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The Effect of the Yield Strength Coefficient and Natural Vibration Period on the Damage Potential Ranking of Ground Motions

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Abstract: To analyze the effect of structural parameters on the damage potential ranking of ground motions, the effect of the yield strength coefficient (C_y) and natural vibration period (T) on the damage potential ranking of ground motions is analyzed based on the bilinear model and the modified Clough model, which are the most commonly used hysteretic models in structural dynamic analysis. The displacement response (S_d) spectrum under nonlinear conditions is taken as the damage potential intensity measure (IM) of ground motions, and the effect of the C_y and T on the S_d mean spectrum is also analyzed for comparative analysis. The results show that: (1) in the short-period range, C_y has a great effect on the displacement response ranking. On the other hand, in the medium- and long-period ranges, C_y has little effect on the S_d ranking; (2) with the change of T in medium- and long-period ranges, the variation of S_d values is obvious when the change of T is small, but the variation of S_d ranking is very small. This conclusion can provide a theoretical basis for evaluating the damage potential of ground motions and selecting input ground motions.

Keywords: yield strength coefficient; displacement response spectrum; natural vibration period; damage potential ranking

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1. Introduction

The structural damage and the resulting casualties and property losses under the action of strong earthquakes are very painful. Therefore, the accurate evaluation of the damage of ground motions to structures (that is, the damage potential of ground motions) is very important to select the input ground motions for seismic design. In recent years, a number of studies [1–7] on the evaluation of the damage of ground motions to structures have been published. Researchers first believe that ground motion load is the root cause of damage to engineering structures. It was found that there are many intensity measures (*IMs*) that can represent the damage potential of ground motion, and the *IMs* in the early studies are mainly obtained from the ground motion record itself. Krame et al. [8] discussed and analyzed the commonly used damage potential parameters such as peak acceleration (*PGA*), peak velocity (*PGV*), peak displacement (*PGD*), Arias strength (*AI*), and so on. Hu et al. [9] found that the *PGV* of ground motion can characterize well the destructive strength of ground motion to medium- and long-period reinforced concrete frame structures. Cabanas et al. [10] studied the efficiency of cumulative velocity (*CAV*), *AI*, and structural response and obtained a small dispersion between them. However, the study found that a damage potential *IM* containing seismic and structural characteristic information may better describe the structural damage caused by ground motions [11,12]. Some experts study the *IMs* obtained from the elastic or inelastic response of the structure as the damage potential *Ims* of ground motions, such as acceleration response (S_a) spectrum, velocity response (S_v) spectrum, displacement response (S_d) spectrum, displacement ductility (u) and hysteretic energy (E_H), and so on [13–15].

When the damage potential *Ims* of ground motions include both seismic and structural information, the changes in seismic or structural parameters will change the damage potential parameter values. Some researchers have studied the effect of seismic factors on the constant-strength response spectrum and the constant-ductility response spectrum [16,17]. Miranda [18] explained the effect of seismic information factors such as magnitude and epicenter distance on the constant-ductility response spectrum in detail. Some experts have also studied the variation law of the response spectrum subjected to different types of ground motions, such as ground motions with different duration [19], main shock-aftershock sequence ground motions, pulse-like ground motions [13–15], and extracting high-frequency and low-frequency ground motions, respectively [20], etc. Considering structural parameters, Xie and Zhai [11] use u and E_p as damage potential *IMs* when selecting the most unfavorable design ground motions. At the same time, the effect of structural parameters such as damping ratio and post-yield stiffness on the hysteretic energy spectrum are analyzed. It is important to note that the hysteretic energy is the one associated with the work performed by rate-independent hysteretic forces [21]. It is concluded that the variation of the hysteretic energy spectrum has little variation under different damping ratios and post-yield stiffness. Palanci and Senel [22] studied the effect of lateral strength ratio, stiffness degradation, and pinching effect on the relative displacement response spectrum. It is concluded that strength degradation has little effect on the nonlinear response spectrum, stiffness degradation has a certain influence on the nonlinear response spectrum, and the pinching effect cannot be ignored in the study of the nonlinear response spectrum. Other experts have also carried out related studies [15,23,24].

When the *IMs* obtained from the nonlinear response of the structure are used as the damage potential *IMs* of ground motions, many experts analyze the effect of different structural factors on the damage potential parameter of ground motion and get the variation law of the damage potential with each structural parameter. The attenuation relation is also obtained [13,14,19]. These studies mainly discuss the effect of different factors on the damage potential parameters. However, few people have studied the relative variation of the damage potential of different ground motions when these factors change [25,26]. This paper makes related research on this issue. The displacement response (S_d) spectrum of the nonlinear response of systems with a single degree of freedom (SDOF) is used as the damage potential *IM* of ground motions in this paper, and ranking the ground motions based on the values of damage potential parameters and 367 ground motion records. The effect of structural yield strength coefficient (C_y) and natural vibration period (T) on damage potential value and damage potential ranking are studied based on bilinear and modified Clough rate-independent hysteretic models.

2. Selection of Ground Motion Records

To explain the effect of different C_y and T on the damage potential ranking of ground motion, a total of 367 ground motions are obtained from the NGA-west2 database. The selected ground motions are classified based on the USGS site classification method and the classification result is shown in Table 1. The magnitude-epicenter distance distribution results of the selected ground motion records are shown in Figure 1. It can be concluded from the results that the magnitude ranges from 3.9 to 7.8. The magnitude of most ground motion records is above five, indicating that the selected ground motion records almost come from strong earthquakes. The epicenter distance is mainly larger than 30 km. It shows that most of the selected ground motion records belong to far-field ground motions.

Table 1. Classification site results of selected ground motions.

Type of Sites	V_{s30} (m/s)	Number
AB	>750	58
C	360–760	113
D	180–360	115
E	<180	81

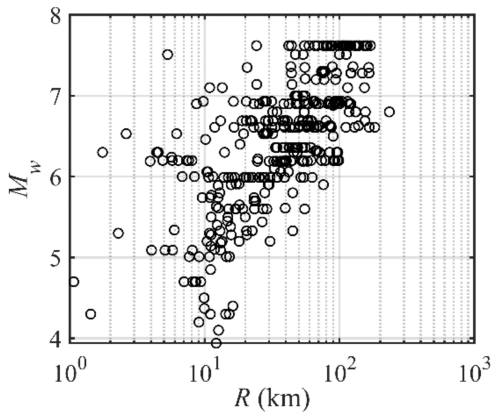


Figure 1. Magnitude-epicentral distance distribution of the selected ground motions.

3. Selected Damage Potential IM and Statistical Parameters

3.1. Damage Potential IM

At present, the commonly used seismic design code [27–29] stipulates that the collapse of reinforced concrete frame structures under earthquakes is mainly controlled by the maximum inter-story displacement ratio. Therefore, this paper is mainly based on the constant-strength displacement spectrum (S_d) as the damage potential parameters to be analyzed. It is calculated as shown in Equation (1) [30]

$$S_d = \omega' \left| \int_0^t \ddot{X}(\tau) e^{-\lambda\omega(t-\tau)} \left[\left(1 - \frac{\lambda^2}{1-\lambda^2} \right) sin\omega'(t-\tau) + \frac{2\lambda}{\sqrt{1-\lambda^2}} cos\omega'(t-\tau) \right] d\tau \right|_{max} \quad (1)$$

where $\ddot{X}(\tau)$ is the acceleration time history of ground motion, w' is the frequency, and λ is the damping ratio.

To eliminate the difference in results that may be caused by different hysteretic models, both the bilinear model and modified Clough model are selected for analysis, and the skeleton line of the two hysteretic models is shown in Figure 2. f_y is the yield strength, K_0 is the initial stiffness, k_2 is the post-yield stiffness ratio, u_y is the yield displacement, and u_{max} is the maximum displacement.

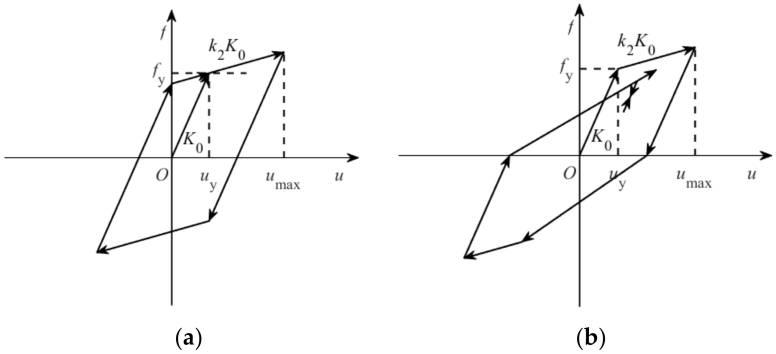


Figure 2. Force-displacement hysteresis loops simulated by the (**a**) bilinear and (**b**) modified Clough models.

3.2. Statistical Parameters

(1) Spearman correlation coefficient

To calculate the correlation of the damage potential ranking under different C_y and T conditions, the Spearman correlation coefficient (ρ) is selected as the criterion of correlation analysis. The Spearman correlation coefficient is suitable for measuring the correlation of the ranking of two variables. The calculation method is shown in Equation (2) [31]

$$\rho = 1 - \frac{6\sum_{i=1}^{n}(U_i - V_i)^2}{n(n^2-1)} \tag{2}$$

where U and V are the damage potential rankings under different T and C_y conditions, respectively. The ρ is not directly calculated by the damage potential value, but by its ranking result.

(2) Standard deviation and coefficient of variation [31]

The standard deviation or coefficient of variation is generally used as the criterion to analyze the discreteness of the two variables such as in Equation (3). However, the size of the standard deviation is related to the average value of the sample, so this paper chooses the coefficient of variation as the discriminant coefficient, as shown in Equation (4):

$$\delta = \sqrt{\frac{\sum_{i=1}^{n}(U_i - V_i)^2}{n}} \tag{3}$$

$$C.V = \frac{\delta}{\overline{X}} \tag{4}$$

where X_i is the average of the rankings, and n is the number of samples.

4. Effects of C_y and T on S_d Spectrum

C_y is the ratio of the yield strength to the strength of the complete elastic response. It can reflect the elastic-plastic deformation degree of the structure. The effect of C_y and T on the S_d is mainly analyzed from the mean displacement response spectrum and dispersion. When the structure has a nonlinear response, the structure will yield. The C_y values range from 0 to 1. The smaller the C_y is, the greater the nonlinear degree of the structure is, and the more flexible the structure is. To explain the effect of C_y on structural nonlinear response in detail, nine values of C_y = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 are selected for detailed analysis.

4.1. Analysis of the S_d mean spectrum

The S_d mean spectrum under different C_y conditions is calculated based on two different hysteretic models. The damping ratio is 0.05. The post-yielding stiffness is 0. The calculated results are shown in Figure 3. The following conclusions can be drawn from the results.

(1) The variation law of the S_d mean spectrum under different C_y conditions is the same with the same T based on the two hysteretic models. The larger the T is, the larger the displacement response mean spectrum is.
(2) Although the variation law of the S_d mean spectrum increases with the increase in T, the change speed of the S_d mean spectrum is obviously different under different C_y conditions. The smaller the C_y is, the greater the nonlinear degree of the structure is, and the larger the S_d mean spectrum is in the short- and medium-period ranges, but the smaller the S_d mean spectrum is in the long-period range.
(3) When C_y is equal to 0.1, the change law of the S_d mean spectrum is quite different from that under other C_y conditions. The main reason is that when C_y is equal to 0.1,

the yield strength of the structure is only 10% of that of full elasticity, and the character of the SDOF system is too flexible. In addition, it should be analyzed separately.

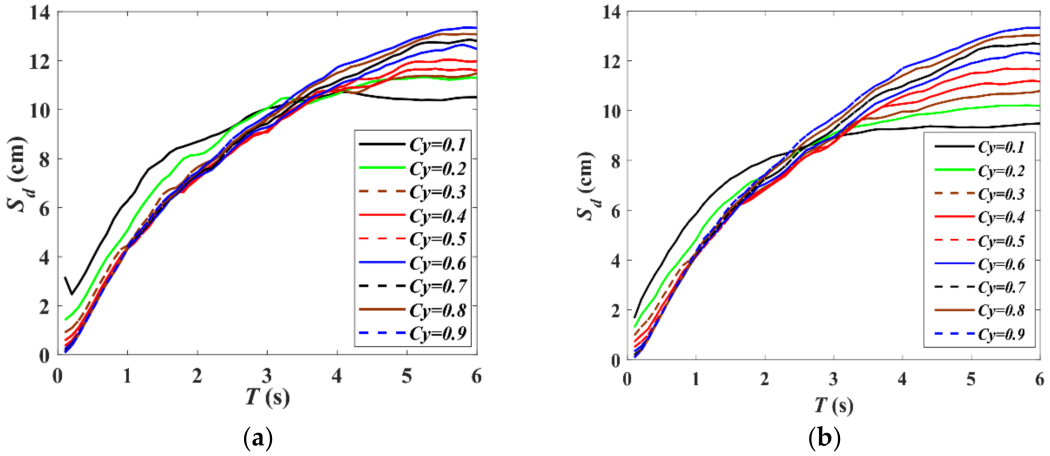


Figure 3. The S_d mean spectrum under different C_y conditions. (**a**) Bilinear model, (**b**) modified Clough model.

4.2. Discreteness Analysis of S_d Spectrum

The discreteness of the S_d mean spectrum is analyzed under different C_y conditions, and the calculated results are shown in Figure 4. It can be found from the results that the coefficient of variation at different periods ranges from 0.9 to 2. It shows that when we calculate the S_d mean spectrum based on the unscaled ground motions, the discreteness of the structural displacement response is very large. Therefore, it is not sufficient to study the variation law of the S_d mean spectrum, and it should also be studied by the variation law of the S_d ranking next step.

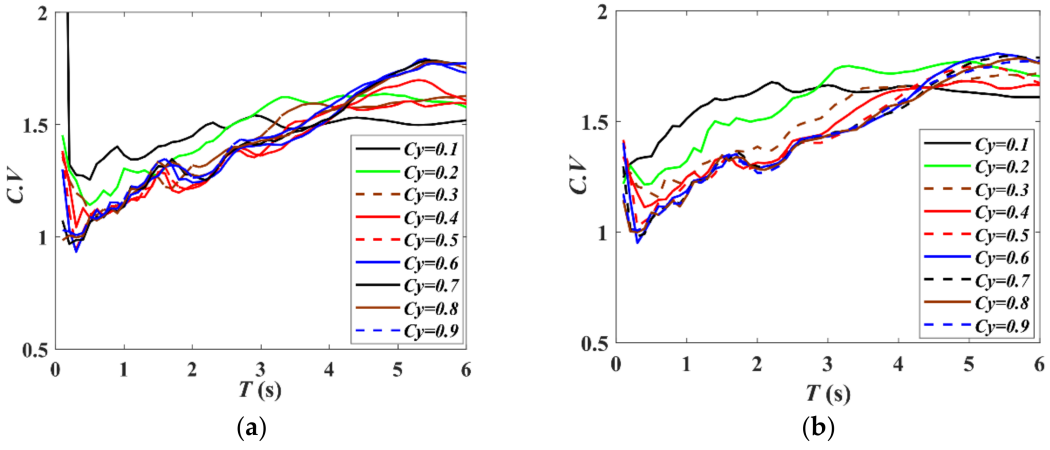


Figure 4. Analysis of the effect of different yield strength coefficients on the discreteness of the S_d spectrum. (**a**) Bilinear model, (**b**) odified Clough model.

5. Correlation Analysis of C_y and T on the S_d Ranking

It is concluded that the discreteness of S_d calculated by different ground motions is very large based on the bilinear model and modified Clough model. Therefore, this section mainly analyzes the correlation of the S_d rankings calculated at different C_y and different periods. The C_y is taken as the nonlinear response parameter to characterize the degree of nonlinear response. The T is closely related to the dynamic response of the structure.

Hu et al. [25] first proposed the concept of damage potential ranking. The damage potential ranking of ground motions refers to ground motions that are ranked according to the intensity measures (*IMs*) that can characterize the structural damage subjected to

ground motions. When the damage potential *IM* of ground motions is determinate (S_d is selected in this paper), and the damage potential values (S_{d1}, S_{d2}, S_{d3}, . . . , S_{dn}) of different ground motion records (a_1, a_2, a_3, . . . , a_n) are calculated, the damage potential ranking of ground motions can be obtained by ranking these damage potential values. The damage potential value will change when the structural parameters are changed. It is important to analyze how the damage potential ranking change with structural parameters. To ensure the correctness and simplify the calculation of the conclusion, four different values of C_y = 0.2, 0.4, 0.6, and 0.8 are selected for analysis in this section.

5.1. Analysis of S_d Ranking under Different T and Same C_y Condition

When the C_y is constant, the correlation analysis of the S_d ranking under different T conditions is analyzed, and the calculated results are shown in Figure 5. The ordinate is the correlation coefficient, and the following conclusions can be obtained from the results in the diagram:

(1) In the short-period range (T < 0.5 s), the correlation coefficients of S_d rankings under different C_y condition is less than 0.8. Especially when the change of C_y is large, the correlation is poor. In the medium- and long-period ranges (T $\geq$ 0.5 s), the correlation coefficient of the S_d ranking under different C_y conditions is higher, and the correlation is very good. When the C_y changes, the S_d values will change, but the variation of the S_d rankings is small. It can be concluded that the damage potential rankings in the short-period range are more sensitive to the change of C_y than that in the medium- and long-period.

(2) When the change of C_y is smaller, the larger the correlation coefficient of the corresponding S_d rankings is, the smaller the variation of S_d ranking is. On the contrary, when the difference between the S_d rankings under different C_y conditions is larger, the smaller the correlation coefficient of the corresponding S_d rankings is.

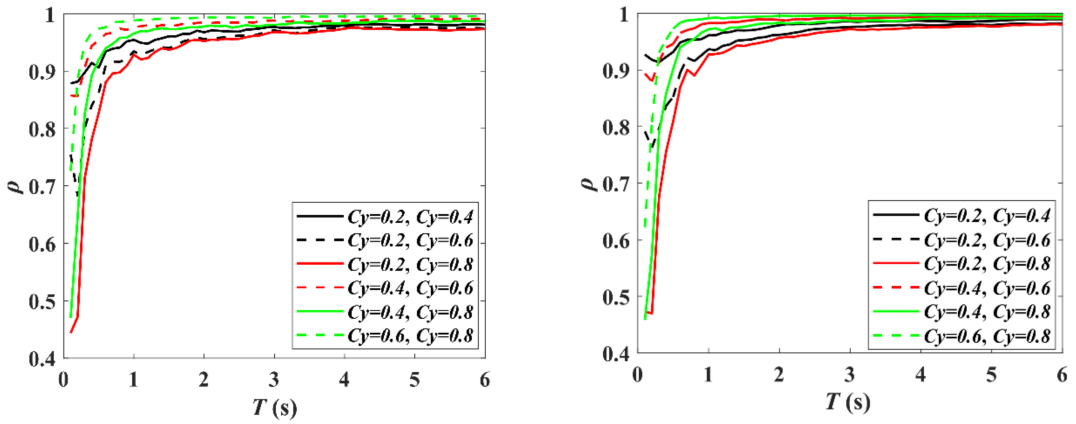


Figure 5. Correlation analysis of S_d rankings under different C_y conditions. (**a**) Bilinear model, (**b**) modified Clough model.

5.2. Correlation Analysis of the S_d Ranking under Different T and Same C_y Condition

When the C_y is constant, the correlation analysis of S_d ranking under different T conditions is analyzed, and the calculated results are shown in Figures 6 and 7, in which abscissa and ordinates are both T, and different colors represent the value of the ρ. The following conclusions can be drawn from the results:

(1) The variation law of the S_d ranking at different T is the same. When the ΔT of the two periods is small, the ρ of the corresponding S_d rankings is larger, and the variation of the damage potential ranking is small. On the contrary, when the ΔT of the two periods is larger, the ρ of the corresponding S_d ranking is smaller.

(2) The S_d rankings are more sensitive to the change of T in the short-period compared with the medium- and long-period. More periods need to be selected for research in short-period.

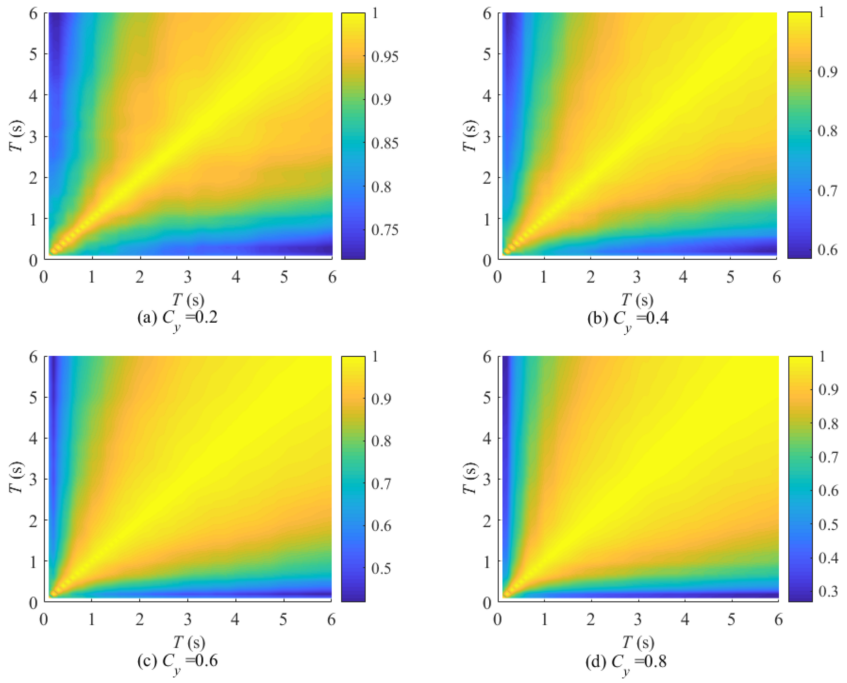


Figure 6. Correlation analysis of S_d rankings at different periodic points (Bilinear model).

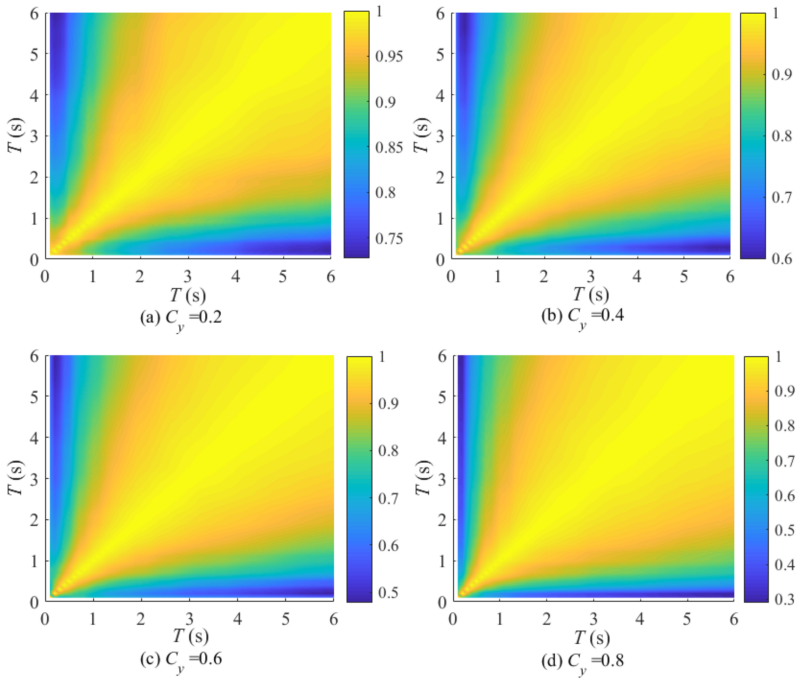


Figure 7. Correlation analysis of S_d rankings at different periodic points (modified Clough model).

5.3. Comparative Analysis of the Damage Potential Ranking under Specific C_y and T Condition

The effect of different C_y and T on the damage potential ranking is analyzed in detail in this paper, and the degree of influence is mainly reflected by the correlation coefficient of S_d rankings. Based on the two hysteretic models, this section selects the specific S_d ranking results under 12 conditions of different C_y and T for comparative analysis, and the size of

the S_d ranking of ground motions is expressed in different colors to verify the rationality of the previous conclusions. The results are shown in Table 2, Figures 8 and 9.

Table 2. Correlation and discreteness of earthquake potential damage potential ranking under different C_y and T.

Ground Motion Ranking		Bilinear Model		Modified Clough Model	
Ranking 1	**Ranking 2**	ρ	$\frac{\delta}{\overline{X}}$	ρ	$\frac{\delta}{\overline{X}}$
C_y = 0.6, T = 0.8 s	C_y = 0.6, T = 1.0 s	0.958	0.168	0.965	0.152
	C_y = 0.6, T = 4.0 s	0.791	0.290	0.782	0.381
C_y = 0.4, T = 0.2 s	C_y = 0.6, T = 0.2 s	0.856	0.310	0.879	0.284
	C_y = 0.8, T = 0.2 s	0.647	0.485	0.572	0.533
C_y = 0.4, T = 2.0 s	C_y = 0.6, T = 2.0 s	0.984	0.102	0.988	0.089
	C_y = 0.8, T = 2.0 s	0.978	0.122	0.983	0.105

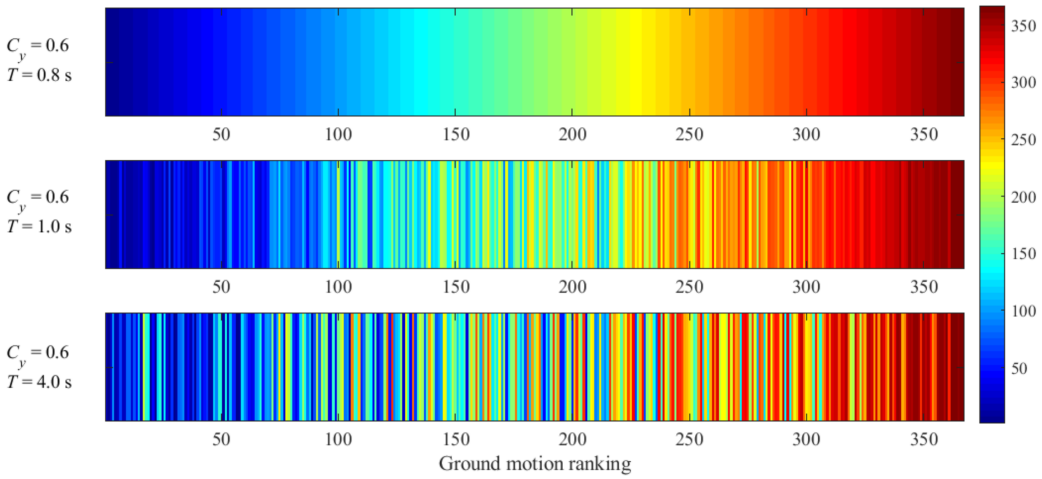


Figure 8. Comparison of displacement response rankings at different periodic points when the yield strength coefficient is constant. (**a**) Bilinear model (C_y = 0.6), (**b**) modified Clough model (C_y = 0.6).

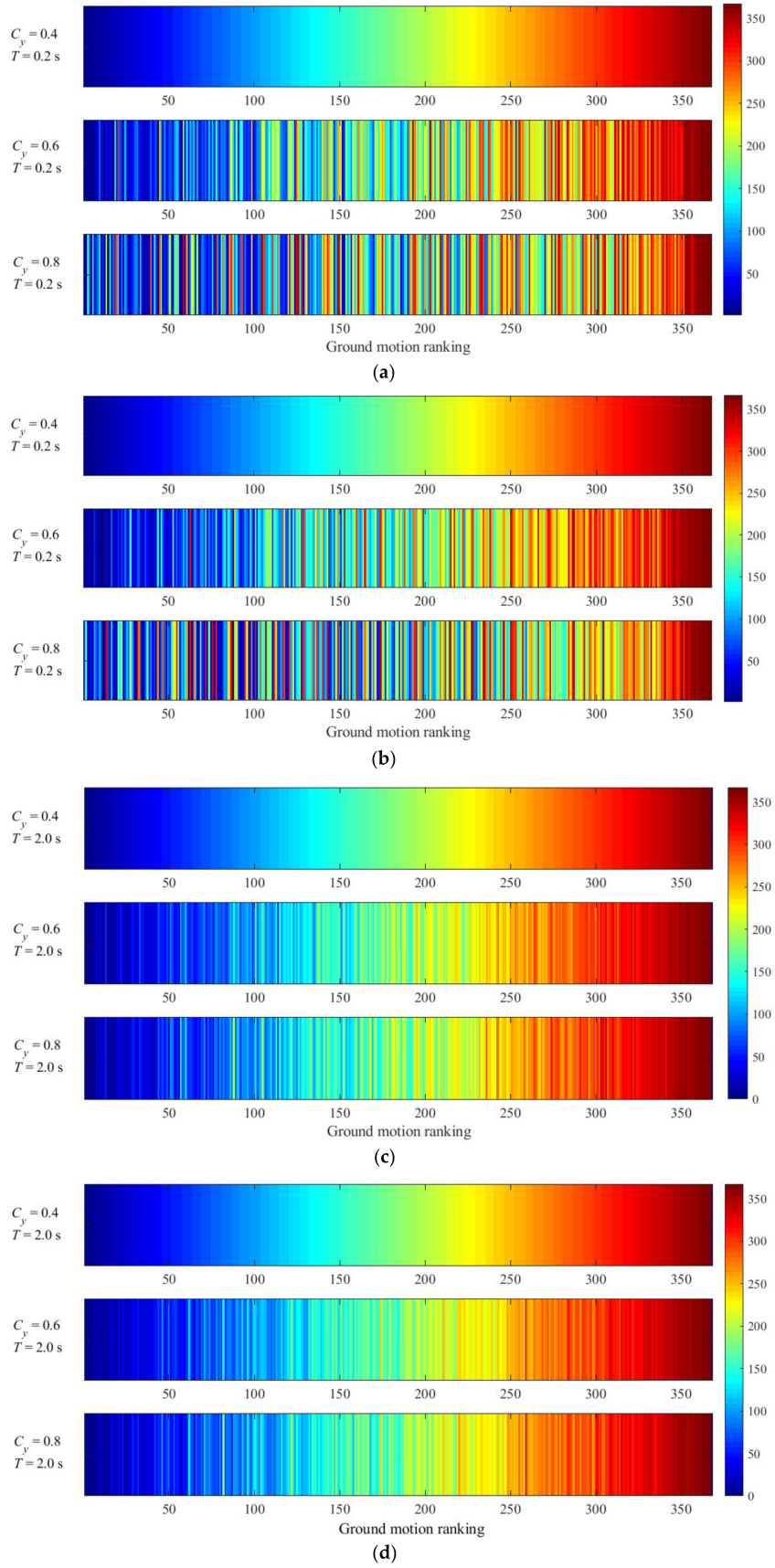


Figure 9. Comparison of displacement response rankings under different C_y with a constant T. (**a**) Bilinear model (T = 0.2 s), (**b**) modified Clough model (T = 0.2 s), (**c**) bilinear model (T = 2.0 s), (**d**) modified Clough model (T = 2.0 s).

(1) According to the results of Figure 8 and Table 2, when the T is equal to 0.8 s and 1.0 s, respectively, with a constant C_y value of 0.6, the corresponding ΔT is smaller, and the corresponding damage potential rankings of ground motions have a strong correlation and a smaller discreteness. Whereas the corresponding damage potential rankings results are also quite different when the T is equal to 4.0 s. The coefficient of variation ($\frac{\delta}{\overline{X}}$) is increased by 70% and 150%, respectively, based on the bilinear model and modified Clough model compared with the former condition. The corresponding correlation becomes weaker and the discreteness increases.

(2) From the results of Figure 9a,b and Table 2, it can be seen that when T is determined (T = 0.2 s, short-period range), there is much difference in S_d ranking under different C_y conditions, and the corresponding coefficient of variation ($\frac{\delta}{\overline{X}}$) of the damage potential of ground motions is very large and the correlation coefficient is small. However, it can be seen from Figure 9c,d that when T is determined (T is equal to 2.0 s, medium- and long-period range), the corresponding S_d rankings under different C_y conditions change little. It can be also concluded that the damage potential ranking in the short-period range is more sensitive to the change of C_y than that in the medium- and long-period range.

6. Conclusions

The damage potential of ground motions is represented by the S_d, and the S_d under different T and C_y conditions is analyzed based on a bilinear and modified Clough hysteretic model. Not only the variation of the S_d values and discreteness under different T and C_y conditions are analyzed, but more importantly, the variation of S_d ranking is also analyzed. The conclusions are as follows.

(1) When C_y is constant, the average value of S_d increases with the increase in T. When T is constant, the smaller the C_y in the short- and medium-period ranges, the larger the average value of S_d. On the contrary, the smaller the C_y, the smaller the average value of S_d in the long-period range.

(2) The correlation coefficient of the S_d ranking under different C_y conditions is less than 0.8 in the short-period range. Especially when the difference of C_y is large, the correlation of the corresponding S_d rankings is poor, which indicates that C_y has a great effect on the S_d rankings. In the medium- and long-period range, the correlation coefficient of S_d values corresponding to different C_y is higher, and the correlation is very good, indicating that C_y has almost no effect on the S_d ranking.

(3) In the medium- and long-period range, with the change of T, and when the change of T is small, the S_d value changes obviously, but the change of S_d ranking is very small. When T changes greatly, the S_d value and S_d ranking change greatly.

It is worth noting that only the SDOF system is used to analyze the damage potential ranking in this paper, and the multi-degree-of-freedom structures need to be used in the next study.

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