Study on characteristic parameters of near-fault response spectrum

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Abstract. 883 vertical earthquake records within the fault distance of 100 km were selected to study that whether the vertical design response spectrum characteristic parameter should be also used for the seismic design of engineering structure in near-fault region. Considering the influence of site conditions, fault distance and velocity pulse characteristics, the platform value, the first turning point period, the characteristic period, and the attenuation index of the dynamic amplification coefficient spectrum were studied respectively. This study concludes: the platform value, the first turning point period, the characteristic period, and the attenuation index are affected by site condition, fault distance, and velocity pulse characteristics. Chinese building seismic design code takes the platform value, the first turning point period, and the attenuation index as fixed values which may not be reasonable, and it should take into account the influence of site condition and fault distance. For the vertical ground motions in near-fault region, the platform values, the first turning point period, and the characteristic period of the dynamic amplification coefficient spectrum should be reasonably increased to improve the safety reserve of the engineering structures in near-fault region.

1. Introduction
Under earthquake action, the destruction of the engineering structure may be caused by horizontal ground motion, or it may be closely related to vertical ground motion. Especially for large-span space structures and high-rise building structures, vertical ground motion is a potential damage that cannot be underestimated in seismic design [1, 2]. Studies had shown that vertical ground motions, especially vertical ground motions in the near-fault region, had some new features. Vertical ground motions had large acceleration peaks, and vertical acceleration response spectra were sensitive to fault distance. In the case of near-fault horizontal ground motion, the vertical ground motion of the near fault contained more high-frequency components [3, 4]. The relationship between vertical and horizontal response spectra of near-fault ground motion indicated that the vertical and horizontal acceleration response spectrum ratios were closely related to natural period, fault distance, magnitude, focal mechanism, and site condition, and the ratio of short-period near faults was the largest. The ratio between the vertical and horizontal acceleration response spectrum in the short-period segment exceeded 2/3, especially in the near-fault region, and 2/3 of ratio as a quantitative relationship between vertical and horizontal ground motions was not reasonable. The impact of vertical ground motion should not be ignored in the seismic design of the engineering structure near the fault region [5, 6]. At present, 65% of horizontal seismic influence coefficient is taken as the maximum value of the vertical seismic influence coefficient in China's building seismic design code to calculate the vertical seismic effect. The characteristic period of the vertical acceleration design response spectrum is designed according to the characteristic period of the horizontal design response spectrum [7]. It is worthwhile to study whether the vertical design response spectrum based on the horizontal design response spectrum is applicable...
to the seismic design of engineering structure in the near-fault region.

In this paper, we discuss the characteristics of the platform value, the first turning point period, the characteristic period, and the attenuation index of the dynamic amplification coefficient spectrum of vertical ground motions.

2. Ground Motion Data
883 vertical ground motion records from 80 worldwide earthquakes collected in this paper serve as the basis of statistical analysis. These records are sourced from the Strong Earthquake Database of the Pacific Earthquake Engineering Center and the Wenchuan Earthquake Record of China. Based on the vertical earthquake records obtained by the above principle, 29 vertical pulse-type ground motion records of near fault were screened according to the method of identification of near-fault pulse-type ground motion records proposed by Wei T [10]. Site categories are divided into four categories. Collecting ground motion records of site category IV are too few to study in this paper.

3. Determination Method of Characteristic Parameters
Characteristic parameters are calibrated according to the design response spectrum curve form of the "Seismic ground motion Parameters Zonation map of China" (GB18306-2015), as follows equation (1).

\[
\beta(T) = \begin{cases} 
1 + (\beta_{\text{max}} - 1.0) \frac{T}{T_0} & 0 < T \leq T_0 \\
\beta_{\text{max}} & T_0 < T \leq T_g \\
\beta_{\text{max}} \left( \frac{T}{T_g} \right)^{\gamma} & T_g < T \leq T_w 
\end{cases}
\]

(1)

\(\beta_{\text{max}}, T_0, T_g, \) and \(\gamma\) respectively represent the platform value, the first turning point period, the characteristic period, and the attenuation index of the dynamic amplification coefficient spectrum. In the process of determining the characteristic parameters of the design response spectrum, the \(T_m\) is taken as 6s. The fitted spectrum obtained by directly fitting the response spectrum using the least squares method is closer to the shape of the original response spectrum, and the error is smaller [11]. Therefore, the least squares method is used to fit the dynamic amplification coefficient spectrum of each seismic record, and the principle of sum of error square is the minimum. The sum of error square \((Q)\) is given in equation (2).

\[
Q = \sum_{i=1}^{N} [\beta(T) - \beta_i(T)]^2
\]

(2)

The period interval is taken as 0.01s, where \(N\) is taken as 600. In order to determine the characteristic parameters – e.g. \(\beta_{\text{max}}, T_0, T_g, \) and \(\gamma\), it is necessary to minimize \(Q\), and the following equation needs to be satisfied:

\[
\begin{align*}
\frac{\partial Q}{\partial \beta_{\text{max}}} &= 0 \\
\frac{\partial Q}{\partial T_0} &= 0 \\
\frac{\partial Q}{\partial T_g} &= 0 \\
\frac{\partial Q}{\partial \gamma} &= 0
\end{align*}
\]

(3)

Equation (1) is used to fit 883 dynamic amplification coefficient spectrum with 5% damping ratio to determine the characteristic parameters by equation (2) and equation (3).
4. Analysis of Influence Factors of Characteristic Parameters

4.1. Analysis of Influence Factors of Platform Value ($\beta_{\text{max}}$)
This paper considers the impact of site type, fault distance, and pulse characteristics on the platform value. The mean value of platform values is listed in Table 1.

Table 1. Statistical results of platform value

| Fault distance (km) | Site category | Site category | Site category |
|---------------------|---------------|---------------|---------------|
|                     | $\beta_{\text{max}}$ | $\sigma$ | $\beta_{\text{max}}$ | $\sigma$ | $\beta_{\text{max}}$ | $\sigma$ |
| 0-20 (pulse type)   | 2.04          | 0.58         | 2.42         | 0.63         | 2.47         | 0.57         |
| 0-20 (non-pulse type)| 2.44          | 0.60         | 2.53         | 0.68         | 2.67         | 0.60         |
| 20-60               | 2.49          | 0.54         | 2.62         | 0.65         | 2.46         | 0.76         |
| 60-100              | 2.74          | 0.75         | 2.75         | 0.56         | 2.92         | 0.61         |

Table 1 shows that, in addition to the $\beta_{\text{max}}$ of the near-fault pulse-type ground motion at the site category I being less than the code value 2.25, other parts is greater than the norm 2.25. $\beta_{\text{max}}$ of near-fault vertical non-pulse ground motion is greater than 2.25. The $\beta_{\text{max}}$ of the vertical non-pulsed ground motion of near fault is higher than the corresponding $\beta_{\text{max}}$ of the near-fault pulse-type ground motion. The $\beta_{\text{max}}$ of various types of near-fault vertical ground motion is basically smaller than the $\beta_{\text{max}}$ corresponding to the vertical far-field ground motion. The $\beta_{\text{max}}$ of various site categories increases with the increasing of fault distance, indicating that the fault distance has a certain influence on $\beta_{\text{max}}$. The $\beta_{\text{max}}$ of the near fault gradually increases with the softening of the site soil, indicating that the site conditions have a significant influence on the $\beta_{\text{max}}$ corresponding to the near-fault vertical ground motion. The law of change with site conditions of the $\beta_{\text{max}}$ of the far field is not consistent.

4.2. Analysis of Influence Factors of the First Turning Point Period ($T_0$)
The first turning point period ($T_0$) of the vertical design response spectrum is taken as a fixed value of 0.1s in Chinese building seismic design code (GB 50011-2010), which is one of the important control parameters of the vertical design response spectrum, regardless of whether the influence of other factors is reasonable. In this problem, this section mainly studies the effect of fault distance, site condition, and pulse characteristics on the first turning point period ($T_0$) to determine characteristics of its value in the near-fault region. The mean value of the first turning point period ($T_0$) is listed in Table 2.

Table 2. Statistical results of the first turning point period

| Fault distance (km) | Site category | Site category | Site category |
|---------------------|---------------|---------------|---------------|
|                     | $T_0$ (s) | $\sigma$ (s) | $T_0$ (s) | $\sigma$ (s) | $T_0$ (s) | $\sigma$ (s) |
| 0-20 (pulse type)   | 0.14          | 0.05         | 0.12         | 0.02         | 0.11         | 0.05         |
| 0-20 (non-pulse type)| 0.12          | 0.02         | 0.11         | 0.07         | 0.08         | 0.04         |
| 20-60               | 0.13          | 0.04         | 0.16         | 0.06         | 0.08         | 0.05         |
| 60-100              | 0.25          | 0.05         | 0.15         | 0.06         | 0.10         | 0.06         |

Table 2 shows that the first turning point period of the vertical ground motion of near fault is larger than the 0.1s of the code value except the first turning point period of the vertical ground motion of near fault of site category III. and the first inflection point period corresponding to the vertical non-pulse ground motion of near fault on all kinds of site categories is less than the vertical pulse-like ground motion and far-field vertical earthquake on the corresponding site category. With the increase of fault distance, the first turning point period of the vertical non-pulse ground motion on the site
category II firstly increases and then decreases. The first turning point period of the vertical ground motion of near fault tends to gradually decrease with the softening of the site soil, while the first turning point period the far-field vertical ground motion doesn't have the same pattern of change.

### 4.3. Analysis of Influence Factors of Characteristic Period ($T_g$)

This section mainly discusses the characteristics of the characteristic period of the response spectrum of the near-fault ground motion to analyze of the applicability of the characteristic period of Chinese building seismic code to the seismic design of engineering structures in the near-fault region. The mean value of characteristic period ($T_g$) is listed in Table 3.

#### Table 3. Statistical results of characteristic period

| Fault distance (km) | Site category | $T_g$(s) | $\sigma$(s) | $T_g$(s) | $\sigma$(s) | $T_g$(s) | $\sigma$(s) |
|--------------------|---------------|----------|-------------|----------|-------------|----------|-------------|
| 0-20 (pulse type)  | I             | 0.56     | 0.86        | 0.63     | 0.52        | 0.73     | 0.04        |
| 0-20 (non-pulse type) | II          | 0.39     | 0.36        | 0.45     | 0.33        | 0.49     | 0.32        |
| 20-60              |               | 0.43     | 0.31        | 0.47     | 0.37        | 0.55     | 0.27        |
| 60-100             |               | 0.46     | 0.33        | 0.54     | 0.37        | 0.62     | 0.28        |

Table 3 shows that the characteristic period of the near-fault vertical pulse-type ground motion on each site is greater than the characteristic period of the vertical non-pulse type ground motion and is far greater than the characteristics period specified in Chinese building seismic design code (GB 50011-2010) on the corresponding site category. The characteristic period corresponding to near-fault non-pulse ground motion on all kinds of site categories is smaller than the characteristic period of far-field non-pulse type ground motion on the corresponding site. Therefore, it is appropriate to increase its value based on the Chinese building seismic design code (GB 50011-2010). The characteristic period of the vertical non-pulse type ground motion on various site categories increases with the increase of fault distance, and the characteristic period of the non-pulse type ground motion gradually increases with the softening of the site soil, indicating that the fault distance and site conditions have a significant influence on the characteristic period. Therefore, the effects of site condition and fault distance should be considered comprehensively to reflect the characteristics of the characteristic period of the near-fault vertical ground motion in Chinese building seismic design code (GB 50011-2010).

### 4.4. Analysis of Influence Factors of Attenuation Index ($\gamma$)

The attenuation index of the design response spectrum in Chinese building seismic code is taken as 0.9, ignoring the influence of other factors. In this section, based on the influence of site condition and fault distance on the attenuation index, the influence of near-fault pulse characteristics on the attenuation index is further studied to determine the value of the attenuation index. The mean value of attenuation index is listed in Table 4.

#### Table 4. Statistical results of attenuation index

| Fault distance (km) | Site category | I  | $\gamma$ | $\sigma$  | II | $\gamma$ | $\sigma$  | III | $\gamma$ | $\sigma$  |
|--------------------|---------------|----|----------|-----------|----|----------|-----------|-----|----------|-----------|
| 0-20 (pulse type)  | I             | 1.10 | 0.52     | 1.03      | 0.29 | 0.82     | 0.44      |     |          |            |
| 0-20 (non-pulse type) | II          | 1.21 | 0.44     | 1.13      | 0.45 | 1.03     | 0.43      |     |          |            |
| 20-60              |               | 1.20 | 0.40     | 1.17      | 0.43 | 1.08     | 0.36      |     |          |            |
| 60-100             |               | 1.43 | 0.37     | 1.22      | 0.41 | 1.20     | 0.37      |     |          |            |
Table 4 shows that the attenuation index of the vertical pulse type ground motion of near fault on all types of sites is smaller than the attenuation index of the vertical non-pulse type ground motion, indicating that the vertical pulse characteristic of near-fault ground motion have a great impact on values in the long period of the spectrum. Except for the slightly lower attenuation index of the near-fault vertical pulse-type ground motion in site category III, the attenuation indexes obtained in this paper, are greater than 0.9. The attenuation index corresponding to the vertical non-pulse ground motion shows an increasing trend with the increase of fault distance. While the site soil becomes softer, the attenuation index at different fault distances gradually decreases, indicating that the site condition has a great influence on the attenuation index.

5. Conclusions
Taking into account the influence of site condition, fault distance, and pulse characteristics, the statistical analysis of the platform values, the first turning point period, the characteristic period, and the attenuation index corresponding to the dynamic amplification coefficient spectrum of 883 vertical ground motion can be summarized. The following conclusions are drawn:

The platform value is significantly affected by the pulse characteristics of the near-fault vertical ground motion. The site conditions influence the platform value corresponding to the near-fault ground motion. The platform value of the dynamic amplification coefficient spectrum in Chinese building seismic design code (GB 50011-2010) may be low.

The first turning point period corresponding to the vertical ground motion of the near fault should consider the influence of the site conditions. When the influence of the vertical pulse-type ground motion of near fault is considered, the first turning point period should be appropriately increased.

The characteristic period is significantly affected by the site conditions, fault distance and pulse characteristics. It increases with the softening of the site soil and increases with the increase of the fault distance. When the code determines its value, the influence of the fault distance should be fully considered. When considering the influence of vertical pulse-type ground motion of near fault, it can be appropriately increased based on the code value.

The attenuation index is significantly affected by site condition, fault distance and pulse characteristic. The attenuation index corresponding to the near-fault vertical ground motion is smaller than the corresponding attenuation index for the far field. The attenuation index in the code should take into account the influence of site conditions and fault distance.

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