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An improved defining parameter for long-period ground motions with application of a super-tall building

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ABSTRACT

This paper focuses on defining long-period ground motions and analyzing the effect of them on building structures. Increasing attention has been paid to the effect of long-period ground motions on building structures. However, long-period ground motions are not quantitatively defined due to the lack of numerous ground motion investigations. In this paper, based on the statistical analysis of 39,744 ground motions, an improved frequency-domain defining parameter, namely β_l, is firstly proposed to identify long-period ground motions without the necessity of seismological information. Then, based on the definition, long-period ground motions are selected for the time history analysis of a super-tall building structure. The structural responses are obtained under three scenarios: the original ground motion record, the ground motions scaled to minor earthquakes and major earthquakes. To assess the validity of the proposed parameter β_l in identifying long-period ground motions, correlation between the structural response and the defining parameter is obtained.

1. Introduction

Ground motions with apparent long-period characteristics or rich low-frequency components are referred to as "long-period ground motions". They can be mainly divided into two types of special ground motions, one is the near-fault pulse-like ground motion, and the other is the far-fault simple harmonic ground motion. Researches show that both types of ground motions have obvious long-period characteristics [1]. The near-fault pulse-like ground motion (hereinafter referred to as "the near-fault long-period ground motion") is generally happened in near-fault areas, which is caused by direct plate fracture effects; the far-fault simple harmonic ground motion (hereinafter referred to as "the far-fault long-period ground motion") is usually generated by a strong earthquake through a long effective propagation path, which is generally near coast earthquake, and also due to the basin response effect.

Damage investigation and analysis show that long-period ground motions can adversely affect the response of long-period structures, especially tall and super-tall buildings, isolated structures, timberworks and oil storage tanks with longer structural periods. Shekari [2] investigated the effect of the frequency content on seismic behavior of base-isolated concrete rectangular liquid tanks. Asai et al [3] did the research of high-rise buildings subject to long period earthquakes. Mazza et al [4,5] evaluated the seismic demand of base-isolated irregular structures subjected to pulse-type earthquakes and did the analysis of R.C. framed buildings located in a near-fault area. In general, the response of long-period structures is more obvious under long-period excitation, especially when the long-period component of the ground motion is richer, the natural period of the site is longer, and the fundamental period of the structure is basically close to the natural period of the site, which is called "double resonance".

The long-period ground motion was first observed and identified in 1968 Hokkaido Tokachi-oki Earthquake (M8.2) [1], and the ground motion showed a large amplitude and a predominant period up to 2.5 s. In the 1985 Michoacan Earthquake (M8.0), Mexico City, 400 km away from the epicenter, suffered collapse of about 300 buildings, serious damages of about 800 buildings and casualties of 20,000 people, which was caused by long-period ground motions with predominant periods of about 2–4 s. In the 2005 Niigata Earthquake (M6.6), Tokyo, 150–200 kilometers away from the epicenter, experienced more than five minutes of strong earthquakes (maximum ground displacement > 5 cm), and the measured predominant period was about 7 s [6].

Among previous researches, there has been a few clear definitions of long-period ground motions. From the view of predominant period, ground motions with predominant period of 1 s or below are usually defined as short-period ground motions, and that with predominant period of 1–10 s or longer are usually defined as long-period ground motions [7]. In addition, based on the characteristics of the ground motion time history curve, ground motions exhibit long-period pulse-like or simple harmonic vibration characteristics [8] can be seen as the long-period ground motion.

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Researchers have proposed several parameters to identify long-period ground motions recently [9,10]. That is, based on the conventional time-domain and frequency-domain parameters of ground motions, the defining parameter for long-period ground motions with strong correlation and reliability is refined and proposed. Then, relying on the ground motion data rather than the seismological parameters, identifying long-period ground motions can be realized. This method can quickly and efficiently identify long-period ground motions only on the basis of simple processing of ground motion data.

For parameters from ground motion records, the predominant period was early used for indicating part of the spectral characteristics, but it cannot describe what the spectrum is like around the maximum point and the overall spectral shape. Another problem with the predominant period is that when a spectrum has multiple peaks, slight changes of the input ground motion may cause large variation of the predominant period. Then, Rathje et al. [11] proposed the smoothed predominant period T_0, which averages the amplitude over certain period range, thus the smoothed spectrum is not affected by multiple peaks. And Rathje et al. [9,11] also proposed the mean period T_m, which is an averaged period of the computed Fourier amplitude spectrum, to further consider the longer fundamental periods of super-tall buildings and to better represent frequency contents of strong ground motions. However, because of the narrow period range considered by these parameters, long-period ground motions cannot be adequately considered. Some attempts to model long-period ground motions by simple multiple impulses have also been done by Kojima et al. [12,13] and Hayashi et al. [14]

Based on the statistical analysis of 39,744 ground motions in the PEER NGA-West2 ground motion database (short for "PEER database") [15], this paper proposes an improved frequency-domain defining parameter for long-period ground motions with considerable reliability. And with a finite element model of a super-tall building, the time history analysis is conducted to find out the realistic relation between the structural seismic responses and the defining parameter, which is used to prove the efficiency of the parameter. In this paper, the ground motion data is rich, and the long-period ground motion is studied both from statistical analysis and structural calculation. The proposed parameters can efficiently identify the long-period ground motion without complex seismological parameters, which provides an important reference for the analysis of structures with long periods.

2. An improved defining parameter for long-period ground motions

Based on the analysis of ground motion energy characteristics with Hilbert-Huang transformation, Li et al. [16] proposed a defining parameter, based on the weighted average of the response spectrum value and the square of the period, for long-period ground motions. This defining parameter, however, had no validation of a large number of ground motion data. In this section, by the analysis of the abundant data in the PEER database [15], an improved defining parameter for long-period ground motions with considerable reliability is proposed, which does not depend on the seismological parameters and just based on the ground motion data, to efficiently identify long-period ground motions.

First, the weighted average β_l of the response spectrum shown in the following Eq. (1) is used as an improved defining parameter for long-period ground motions. Since the weight is positively correlated with the period, the longer the period is, the larger the weight is. So it highlights the long-period characteristics of ground motions.

$$\beta_l = \frac{\sum T_i^{\alpha}\beta_a(T_i)}{\sum T_i^{\alpha}} \tag{1}$$

where β_a is the normalized acceleration response spectrum value of the ground motion, T_i is the i-th period point (within the period range of [0, 10]s with interval of 0.01 s), T_i^{α} is the weight coefficient of the spectrum value $\beta_a(T_i)$, and α is the exponent of the period T_i which need to be optimized by further analysis. And from the structural engineering viewpoint, Eq. (1) reflects the proportion of long-period components of the ground motion in the normalized acceleration response spectrum.

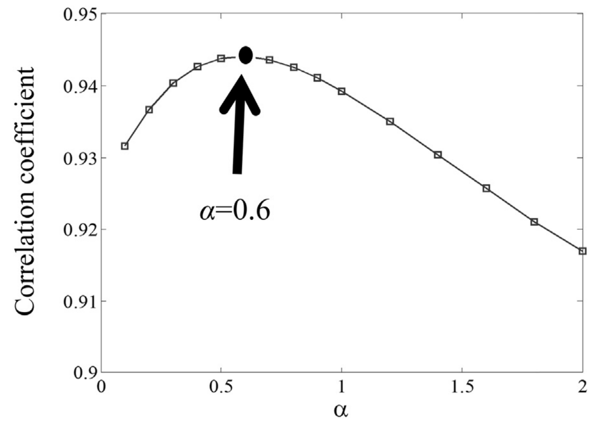

Fig. 1. Correlation coefficient between β_l and PGV/PGA.

Then, the β_l value of 39,744 horizontal ground motions from PEER database [15] with different values of α are calculated. From the time-domain perspective, previous researches have shown that the parameter PGV/PGA can well reflect the long-period characteristics of ground motions [17–20] and be further used as a defining parameter for long-period ground motions. So, the correlation coefficients between β_l and PGV/PGA with different values of α from 0 to 2.0 are also analyzed. The curve is shown in Fig. 1. It can be seen that, the correlation coefficient between β_l and PGV/PGA increases when $\alpha < 0.6$ but decreases when $\alpha > 0.6$, so when $\alpha = 0.6$, the correlation coefficient reaches a maximum value of 0.944. In this situation, the scatter between β_l and PGV/PGA is also shown in Fig. 2, and the results show a strong positive correlation between these two parameters. Thus, when $\alpha = 0.6$, improved parameter β_l can be well used to identify the long-period characteristics of ground motions, and it has greater correlation with PGV/PGA than previous parameter ($\alpha = 2.0$) which uses the weighted average of the response spectrum value and the square of the period proposed by Li et al. [16]

Based on the statistical analysis of the tremendous amount of data above, the following Eq. (2) can be used as the defining criteria for long-period ground motions.

$$\beta_l = \frac{\sum T_i^{0.6}\beta_a(T_i)}{\sum T_i^{0.6}} \begin{cases} \le 0.4 & \text{Normalgroundmotions} \\ 0.4\text{~}0.6 & \text{Medium-long-period ground motions} \\ \ge 0.6 & \text{Long-period ground motions} \end{cases} \tag{2}$$

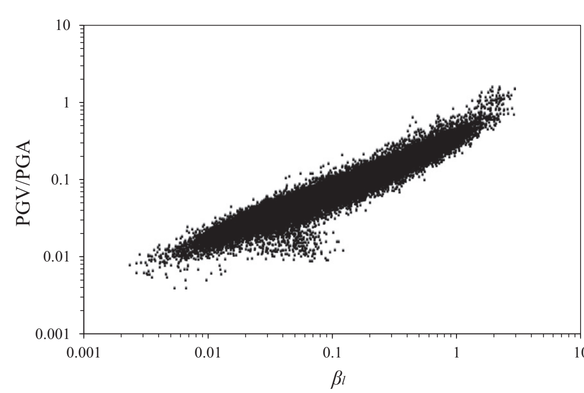

Fig. 2. Scatter between β_l and PGV/PGA.