonance was set up in buildings due to the soft Tacubaya Clays near the surface of the lake bed in Mexico City, Abiss(1), resulting in extensive damage.

In this work, the seismic excitation is represented by its power spectrum, the building is modeled as a multi-degree-of-freedom system, the soil foundation is expressed in terms of translation and rocking motions resulting in 2DOF possessing mass, stiffness and damping elements, and the human is represented by a 3DOF model simulating a standing human.

2. System modeling

The computation of the building serviceability requires the modeling of the human, the building, the soil-structure interaction, and the seismic excitation.

2.1 Biomechanical model

The human body is highly sensitive to vibration, especially in the standing position. A suitable biomechanical model of a standing human in the fore and aft mode was developed by Farah(6) and is shown in Fig. 1. The parameters of the model were obtained by fitting its frequency response to available experimental data. Based on this model, the absorbed power for the thresholds of perception, annoyance and intolerance in residential buildings are 1.33×10^{-4} W, 8×10^{-4} W and 1.7W respectively. Note that there is great variation in human response to vibration among individuals, and thus the response of the biomechanical model used in this work should be considered only as being a reasonable representation. The biomechanical model has three resonant frequencies, 0.58, 11.10, and 17.00 Hz. Note that the fundamental frequency lies within the range of the fundamental frequencies of tall and medium-height buildings.

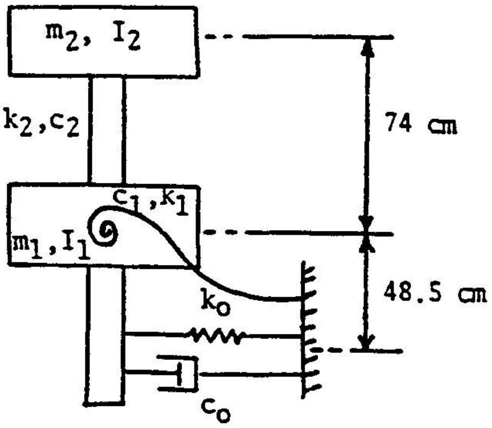

Fig.1 Three-degree model of standing man in the fore and aft mode

2.2 Building model

The building is represented as a multi-degree-of-freedom(MDOF) lumped-parameter system consisting of masses, springs, and viscous damping elements as shown in Fig. 2. The structure has as many degrees-of-freedom as it has stories. The mass and stiffness matrices are first determined, then empirical techniques such as Biggs' method(2) are used to generate a damping matrix for the building based on assumed critical damping ratios.

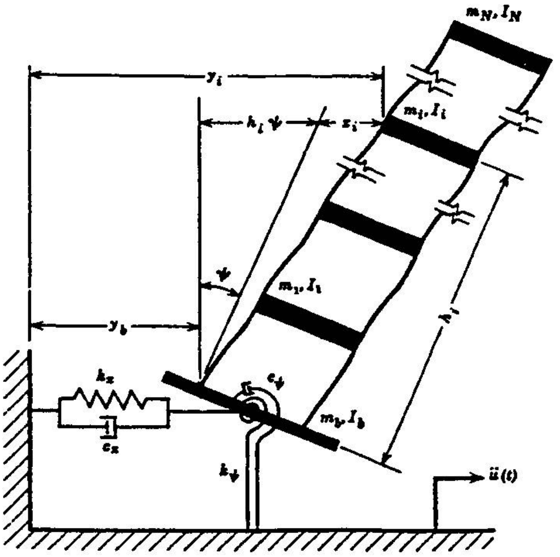

Fig.2 Configuration of flexible-base structure for horizontal seismic excitation (after Tsai)

2.3 Soil-structure interaction model

During an earthquake, the response of a building is greatly influenced by the flexibility of the soil foundation and its interaction with the structure. This interaction modifies the resonant frequencies as well as the amplitude of the structural vibrations. The soil-structure interaction impedances are represented by equivalent springs and dashpots to simulate the soil stiffness and damping. The virtual mass of the soil is calculated by a suitable formula and added to the mass of the base of the building. Generally the soil foundation characteristics are frequency dependent, however, for engineering applications these parameters can be treated as being frequency independent, Tsai(9). Only the translation and rotation(rocking) motions of the foundation are considered in this work. This results in a soil-structure system with 2DOF greater than the number of DOF of the structure by itself. The values of the frequency-independent parameters are computed based on formulae developed with the soil being treated as an elastic half-space, Clough and Penzien(5). The soil properties involved in these calculations are the shear velocity, mass density of the soil, and the radius of the rigid disk representing the foundation half-space. The latter is usually taken as half the width of the building.

2.4 Seismic excitation model

Earthquake ground motions are usually treated as stochastic processes. While the simplest model represents ground accelerations as a white noise process with a constant power spectral density, accelerograms from earthquakes indicate that the spectral amplitudes of seismic energy are frequency dependent. Commonly used models of acceleration power spectra are those due to Kanai-Tajimi and Clough-Penzien.

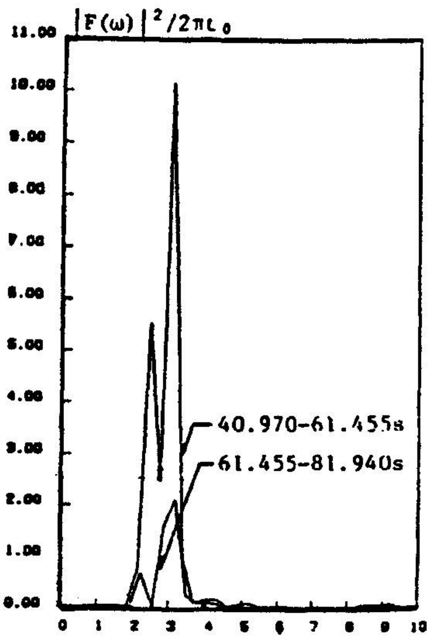

Fig. 3 Acceleration power spectrum of SCT-EW 1985 Mexico earthquake (after Grigoriu et al)

The power spectra used in this study were obtained by fitting, in a least squares sense, available power spectra from the 1985 Mexico earthquake to rational functions which are capable of capturing three peaks in the power spectrum function as shown in Fig. 3.

3. Equations of motion

The effect of the soil-structure interaction on the building is to change its structural response. This results from the incorporation of two additional degrees-of-freedom, horizontal translation and rotation, representing the soil foundation. This in turn increases the number of frequencies by two. Thus, there are N+2 equations of motion describing the soil-structure system response, where N refers to the number of stories in the building. The resulting equations of motion, based on Fig. 2, can be written in the following partitioned matrix form, Tsai(9):

$$\left[\begin{array}{c|c} [M] & [0] \\ \hline [0] & [m] \end{array}\right]\{\ddot{v}\} + \left[\begin{array}{c|c} [C] & [C_1] \\ \hline [C_2] & [C_3] \end{array}\right]\{\dot{v}\} + \left[\begin{array}{c|c} [k] & [k_1] \\ \hline [k_2] & [k_3] \end{array}\right]\{v\} = -\ddot{u}(t)\left\{\begin{array}{c} \{M\} \\ \hline m_b \\ \hline 0 \end{array}\right\} \qquad (1)$$

where $[m] = \begin{bmatrix} m_b & 0 \\ 0 & I_s \end{bmatrix}$ with m_b being the mass of the base and I_s representing the sum of the mass moments of inertia of the structure and the foundation; [M], [C], and [K] refer to the mass, damping, and stiffness matrices of the structure respectively, and are of size NxN; $[C_1]$, $[C_2]$, $[C_3]$ and $[K_1]$, $[K_2]$, $[K_3]$ are damping and stiffness matrices that couple the structure and the flexible foundation; $\ddot{u}$ (t) is the seismic acceleration and $\{v\}=\left\{\begin{array}{c}\{y\}\\ \hline y_b\\ \hline \psi\end{array}\right\}$.

4. Calculation of absorbed power

Absorbed power is calculated by considering the velocity and the force of interaction, between the human and the floor, at the point of contact. The force and velocity can be related to the displacement of the point of contact in the frequency domain, thus relating the biomechanical model response to that of the floor. The floor response power spectrum, $S_f(\omega)$, can be related to the seismic power spectrum, $S_a(\omega)$, by:

$$S_f(\omega)=|H(i\omega)|^2 S_a(\omega) \tag{2}$$

where $H(i\omega)$ is the complex frequency response function of the floor level where the biomechanical model is located. It can be shown, Farah(7) that the absorbed power, P, through the biomechanical model can be evaluated from the integral:

$$P=-\frac{1}{\pi}\int_0^\infty \omega \,\mathrm{Im}[G(i\omega)]S_f(\omega)d\omega \tag{3}$$

where $G(i\omega)$ is the complex frequency function between the force and displacement at the point of contact between the floor and the biomechanical model. The determination of $H(i\omega)$ requires that Eq. 1 be transformed to the frequency domain and the resulting matrix is inverted in closed form and $H(i\omega)$, for the various floor levels, is then obtained from the inverse matrix. The efficient inversion technique was developed by the author based on the Fadeev-Leverrier method. Note that the normal mode decomposition method cannot be used directly in this case due to the coupling terms in the damping matrix resulting from the soil-structure interaction.

4. Results and discussion

To illustrate the procedure described above, absorbed power values were calculated for the floors of an 8-story building and for various critical damping ratios. The power spectra of the seismic excitation were those of the Sept. 1985 Mexico earthquake as given by Grigoriu et al(8). The response of these buildings was evaluated for three site shear velocities 50m/s, 75m/s, and 400m/s. The shear velocity impacts the values of the damping and stiffness elements of the soil foundation. Note that both the damping and stiffness are proportional to the shear velocity and its square respectively, and that generally, the shear velocity is lower in softer soils. Fig. 4 shows that the response corresponding to the 50m/s is higher than that for the 75m/s velocity, and that the absorbed power for a given floor is larger than that corresponding to a lower floor as would be expected since higher values of absorbed power are associated with a lower comfort

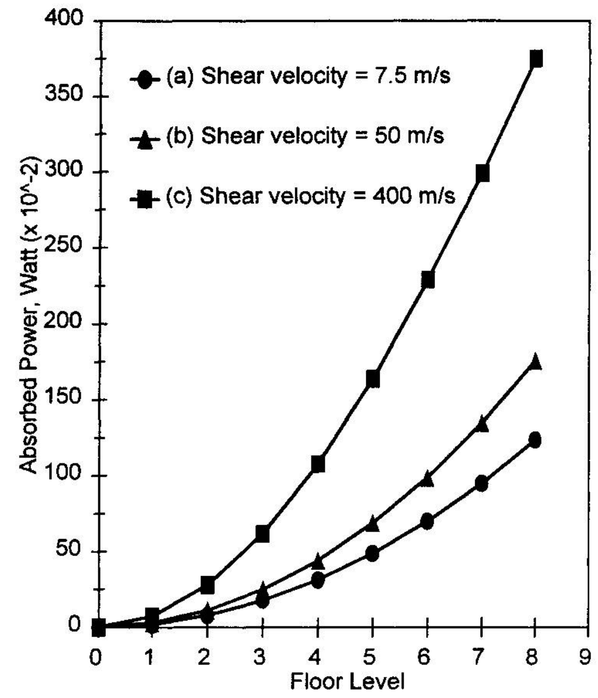

Fig. 4 Absorbed power for an 8-story building with SCT power spectrum

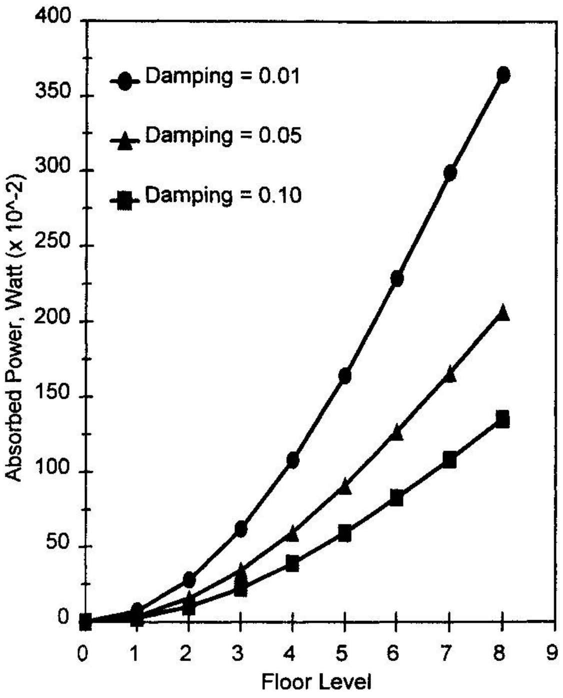

Fig. 5 Effect of damping ratios in structure on absorbed power (shear velocity = 400 m/s)

level. In addition, the response of all floors and for all shear velocities is greater than the level required for the threshold of annoyance which is equal to $8x10^{-4}$ W. However, the absorbed power values for floors 6, 7 and 8 for the 400m/s shear velocity are even larger than the value of 1.7 W which corresponds to the threshold of intolerance. Such high values of absorbed power are indicative of an unacceptably severe building response such as that which occurred during the Mexico earthquake. It is also important to emphasize that for a large building response, the building behavior will not remain elastic and thus the absorbed power values would be different from those given above. The high absorbed power values for the 400m/s shear velocity were produced due to the introduction of frequencies in the soil-structure system which are very close to those of the seismic power spectrum and the first frequency of the biomechanical model. This situation arose because the fundamental frequency of the soil-structure system is 3.2r/s, that of the biomechanical model is 3.64r/s, and the dominant frequency of the earthquake power spectrum is 3.1r/s. In effect a quasi-resonance behavior was setup with the resulting large response.

The effect of the damping in the structure is very significant when the system is in a resonant vibration state. Fig. 5 shows the absorbed power in the building corresponding to a shear velocity of 400m/s. It is seen that the absorbed power on the eighth floor for a damping ratio of 0.01 results in a value of 3.75 W and the corresponding values for damping ratios of 0.05 and 0.10 are 2.07 W and 1.35 W respectively. However based on other results obtained in this study, the impact of damping in the structure is not as significant if resonant or quasi-resonant conditions are not generated.

5. Conclusions and recommendation

It has been shown that absorbed power can be a good indicator of the level of human response to building vibration subjected to seismic excitations, and has the capacity to distinguish human comfort at different floor levels. The damping in the structure is mainly important in reducing the response in a resonant or quasi-resonant vibrational environment. The properties of the soil foundation greatly influences the building behavior, with softer soils, associated with lower seismic shear velocities, generally producing higher absorbed power values except for situations where higher shear velocities generate resonant conditions. The ability to estimate the absorbed power should be invaluable to the engineer in achieving a serviceable building design.

Although this study has demonstrated the potential of absorbed power as a criterion for assessing buildings serviceability to earthquakes, further research is recommended in the following areas:

1. Development of a human model suitable for determining absorbed power under simultaneous horizontal and vertical vibration.
2. Calibration of absorbed power to various earthquake magnitudes and frequency characteristics associated with various site conditions.
3. Determination of the impact of nonlinear behavior of structures on absorbed power and therefore its serviceability.
4. Assessment of the effect of external damping devices such as viscoelastic dampers on the serviceability and safety of structures.

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