Geomechanics and Engineering, *Vol. 11, No. 2 (2016) 309-323*
DOI: http://dx.doi.org/10.12989/gae.2016.11.2.309

An approach of seismic design for sheet pile retaining wall based on capacity spectrum method

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(*Received February 01, 2015, Revised April 05, 2016, Accepted April 29, 2016*)

Abstract. As the forefront of structural design method, capacity spectrum method can be applied conveniently, and through this method, deformation demand of structure can be considered. However, there is no research for the seismic application in the structure of sheet pile retaining wall to report. Therefore, focusing on laterally loaded stabilizing sheet pile wall, which belongs to flexible cantilever retaining structure and meets the applying requirement of capacity spectrum method from seismic design of building structure, this paper studied an approach of seismic design of sheet pile wall based on capacity spectrum method. In the procedure, the interaction between soil and structure was simplified, and through Pushover analysis, seismic fortification standard was well associated with performance of retaining structure. In addition, by comparing the result of nonlinear time history analysis, it suggests that this approach is applicable.

Keywords: capacity spectrum method; pushover analysis; sheet pile wall; interaction between soil and structure

1. Introduction

The most reliable method of seismic performance evaluation is nonlinear time history analysis. However, this method needs large amount of calculation, and leads to complicated results. Meanwhile, the uncertainty of earthquake motion input parameters and its restoring force model causes limited application (Saygili 2008, Rathje *et al*. 2014, Zekri *et al*. 2015).

In contrast, capacity spectrum method takes elastic-plastic performance from components into account, and it also makes the calculation easier. Therefore, it becomes a research hot topic in seismic design of structure (Priestley *et al*. 2008, Dolsek 2010, Ye *et al*. 2013). However, the CSM is not a dynamical and time-history analysis (Chopra and Goel 2002), can't reflect the influence of the seismic time , and the capacity curve obtained by the CSM can also not express the effect of seismic waves (Liu *et al*. 2009) .

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http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

About the CSM, some researches have been carried out. Freeman (1975) first proposed the simple and practical method through Pushover analysis, and figured out that it is a pseudo-static seismic assessment method of elastic-plastic structures based on displacement. After development, Pushover analysis was combined with seismic demand spectrum, it becomes CSM method. Through graphic correlations of structural capacity spectrum curve and demand spectrum curve, this method can directly evaluate the structural performance under ground motions (Araki and Hjelmstad 2000). Fajfar (1999) described the application of CSM for seismic design based on force or displacement. For single-degree-of-freedom system (SDOF), Xue (2001) established an approach of seismic design for structures based on displacement. This approach used deduced formulas from CSM and inelastic demand spectrum proposed by Newmark and Hall (1982). In addition, Xue (2001) extended this approach to multi-degree-of-freedom system (MDOF) with equivalence relationships. Nozu *et al*. (2004) conducted a preliminary pushover analysis for wharf pile retaining structure by using damage survey results in Kobe earthquake. Gu and Miao (2011) proposed a displacement -based pushover method, and obtained the structural capacity curve. Song *et al*. (2014) proposed a stochastic CSM based on the first order reliability, and through numerical analysis, it shows that the presented method can effectively conduct seismic fragility analysis and can overcome the low computation efficiency of the standard Monte Carlo simulation. Currently, this method has been further studied by more and more researchers, and has been officially adopted by Japanese Highway and Bridge Seismic Design Code (Japan Road Association 2002), ATC-40 (Applied Technology Council 1996), FEMA356 (Federal Emergency Management Agency 2000) *et al*.

However, due to the complexity of soil-structure interaction, CSM is seldom applied in slope stabilizing sheet pile retaining wall. The limited research mostly focused on the aspects of pile-soil-structure interaction (Cilingir *et al*. 2011).

As the sheet pile wall is high and light, it belongs to flexible cantilever retaining structures, and has possibility of conducting seismic design of CSM (Huang *et al*. 2013, Cardone 2014). Therefore, this paper carried out an applied research of CSM in sheet pile wall.

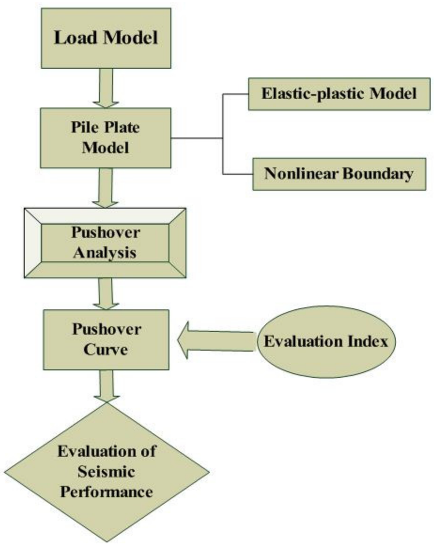


Fig. 1 Process of the performance evaluation

2. Principle of capacity spectrum method

The process of the performance evaluation is shown in Fig. 1.
The detailed steps of calculation and analysis are as follows:

Stage 1: Establishment of capacity spectrum. Considering the own weight of structure, a set of lateral loads was applied along the height direction. The lateral loads were used to approximately represent the inertia force of structure under ground motion. The lateral load was increased progressively. In each stage of loading, the structural elements need to be tested whether plastic hinge appeared. If plastic hinge appeared, the effective stiffness matrix needed to be changed and the unbalanced force would be calculated, and then lateral loads continued to be applied. This process was repeated constantly till the structure experienced all stages, such as cracking of the concrete in the protective layer, and the ultimate collapse due to yield of longitudinal steel bars, etc. Finally, the characteristics of internal forces, bearing capacity and structural deformation were obtained. Through the process, Pushover curve was obtained. According to the method of Pushover analysis, we can get the curve of the relationship of the base shear of structure V_b and top displacement of structure δ, then equivalently convert the relationship to the capacity curve of spectrum acceleration S_a and spectrum displacement S_d. The conversion formula is shown in Eq. (1).

$$S_a = \frac{V_b}{M_1^*}, \qquad S_d = \frac{\delta_n}{\gamma_1 X_{n1}} \tag{1}$$

In the Eq. (1), γ_1, M_1^* is participation factor and generalized mass in first vibration mode of structure respectively. The calculation is shown in Eq. (2).

$$\gamma_1 = \frac{\sum_{i=1}^{n}(m_i X_{i1})}{\sum_{i=1}^{n}(m_i X_{i1}^2)}, \quad M_1^* = \frac{\left[\sum_{i=1}^{n}(m_i X_{i1})\right]^2}{\sum_{i=1}^{n}(m_i X_{i1}^2)} \tag{2}$$

In the Eq. (2), m_i is the mass of the particle in the layer i, X_{i1} is the amplitude of the particle in first vibration model of the layer i; n is the number of particles.
In Pushover analysis, MDOF can be equivalent to SDOF, which is based on displacement mode. Dynamic equation of MDOF system under ground motion can be expressed in Eq. (3).

$$[M]\{\ddot{y}\} + [C]\{\dot{y}\} + \{F(y)\} = -[M]\{1\}\ddot{y}_0 \tag{3}$$

Where, $[M]$ is Structural mass matrix; $[C]$ is Structural damping matrix; $\{y\}$ is Structural relative displacement matrix; $\ddot{y}_0$ is Ground acceleration; $\{F(y)\}$ is Structural elastic-plastic restoring force.
$\{y\}$ is assumed to be represented by structural top displacement y_t and displacement mode vector $\{u\}$. In Eq. (3), $\{y\} = \{u\}y_t$. Then, the Eq. (3) can be expressed in Eq. (4).

$$[M]\{u\}\ddot{y}_t + [C]\{u\}\dot{y}_t + \{F(y)\} = -[M]\{1\}\ddot{y}_0 \tag{4}$$

Multiplied by $\{u\}^T$ on both sides of Eq. (4), the dynamic equation of SDOF can be deduced, as shown in Eq. (5).

$$M_e\ddot{y}_e + C_e\dot{y}_e + F_e = -M_e y_0 \tag{5}$$

Where, $M_e = \{u\}^T[M]\{1\}$ is the equivalent mass; $y_e = \frac{\{u\}^T[M]\{u\}}{\{u\}^T[M]\{1\}}$ is the equivalent displacement; $C_e = \{u\}^T[C]\{u\}\frac{\{u\}^T[M]\{1\}}{\{u\}^T[M]\{u\}}$ is the equivalent damping; $F_e = \{u\}^T\{F(y)\}$ is the equivalent restoring force.

$$S_d = \left(\frac{T}{2\pi}\right)^2 S_a \tag{6}$$

Stage 2: Establishment of demand spectrum. Pushover analysis merely can obtain force-displacement curve, but the seismic demand of structure is not clear, therefore the elastic or inelastic demand spectrum is required. The spectrum curve is divided into elastic spectrum and elastic-plastic demand spectrum. Elastic demand spectrum can be obtained from seismic design codes for buildings, roads or railways. In the case of damping is not large (damping ratio is 5%), according to the dynamic equation in elastic system, the value of response spectrum displacement S_d can be approximately determined with the following Eq. (6) by spectrum acceleration S_a.

In the Eq. (6), T is the basic period of structure, which is determined by first vibration mode of structure in the proposed approach. The obtained $S_a - S_d$ curve is demand spectrum. Elastic response spectrum does not take the nonlinear plastic performance of structure into account. Chopra and Goel (1999) recommended that the nonlinear plastic performance of structure can be considered through acting the inelastic design spectrum as the demand spectrum.

The establishment of the inelastic demand spectrum is as follows. Elastic response spectrum in the Specifications can be converted to spectrum acceleration-spectrum displacement format from the acceleration-period format. Then depending on the R-μ-T strength reduction model, elastic-plastic demand spectrum curve corresponding to different ductility factor μ can be calculated according to Eq. (7).

$$S_a = \frac{S_{ae}}{R}, \qquad S_d = \frac{\mu}{R}S_{de} = \frac{\mu}{R}\frac{T^2}{4\pi^2} = \mu\frac{T^2}{4\pi^2}S_a \tag{7}$$

The definitions of strength reduction factor R and ductility factor μ are shown in Fig. 2.

The reduction formula for R-μ-T is not only related with the period of structure, but also influenced by factors of earthquake source mechanism, magnitude, site condition, transmission route of seismic wave, damping ratio, and hysteretic model, etc. Newmark and Hall (1973), Vidic *et al.* (1994) and Qu *et al.* (2011) all have ever established the relationship model of R-μ-T considering different influence factors.

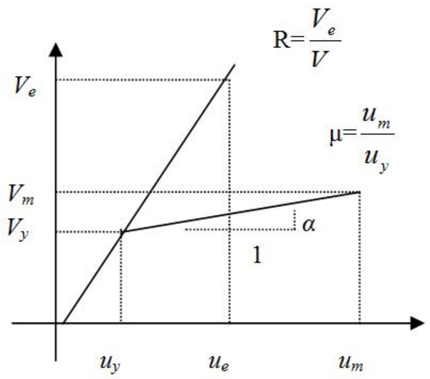


Fig. 2 Definitions of strength reduction factor and ductility factor

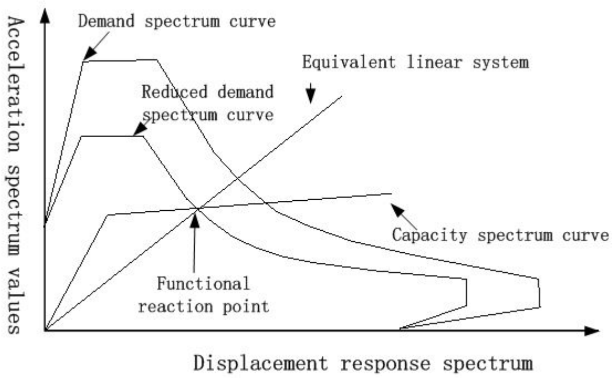


Fig. 3 Determination of performance point

Stage 3: Determination of seismic structural performance. Plot out capacity spectrum and demand spectrum in the same acceleration-displacement coordinate system. Functional response point (performance point) is the intersection point of capacity spectrum and demand spectrum with corresponding damping ratio or ductility factor (Ji and Dong 2009). Capacity spectrum intersects with the inelastic demand spectrum which has different values of displacement ductility factor μ. The performance point is confirmed according to the principle that the value of μ in the capacity spectrum should be equal to the value of μ in the inelastic demand spectrum. If the limited point of the capacity curve is greater than the functional response point, it suggests that the seismic performance of the structure meets the requirements, as shown in Fig. 3.

3. Methodology in the seismic design of sheet pile retaining wall based on performance

In the Pushover analysis of sheet pile retaining wall, seismic inertial force (landslide thrust under the earthquake or Coulomb earth pressure) acts on concentrated mass points. Take rock

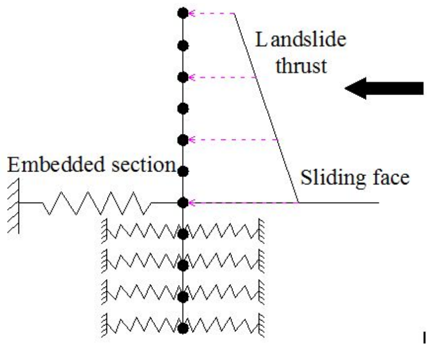
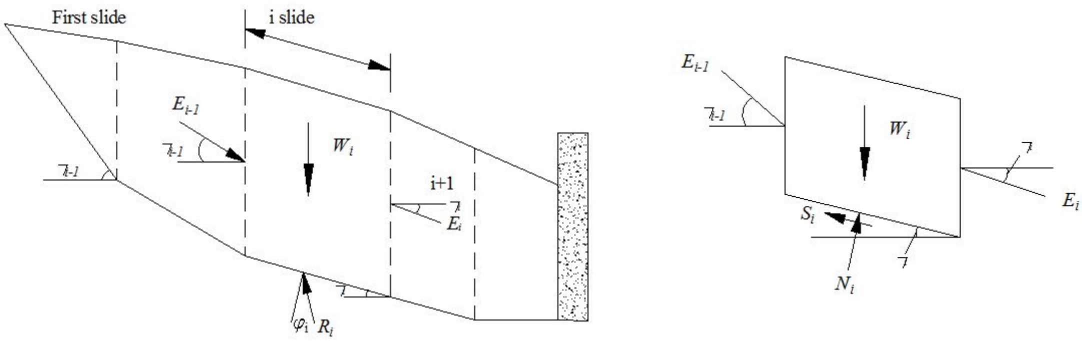


Fig. 4 Model of rock-embedded sheet pile wall



(a) Block diagram of slope (b) Force diagram of i block

Fig. 5 Transfer coefficient method

embedded pile as an example, the embedded section has great rigidity, therefore the structural deformation is dominated by cantilever deflection. In view of this, landslide thrust can be acted in a certain distribution pattern on cantilever, and embedded section can be treated as springs (Chopra and Goel 2004, Goel 2010, Liu *et al*. 2014). The springs can only be compressed, and can't be stretched, as shown in Fig. 4, in which the calculation of landside thrust under the earthquake can be conducted according to literature (Qu and Zhang 2013).

The landslide thrust is calculated by the transfer coefficient method (TCM), which is widely used in slope stability analysis of railway and highway departments in China.

In the TCM, landslide is assumed to be incompressible, and it ignores the extrusion deformation between slider. Between the sliders, there is only the thrust, and the tension is ignored, as shown in Fig. 5.

According to the TCM, the landslide thrust can be calculated from Eq. (8).

$$E_i = W_i \sin\alpha_i - W_i \cos\alpha_i \tan\varphi_i - c_i l_i + \psi_i E_{i-1} \tag{8}$$

In the Eq. (8), E_i is the landslide thrust of i slider; E_{i-1} is the landslide thrust of i-1 slider; W_i is the weight of i slider; c_i is the cohesive force of i slider; ψ_i is the transfer coefficient; $\psi_i = \cos(\alpha_{i-1} - \alpha_i) - \sin(\alpha_{i-1} - \alpha_i)\tan\varphi_i$; l_i is the length of slip surface of i slider; φ_i is the internal friction angle of i slider; α_i is the dip of slip surface of i slider.

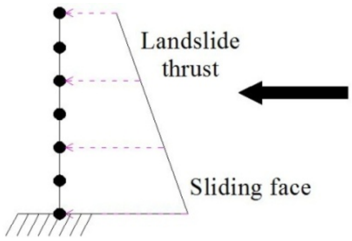


Fig. 6 Model of cantilever of retaining wall

To simplify and explain the problems, the paper focuses on the working condition in which the rock-embedded section cannot dislocate. Therefore, the pile is simplified as cantilever beam, and the end is fixed, as shown in Fig. 6.

After Pushover analysis for simplified model above, the curve of base shear V_b - top displacement δ can be obtained. Then, it can be converted to the curve of spectrum acceleration - displacement spectrum in equivalent SDOF. Then the curve is fold-lined, finally the capacity spectrum can be obtained (Liao and Goel 2014).

Due to complexity of soil-structure interaction system, and the CSM cannot reflect the influence of the seismic time, here we assume that the interaction between cantilever section and soil mass is the landslide thrust calculated by pseudo static method, which is not changing with seismic time. The design response spectrum which is from Specification of Seismic Design in Highway Engineering can be adopted as the demand spectrum. Meanwhile, reduction is conducted with different ductility, then the capacity spectrum and inelastic demand spectrum after the reduction can be drawn in the same coordinate system. The functional response point can be got through iterative computation. Then the target displacement and base shear of the original structure can be calculated, and also the ductility factor and equivalent damping ratio corresponding to the coordinate point can be obtained. Depending on the evaluation index, we can conduct assessment about seismic performance of structure under seismic intensity. Due to the evaluation process is based on the establishment of Chinese seismic specifications, assessment results also naturally meet the relevant requirements of Chinese specifications and has a strong guiding significance (Liu and Jia 2011).

4. Verification with numerical analysis

(1) Model of numerical analysis

To check the applicability of presented method, the model of simple sheet pile retaining wall is taken into the calculation, as shown in Fig. 7. The ground is Class II. The length of pile is 10 m, section dimension is 1.2 m × 0.9 m, embedded depth is 4 m and pile distance is 3.4 m. The sliding surface is divided into two sections with upper angle is 60° and lower section is 20°. The Koyna seismic wave was loaded, and peak value is normalized as 0.2 g. The material parameters of the model are shown in Table 1. Calculated displacement is shown in Fig. 8. The final displacement of pile top is 11.2 cm.

(2) Verification of presented approach

In the seismic intensity zone of 8-degree (peak ground acceleration is 0.2 g), the landslide

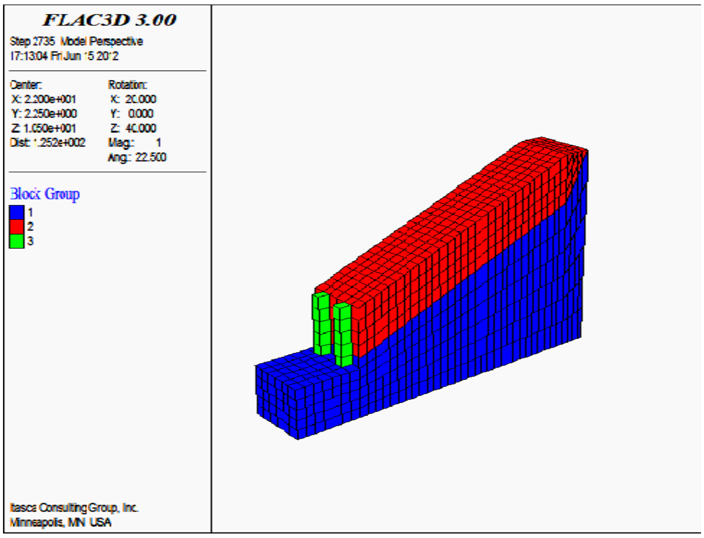


Fig. 7 Calculation model of the sheet-pile retaining wall

Table 1 Material parameters of the model

Material group	Chosen model	Bulk density	Cohesion	Internal cohesion	Bulk modulus	Shear elasticity	Bearing capacity
		kN/m^3	kPa	Degree	kPa	kPa	kPa
Slip mass	Mohr-Coulomb	19	19	24	8.04E+04	3.71E+04	100
Slip bed	Mohr-Coulomb	24	50	40	1.66E+06	1.11E+06	500
Slide face	Interface	-	10	18	8.04E+04	3.71E+04	-
Pile board	Elastic	25	-	-	1.72E+07	1.29E+07	-

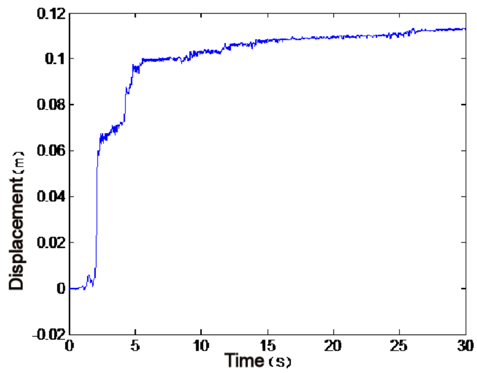


Fig. 8 Displacement curve of pile top

thrust of this model is 3109.094 kN between two piles, which acts on cantilever of pile as a trapezoidal distribution force. After pushover analysis by using SAP2000, the capacity spectrum can be obtained, as shown in Fig. 9

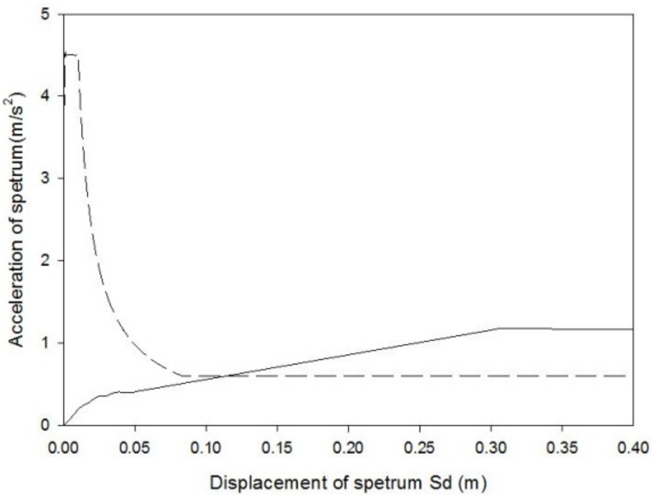


Fig. 9 Calculation of performance point in seismic intensity zone of 8-degree with presented approach

The design response spectrum from Specifications of Earthquake Resistant Design for Highway Engineering was then used as the demand spectrum to calculate. Through calculation, the spectrum displacement of performance point in seismic intensity zone of 8-degree is 0.11 m, namely the abscissa value of the intersection point of Fig. 9. Through Eq. (1), the corresponding displacement of pile top can be determined as 0.242 m. The final displacement of pile top through time-history analysis with FLAC^{3D} is 0.112 m (as shown in Fig. 8), it is obvious that the displacement is smaller than the CSM result. The reason is that plastic of material is not considered.

Capacity spectrum intersects with the inelastic demand spectrum which has different values of displacement ductility factor μ. The performance point is confirmed according to the principle that the value of μ in the capacity spectrum should be equal to the value of μ in the inelastic demand spectrum.

For high accuracy and convenient application, far-field effects are mainly considered. The reduction is conducted to the specified elastic response spectrum based on the reduction model proposed by Qin and Luo (2006). The R-μ-T relationship is described in Eqs. (9)-(11).

$$R = c_1(\mu - 1)^{C_R}\frac{T}{T_0} + 1 \qquad T \le T_0 \tag{9}$$

$$R = c_1(\mu - 1)^{C_R} + 1 \qquad T > T_0 \tag{10}$$

$$T_0 = c_2 \mu^{C_T} T_g \tag{11}$$

In above Eqs. (9)-(11), T_g is the characteristic period of the structure. μ is the displacement ductility factor of the structure, c_1, c_2, C_R, C_T are parametes depending on the structural damping ratio and hysteresis characteristics. Here are taken as 1.34, 0.95, 0.75, 0.20.

In the sites of Class II, when the characteristic cycle T_c = 0.4S, μ = 1.5, 1.5, 2, inelastic response

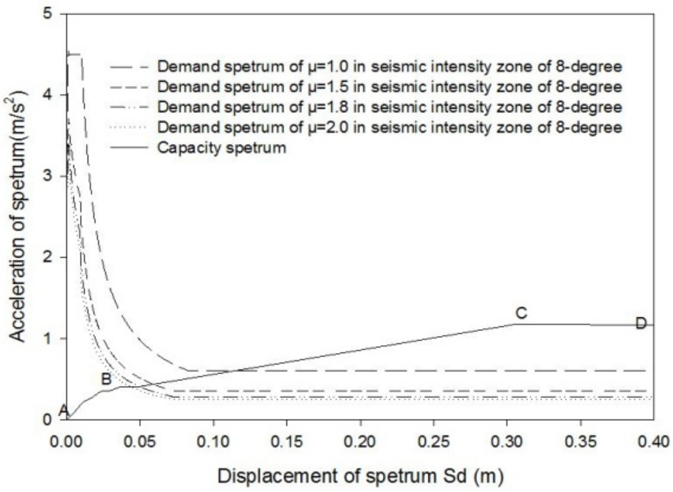


Fig. 10 Response displacement in seismic intensity zone of 8-degree with CSM

spectrum is shown in Fig. 10. The values of μ corresponding to crossing points with capacity spectrum are 2.12, 1.766, 1.586. The performance points can be determined according to the principle that ductility factor μ equals to the displacement ductility factor μ in the curve. Obviously, when μ = 1.8 in the demand spectrum curve, we can get μ' = 1.766 after the calculation and the relative error is $1.9\% < 5\%$. Therefore, the final performance point is chosen, and the corresponding displacement of pile is 11.4 cm, which is close to the calculation.

5. Fortification standards for sheet pile retaining wall

CSM is given great attention in seismic design based on displacement performance. However, sole Pushover capacity spectrum method cannot complete the performance design. It must combine with the performance design standards of structure (Li *et al*. 2010a, b). After that, we can assess seismic capacity of structure under the specific earthquake action.

The seismic design theory based on displacement performance was first proposed by U.S. researchers in the 1990s (ATC-40, FEMA-273). The basic idea is that the structural design is based on the seismic performance analysis (Yang *et al*. 2000). For each fortification standard (For example, in 50 years, the probability of ground motions goes beyond 63.2 %, 10 % and 2 %), the seismic performances of structures are divided into different levels. The design can be carried out by applying reasonable seismic performance targets with appropriate seismic measures.

As people have many different kinds of requirements on the seismic performance of structure, the seismic performance design must reach target that People expected. For retaining structures, the performance design standards of the gravity retaining walls and sheet pile wall in marine engineering are proposed in the literature (International Navigation Association), as shown in Table 2. The levels of the earthquake damage I, II, III, IV correspond to four performance targets in which performance are in good condition, continuous performance, ensuring safety and near collapse respectively.

The seismic performance requirements for structures are provided as follows in literature (Zhang *et al*. 2009).

Table 2 Fortification standards for gravity retaining wall and sheet pile wall in marine engineering

Type of retaining wall	Earthquake damage level		I	II	III	IV
Gravity retaining wall	Top horizontal residual displacement index		< 1.5%	1.5~5%	5~10%	> 10%
	Residual Angle in the direction of the sea		< 3°	3~5°	5~8°	> 8°
Sheet pile wall	Top horizontal residual displacement index		< 1.5%	N/A	N/A	N/A
	Residual angle in the direction of the sea		< 3°	N/A	N/A	N/A
	Dynamic stress strain response	Above mudline	Elastic	Produce plastic deformation (Less than the ductility index)	Produce plastic deformation (Less than the ductility index)	Produce plastic deformation (bigger than the ductility index)
		Under mudline	Elastic	Elastic	Produce plastic deformation (Less than the ductility index)	Produce plastic deformation (bigger than the ductility index)

Performance requirement I: structures have minor damage or no damage after the earthquake, and can maintain its normal function, structures are still in elastic work stage.

Performance requirement II: structures may be damaged after the earthquake, but after repairing, in a short term, can resume normal function, and structures are in inelastic stage.

Performance requirements III: structures may have a greater damage after the earthquake, but the overall collapse does not occur, and structures are in plastic work stage.

According to the damage survey of retaining structures in Wenchuan Earthquake, seismic performance requirements were proposed by Zhang *et al*. (2009), as shown in Table3.

At present, there is little research about the performance design standards for sheet pile retaining wall. Therefore, it is necessary to propose a reference depending on existing research. As the statistical basis of Zhang *et al*. (2009) mainly focus on the rigid retaining structures, the comparison should be carried out referring to the standards of gravity retaining wall in Table 3. In view of the results mainly based on the actual investigation and there is more or less difference between marine engineering and geotechnical engineering, the standards proposed by Zhang *et al*. (2009) can be applied in performance requirements for rigid rotating pile under the conditions of Class I, II. Because sheet pile retaining wall permits a greater rotation angle compared with gravity retaining wall, the standards proposed by International Navigation Association can be applied in performance requirements under the conditions of Class III and IV. About the seismic performance of deflection deformed pile, it is no longer applicable from the perspective of displacement. We

Table 3 Seismic performance evaluation standards of retaining structures

Displacement control	Using function	Damage degree	Quantitative index
Performance requirements I	Normal use	Undamaged or minor damage	Displacement index ≤ 1.0%
Performance requirements II	Return to normal use in short time	Local damage	Displacement index ≤ 3.5%
Performance requirements III	Speed limit after repair can be opened to traffic	Wall has great deformation and there is no collapse	Displacement index ≤ 6.0%

Table 4 Seismic performance assessment standards of sheet pile retaining wall

<table>
<tr><th>Retaining wall type</th><th colspan="2">Earthquake damage level</th><th>I</th><th>II</th><th>III</th><th>IV</th></tr>
<tr><td>Rigid rotation</td><td colspan="2">Residual deformation index at the top of pile</td><td>< 1%</td><td>1~3.5%</td><td>3.5~10%</td><td>> 10%</td></tr>
<tr><td rowspan="3">Deflection deformation</td><td colspan="2">Residual deformation index at the top of pile</td><td>< 1.5%</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="2">Dynamic response of stress and strain</td><td>Cantilever section</td><td>Elastic</td><td>Produce plastic deformation (Less than the ductility index)</td><td>Produce plastic deformation (Less than the ductility inde)</td><td>Produce plastic deformation (bigger than the ductility index)</td></tr>
<tr><td>Build-in section</td><td>Elastic</td><td>Elastic</td><td>Produce plastic deformation (Less than the ductility index)</td><td>Produce plastic deformation (bigger than the ductility index)</td></tr>
</table>

should focus on working status of structural components. Combining with Table 2, in this paper, the seismic performance assessment standards of sheet pile retaining wall are proposed in Table 4.

CSM provides a good idea for seismic performance assessment for deflection deformed sheet pile retaining wall. Combining with three-stage fortification standards of performance design, assessments about the performance point calculated by example are conducted. Obviously, in the Fig. 10, the segment AB is corresponding to the stage of performance requirements I, section BC is corresponding to the stage of performance requirements II, section CD is corresponding to the stage of performance requirements III. It can be seen that the structure is in the section BC in seismic intensity zone of 8-degree, the cantilever has plastic deformation, and the displacements of pile top in the points of B, C are 6.7 cm and 64 cm, which are consistent with the fortification standards proposed in Table 4.

6. Conclusions

CSM has clear conception, convenient application, and can intuitively express the relationship between seismic capacity and demand of structures through figures. In addition, it can consider structural deformation demand under the different seismic standard, combining with two stage design. Therefore, it is the inevitable development direction of geotechnical seismic engineering. Through the research of this paper, conclusions can be obtained as follows:

(1) Through simplifying the soil-structure interaction, an approach for application of CSM in laterally loaded sheet pile wall was presented.
(2) Through Pushover analysis, displacement seismic fortification standard was well associated with performance of retaining structures, which is an advance for retaining structural seismic design based on performance.
(3) The elastic-plastic dynamic response results from CSM were compared with time history analysis. The comparison illustrates the presented approach is applicable.

It is important to note that applying structural CSM to seismic design for sheet pile wall has certain creativity as an attempt. However, due to complexity of soil-structure interaction under the laterally loaded condition, and assumptions and deviations in aspects of reduction of demand spectrum, selection of the restoring force model, and equivalent degree of freedom, etc. The approach has some omissions and mistakes in program inevitably. Therefore, further research in its promotion and application is necessary.

Acknowledgments

This study is supported by the Foundation of Education Office of Sichuan province (Contract No. 14ZB0056), Foundation for Research and Science and Technology of Southwest Petroleum University (Contract No. 2013XJZ020), scientific research starting project of SWPU (No. 2014PYZ014), and Young Scholars development fund of SWPU(Contract No. 201331010046).

References

Araki, Y. and Hjelmstad, K.D. (2000), "Criteria for assessing dynamic collapse of elastoplastic structural systems", *Earthq. Eng. Struct. Dyn.*, **29**(8), 1177-1198.

Applied Technology Council (1996), ATC-40 Seismic Evaluation and Retrofit of Concrete Buildings;, Applied Technology Council, Redwood City, CA, USA.

Cardone, D. (2014), "Displacement limits and performance displacement profiles in support of direct displacement-based seismic assessment of bridges", *Earthq. Eng. Struct. Dyn.*, **43**(8), 1239-1263.

Chopra, A.K. and Goel, R.K. (1999), "Capacity-demand-diagram methods for estimating seismic deformation of inelastic structures: SDOF systems", Pacific Earthquake Engineering Research Center; University of California Berkeley, CA, USA.

Chopra, A.K. and Goel, R.K. (2002), "A modal pushover analysis procedure for estimating seismic demands for building", *Earthq. Eng. Struct. Dyn.*, **31**(3), 561-582.

Chopra, A.K. and Goel, R.K. (2004), "A modal pushover analysis procedure to estimate seismic demands for unsymmetric-plan buildings", *Earthq. Eng. Struct. Dyn.*, **33**(8), 903-927.

Cilingir, U., Haigh, S.K., Madabhushi, S.P.G., and Zeng, X. (2011), "Seismic behaviour of anchored quay walls with dry backfill", *Geomech. Geoeng.*, **6**(3), 227-235.

Cornell, C.A. and Krawinkler, H. (2000), "Progress and challenges in seismic performance assessment", *Peer Center News*, **20**(2), 130-139.

Dolsek, M. (2010), "Development of computing environment for the seismic performance assessment of reinforced concrete frames by using simplified nonlinear models", *Bull. Earthq. Eng.*, **8**(6), 1309-1329.

Freeman, S.A. (1975), "Evaluations of existing buildings for seismic risk – A case study of Puget Sound Naval Shipyard Bremerton", Washington Proceedings of the U.S. National Conference on Earthquake Engineers, Berkeley, CA, USA.

Fajfar, P. (1999), "Capacity spectrum method based on inelastic demand spectra", *Earthq*. *Eng*. *Struct*. *Dyn*., **28**(9), 979-993.

Federal Emergency Management Agency (1997), FEMA273 NEHRP guidelines for the seismic rehabilitation of buildings; Washington D.C., USA.

Federal Emergency Management Agency (2000), FEMA356 Prestandard and Commentary for the Seismic Rehabilitation of Buildings; Washington D.C., USA.

Goel, R.K. (2010), "Simplified procedure for seismic evaluation of piles with partial-moment connection to the deck in marine oil terminals", *J*. *Struct*. *Eng*., **136**(5), 521-531.

Gu, R.R. and Miao, Z.W. (2011), "Assessment on structural performance by displacement-pattern-based capacity spectrum method", *J*. *Xi*'*an Univ*. *Architect*. *Technol*., **43**(6), 790-794. [In Chinese]

Huang, C., Ren, W.Z. and Kong, L.W. (2013), "New mathematical modelling of stabilizing pile with prestressed Tieback Anchors", *Math*. *Problem*. *Eng*., **2013**(4), 561-576.

International Navigation Association (2001), Seismic design guidelines for port structures; Tokyo, Japan.

Japan Road Association (2002), Specifications for Highway Bridges V Seismic design series; MARUZEN Co. Ltd., Tokyo, Japan.

Ji, X.P. and Dong, J. (2009), "Principle and application of pushover capacity spectrum", *Sichuan Build*. *Sci*., **35**(3), 148-151.

Kuramoto, H., Teshigawara, M., Okuzono, T., Koshika, N., Takayama, M. and Hori, T. (2000), "Predicting the earthquake response of buildings using equivalent single degree of freedom system", *Proceedings of the 12th World Conference on Earthquake Engineering*, Auckland, New Zealand, February.

Li, Y., Gong, J.X. and Wu, P. (2010a), "Research on pushover analysis method for seismic performance of pile-supported wharf structure", *Hydro-Sci*. *Eng*., **4**, 73-80. [In Chinese]

Li, X.P., He, S.M. and Wu, Y. (2010b), "Seismic displacement of slopes reinforced with piles", *J*. *Geotech*. *Geoenviron*. *Eng*., **136**(6), 880-884.

Liao, W.C. and Goel, S.C. (2014), "Performance-based seismic design of RC SMF using target drift and yield mechanism as performance criteria", *Adv*. *Struct*. *Eng*., **17**(4), 529-542.

Liu, L.J. and Jia, M.M. (2011), "Application of capacity spectrum method in structural seismic performance assessment", *Build*. *Struct*., **41**(s1), 242-244.

Liu, J.B., Liu, X.Q. and Xue, Y.L. (2009), "Study on applicability of a Pushover analysis method for seismic analysis and design of underground structures", *Eng*. *Mech*., **26**(1), 49-57. [In Chinese]

Liu, J.B., Wang, W.H. and Gautam, D. (2014), "Pushover analysis of underground structures: Method and application", *Sci*. *China Technol*. *Sci*., **57**(2), 423-437. [In Chinese]

Newmark, N.M. and Hall, W.J. (1973) , "Seismic design criteria for nuclear reactor facilities", Building Practice for Disaster Mitigation, National Bureau of Standards, U.S. Department of Commerce.

Newmark, N.M. and Hall, W.J. (1982), "Earthquake spectra and design", *Earthq*. *Eng*. *Res*. *Inst*., Berkeley, CA, USA.

Nozu, A., Ichii, K. and Sugano, T. (2004), "Seismic design of port structures", *J*. *Japan Assoc*. *Earthq*. *Eng*., **4**(3), 195-208.

Priestley, M.J.N., Calvi, G.M. and Kowalsky, M.J. (2008), "Displacement-based seismic design of structures", *Earthq*. *Spectra*, **24**(2), 555-557.

Qu, H.L. and Zhang, J.J. (2013), "Research on seismic response of anti-sliding sheet pile wall by shaking table test", *Rock Soil Mech*., **34**(3), 743-750. [In Chinese]

Qu, H.L., Zhang, J. and Zhao, J.X. (2011), "Strength reduction factor (R factor) against near-fault ground motion", *Earthq*. *Eng*. *Eng*. *Vib*., **10**(2), 195-209.

Qin, J.C. and Luo, Q.F. (2006), "ATC-40 Capacity spectrum method applied to estimate the deformation of structure", *Earthq*. *Eng*. *Eng*. *Vib*., **26**(6), 64-70.

Rathje, E.M., Wang, Y., Stafford, P.J., Antonakos, G. and Saygili, G. (2014), "Probabilistic assessment of the seismic performance of earth slopes", *Bull*. *Earthq*. *Eng*., **12**(3), 1071-1090.

Saygili, G. (2008), "Probabilistic Seismic Hazard Analysis for the Sliding Displacement of Slopes: Scalar and Vector Approaches", *J. Geotech. Geoenviron. Eng.*, **134**(6), 804-814.
Song, P.Y., Lu, D.G. and Yu, X.H. (2014), "Seismic fragility analysis based on capacity-spectrum method", *Proceeding of 23rd National Structure Engineering Academic Conference*, Wu Han, China, August. [In Chinese]
Vidic, T., Fajfar, P. and Fischinger, M. (1994), "Consistent inelastic design spectra: Strength and displacement", *Earthq. Eng. Struct. Dyn.*, **23**(5), 507-521.
Xue, Q.A. (2001), "A direct displacement-based seismic design procedure of inelastic structures", *Eng. Struct.*, **23**(11), 1453-1460.
Yang, P., Li, D., Li, Y. and Lai, M. (2000), "The progress of push-over analysis method for earthquake-resistance structures", *J. Chongqing Jianzhu Univ.*, **22**, 87-92.
Ye, L.P., Ma, Q.L. and Miao, Z.W. (2013), "Numerical and comparative study of earthquake intensity indices in seismic analysis", *Struct. Des. Tall Special Build.*, **22**(4), 362-381.
Zekri, A., Ghalandarzadeh, A., Ghasemi, P. and Aminfar, M. (2014), "Experimental study of remediation measures of anchored sheet pile quay walls using soil compaction", *Ocean Eng.*, **93**, 45-63.
Zhang, J.J., Feng, J. and Xiao, S.G. (2009), "Discussions on two key technical problems for seismic design of retaining structures", *J. Southwest Jiaotong Univ.*, **44**(3), 321-326. [In Chinese]

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