Performance-Based approach in seismic design of embedded retaining walls

Approche fondée sur la performance dans la conception sismique de murs de soutènement embarqués

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ABSTRACT
The common procedure used in the seismic design of earth retaining systems is based on a force-balance, assuming a limit equilibrium condition of the soil masses interacting with the wall. It does not provide any information on the performance of the structure if the limit values of the strengths are exceeded. In the Performance-Based Design philosophy, the response of the construction, both in terms of stresses in the structural elements and displacements in the soils should be described by predicting the performances of the system when it is subjected to the dynamic actions related to the expected earthquake motion.
The paper illustrates the damage parameters and some acceptability limit values used for the retaining walls. The application of the hierarchical strength criteria and the preferential sequence of yields are also shown. Simplified analyses and static nonlinear incremental analyses are illustrated. The latter are presented with reference to a cantilever RC diaphragm embedded in dry loose and dense sand.

RÉSUMÉ
La procédure habituelle utilisée pour la conception sismique de murs est fondé sur un équilibre de force hypotizing une limite d'équilibre des masses du sol en interaction avec la paroi. Elle ne fournit aucune information sur la performance de la structure si les valeurs limites des forces sont dépassées. Dans le Performance-Based Design philosophie, la réponse de la construction, tant en termes de contraintes dans les éléments structuraux et les déplacements dans les sols, doit être décrite par la prévision des performances du système quand il est soumis à des actions dynamique liées à la tremblement de terre.
Le document illustre les dégâts et certains paramètres de l'acceptabilité des valeurs limites pour les murs de soutènement. L'application de la hiérarchie des critères de solidité et de la séquence des rendements préférentiels sont également indiqués. Simplifié et analyses statiques et non linéaire incrémental sont illustrées. Ces dernières sont présentées en référence à un mur en béton armé réalisé en sable sèche.

Keywords : performance-based design, earth retaining walls, hierarchical strength criteria

1 INTRODUCTION

Seismic design of earth retaining systems is usually conducted by adopting a limit equilibrium approach and modeling the dynamic soil pressures as pseudostatic forces acting on the wall. The stability and the internal stresses of the structure are evaluated simply by imposing a force-balance between the active and passive thrusts explicated by the soil masses interacting with the wall and supposed in limit conditions. Many researchers have highlighted the limitations of this approach (i.e., Callisto, 2006). Furthermore, when the force-balance limit is exceeded, the method is not able to provide information on the performances of the construction.

In the following, the main concepts of the Performance-Based Design PBD philosophy and the hierarchical strength criteria are recalled and applied to the seismic design of embedded retaining walls. The damage parameters are also indicated. Finally, different type of seismic analyses characterized by increasing levels of accuracy and required information are recalled, focusing the attention to simplified and pushover analyses.

2 PERFORMANCE-BASED DESIGN METHODOLOGY AND DAMAGE CRITERIA

The Performance-Based Design, PBD, is a modern design methodology, which was born from the lessons learned from earthquakes in the 1990s (SEAOC, 1995). Its goal is to overcome some of the limitations of conventional seismic design. The construction/retrofitting cost of a structure designed not to exceed limit equilibrium for the relatively high intensity ground motions (associated with a rare seismic event) will be most likely too high. If the force-balance design is based on a more frequent seismic event, then it is difficult to estimate the seismic performance of the structure when subjected to ground motions that are greater than those used in design.

In PBD, the acceptable level of damage, i.e. the damage criteria, should be specified in engineering terms such as displacements, limit stress state and ductility/strain limit based on the function and seismic response of the structure.

Seismic performance of a sheet pile wall may be specified based on serviceability and in terms of structural damages regarding stress states as well as displacements. Examples of parameters for specifying damage criteria are those listen below (PIANC, 2001):

Displacements:

- sheet pile wall: horizontal displacements, settlements, differential displacements, tilting;
- apron: settlements, differential settlements;
- anchor: differential settlements, ground surface cracking at anchor, pull-out displacements of battered pile anchors.

Stresses:

- sheet pile wall (above and below the dredge level);
- tie-rod (including joints);
- anchor.

Damage criteria should be established by choosing and specifying appropriate parameters from those mentioned above. Quantitative indications on their acceptable values can be found in PIANC (2001), both with reasonable sequence of yields of the structural parts of the retaining system.

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3 TYPE OF ANALYSIS FOR THE SEISMIC DESIGN OF EMBEDDED RETAINING WALLS.

The objective of analysis in performance-based design is to evaluate the seismic response of the embedded retaining walls with respect to allowable limits (e.g. displacements, stress, and ductility/strain). Higher capability in analysis is generally required for a higher performance grade facility. The selected analysis methods should reflect the analytical capability required in the seismic performance evaluation.

A variety of analysis methods are available for evaluating the seismic response of retaining walls. These methods can be broadly categorized as follows:

a) *simplified analyses*: appropriate for evaluating approximate threshold limit for displacements and/or elastic response limit and an order-of-magnitude estimate for permanent displacements due to seismic loading;
b) *simplified dynamic analyses*: allow evaluating the extent of displacement/stress/ductility/strain based on failure modes;
c) *static nonlinear analyses*: able to entirely describe the response of the system for increasing levels of seismic actions;
d) *dynamic analyses*: possible evaluating of both the failure modes and the extent of displacement/stress/ductility/strain.

If a higher performance grade is request the structure should be design using more enhanced methods. Less sophisticated procedures might be allowed for preliminary design, screening purposes or response analysis for low levels of excitation.

In the following, due to lack of space, attention will be focused on methods (a) and (c) only.

3.1 *Simplified analyses.*

The Blum method is currently adopted in the engineering practice to the dimensioning of the depth of embedment of flexible walls. In the static case, the earth pressure coefficients can be evaluated according to Padfield & Mair (1984) suggestions on the soil-wall friction angles values for active ($\delta_A = 2/3\phi'$) and passive ($\delta_P = 1/2\phi'$) conditions. It seems to be reasonable the directly extend this simplified procedure for evaluating the safety conditions of a cantilever retaining wall.

In the pseudostatic analyses of a free embedded wall, the seismic actions may be represented by horizontal static forces equal to the product of the gravity forces and an equivalent horizontal seismic coefficient k_h. In absence of specific studies, k_h can be evaluated as (NTC, 2008):

$$k_h = \alpha \cdot \beta \cdot \frac{Sa_g}{g} \tag{1}$$

where $\alpha \leq 1$ and $\beta \leq 1$ account for the deformability of the soil that interacts with the wall and for the capability of the structure to accept displacements without losses of strength. S accounts for stratigraphic and topographic soil amplification.

Different opinions exist on the point of application of the forces due to dynamic earth pressures. The New Italian Building Code (NTC, 2008) states that the points of application of the seismic thrust increments can be assumed as the same of the static ones, if the wall can accept displacements. When the wall movements are constrained, instead, the seismic increments should be taken to lie at mid-height of the wall, in absence of more detailed studies.

For cantilever walls, free displacements condition can be often assumed. Then, triangular earth pressure distributions can be adopted.

The values of seismic earth pressure coefficients K_{AE} and K_{PE} can be evaluated adopting the Mononobe-Okabe and Lancellotta (2007) theories.

The moment equilibrium in seismic conditions gives the following relationships between the earth pressure coefficients and the limit depth ratio d/h of embedment:

$$\frac{d}{h} = \frac{1.2}{\sqrt[3]{K_{PE}/K_{AE}} - 1} \tag{2}$$

The maximum bending moment M_{max} can be computed by:

$$M_{max} = \frac{\gamma}{6}\left[K_{AE}(h+x)^3 - K_{PE}x^3\right] \tag{3}$$

where $x = h/\left(\sqrt{K_{PE}/K_{AE}} - 1\right)$ is the depth of the zero shear force from the dredge level.

The ratio between the depth of embedment and the height of excavation d/h and the normalized bending moment $M_{max}/\gamma h^3$ evaluated by means of the equations (2) and (3) are reported in Figures 2 and 3. These charts can be used for preliminary design of free embedded RC walls. Being the factors of safety not introduced in the analysis, the soil friction angle ϕ' should be interpreted as the design value ϕ'_d. By fixing an acceptable limit horizontal displacement for the wall, one can define the seismic demand in terms of horizontal coefficient k_h by means of (1) and pre-dimensioning the required depth of embedment and the maximum bending moment. At the same time, for an existing wall, the threshold seismic coefficient k_{crit} can be also evaluated by entering into the charts with the couple (ϕ'; d/h) in Figure 2 and (ϕ'; $M_y/\gamma h^3$) in Figure 3, where M_y is the yielding moment of the wall, and estimating the reference curves of k_h. Computing the value of β from equation (1), the maximum displacement, upon of which large movements of the retained backfill are expected, can also be determined. However, the displacements of the wall can be better estimated by using empirical relationships and charts (see for instance Richards and Elms, 1979; Whitman and Liao, 1985; Uwabe, 1983).

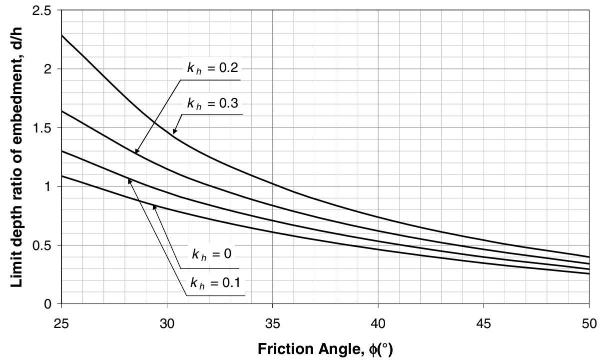

Figure 2. Limit depth ratio of embedment computed by the Blum method in seismic conditions for a free embedded wall.

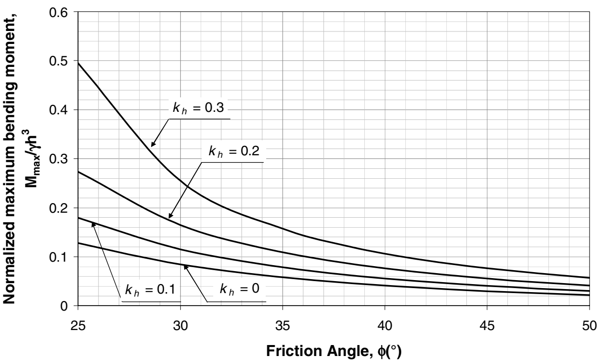

Figure 3. Normalized maximum bending moment computed by the Blum method in seismic conditions for a free embedded wall.

In the design phase of a wall, the factor of safety FS against the earthquake for rotational and structural failure modes is defined by (PIANC, 2001):

$$FS = \frac{k_{crit}}{k_h} \tag{4}$$

3.2 *Static nonlinear incremental analyses.*

A more sophisticated method for the evaluation of k_{crit} for an embedded retaining wall is based on nonlinear FEM/FDM pseudostatic analyses. The procedure can be included in the framework of the "pushover analyses" and was applied for retaining walls by Visone & Santucci de Magistris (2007).

Pushover analysis is a static nonlinear procedure in which the magnitude of the loading is incrementally increased following a certain predefined pattern. With the increase of the loading magnitude, weak links and failure modes of the structure can be found. The sequence of yields in the structure and the transition from elastic to the ultimate state response may also be identified. Static pushover analysis is a consolidated methodology in the structural engineering for evaluation of the real strength of the structures and it seems to be a useful and effective in the view of the PBD philosophy.

In geotechnical engineering, only few applications of pushover analyses can be found in the literature (e.g. Pile-supported wharves – PIANC, 2001). This is maybe due to the difficulties in recognizing the vibration modes of the geotechnical system to establish the shape of the seismic loadings.

The methodology requires the use of FE or FD simulations. To this end, the soil can be modeled by the subgrade reaction method (FE1D analysis) or as an elasto-plastic continuum.

The static conditions of the soil-wall system should be studied to take into account the nonlinearities of the soil and wall behaviours. Then, starting from the deformed configuration, the seismic loadings are applied to the structure through pressure distributions on the wall towards the excavation.

Aspects that should be considered in this analysis are:

- geometrical nonlinearities: when the system reaches the collapse the small deformations hypothesis is violated, hence, continuous updating of the configuration is needed;
- material nonlinearities: the stress-strain behaviour of the soil, the structural element, the soil-structure interface and of the other elements (anchors, props, etc.) should be represented with suitable constitutive models that implement plasticity;
- load advancement to the ultimate level: the external load should be applied incrementally in order to obtain a load-displacement relationship that permits detecting the displacements of the system when it is subjected to design actions (seismic demand).

The main results of the analysis are load-displacements curves that represent the capacity of the system to resist seismic actions (seismic capacity).

Generally, two different linear pressures distributions might be considered:

1. Triangular (TRD), with a maximum at the base of the wall, suitable for low frequencies motions, as shown for instance by Steedman & Zeng (1990). This distribution agrees with the provisions given by the Italian Building code (NTC, 2008).
2. Rectangular (RTD), following the indications of Eurocode EC8-5.

The following expressions of the seismic horizontal coefficient are associated with these pseudostatic loadings (Visone & Santucci de Magistris, 2009):

$$k_{crit} = \frac{p_{max}}{\gamma H \tan(90° - \alpha_{crit}) + 2\gamma_{RC} s} \qquad \text{TRD} \tag{5}$$

$$k_{crit} = \frac{2p_{max}}{\gamma H \tan(90° - \alpha_{crit}) + 2\gamma_{RC} s} \qquad \text{RTD} \tag{6}$$

where p_{max} is the maximum pressure applied in the loading step, H = h + d, s and γ_{RC} are the total length the thickness and the unit weight of the wall, respectively, and α_{crit} is the slope of the failure surface of the mobilized soil with respect to the horizontal direction. The adopted notations are shown in Figure 4.

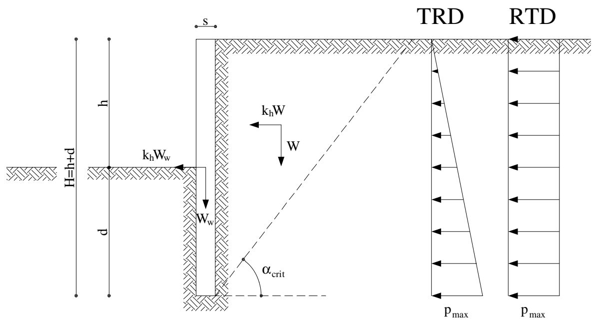

Figure 4. Seismic loadings for a pushover analysis of a free embedded wall.

For a given geometry of a retaining wall, the value of k_{crit} can be obtained by a pseudostatic numerical analysis in which, starting from the static deformed configuration after the excavation, an incremental load is applied on the structure until the failure is reached. It should be noted that the value α_{crit} depends on the seismic coefficient k_h. However, a simple trial and error procedure is sufficient to determine step by step k_h and α_{crit} (see for instance Visone, 2008).

With this approach, the seismic performance of the retaining system can be described by means of capacity curves in which its response (i.e., maximum horizontal and vertical displacement, maximum bending moment on the wall, maximum axial forces in the props or stresses in the anchors) is plotted against the increasing seismic horizontal coefficient. In this manner, the yield sequence of the various structural parts can be predicted and hierarchical strength criteria may be applied in their dimensioning.

For a design problem, after the definition of a threshold limit for the displacement, the seismic coefficient k_h can be defined by means of equation (1). Then, the expected values of the displacement can be read on the capacity curves and their acceptability can be established. On the other hand, for an existing wall, the seismic performances are completely described by the pushover curves.

Another possible strategy to evaluate the threshold seismic acceleration a_{crit} with FE or FD methods is the application of an incremental horizontal acceleration a_h (Horizontal Acceleration Incremental Procedure, HAIP)on the mesh nodes of the 2D numerical model. The a_{crit} value of the soil-wall system can be defined as the value for which the pseudostatic equilibrium is not satisfied. Visone (2008) shows the comparisons between the results of the static nonlinear analyses and complete dynamic analyses of cantilever diaphragms embedded in dry elasto-plastic layers. The obtained positive results encourage the use of this approach for the prediction of the seismic performance of retaining systems.

Examples of capacity curves for cantilever RC diaphragms embedded in dry loose and dense sandy layers are shown in Figure 5 (Visone, 2008).The analyses were conducted by using the computer code Plaxis v.8.2 (Brinkgreve, 2002). The soil was modeled as an elasto-plastic layer with Mohr-Coulomb failure criterion. The elastic moduli were increased with the depth

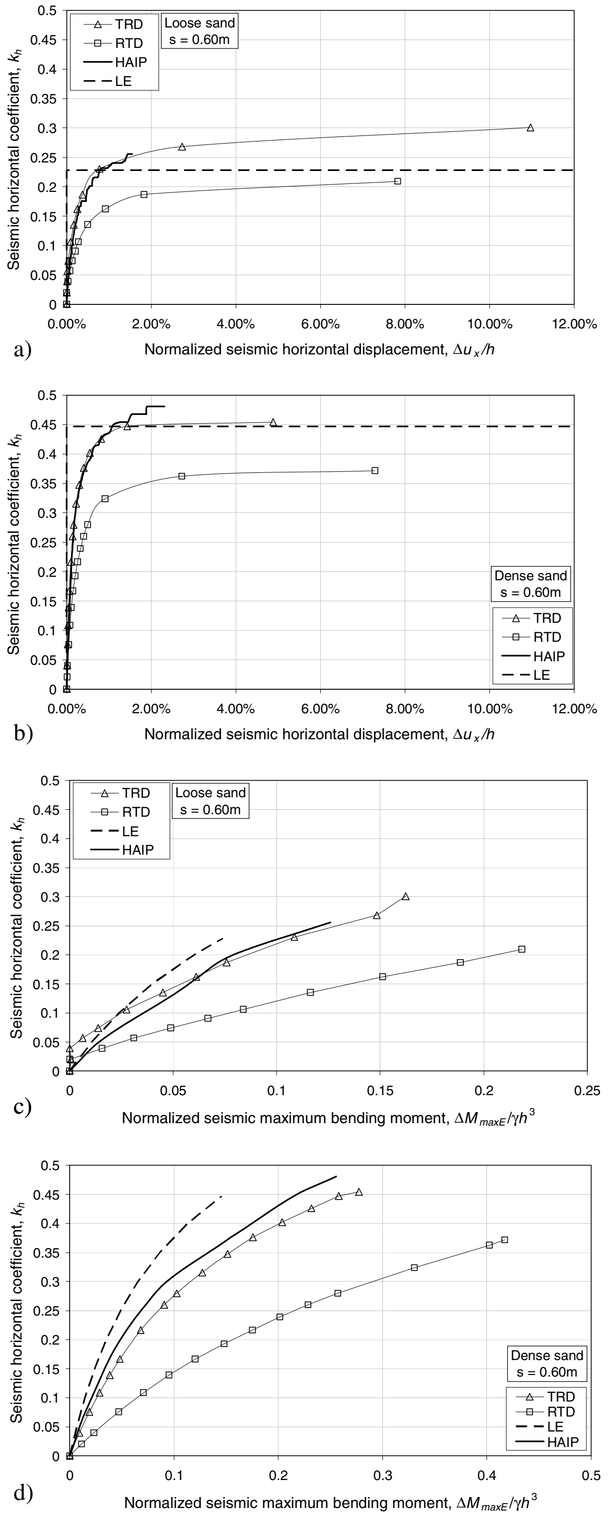

Figure 5. Examples of seismic capacity curve of a cantilever RC diaphragm embedded in dry loose (a, c) and dense (b, d) sandy layers (Visone, 2008): a) and b) maximum horizontal displacements; c) and d) maximum bending moment.

according to a power law. The cohesion was fixed equal to zero while the friction angles were assumed to be 33° and 40°, for loose and dense layers, respectively. The diaphragm was schematized as an elastic plate and the soil-wall friction was taken into account by means of an interface element characterized by a parameter $R_{int} = \tan\delta/\tan\varphi$. In the figure, the comparisons among the results of the static nonlinear analyses for the different pseudostatic loading distributions and of the limit equilibrium method, as presented in the previous section, are reported. Worth noticing the very good agreement between the TRD and the HAIP analyses. This confirms the capability of the pushover analysis for the design of this type of structure.

4 CONCLUSIONS

The limit equilibrium method commonly adopted in the seismic design of the earth retaining system is not able to provide any information on the performance of the structure if the strength limits are exceeded. In the Performance-Based Design philosophy, the performance of the construction, in terms of stresses and displacements, should be predicted when the structure is subjected to the dynamic actions related to the expected earthquake motion.

In the present paper, the importance of the definition of damage parameters and threshold values for the retaining walls is highlighted. The application of the hierarchical strength criteria and the preferential sequence of yields are also shown. Finally, after a brief review of the different seismic design methods characterized by an increasing level of accuracy, simplified and static nonlinear analyses for cantilever diaphragms are presented and the results are compared for a cantilever diaphragm embedded in dry loose and dense sandy layers. The results strongly encourage deepening the use of the pushover analyses in geotechnical earthquake engineering.

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