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Review

Building earthquake resilience in sustainable cities in terms of input energy

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ABSTRACT

Input energy to building structures during earthquakes is an important index to measure the influence of earthquake ground motions on building structures. Such input energy can be defined after the structural system is specified and the input mechanism is described clearly. The energy input to structures consists mainly of the energy dissipated by hysteretic deformation and that by viscous damping. The excessive dependence on the former mechanism leads to unrepairable and unpreferable states of structures after earthquakes which should be avoided from the viewpoint of sustainability of building structures and cities. In this sense, the measure of energy is appropriate from the viewpoint of total management of buildings in a sustainable city. Then the upper bound of earthquake input energy is derived and discussed under uncertain conditions on input ground motions. It is shown that the earthquake energy input rate is another key parameter for measuring the instantaneous effect of earthquake ground motions on structural responses. A historical review is also made on the development of treatment of earthquake input energy into buildings and on its role into greater building earthquake resilience in sustainable cities.

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1. Introduction

When an earthquake occurs beneath or near a city, all the buildings in the city are shaken more or less. In the conventional seismic structural engineering, the deformation and force are treated as major key indices and their relations with the deformation limit and strength play key roles. However the factor of the size of buildings

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is not reflected in these indices. The energy dissipated in a building during an earthquake is an alternate measure and can reflect the size of the building because all the energies dissipated in parts of the building are summed up over the building. It is discussed in this review article that the measure of energy is appropriate from the viewpoint of total management of buildings in a sustainable city.

It has been recognized for many years that, if the total mass of a building is given, the earthquake input energy is constant irrespective of the stiffness and strength of the building, i.e. the damage level of the building (Akiyama, 1985; Housner, 1956, 1959). The earthquake input energy is transformed principally into (1) the energy dissipated by hysteretic deformation and viscous (or frictional) damping system and (2) the kinetic energy which will diminish during a damping process. It is usually believed that the energy consumption by hysteretic deformation is related to the structural damage. On the other hand, the energy consumption by viscous (or frictional) damping is not related to the structural damage directly. In the earthquake structural engineering community, it is accepted that a certain limited damage is allowed from the viewpoint of the building cost. The key issue is how the damage level is controlled in comparison with the shaking level of ground motions. The introduction of smart passive control technologies (Murase, Tsuji, & Takewaki, 2013; Takewaki, Fujita, Yamamoto, & Takabatake, 2011; Lang, Guo, & Takewaki, 2013) may be one approach to provide a reasonable and acceptable solution to such difficult problems.

First of all, it is shown that the constancy of earthquake input energy is directly related to the uniformity of 'the Fourier amplitude spectrum' of ground motion acceleration with respect to frequency, not the uniformity of the velocity response spectrum with respect to natural period. Since the earthquake ground motions are highly uncertain in both aleatory and epistemic senses, the description of such uncertainties is important for reliable design of structures under the earthquake ground motions. The worst-case analysis is promising (Moustafa, Ueno, & Takewaki, 2010; Fujita & Takewaki, 2011; Takewaki, Moustafa, & Fujita, 2012; Takewaki, 2013a, 2013b) and the bounds of earthquake input energy play an important role. The bounds under acceleration and velocity constraints (time integral of the squared base acceleration and time integral of the squared base velocity) are clarified through numerical examinations for recorded ground motions to be meaningful in the short and intermediate/long natural period ranges, respectively.

2. Earthquake input energy to fixed-base SDOF models

A lot of works have been accumulated on earthquake input energy. The representative ones are Akiyama (1985), Berg and Thomaides (1960), Fajfar and Vidic (1994), Goel and Berg (1968), Housner and Jennings (1975), Housner (1956, 1959), Kuwamura, Kirino, and Akiyama (1994), Leger and Dussault (1992), Mahin and Lin (1983), Ordaz, Huerta, and Reinoso (2003), Riddell and Garcia (2001), Tanabashi (1956), Uang and Bertero (1990) and Zahrah and Hall (1984). Different from most of the conventional works, the earthquake input energy was formulated in the frequency domain (Kishida & Takewaki, 2006; Kishida & Takewaki, 2007; Lyon, 1975; Ordaz et al., 2003; Page, 1952; Takewaki et al., 2011; Takewaki, Fujita, & Yoshitomi, 2013; Takewaki, 2004a, 2004b; Takewaki, 2005a, 2005b, 2005c, 2005d; Takewaki, 2006a, 2006b, 2006c; Takewaki, 2007a, 2007b; Takewaki, 2013a, 2013b; Takewaki & Fujimoto, 2004; Takewaki & Fujita, 2009) to facilitate the formulation of critical excitation methods and the derivation of bounds of the earthquake input energy.

Consider a damped, linear elastic SDOF system of mass m, stiffness k and damping coefficient c as shown in Fig. 1. Let $\Omega = \sqrt{k/m}$, $h = c/(2\Omega m)$ and x denote the undamped natural circular

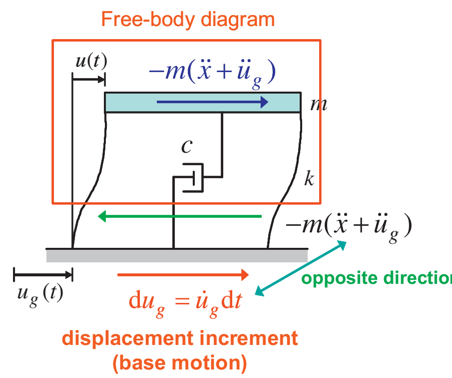

Fig. 1. Schematic diagram for evaluating input energy to SDOF model.

frequency, the damping ratio and the displacement of the mass relative to the ground. An over-dot indicates the time derivative. The input energy to the SDOF system by a horizontal ground acceleration $\ddot{u}_g(t) = a(t)$ from $t = 0$ to $t = t_0$ (end of input) can be defined by the work of the ground on the SDOF structural system and is expressed by

$$E_I = \int_0^{t_0} m(\ddot{u}_g + \ddot{x})\dot{u}_g dt \quad (1)$$

The term $-m(\ddot{u}_g + \ddot{x})$ in Eq. (1) indicates the inertial force and is equal to the sum of the restoring force kx and the damping force $c\dot{x}$ in the model. Fig. 1 shows a schematic diagram for evaluating the input energy to this SDOF model. It can be observed that the restoring force equilibrating with the inertial force has an opposite direction to the base motion increment.

Integration by parts of Eq. (1) yields

$$\begin{aligned} E_I &= \int_0^{t_0} m(\ddot{x} + \ddot{u}_g)\dot{u}_g dt = \int_0^{t_0} m\ddot{x}\dot{u}_g dt + \left[\frac{1}{2}m\dot{u}_g^2\right]_0^{t_0} \\ &= [m\dot{x}\dot{u}_g]_0^{t_0} - \int_0^{t_0} m\dot{x}\ddot{u}_g dt + \left[\frac{1}{2}m\dot{u}_g^2\right]_0^{t_0} \end{aligned} \quad (2)$$

Assume that $\dot{x} = 0$ at $t = 0$ and $\dot{u}_g = 0$ at $t = 0$ and $t = t_0$. Then the total input energy can be simplified to the following form.

$$E_I = -\int_0^{t_0} m\ddot{u}_g\dot{x}dt \quad (3)$$

It is known (Lyon, 1975; Ordaz et al., 2003; Takewaki, 2004a, 2004b; Page, 1952) that the total input energy per unit mass to the SDOF system can also be expressed in the frequency domain by use of Fourier transformation.

$$\begin{aligned} \frac{E_I}{m} &= -\int_{-\infty}^{\infty} \dot{x}a dt = -\int_{-\infty}^{\infty}\left[\frac{1}{2\pi}\int_{-\infty}^{\infty} \dot{X}e^{i\omega t}d\omega\right]a dt \\ &= -\left(\frac{1}{2\pi}\right)\int_{-\infty}^{\infty} A(-\omega)\{H_V(\omega;\Omega,h)A(\omega)\}d\omega \\ &\equiv \int_0^{\infty} |A(\omega)|^2 F(\omega)d\omega \end{aligned} \quad (4)$$

In Eq. (4), the function $H_V(\omega;\Omega,h)$ is the velocity transfer function defined by $\dot{X}(\omega) = H_V(\omega;\Omega,h)A(\omega)$ and $F(\omega) = -Re[H_V(\omega;\Omega,h)]/\pi$. The function $F(\omega)$ is called the energy transfer function and plays a key role in evaluating the upper bound of input energy which will be discussed in the following section. $\dot{X}(\omega)$ and $A(\omega)$ denote the Fourier transforms of $\dot{x}$ and $\ddot{u}_g(t) = a(t)$. The