Classification Research and Improvement on the Ground Motion Selection and Scaling for Time History Analysis

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Abstract. Some representative methods of selecting and scaling ground motion are classified into two groups based on the different goals of adjustment, including peak/spectral value matching method and spectrum shape matching method. The both methods do not consider the effect of duration. And the amplitude is adjusted based on the fixed amplitude modulation coefficient, but not according to the characteristics of ground motion energy distribution. Therefore, the method of scaling and selecting ground motion based on maximum instantaneous input energy is proposed. The amplitude is adjusted according to the characteristics of energy distribution of the seismic wave in the new method. Meanwhile, the effect of duration is taken into account. In addition, the method has loosened selection condition of the seismic wave, small calculation and low dispersion of results.

1. Introduction

The Chinese “Code for seismic design of buildings”(GB50011-2010)\textsuperscript{[1]} stipulates that for particularly irregular buildings, the buildings of class a, and high-rise buildings that exceed a certain height range, time history analysis methods should be used for supplementary calculations under the action of frequent earthquake. The basic principle of the time history analysis method is to directly integrate the dynamic equations according to the selected restoration model curve of the seismic wave and the structure, and the step-by-step integration method is adopt to directly integrate the dynamic equations. The time history responses of the structure like displacement, velocity, and acceleration can be obtained.

In time history analysis, the uncertainty of ground motion input is the most important factor affecting the structural reaction uncertainty. With the frequent occurrence of earthquakes in the world, seismic databases have been increasingly perfect. This has also added difficulties and workload to the time history analysis of seismic wave selection. The same records that set the seismic environment need to be found in a huge database by researchers. Therefore, a scientific and effective wave selection method to quickly obtain suitable seismic input from huge data can be proposed is a meaningful work. In previous studies, a variety of seismic wave selection and adjustment methods, which based on record of magnitude and epicenter distance, based on magnitude, epicenter distance and extra parameters, based on spectrum matching, and based on actual ground motion, had been proposed. However, the selection and adjustment of ground motion cannot be accurately summarized by these methods. In this paper, more than 10 kinds of represent wave selection methods are divided into two
groups according to the different objectives of adjustment: peak/spectral value matching method and spectral shape matching method. These two types of methods have their own advantages and disadvantages. However, the amplitude, which has not been adjusted according to the characteristics of its energy distribution, only adjusted based on the fixed amplitude modulation coefficient, and the impact of duration time was not considered. Meanwhile, the results calculated repeatedly still do not accord with the requirements. According to the duration time can be reflected by the energy index, the method of scaling and selecting ground motion based on maximum instantaneous input energy is proposed.

2. Peak/spectral value matching method

In this method, the scaling coefficient is determined based on the peak value or a specific spectrum value to ensure that the peak value recorded after adjustment and the characteristic response spectrum values are equal. Such methods include the response peak method, the effective peak acceleration (EPA) method [2] [3], the maximum incremental velocity (MIV) method [4], and the severest design earthquake ground motion method [5] are mentioned in this paper.

A large number of ground motion time history that meet the requirements are more easily selected by using the peak/spectral matching method. The modification method is relatively simple and easy to satisfy, and the spectrum of the original ground motion history will not be affected. However, recent studies [6][7][8] have also shown that the large calculation results of discreteness will be caused by simple conditions for wave selection. and the effect of time effects is not considered. Meanwhile, each seismic wave is adjusted to a fixed amplitude, and the difference in the energy distribution characteristics between seismic waves is neglected. The calculated results are difficult to be applied in engineering.

3. Spectrum shape matching method

Different from the peak/spectral value matching method, the ground motion record according to the magnitude and distance of the set seismic environment is selected by spectrum shape matching method. Such methods include the generating compatible dynamic response spectrum method of ground motion under non-stationary phase [9], the dual-band control method [10], the method in American seismic design code [11][12], the uniform hazard spectrum (UHS) method [13][14], the conditional mean spectrum (CMS) method [15] and the selection and scaling method considering inelastic spectral displacement are mentioned [16] in this paper.

The calculation of this method is larger than that of the first method, but the result of the dispersion is less than that of the first method and is more accurate and easier to be used by the project. However, the seismic waves with different energy distribution characteristics have to be adjusted to a fixed amplitude, and the influence of duration time has not been taken into account. The adjusted seismic wave may still not meet the requirements.

4. The method of scaling and selecting ground motion based on maximum instantaneous input energy

The common disadvantage of the above two types of ground motion selection and adjustment methods is that the effect of holding time is not considered, only the spectral characteristics and amplitude characteristics of the ground motion are considered, and the discreteness of the analysis results obtained is still large, which causes a suitable ground motion record cannot be accurately selected. Meanwhile, the differences in energy distribution characteristics of ground motions have not been considered. Xiao M K [17] conducted comparative studies on different time-keeping waves of the same acceleration response spectrum. The influence of the holding time on the structure was found to be significant, and the energy index was able to respond favorably to the duration time. The duration time is suggested as a supplementary indicator in the form of input energy. Therefore, the method of scaling and selecting ground motion based on maximum instantaneous input energy is proposed in this paper.
4.1. Method principle

In this method, the ground motion selected by using the maximum instantaneous input energy ($\Delta E_{\text{max}}$) as an index is input into the structure, so that the structural base shear under the selected earthquake action can more easily meet standard requirements: The base shear obtained by the elastic time history analysis of the single ground motion time history curve should be greater than 65% of the base shear force obtained by the vibration mode decomposition response spectrum analysis, and the base shear force obtained from the time history curve of multiple ground motions and the elastic time history analysis of the structure should be greater than 80% of the bottom shear force obtained by the analysis of the mode response spectrum method.

According to the “Code for seismic design of buildings”, multiple seismic waves are selected to act on multiple structures and perform the time history analysis and the calculation of the maximum instantaneous energy to establish the relationships in Figure 1. Meanwhile, the relation can be given by the equation (1).

![Figure 1. Relationship between the structural top displacement, base shear and maximum instantaneous input energy](image)

$$\Delta E_{\text{max}} = A_{\text{max}}^2 \times (1.17 \times 10^{-2}d_1^2 - 1.45 \times 10^{-5}d_1 \times Q_{d1} + 1.08 \times 10^{-3}Q_{d1})$$

(1)

where: $\Delta E_{\text{max}}$–maximum instantaneous input energy proposed in the statistical sense of the input structure; $A_{\text{max}}$–The maximum acceleration of ground motion used in the time history analysis required by the “Code for seismic design of buildings”; $d_1$–the structural top displacement; $Q_{d1}$–base shear.

The $d_1$ and $Q_{d1}$ of the structure are calculated by the mode-superposition response spectrum method and substituting the results into equation (1) to obtain the $\Delta E_{\text{max}}$.

The amplitude of the input seismic wave is adjusted according to $A_{\text{max}}$ and input to the single degree of freedom system with the structural natural vibration period, and the $\Delta E_{\text{max}}$ (maximum instantaneous input energy by the “Code for seismic design of buildings”) is calculated.

According to the kinetic energy theorem, the following equation is derived:

$$\frac{A_{\text{max}}}{A_{\text{max}}} = \sqrt{\frac{\Delta E_{\text{max}}}{\Delta E_{\text{max}}}}$$

(2)

where: $A_{\text{max}}$–the maximum acceleration value that can be adjusted according to the maximum instantaneous input; $A_{\text{max}}$–the maximum value of acceleration adjusted according to the “Code for seismic design of buildings”; $\Delta E_{\text{max}}$–maximum instantaneous input energy proposed in the statistical sense of the input structure; $\Delta E_{\text{max}}$–Maximum Instantaneous Input Energy Adjusted by the “Code for seismic design of buildings”.

The ground motion is adjusted according to $A_{\text{max}}$, which can be obtained from equation (2), and input into the structure for elastic time history analysis.
4.2. Results and discussion

According to China's "Code for seismic design of buildings", a three-dimensional finite element model of a 10-story frame structure type was designed for analysis. From the mode-superposition response spectrum method, the results are shown in table 1.

| Table 1. Analytical results of the mode-superposition response spectrum method |
|--------------------------------------------------------------------------------------------------|
| Structural model          | Natural vibration period T/s | Base shear \(Q_a/\text{KN}\) | The most story drift angle/ \(\theta_{max}\) | The maximum displacement of the frame structure/mm |
|---------------------------|-------------------------------|-------------------------------|---------------------------------|---------------------------------|
| 10-story frame structure  | 1.085                         | 4157.00                       | 1/876                           | 27.97                           |

| Table 2. The basic information of seismic waves |
|-----------------------------------------------|
| No.    | PEER number | Year | Earthquake         | Station                               | direction |
|--------|-------------|------|--------------------|---------------------------------------|-----------|
| Dzb1   | -           | -    | Lanzhou3           | artificial seismic wave                | -         |
| Dzb2   | RSN1087     | 1994 | Northridge-01      | Tarzana - Cedar Hill A                | 90        |
| Dzb3   | RSN1087     | 1994 | Northridge-01      | Tarzana - Cedar Hill A                | 360       |
| Dzb4   | RSN163      | 1979 | Imperial Valley-06 | Calipatria Fire Station               | 225       |
| Dzb5   | RSN163      | 1979 | Imperial Valley-06 | Calipatria Fire Station               | 315       |
| Dzb6   | RSN1838     | 1999 | Hector Mine        | Whitewater Trout Farm                 | 065       |
| Dzb7   | RSN1838     | 1999 | Hector Mine        | Whitewater Trout Farm                 | 155       |
| Dzb8   | RSN187      | 1979 | Imperial Valley-06 | Parachute Test Site                   | 315       |
| Dzb9   | RSN2108     | 2002 | Denali_Alaska      | Eagle River - AK Geologic Mat         | 90        |
| Dzb10  | RSN3768     | 1994 | Northridge-06      | Tarzana - Club House                  | 205       |
| Dzb11  | RSN68       | 1971 | San Fernando       | LA - Hollywood Stor FF                | 180       |
| Dzb12  | RSN6        | 1940 | Imperial Valley-02 | El Centro Array #9                    | NS        |
| Dzb13  | RSN737      | 1989 | Loma Prieta        | Agnews State Hospital                 | 00        |
| Dzb14  | RSN737      | 1989 | Loma Prieta        | Agnews State Hospital                 | 90        |
| Dzb15  | RSN807      | 1989 | Loma Prieta        | Sunol-Forest Fire Station             | 90        |
| Dzb16  | RSN807      | 1989 | Loma Prieta        | Sunol-Forest Fire Station             | 180       |

According to the requirements of the “Code for seismic design of buildings”, 15 natural seismic waves of type II site soil and 1 artificial seismic wave in the database of Pacific Earthquake Engineering Research Center were selected. The basic information of seismic waves is shown in table 2. These 16 seismic waves were adjusted according to the standard method and this paper's method, respectively, and the adjusted seismic waves were input into the structure for structural elastic time history analysis under frequent earthquake. The results are shown in Figure 2 and Figure 3.
From the results of the base shear, the ratio of the base shear obtained by the standard method to the base shear obtained by the mode-superposition response spectrum method are obviously larger than the paper's method. In addition, the ground motion No 1, 2, 3, 10, 11 of the standard method are also less than 65% of the base shear of the response spectrum and do not meet the standard requirements. The ratio of the base shear obtained by the paper’s method to the base shear obtained by the mode-superposition response spectrum method is 92.6%, and is greater than 65% of the base shear of the response spectrum. At the same time, the most story drift angle under the action of each seismic wave is greater than 1/550, which meets the specification requirements. It shows that the paper's method is feasible, less discrete, more stable, and can reduce the repeated screening of seismic waves.

Figure 2. The results of base shear

Figure 3. The results of the most story drift angle

The standard deviations and dispersion coefficients of the structural responses for which the base shear meets the requirements under the single ground motion of the two methods are compared, as shown in table 3. From table 3, it can be seen that the indexes of this paper's method are better than those of the standard method, and have more stability and reliability.

From this example, it can be seen that the spectral characteristics and amplitude characteristics of ground motion are taken into account. Besides, the duration and the characteristics of ground motion energy distribution are also considered; this method makes it easier to select suitable seismic waves and reduce the workload of wave selection; and compared with the above two methods, this method has small dispersion and stability and is suitable for seismic wave selection of frame structures. Meanwhile, this method only perform the elastic time history analysis, and the elastoplastic time history analysis has not yet been performed.

Table 3. Comparison of the two methods

| Structural model          | Method      | Base shear | The most story drift angle | Maximum displacement |
|---------------------------|-------------|------------|----------------------------|----------------------|
|                           |             | Standard deviation | Dispersion coefficient/ % | Standard deviation | Dispersion coefficient/ % | Standard deviation | Dispersion coefficient/ % |
| 10-story frame structure  | Standard method | 855.72     | 20.99                      | 2.86×10⁻⁴          | 26.06                     | 8.08               | 30.15                     |
|                           | Paper's method | 359.12     | 8.27                       | 1.87×10⁻⁴          | 15.00                     | 4.02               | 14.98                     |

5. Conclusion

In this note, some representative methods for selecting and adjusting ground motions are used for classification analysis and evaluation. According to the different adjustment objectives, peak/spectral value matching method and spectral shape matching method are divided. This classification method
can include widely used methods of ground motion selection and adjustment. However, these two methods do not consider the effect of duration. Thus, the characteristics of ground motion energy distribution and time duration are considered in this paper. Based on the energy index can reflect the time, the time history analysis of the maximum instantaneous input energy is presented. This method has loose wave selection conditions, low workload, small dispersion of results, and high accuracy. And the elastic time history analysis of the structure in this paper provides the foundation for the next-step structural elastoplastic time history analysis.

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