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# *Average Normalized Time-Frequency Response Spectrum for Different Types of Sites*

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***Abstract:*** The normalized time-frequency response spectrum is a three-dimensional spectrum that includes the three essential components of seismic motion: amplitude, frequency spectrum, and duration. It can effectively compensate for the shortcomings of traditional response spectrum theory and elastoplastic time history analysis. To better study the structural damage mechanism and predict the potential destructiveness of seismic motion, the structural damage curve must be combined with the normalized time-frequency response spectrum. According to four site categories, 10 seismic records were selected from the Pacific Earthquake Engineering Research Center earthquake motion database. The site categories in the US are classified based on the equivalent shear wave velocity $V_{s30}$ of the surface soil layer thickness up to 30m. Sites with a shear wave velocity $V_{s30}$ above 510 m/s correspond to Category I sites in Chinese standards; $V_{s30}$ between 510 m/s and 260 m/s correspond to Category II sites; $V_{s30}$ between 260 m/s and 150 m/s correspond to Category III sites; and $V_{s30}$ below 150 m/s correspond to Category IV sites in Chinese standards. Through statistical analysis, the normalized time-frequency response spectrum for each site category was calculated and then averaged, resulting in what is referred to as the average normalized time-frequency response spectrum for each site category. This provides a reference basis for subsequent structural seismic verification, seismic design of buildings, and the revision of seismic regulations.

## 1. Introduction

Chinese Code for Seismic Design of Buildings [1] stipulates that structural strength verification under multiple earthquake conditions and seismic deformation verification under rare earthquake conditions should be conducted, and it also specifies the maximum inter-story drift angle limit. If the inter-story drift angle of the structure under seismic effects does not exceed the limits set by the code, the structure is considered safe. In most cases, due to the relatively small seismic effects, the structure is basically in an elastic state, making this consideration relatively reasonable. However, in the case of strong earthquakes that last for a long time, the continuous damage to the structure may lead it to gradually enter the plastic state, potentially resulting in final failure due to cumulative damage to the structure. Supplementary calculations for elasto-plastic time history analysis have considered the elasto-plastic performance of structural components. Although this method takes into account the duration characteristics of seismic motion, it is complicated and time-consuming. The accuracy of the results depends on the precision of the model element division, material constitutive relations, and selection of seismic waves, making it labor-intensive and costly. Therefore, it is currently only used for important buildings such as nuclear power plants, large dams, large bridges, and high-rise buildings. R. Greco, G.C. Marano, and D. Foti (1999) simulated the response of a base-isolated building under seismic effects, finding that systems with high deformation capacity are affected more by the duration than by the root mean square value of the excitation [2]. Julian J. Bommer, Guido Magenes, Jonathan Hancock, et al. (2004) concluded that the seismic assessment of masonry structures should be improved to account for the duration of seismic motion after studying the responses of seven typical masonry structure models under about 500 strong earthquake records [3]. Hancock Jonathan and Bommer Julian J. (2006) reviewed hundreds of papers that directly or indirectly linked structural damage to parameters related to the duration of strong ground motion and found that research on failure modes related to energy accumulation generally concluded a positive correlation between the duration of strong ground motion and structural failure [4]. Zuyan Shen and Aihui Wu (2007) conducted studies to develop reliable analytical models for seismic analysis of steel structures. They proposed a nonlinear cumulative damage hysteresis model considering stiffness degradation, strength, and strain hardening, and compiled a program that can calculate the hysteretic model of steel components, predict damage states and initiation points, and perform nonlinear seismic time history analysis for steel structures. The results obtained from the model matched well with the experimental results, indicating that cumulative damage effects are very important in structural seismic analysis [5]. The time-frequency response spectrum [6-7] also reflects changes in the seismic response of structural systems concerning periodic and sustained durations, partially compensating for the elastic response spectrum theory's failure to consider cumulative damage effects due to duration, without the need for the tedious calculations in elasto-plastic time history analysis.

The structural damage curve should be studied in conjunction with the normalized time-frequency response spectrum to better understand the mechanism of structural damage and predict the potential destructiveness of seismic motion [8]. This paper provides recommended normalized time-frequency response spectra for various site categories. The specific approach involves selecting 10 earthquake records according to each site category, calculating the corresponding normalized time-frequency response spectrum, and then averaging the results. The obtained normalized time-frequency response spectrum is referred to as the average normalized time-frequency response spectrum for each site category.The selected earthquake records are sourced from the Pacific Earthquake Engineering Research Center's earthquake motion database in the United States. However, the classification of site categories in China differs from that in the United States, necessitating some conversion. In the U.S., site categories are classified based on the equivalent shear wave velocity $V_{s30}$ of the top 30m soil layer. Generally, $V_{s30}$ with shear wave velocities above 510 m/s correspond to Class I; $V_{s30}$ in Chinese standards; $V_{s30}$ with shear wave velocities between 510 m/s and 260 m/s correspond to Class II sites; $V_{s30}$ with shear wave velocities between 260 m/s and 150 m/s correspond to Class III sites; and $V_{s30}$ with shear wave velocities below 150 m/s correspond to Class IV sites [9-10].

## 2. Normalized time-frequency response spectrum for each type of site

### 2.1 Average normalized time-frequency response spectrum for Class I sites

We select 10 seismic records from the Pacific Earthquake Engineering Research Center's database with site seismic motions above 510 m/s (corresponding to Class I sites according to Chinese standards) (Tab. 1). The normalized time-frequency response spectra of each seismic wave are averaged to obtain the average normalized time-frequency response spectrum for Class I sites (Fig. 1) and the contour map (Fig. 2).

Table 1 Class I site earthquake records

| Earthquake event | Time | Seismic recording station | Magnitude | $V_{s30}$ (m/s) |
|---|---|---|---|---|
| VICTORIA, MEXICO | 1980 | CERRO PRIETO 045 | 6.33 | 659.6 |
| SAN FERNANDO | 1971 | FAIRMONT DAM 056 | 6.61 | 684.9 |
| SAN FERNANDO | 1971 | FAIRMONT DAM 326 | 6.61 | 684.9 |
| SAN FERNANDO | 1971 | LAKE HUGHES#9 021 | 6.61 | 670.8 |
| SAN FERNANDO | 1971 | LAKE HUGHES#12 021 | 6.61 | 602.1 |
| SAN FERNANDO | 1971 | PEARBLOSSOM PUMP 000 | 6.61 | 529.1 |
| SAN FERNANDO | 1971 | PUDDINGDTONE DAM 055 | 6.61 | 597.1 |
| SAN FERNANDO | 1971 | SANTA ANITA DAM 003 | 6.61 | 684.9 |
| PARKFIELD | 1966 | TEMBLOR PRE 205 | 6.19 | 527.9 |
| PARKFIELD | 1966 | TEMBLOR PRE 295 | 6.19 | 527.9 |

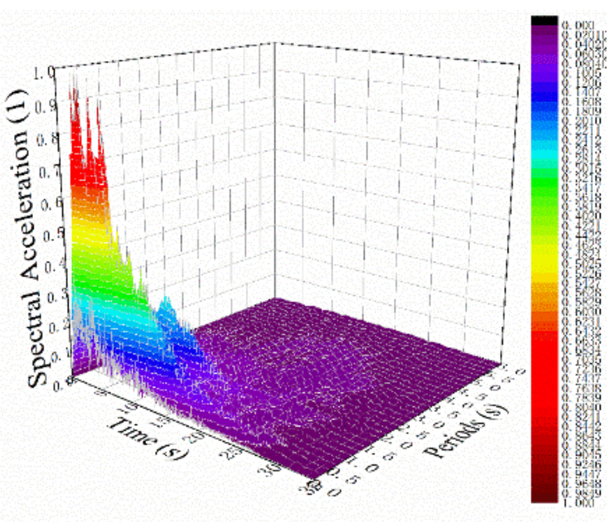


Figure 1: Average normalized time-frequency response spectrum for Class I sites

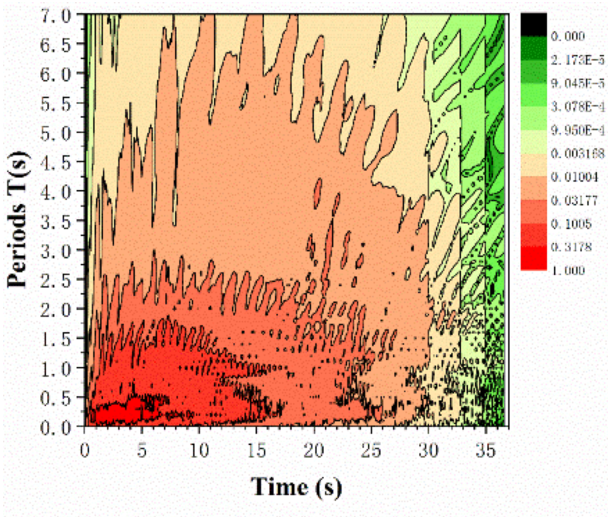


Figure 2: Contour map of the average normalized time-frequency response spectrum for Class I sites

It can be seen that the primary peak ridge area of the average normalized time-frequency response spectrum for Class I sites primarily covers the range of natural vibration periods from 0.0s to 0.5s and durations from 0.0s to 7.0s; the secondary peak ridge area mainly covers the range of natural vibration periods from 0.0s to 1.6s and durations from 0.0s to 15.0s. Therefore, the seismic motion represented mainly poses a significant potential danger to short-period structures, which is consistent with the fact that Class I site soils are relatively hard, and thus seismic motion is relatively destructive to shorter and stiffer structures based on damage experience. However, as long as the structure does not suffer significant damage in the first few seconds of the seismic motion, it is relatively safe; if the structure incurs significant damage early in the seismic motion and experiences a substantial increase in natural vibration period, although it may exit the primary peak ridge area of the average normalized time-frequency response spectrum, it will still be subjected to the impact of the secondary peak ridge, making the structure relatively dangerous.

## 2.2 Average normalized time-frequency response spectrum for Class II sites

We select 10 site ground motion records from the Pacific Earthquake Engineering Research Center seismic database with $V_{s30}$ between 510 m/s and 260 m/s (corresponding to Category II sites in Chinese standards) (Tab. 2), averageing the normalized time-frequency response spectra of each seismic wave to obtain the average normalized time-frequency response spectrum for Category II sites (Fig. 3) and the contour map (Fig. 4).

Table 2 Class II site earthquake records

| Earthquake event | Time | Seismic recording station | Magnitude | $V_{s30}$ (m/s) |
|---|---|---|---|---|
| SAN FERNANDO | 1971 | ANZA POST OFFICE 045 | 6.61 | 338.5 |
| SAN FERNANDO | 1971 | CARBON CANYON DAM 130 | 6.61 | 477.7 |
| SAN FERNANDO | 1971 | CASTAIC OLD RIDGE ROUTE 021 | 6.61 | 450.3 |
| SAN FERNANDO | 1971 | CASTAIC OLD RIDGE ROUTE 291 | 6.61 | 450.3 |
| PARKFIELD | 1966 | CHOLAME#5 085 | 6.19 | 408.9 |
| PARKFIELD | 1966 | CHOLAME#12 050 | 6.19 | 289.6 |
| SAN FERNANDO | 1971 | HEMET FIRE 135 | 6.61 | 338.5 |
| SAN FERNANDO | 1971 | LA HOLLYWOOD STOR LOT 090 | 6.61 | 316.5 |
| SAN FERNANDO | 1971 | LAKE HUGHES#1 021 | 6.61 | 529.1 |
| SAN FERNANDO | 1971 | PALMDALE FIRE 120 | 6.61 | 425.3 |

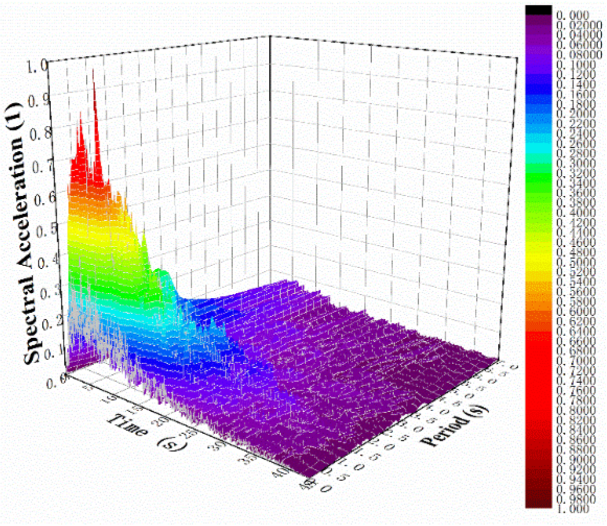


Figure 3: Average normalized time-frequency response spectrum for Class II sites

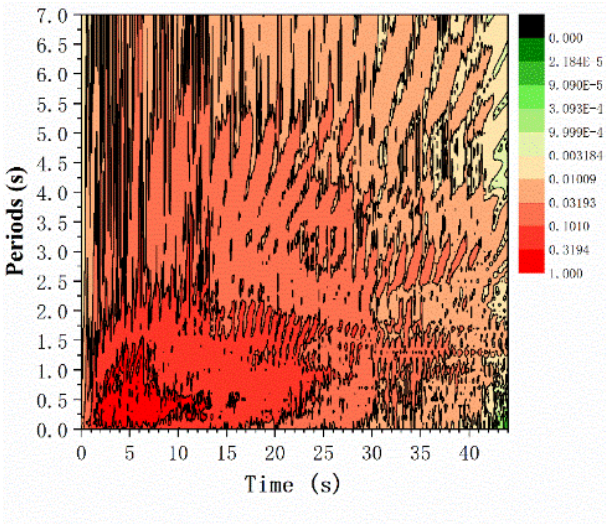


Figure 4: Contour map of the average normalized time-frequency response spectrum for Class II sites

It can be seen that the primary peak ridge area of the average normalized time-frequency response spectrum for Class II sites basically covers the region of natural vibration periods from 0.0s to 1.5s and durations from 0.0s to 10.0s. Therefore, the seismic motion it represents poses a significant potential danger mainly to medium-short period structures, which is consistent with the seismic damage experience of Class II site soils. The duration of the primary peak ridge area for Class II sites is about twice as long as that of Class I sites, reaching approximately 10.0s for natural vibration periods of 0.0s to 1.5s, and about 13.0s for natural vibration periods of 0.0s to 0.5s. The secondary peak ridge area has a required duration approximately 1.5 times longer than that of Class

I sites, reaching about 25.0s, with the natural vibration period reaching about 2.3s. Therefore, if the structure does not experience significant damage during the first 10 seconds of the seismic motion, it is relatively safe. However, if significant damage occurs in the early phase of the seismic motion, leading to a substantial increase in the natural vibration period, even though it may escape the primary peak ridge area of the average normalized time-frequency response spectrum, it will still be subjected to the impact of the secondary peak ridge, making the structure relatively dangerous.

## 2.3 Average normalized time-frequency response spectrum for Class III sites

We select 10 ground motion records from the Pacific Earthquake Engineering Research Center database that $V_{s30}$ between 260 m/s and 150 m/s (corresponding to Class III sites according to Chinese standards) (Tab. 3), normalize and average the time-frequency response spectra of each seismic wave to obtain the average normalized time-frequency response spectrum for Class III sites (Fig. 5) and the contour map (Fig. 6).

Table 3 Class III site earthquake records

| Earthquake event | Time | Seismic recording station | Magnitude | $V_{s30}$ (m/s) |
|---|---|---|---|---|
| IMPERIAL VALLEY | 1979 | BRAWLEY AIRPORT 225 | 6.53 | 208.7 |
| IMPERIAL VALLEY | 1979 | CALEXICO FIRE STA 225 | 6.53 | 231.2 |
| IMPERIAL VALLEY | 1979 | CALIPATRIA FIRE STA 225 | 6.53 | 205.8 |
| IMPERIAL VALLEY | 1979 | EC COUNTY CENTER FF 002 | 6.53 | 192.1 |
| IMPERIAL VALLEY | 1979 | EC MELOLAND OVERPASS FF 000 | 6.53 | 186.2 |
| IMPERIAL VALLEY | 1979 | EL CENTRO ARRAY#8 140 | 6.53 | 206.1 |
| IMPERIAL VALLEY | 1979 | EL CENTRO ARRAY#10 050 | 6.53 | 202.8 |
| IMPERIAL VALLEY | 1979 | HOLTVILLE POST OFFICE 225 | 6.53 | 202.9 |
| IMPERIAL VALLEY | 1979 | NILAND FIRE STATION 090 | 6.53 | 207.5 |
| IMPERIAL VALLEY | 1979 | WESTMORELAND FIRE STA 090 | 6.53 | 193.7 |

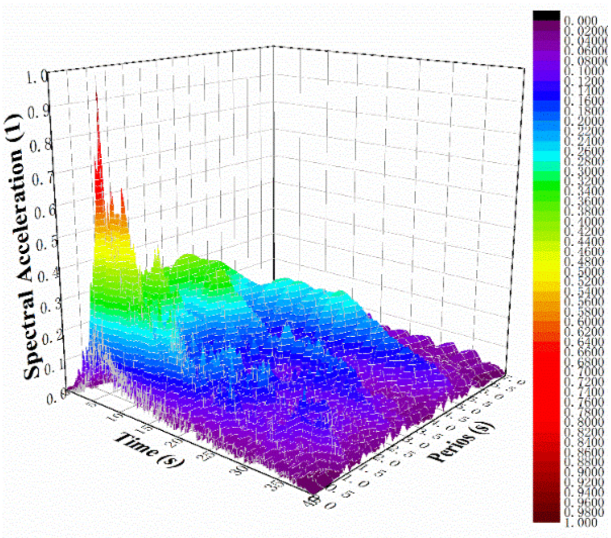

Figure 5: Average normalized time-frequency response spectrum for Class III sites

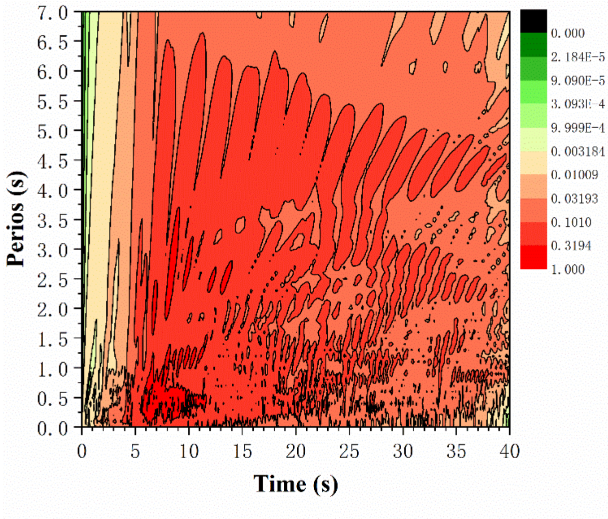

Figure 6: Contour map of the average normalized time-frequency response spectrum for Class III sites

It can be seen that the distribution of the primary peak ridge areas of the average normalized time-frequency response spectrum in Class III sites is relatively scattered. Except for covering the range of natural periods from 0.0s to 1.3s and durations from 6.0s to 12.0s, there are also sporadically distributed narrow band primary peak ridges in the natural period range of 1.5s to 3.7s and durations of 6.0s to 14s. The secondary peak ridge area covers a large area, almost encompassing the entire range of natural periods from 0.0s to 6.2s and durations from 5.0s to 35s. Therefore, the seismic motion represented mainly poses a significant potential danger to intermediate to long-period structures, which aligns with the experience of seismic damage where the soil in Class III sites is relatively soft and can cause considerable damage to intermediate to long-period structures. Due to the extensive coverage of the secondary peak ridge area, as long as significant damage occurs in the primary peak ridge area, the structure will suffer continuous long-duration impacts from the secondary peak ridge area, making it relatively dangerous.

### 2.4 Average normalized time-frequency response spectrum for Type IV sites

We select 10 ground motion records from the Pacific Earthquake Engineering Research Center's seismic motion database with $V_{s30}$ below 150 m/s (corresponding to Class IV sites in Chinese standards) (Tab. 4), and average the normalized time-frequency response spectra of each seismic wave to obtain the average normalized time-frequency response spectrum for Class IV sites (Fig. 7) and the contour map (Fig. 8).

Table 4 Class IV site earthquake records

| Earthquake event | Time | Seismic recording station | Magnitude | $V_{s30}$ (m/s) |
|---|---|---|---|---|
| MORGAN HILL | 1984 | APEEL1 REDWOOD CITY 040 | 6.19 | 116.3 |
| MORGAN HILL | 1984 | APEEL1 REDWOOD CITY 310 | 6.19 | 116.3 |
| LOMA PRIETA | 1989 | APEEL2 REDWOOD CITY 043 | 6.93 | 133.1 |
| LOMA PRIETA | 1989 | APEEL2 REDWOOD CITY 133 | 6.93 | 133.1 |
| MORGAN HILL | 1984 | FOSTER CITY APEEL#1 040 | 6.19 | 116.3 |
| MORGAN HILL | 1984 | FOSTER CITY APEEL#1 310 | 6.19 | 116.3 |
| LOMA PRIETA | 1989 | FOSTER CITY MENHADEN 270 | 6.93 | 126.4 |
| LOMA PRIETA | 1989 | FOSTER CITY MENHADEN 360 | 6.93 | 126.4 |
| LOMA PRIETA | 1989 | FOSTER CITY REDWOOD SHORES 000 | 6.19 | 116.3 |
| LOMA PRIETA | 1989 | FOSTER CITY REDWOOD SHORES 090 | 6.19 | 116.3 |

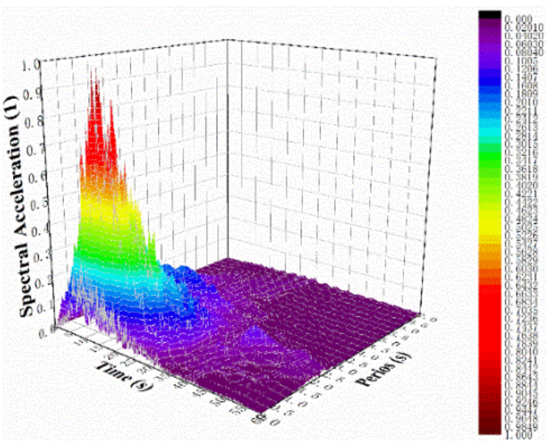


Figure 7: Average normalized time-frequency response spectrum for Class Ⅳ sites

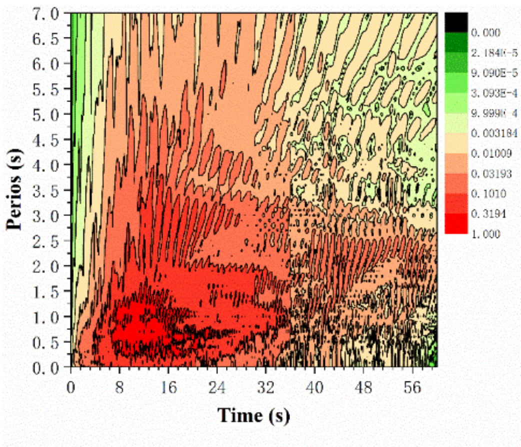


Figure 8: Contour map of the average normalized time-frequency response spectrum for Class IV sites

It can be seen that the area covered by the primary peak ridge of the averaged normalized time-frequency response spectrum for Type IV sites is relatively large, essentially covering the range of natural vibration periods from 0.2s to 1.5s and durations from 7.0s to 18.0s; the area covered by the secondary peak ridge is very large, almost encompassing the entire range of natural vibration periods from 0.0s to 3.7s and durations from 2.0s to 34s. Therefore, the seismic motion it represents poses a significant potential danger, especially to medium and long-period structures. This is consistent with the seismic damage experiences that indicate that softer soils in Type IV sites can cause considerable harm to medium and long-period structures. Structures with natural vibration periods ranging from 0.0s to 3.7s will endure relatively prolonged impacts from the primary peak ridge. Due to the large area covered by the secondary peak ridge, if the structure suffers significant damage in the primary peak ridge area, it will experience continuous long-term impacts from the secondary peak ridge area, making the structure relatively dangerous.

## 3. Conclusions

The normalized time-frequency response spectrum is a three-dimensional spectrum that includes the three essential elements of seismic motion: amplitude, spectrum, and duration. It can effectively compensate for the shortcomings of traditional response spectrum theory and elastoplastic time history analysis. The structural damage curve should be combined with the normalized time-frequency response spectrum to better study the structural damage mechanism and predict the potential destructiveness of seismic motion.

This paper selects 10 earthquake records from the Pacific Earthquake Engineering Research Center database according to site categories. In the U.S., site categories are classified based on the equivalent shear wave velocity $V_{s30}$ of the surface soil layer, which is 30 m thick. According to this classification, sites with an equivalent shear wave velocity $V_{s30}$ above 510 m/s correspond to Class I sites in China's standards; $V_{s30}$ between 510 m/s and 260 m/s correspond to Class II sites; $V_{s30}$ between 260 m/s and 150 m/s correspond to Class III sites; and $V_{s30}$ below 150 m/s correspond to Class IV sites in China's standards. Through statistical analysis, the normalized time-frequency response spectrum for each site category is calculated and then averaged. The resulting normalized time-frequency response spectrum is referred to as the average normalized time-frequency response spectrum for each site category. This provides a reference basis for subsequent structural seismic verification, seismic fortification of buildings, and the revision of seismic standards.

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