Structural Engineering and Mechanics, Vol. 31, No. 1 (2009) 75-91
DOI: http://dx.doi.org/10.12989/sem.2009.31.1.075

Investigation of linear and nonlinear of behaviours of reinforced concrete cantilever retaining walls according to the earthquake loads considering soil-structures interactions

Şenol Gürsoy† and Ahmet Durmuş‡

Karadeniz Technical University, Department of Civil Engineering, Gümühane, Turkey
Karadeniz Technical University, Department of Civil Engineering, Trabzon, Turkey

(Received December 6, 2006, Accepted November 28, 2008)

Abstract. It is known that retaining walls were severely damaged as well in the most recent earthquakes having occurred in the countries in the active seismic belts of the world. This damage can be ascribed to the calculation methods used for the designs of retaining walls in the event of their constructions and employment having been accurately carried out. Generally simplified pseudo-static methods are used in the analysis of retaining walls with analytical methods and soil-structure interaction are not considered. In view of these circumstances, in this article by taking soil interaction into consideration, linear and nonlinear behaviours of retaining walls are analyzed with the assistance of LUSAS which is one of the structural analysis programs. This investigations are carried out per LUSAS which employs the finite element method as to the Erzincan (1992) Earthquake North-South component and the obtained findings are compared with the ones obtained from the method suggested in Eurocode-8, which is still effective today, and Mononobe-Okabe method. Not only do the obtained results indicate the distribution and magnitude of soil pressures are depend on the filling soil but on the foundation soil as well and nonlinear effects should be considered in designs of these walls.

Keywords: retaining walls; foundation soil properties; analytical and numerical methods; linear and nonlinear behaviours.

1. Introduction

Despite the advances in geotechnical earthquake engineering, it is common to see retaining walls experiencing partial or complete failure during strong earthquakes. Effects of earthquakes on retaining walls often include large transitional and rotational displacements, buckled walls, settlement of backfill soils, and failure of structures founded on the backfill. Excessive displacement cannot only induce failure of the wall itself but may also cause damage to the structures nearby (Fig. 1). There have been numerous examples of this type of failure in recent earthquakes, reported by Durmuş such as the Erzincan earthquake of 1992 (Durmuş 1997).

† Assistant Professor, Ph.D., E-mail: sgursoy@ktu.edu.tr
‡ Professor, Ph.D. Ing.

Fig. 1 A real example of retaining wall damaged in Erzincan Earthquake

In order to design economically and safely of retaining walls as to the earthquake, it is necessary that in a realistic way after determining the soil pressure distributions to be formed in behind the wall, resultant forces corresponding to these distributions, and application points of all these stability and structured analyses should be assessed together. On the other hand, there is also a high probability being pushed to a geometrical and/or material-dependent nonlinear behaviour of the structures under the influence of dynamic loads resulting from earthquake. It is clear that nonlinear behaviours of structure members are different than their linear behaviours. For an optimum design to be conscious about the difference between these two behaviours is a strict must.

The first study in terms of determining soil pressures on account of earthquake was done by Mononobe-Okabe (Mononobe 1924, Okabe 1924). To set out the soil pressures acting on retaining walls under the influence of earthquake, today, a pseudo-static approach based on Mononobe-Okabe method has been in use. A great many of researchers later did key studies, so as to evaluate retaining walls and the convenience of this method. Some of the said studies can be summarized as follows:

- Studies concerned with determining the total (static + dynamic) soil pressure acting on the retaining walls due to the earthquake and its distribution (Seed and Whitman 1970, Steedman and Zeng 1989, 1990)
- Studies concerned with determining the shape and extent of displacement of retaining wall during an earthquake (Richard and Elms 1979, Whitman and Liao 1984)
- Studies concerned with retaining wall-soil interaction (Baker *et al.* 1990, Steedman 1999, Al Homoud and Whitman 1999)
- Studies concerned with determining the relation of the behaviour of retaining wall and total soil pressure with input motion (Zhao and Valliapan 1993, Zhao and Xu 1994)
- Experimental studies (Fujiwara *et al.* 1999, Dewoolkar *et al*. 1999, Dewoolkar *et al*. 2000)

The literature review has also indicated that there is a need for understanding the behaviour of retaining wall when it is loaded up to failure. In this paper the behaviour of retaining wall subjected to earthquake load is analyzed by using an incremental-iterative finite element procedure. The material nonlinearity of the soil medium is represented by Drucker-Prager yield criterion (Drucker and Prager 1952). With this purpose, by taking filling and foundation soil interaction into consideration as to the Erzincan (1992) Earthquake North-South component, linear and, in point of material, nonlinear behaviours of a cantilever retaining wall under the influence of earthquake are analyzed per LUSAS (LUSAS 2006a) which employs the finite element method and the obtained results are compared with the ones obtained from Mononobe-Okabe method and the method suggested in Eurocode-8 (Eurocode-8, 2003).

2. Some analytical methods used in designing retaining walls according to earthquakes

It is known that the dynamic soil pressures acting on the retaining walls in the earthquake zones due to ground motions are different from the static pressures as distribution and magnitude. It is clear that it is necessary to set out these pressures properly and exactly in order to decrease the damages to emerge on retaining walls because of these dynamic pressures due to earthquake.

The fundamental philosophy commonly approved in the design of retaining walls as to the earthquake is estimating the load likely to act on the wall due to the earthquake and ensuring the safety considering these loads. Below is emphasized on the main principles of some analytical methods used in determining dynamic pressure distribution acting on retaining walls.

2.1 Mononobe-Okabe method

The first analytical study aimed at specifying the seismic soil pressures acting on the retaining walls was carried out by Mononobe-Okabe (Okabe 1924, Mononobe and Matsuo 1929). In case the filling soil is dry and cohesionless, according to this method developed by using the Coulomb soil wedge theory, the acting seismic forces on the retaining walls are shown in Fig. 2. In addition to the forces that exist under static conditions, the wedge is also acted on by horizontal and vertical pseudostatic forces whose magnitudes are related to the mass of the wedge by the pseudostatic accelerations $a_h = C_h \cdot g$ and $a_v = C_v \cdot g$. In this method

$$K_{at} = \frac{\cos^2(\varphi - \alpha - \lambda)}{\cos\lambda \cdot \cos^2\alpha \cdot \cos(\delta + \alpha + \lambda) \cdot \left[1 + \sqrt{\dfrac{\sin(\delta + \varphi) \cdot \sin(\varphi - i - \lambda)}{\cos(\delta + \alpha + \lambda) \cdot \cos(i - \alpha)}}\right]^2} \tag{1}$$

to show the total active soil pressure coefficient, total active soil thrust is calculated as follows

$$P_{at} = \frac{1}{2} \cdot K_{at} \cdot \gamma \cdot H^2 \cdot (1 - C_v) \tag{2}$$

This active thrust is stated as ($P_{at} = P_{as} + P_{ad}$) static (P_{as}) and dynamic (P_{ad}) component. It is assumed that the application point of the total active soil thrust has a height of $h = 0.33$H from the base of the wall. In this method wall inertia and foundation soil effect on soil pressure were not considered.

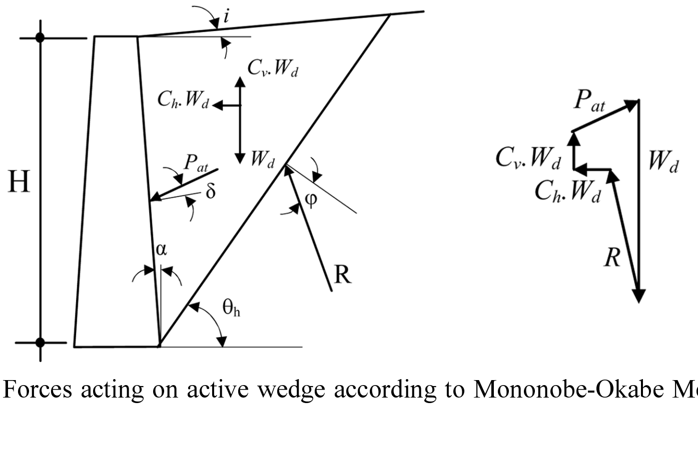


Fig. 2 Forces acting on active wedge according to Mononobe-Okabe Method

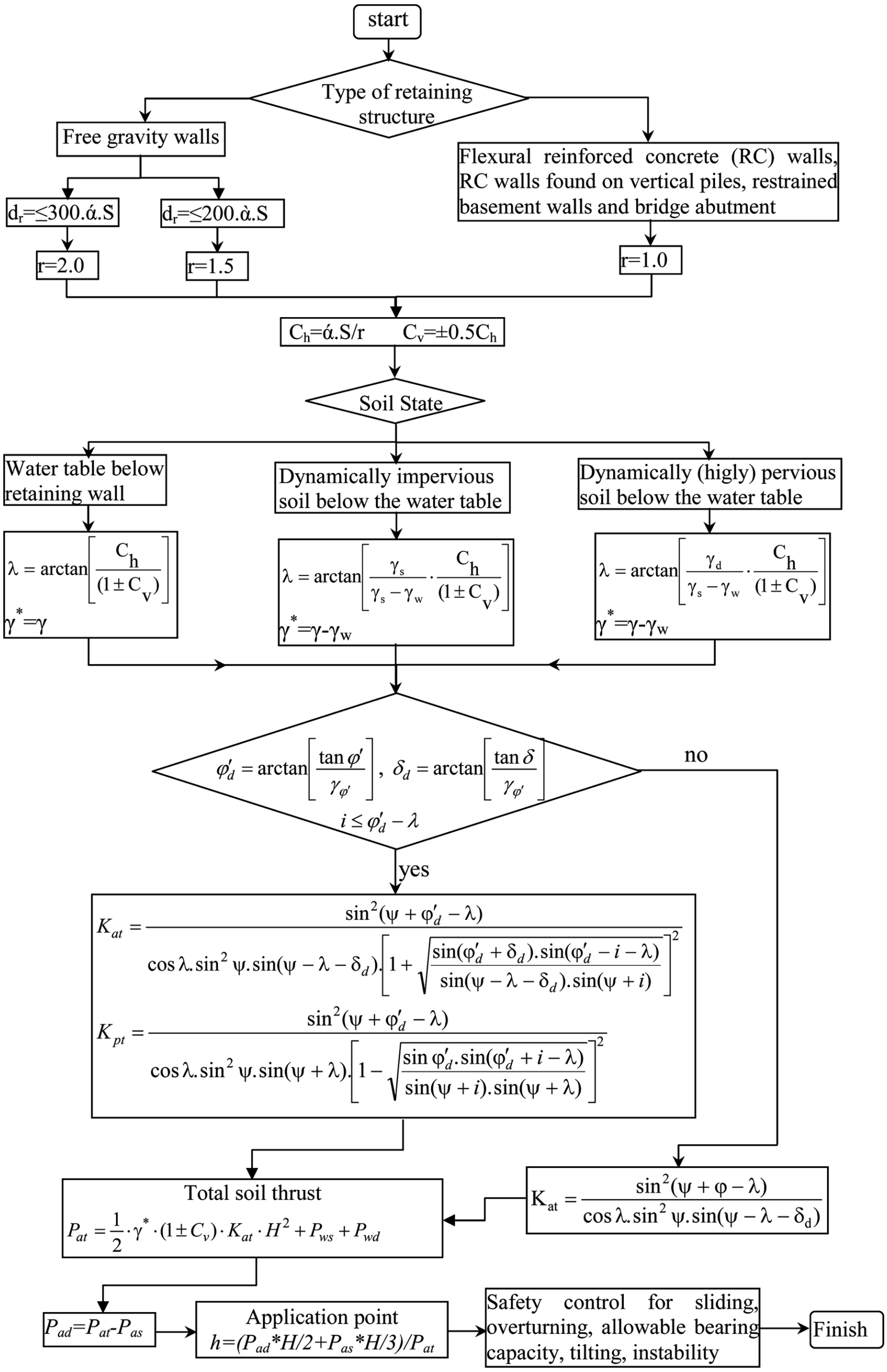


Fig. 3 The flow-chart diagram of designing of retaining walls according to Eurocode-8

Table 1 Values of factor *r* for the calculation of the horizontal seismic coefficient

Type of Retaining Structure	r
Free gravity walls that can accepted a displacement up to $dr = 300.\acute{\alpha}.S$ (mm)	2
Free gravity walls that can accepted a displacement up to $dr = 200.\acute{\alpha}.S$ (mm)	1.50
Flexural reinforced concrete walls, anchored or braced walls, reinforced concrete walls founded on vertical piles, restrained basement walls and bridge abutments	1

2.2 Eurocode-8 requirements

The principles regarding retaining walls to construct in EU countries are given in Eurocode-8. However, requirements for the reinforced concrete retaining walls (cantilever, counterfort) within this standard limited according to the gravity retaining walls. In this regulation, a pseudo-static method is proposed related to the design of retaining walls considering earthquake as well. Calculation steps for the design of earthquake-resistant retaining wall according to this method are presented in Fig. 3. The values of factor **r** in this figure are given in Table 1. The list of the program considering all provisions and suggestions in Eurocode-8 is provided in the reference (Gürsoy 2006).

3. Basic equations for the soil elements

Basic formulation for soil-structure interaction using finite element method with Langrangian approach is summarized below:

1. Soil is compressible. The used finite element is based on a formulation in which the soil strains are calculated from the linear strain-displacement equations. The only strain energy considered is associated with the compressibility of the soil.
2. Displacement field is constrained to be irrotational by introduction of a rotational stiffness.

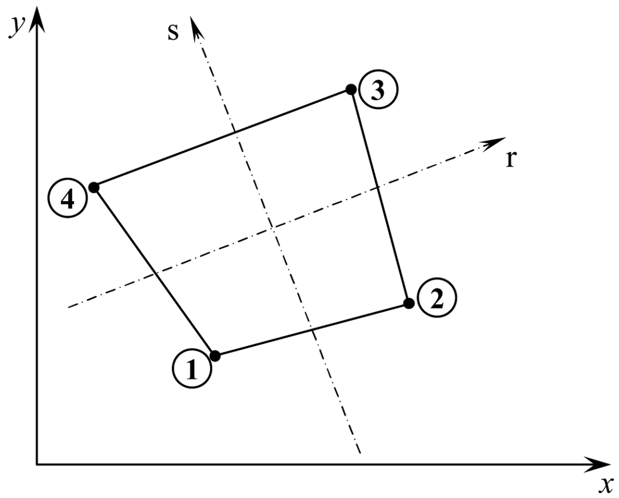


Fig. 4 Soil finite element considered

Two dimensional isoperimetric soil elements with four nodes are considered in Langragian approach. Global (x, y) and local axes (r, s) are given in Fig. 4 for this element.

Expressions for mass and rigidity matrices are given below

$$K = \int_v B^T \cdot E \cdot B \cdot dV \rightarrow K = \sum_i \sum_j \eta_i \cdot \eta_j \cdot B_{ij}^T \cdot E \cdot B_{ij} \cdot \det J_{ij} \tag{3}$$

$$M = \rho \cdot \int_v N^T \cdot N \cdot dV \rightarrow M = \rho \sum_i \sum_j \eta_i \cdot \eta_j \cdot N_{ij}^T \cdot N_{ij} \cdot \det J_{ij} \tag{4}$$

where J is the Jacobean matrix, N_{ij} is the interpolation function, η_i and η_j are weighting functions, ρ is the mass density of soil, B is the strain-displacement matrix which is obtained from $\varepsilon = B \cdot u$ expression. After the mass and rigidity matrices are obtained by Eqs. (3) and (4), total potential and kinetic energy expressions in the finite element can be written as

$$U = \frac{1}{2} \cdot u^T \cdot K \cdot u \tag{5}$$

$$T = \frac{1}{2} \cdot v^T \cdot M \cdot v \tag{6}$$

If the expressions for kinetic and potential energies are substituted into Lagrange equation, which is

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{u}_j}\right) - \frac{\partial T}{\partial u_j} + \frac{\partial U}{\partial u_j} = F_j \tag{7}$$

where u_j is the j^{th} displacement component and F_j is the applied external load, the governing equation can be written as

$$M \cdot \ddot{u} + K \cdot u = R \tag{8}$$

where $\ddot{u}$ is the acceleration and R is a general time varying load vector.

3.1 Material model used for the soil elements

It is required that stress-strains relationship of a material passing from linear zone to nonlinear zone under various loads should have failure criteria. Choosing acceptable failure criteria related to the class of material and type of loading, thence, is important in reaching to the correct result in structured analysis. For this purpose, miscellaneous criteria such as Mohr-Coulomb failure criterion, Tresca failure criterion, Von Misses failure criterion and Drucker-Prager failure criterion have been used (Fig. 5).

It is substantial that nonlinear behaviours of soils having a different characteristic in comparison to structure systems should be regarded with grave concern from the viewpoint of soil-structure interaction. The reason why the behaviour of soils is different than other materials is the increase in their sliding resistance in connection with the stress level and the difference on the behaviour under tensile stress from the one under pressure stress. Therefore, considering a failure criterion to supply the conditions of the soil is unavoidable. Hence, for soil element is generally used Drucker-Prager elasto-plastic failure criterion (Chen and Mizuno 1990). In this study nonlinear behaviour of the

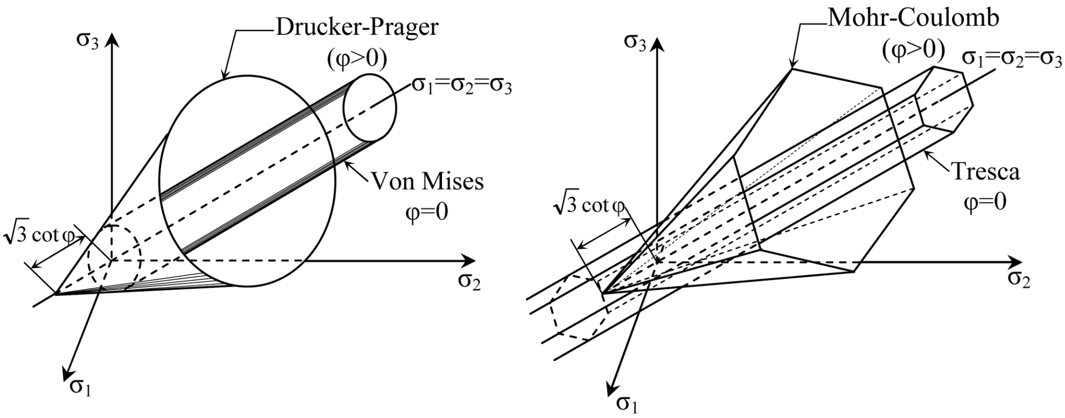


Fig. 5 Schematic failure surfaces at the principal stress space for different failure criteria

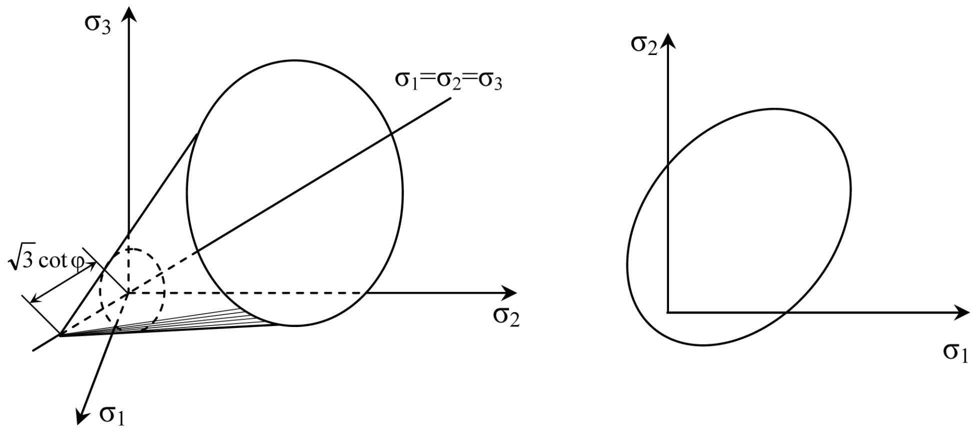


Fig. 6 Drucker-Prager schematic failure surfaces at two dimensional principal stress planes and at three dimensional principal stress spaces

filling and foundation soils are expressed with Drucker-Prager failure criterion (Fig. 6).

In this method, failure surface (f) concerning Drucker-Prager failure criterion is calculated as follows

$$f(I_1, J_2) = \mu \cdot I_1 + \sqrt{j_2} - k = 0 \tag{9}$$

where I_1 shows the first invariant of stress tensor, J_2 the second variant concerning the deviation of this tensor and and k are obtained from as follows

$$\mu = \frac{2 \cdot \sin\varphi}{\sqrt{3} \cdot (3 - \sin\varphi)} \qquad k = \frac{6 \cdot c \cdot \cos\varphi}{\sqrt{3} \cdot (3 - \sin\varphi)} \tag{10}$$

Here, it should be noted that the failure criterion appropriate for any material does not result in the same sensitivity for all materials.

4. Nonlinear incremental-iterative procedure

In the present analysis an incremental loading procedure combined with Newton-Raphson method has been used for solving the nonlinear equations involved in a plasticity analysis. In this method the load is applied in increments, but in each increment successive iterations are performed and in each iteration the stiffness matrix is updated. After each iteration, the step potion of the total loading that is not balanced is calculated and used in the next step to compute an additional increment of displacent. The solution is said to be converged in the equilibrium after a number of iterations when the restoring force equals to the applied loads (or at least to within some tolerance). The details of full Newton-Rahpson method are discussed by LUSAS (LUSAS 2006a).

5. Numerical example

In this article, the dimensions and properties of retaining wall and soil parameters considering for numerical application are shown in Fig. 7. Besides, passive thrust is neglected in the analyses and stability controls. In the example, the Young's modulus and unit weight of retaining wall are taken to be $E_c = 2.85 \times 10^7$ kN/m^2 and $\gamma_c = 25$ kN/m^3, respectively.

5.1 Structural analysis to filling soil-retaining wall interaction

The finite element mesh of this retaining wall which used in the linear and nonlinear analysis with filling soil interaction executed with LUSAS is given in Fig. 8. As can be seen from here on contact surfaces elasto-plastic joint elements (LUSAS 2006b) are used so as to take filling soil-retaining wall interaction into consideration. On the other hand, it is recognized that the length of filling soil affecting the behaviour of retaining wall is five fold of the wall height (5H), the wall is supported

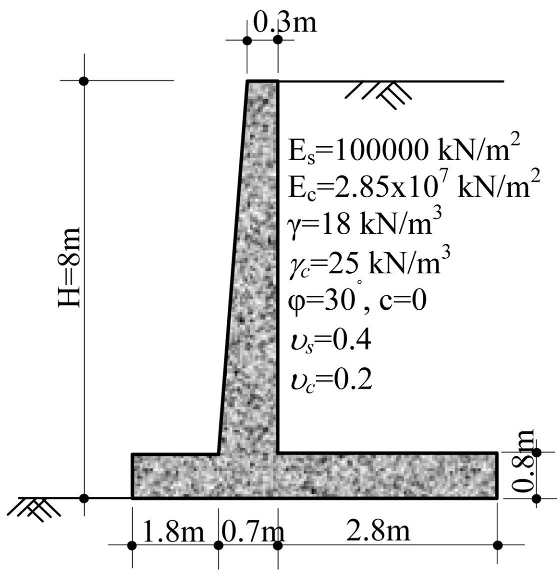
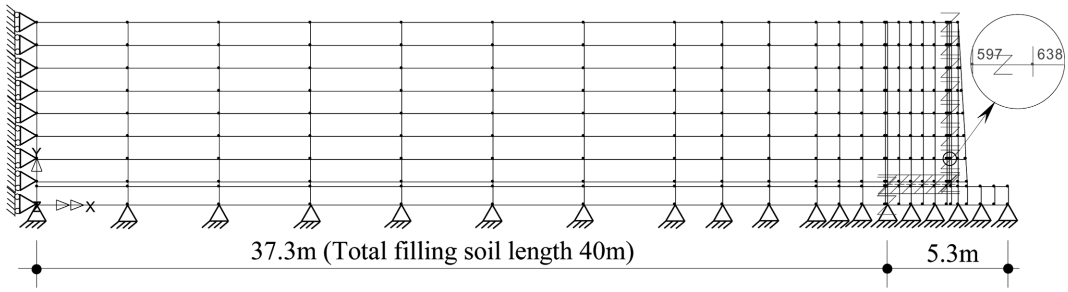


Fig. 7 Example for retaining wall and soil parameters



Model 1

Fig. 8 Finite element mesh used for two dimensional analyses to filling soil-retaining wall interaction

rigidly from the base and vertical boundaries are held in horizontal direction (Gürsoy 2006).

In this study, element dimensions are reduced not until do they have significant effect on the results of analyses, small elements are used especially for the soil models close to the retaining walls on which stress and strains are of very importance. Finite element analysis is carried out with LUSAS V15.7 (LUSAS 2006a) plane strains condition, both for the wall and the soil elements, by using four nodes quadratic quadrilateral isoparametric elements.

- **Linear analysis**

Upon this method, Rayleigh damping coefficients (Bathe 1982) required for step-by-step integration used in the solution are calculated as $\alpha_R = 0.0565$ $\beta_R = 0.04103$ for this model and time interval is considered 0.01s.

With finite element method (FEM), using the first 10s' part (Fig. 9) of the North-South component (Durmuş 1997) of the ground accelaration of the Erzincan earthquake (1992), total

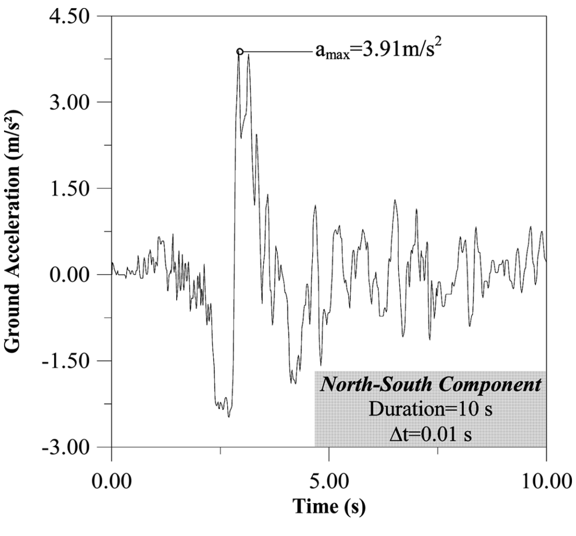


Fig. 9 Ground acceleration of North-South component of March 13, 1992 Erzincan earthquake

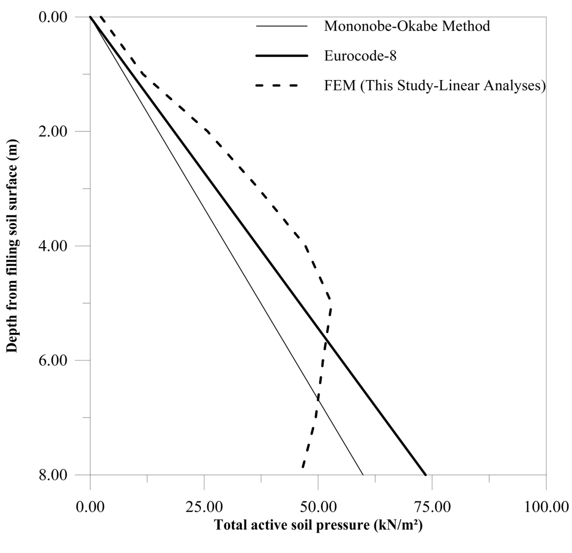


Fig. 10 Total active soil pressure distributions acting on the retaining wall due to the earthquake according to different methods

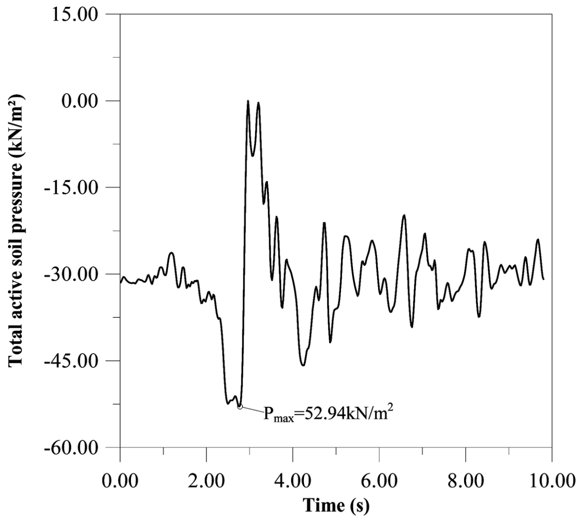


Fig. 11 Time history of total active soil pressure of the retaining wall at 638 node point in model 1

(static + dynamic) soil pressure distributions obtained by the wall depth from the linear analysis having been fulfilled in the time domain are given in Fig. 10 together with the ones calculated by the aid of Mononobe-Okabe method and the method suggested in Eurocode-8.

From this figure, total active soil pressure obtained according to the method suggested in Eurocode-8 and Mononobe-Okabe method constantly increase from the top surface of the soil to the base, total active pressure distribution calculated along the wall depth according to the finite element method is generally larger, however in the part ($z/H > 0.75$) near to the wall base it has smaller values according to the method suggested in Eurocode-8 and Mononobe-Okabe method. Also the pressures calculated with finite element method on the upper surface of the base of the retaining wall are %59 smaller than the ones calculated according to the method suggested in Eurocode-8 and %29.5 smaller than the ones of Mononobe-Okabe method.

Total soil pressure variation acting on the retaining wall which considered in this numerical example occurred throughout the earthquake process on the node point of 638 in model 1 is given in Fig. 11.

The total pressure variation seen in this Fig. belongs to the node points where stand linking elements (joint). Here one can easily infer that amplitudes of pressure increase between 2s-5s, total pressure variation occurring in the said joint is similar to the accelogram given in Fig. 9.

- **Nonlinear analysis**

For the nonlinear analysis of retaining walls taken into consideration at the numerical application, the soil components are modelled with Drucker-Prager failure criterion and the wall components are modelled by using failure parameters tensile and compression strength related to the concrete required for the current computer program.

At the nonlinear analyses carried out in the time domain according to the North-South component of the ground acceleration of Erzincan (1992) earthquake with finite element method, firstly only the nonlinear behaviour of filling soil then the nonlinear behaviour of both the filling soil and retaining wall is considered. Total soil pressure distributions obtained deeply wall are given in

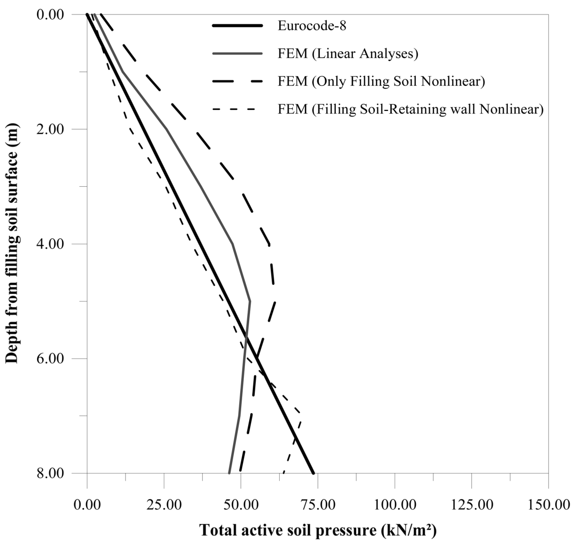


Fig. 12 Total active soil pressure distributions of the retaining wall calculated according to the method suggested in Eurocode-8 and the finite element method for linear and nonlinear analyses

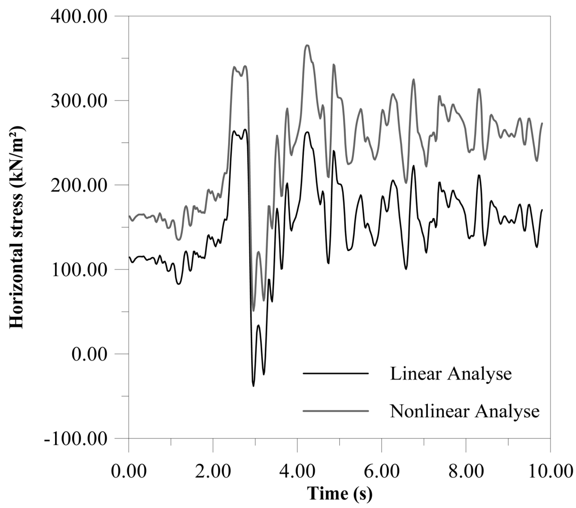


Fig. 13 Time history of normal stress at 638 node point in model 1 of the retaining wall for linear and nonlinear analyses

Fig. 12 together with linear behaviour assumption and the ones calculated with the method suggested in Eurocode-8.

As is seen from this figure, total soil pressure distribution values of retaining wall, in case only the nonlinear behaviour of the filling soil is considered, are greater than the ones obtained from linear assumption and generally greater than the ones calculated according to the method suggested in Eurocode-8. On the other hand, it is found that total soil pressure distribution obtained from the nonlinear analysis of the filling soil and the wall is generally smaller than the distributions in linear case and only in the case where the filling soil is nonlinear, and it is close to the ones calculated according to the method suggested in Eurocode-8. This situation reveals the importance of considering the nonlinear effects in the designs of retaining walls.

In linear and nonlinear cases of filling soil of this retaining wall, at the node point 638 around the wall-medium point where total active soil pressures is maximum, the time history of normal stress is given Fig. 13. As seen from this figure, variation of normal stress (σ_x) obtained throughout earthquake according to the structural solution related to nonlinear behaviour of filling soil is greater than the ones obtained according to the linear structural solution and the maximum normal stress at the said node is around 2.72s where the earthquake acceleration record is maximum, the variation of the normal stress occurring during the earthquake at this node point (638) is similar to earthquake acceleration given in Fig. 9, but their signs are opposite.

Total soil thrust and overturning moment values acting on the retaining wall under the earthquake loads as to Mononobe-Okabe, Eurocode-8 and finite element methods are given in Table 2. As can be seen from this table, the overturning moment value calculated by the nonlinear analysis carried out with finite method is greater than the ones calculated according to the others. This situation refers that this wall designed according to linear assumption with the finite element method or with

Table 2 The soil thrust, application point and overturning moments acting on the retaining wall because of earthquake according to different methods

Methods used		Total active lateral soil thrust (kN)	Overturning moment (kNm)
This Study Method (FEM)	In case Linear Analysis	-	841.211
	In case Nonlinear Analysis	-	1057.285
Eurocode-8 Method		294.16	920.64
Mononobe-Okabe Method		239.36	638.3

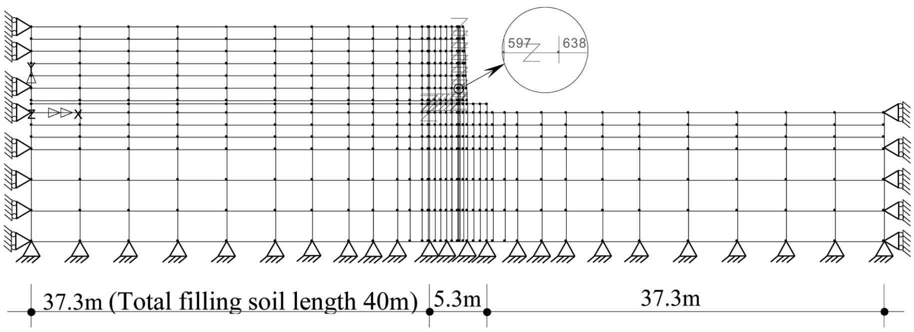
the method suggested in Eurocode-8 may remain unsafe and thus, reveals the importance of considering nonlinear effects of retaining walls according to earthquake.

5.2 Structural analysis to filling soil-foundation soil-retaining wall interaction

In structural solutions as to earthquake structures are generally supporting fixed so the ground motion occur from an earthquake doesn't effected by the structure above of it. In other words the effect on the structure behavior of soil is neglected. However, the reality is not such. Since the structure and the soil generally behave differently during the earthquake, the soil and structure affect the behaviour of each other mutually. Because soft soils expand the amplitude of earthquake waves in opposition to rock soils (Çelebi *et al.* 1987). In such soils, especially the more layer thickness increases, the more the soil dominant period increases.

Finite element mesh of this retaining wall used in the analysis carried out with LUSAS considering soil interaction as well related to properties of the foundation soil is given in Fig. 14. It is accepted that the length of the filling soil effecting the behaviour of this retaining wall is five fold (5H) of the wall height, the depth of the foundation soil is 1.5H fold of the wall height and length of the foundation soil is five fold (5H) of the wall height from each side of wall. Also vertical boundaries only make motion in vertical direction and the wall is being supported rigidly from the foundation base (Gürsoy 2006). A summary of the properties of foundation soil, retaining wall and joint elements are given in Table 3.

Rayleigh damping coefficients (Bathe 1982) required for step-by-step integration used in the



Model 2

Fig. 14 Finite element mesh used for two dimensional analyses to filling soil-foundation soil-retaining wall interaction

Table 3 Properties of retaining wall, foundation soil and joint elements

Material		E (kN/m^2)	υ	γ (kN/m³)
Retaining Wall (Concrete)		2.85×10^7	0.2	25
Foundation Soil	Loose Sand	20×10^3	0.35	19
	Medium Hard Clay	40×10^3	0.4	21
	Rock of Granite Type	77×10^6	0.1	28
Joint	Horizontal	100×10^3	-	-
	Vertical	50×10^3	-	-

solution with finite element method are calculated to be $\alpha_R = 0.0174$, $\beta_R = 0.1285$, $\alpha_R = 0.023$ $\beta_R = 0.1019$, $\alpha_R = 0.0563$, $\beta_R = 0.0411$ in case the foundation soil is loose sand, is medium hard clay and is rock of granite type, respectively. In these finite element analyses are considered with a time increment ($\Delta t = 0.01$).

Here, it is state that the abovementioned Rayleigh damping coefficients are obtained to the properties of retaining wall, filling soil and foundations soils, and in case of not taking the soil-structure interaction into consideration retaining wall is rigidly supported to the soil.

- **Linear analysis**

Total (static + dynamic) soil pressure distributions obtained along the wall depth from analyses carried out in the time domain according to the North-South component of the ground acceleration of the Erzincan earthquake (1992) with finite element method (FEM) for both cases of considering or not considering foundation soil interaction concerning three different types of foundation mentioned above are given in Fig. 15.

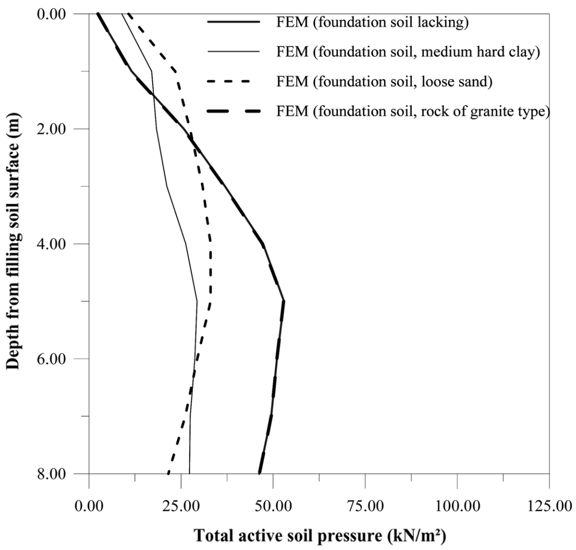


Fig. 15 Total active soil pressure distributions of the retaining wall calculated according to the finite element method for different foundation soil type

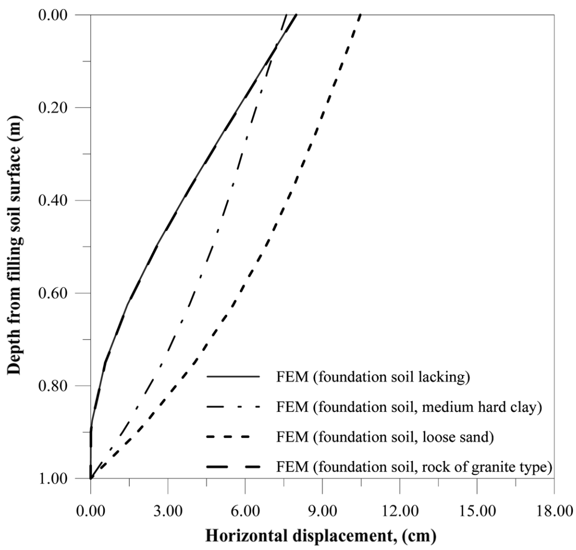


Fig. 16 Horizontal displacements of the retaining wall calculated according to the finite element method for different foundation soil type

From this figure, it is seen that in case of considering foundation soil interaction, total active soil pressure distributions calculated for three different types of the foundation soils except for soil of rock type considerably decrease. Also, particularly coincide with one in case of not being considered the foundation soil interaction of total soil pressure distribution obtained from the case where soil of rock type is used. This finding indicates the accuracy of assumptions in the analysis of selected models and reveals that type of foundation soil effect the behaviour of retaining wall.

For the cases considering or not considering the foundation soil interaction of this retaining wall, horizontal displacement distributions obtained from the analyses carried out according to model 2 are given Fig. 16.

From this figure, displacements of the wall crest node point in case of taking foundation soil interaction into consideration are greater than the one in the case the interaction is not considered. Also displacement value obtained from the case where foundation soil is rock of granite type practically coincides with displacement value in the case the interaction is not taken into account. This finding seen that in case of considering foundation soil interaction, the vibration period of the retaining wall increases and it is important for the design of walls of foundations soil type.

- **Nonlinear analysis**

In nonlinear analysis having been fulfilled as to the North-South component of the ground acceleration of the Erzincan earthquake (1992) in the time domain with finite element method (FEM), only the nonlinear behaviours of the elements of filling soil and foundation soil are taken into consideration. In case of being loose sand of the foundation soil, total soil pressure distributions obtained by the wall depth from the analyses having been fulfilled for the cases of considering or not considering foundation interaction are given in Fig. 17.

As seen from this figure, total active soil pressure distribution values obtained from the nonlinear behaviours assumption of soil are greater than the ones obtained from according to linear assumption. On the other hand, it is understood that total active soil pressure distribution obtained

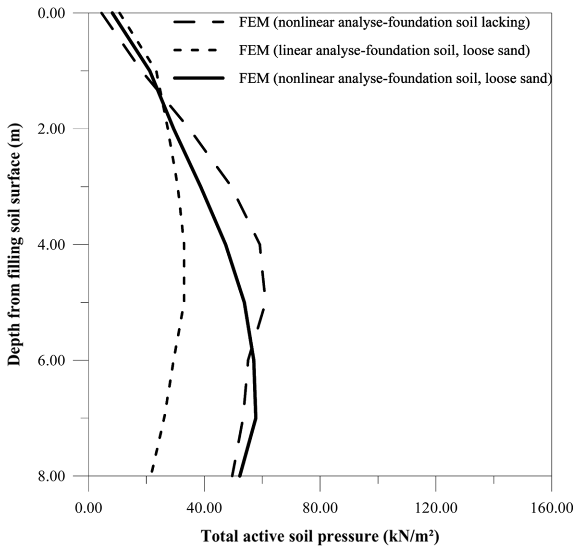


Fig. 17 Total active soil pressure distributions of the retaining wall calculated according to the finite element method for the cases considering or not considering foundation interaction

from nonlinear analysis in case where foundation soil interaction is considered is greater than the ones obtained from nonlinear analysis in case where foundation soil interaction is not considered at top and bottom of the retaining wall.

6. Conclusions

The main conclusions drawn from this study are given below:

1. Overturning moment value obtained from the nonlinear analysis with finite element method of retaining wall is greater than the ones obtained from linear analysis by this method and other analytical methods. This situation is requires to taking nonlinear behaviour consideration in designs of retaining walls.
2. The variation of during earthquake of the normal stress obtained from linear and nonlinear analyses in the time domain according to the earthquake of the retaining wall as the subject matter of our numerical application is similar to the opposite sign of variation of ground motion acceleration occurred from the earthquake. Also normal stress obtained from nonlinear analysis is greater than the ones linear analysis. In this situation, cross-section dimensions determined and the stability controls done with the findings obtained from linear analysis are not able to supply the findings obtained from the nonlinear analysis.
3. Structural solutions carried out to taken consideration to retaining wall-foundation soil interaction which except for the soil of rock type, the more the foundation soil flexibility increases the more wall crest point displacement increases but stresses is decreases and thus importance of interaction is exposes.
4. Overturning moment value obtained from linear analysis carried out in case not considered foundation soil interaction with finite element method is approximate overturning moment value obtained from the suggested method in Eurocode-8. At this, in event of suitable choosing of the element mesh, safety of the retaining wall designed with the finite element method are seen being supply of safety of designs according to suggested method in Eurocode-8.
5. Analytical and numerical researches indicate that designs based on the Mononobe-Okabe method may underestimate the magnitude of dynamic earth pressure. In addition, the non-hydrostatic pressure distribution will cause the application of the soil thrust to increase which in turn will increase the magnitude of overturning moment.
6. It is recommended that the subject on effect of retaining wall flexibility on total (static + dynamic) soil pressure should be investigated and design rules should be presented in the earthquake code.
7. Authors are suggested that, when the findings of this study is taken into account, on account of being safer of design of retaining walls to be built in the earthquake regions at the countries situated in active earthquake zone are making according to nonlinear analyses together by the filling soil-the foundation soil-the retaining wall interaction.

Acknowledgements

This work was supported by the Research Fund of Karadeniz Technical University. Project Number: 2004.112.001.01.

References

Al-Homoud, A.S. and Whitman, R.V. (1999), "Seismic analysis and design of rigid bridge abutments considering rotation and sliding incorporating non-linear soil behavior", *Soil Dyn. Earthq. Eng.*, **18**(4), 247-277.

Bakeer, R.M., Bhatia, S.K. and Ishibashi, I. (1990), "Dynamic earth pressure with various gravity wall movements", *Geotechnical Special Publication-ASCE*, n 25, New York, USA, 887-899.

Bathe, K.J. (1982), *Finite Elements Procedures in Engineering Analysis*, Prentice-Hall Englewood Cliffs, NJ.

Chen, C.P. and Mizuna, E. (1990), *Nonlinear Analysis of Soil Mechanics*, Elsevier Science Publisher, Amsterdam.

Çelebi, M., Prince, J., Dietel, C., Onate, M. and Chavez, G. (1987), "The culprit in mexico city amplifications", *Earthq. Spectra*, **3**, 315-328.

Dewoolkar, M.M., Ko, H.Y. and Pak, R.Y.S. (1999), "Centrifuge modelling of models of seismic effects on saturated earth structures", *Geotechnique*, **49**(2), 247-266.

Dewoolkar, M.M., Ko, H.Y. and Pak, R.Y.S. (2000), "Experimental developments for studying static and seismic behaviour of retaining walls with liquefiable backfills", *Soil Dyn. Earthq. Eng.*, **19**(8), 583-593.

Drucker, D.C. and Prager, W. (1952), "Soil Mechanics and Plastic Analysis of Limit Design", Quart. Applied Mathematics, **10**(2).

Durmuş, A. (1980), "Mechanics behaviour of concrete expose to biaxial compression", *2nd National Mechanics Congress*, Trabzon, Turkey, 249-261 (in Turkish).

Durmuş, A. (1997), "Reasons for being out of service for reinforced concrete structures in erzincan earthquake", *National Prof. Dr. Rfat Yarar Symposium,* Istanbul, Turkey, December, **1**, 531-544 (in Turkish).

Euroce-8 (2003), *Design Provisions for Earthquake Resistance of Structures-Part 5*: Foundations, Retaining Structures and Geotechnical Aspects.

Fujiwara, T., Horikoshi, K. and Sueoka, T. (1999), "Centrifuge modelling of dynamic earth pressure acting on gravity type wall during large earthquake", *Proceeding of the Second International Conference on Earthquake Geotechnical Engineering*, Lisboa, PORTUGAL, **1**, 401-406.

Gürsoy, Ş. (2006), *Investigation of Linear and Nonlinear of Behaviours of Reinforced Concrete Retaining Walls According to the Earthquake Loads Considering Soil-Structures Interactions*, PhD. Thesis, Black Sea Technical University (KTU), Trabzon, Turkey, (in Turkish).

LUSAS (2006a), *Lusas User and Theory Manuals*, Versions 13.7-6, FEA Ltd., Kingston upon Thames.

LUSAS (2006b), *Lusas Element Library*, Versions 13.7-6, FEA Ltd., Kingston upon Thames.

Mononobe, N. (1924), "Consideration into earthquake vibrations and vibration theories", *J. JPN Soc. Civil Eng.*, **10**(5), 1063-1094.

Mononobe, N. and Matsuo, H. (1929), "On the determination of earth pressures during earthquakes", *9th Proceeding of World Engineering Congress*, **9**, 177-185.

Okabe, S. (1924), "General theory of on earth pressures and seismic stability of retaining wall and dam", *J. JPN Soc. Civil Eng.,* **10**(5), 1277-1323.

Richard, R.J. and Elms, D. (1979), "Seismic behavior of gravity retaining walls", *J. Geotech. Eng.*, Division ASCE, **105**, 449-464.

Seed, H.B. and Whitman, R.V. (1970), "Design of earth retaining structures for dynamic loads", *ASCE Special Conf.-Lateral Stresses in the Ground and Design of Earth Retaining Structures*, Cornell, 103-147.

Steedman, R.S. and Zeng, X. (1989), *The Influence of Phase on the Calculation of Pseudo-Static Earth Pressure on the Retaining Wall,* Rpt CUED/D-soils TR222, Cambridge University, UK.

Steedman, R.S. and Zeng, X. (1990), "The seismic response of waterfront retaining walls", *Geotechnical Special Publication*, 25, ASCE, New York, USA, 872-886.

Steedman, R.S. (1999), "Seismic soil-structure interaction of rigid and flexible retaining walls", *Proceeding of The Second International Conference on Earthquake Geotechnical Engineering,* Lisboa, PORTUGAL, **3**, 949-956.

Whitman, R.V. and Liao, S. (1984), "Seismic design of gravity retaining walls", *Proc. 8th World Conference on Earthquake*.

Zhao, C. and Valliapan, S. (1993), "Dynamic analysis of a reinforced retaining walls using finite and infinite elements coupled method", *Comput. Struct.,* **47**(2), 239-244.

Zhao, C. and Xu, T.P. (1994), "Effects of backfill soils and incident wave types on seismic response of a reinforced retaining wall", *Comput. Struct.*, **53**(1), 105-117.

Notation

a_h : Horizontal acceleration
a_v : Vertical acceleration
C_h : Horizontal acceleration coefficient
C_v : Vertical acceleration coefficient
c : Soil cohesion
d_r : Displacement of retaining wall
E_c : Young's modulus of the concrete
E_f : Young's modulus of the foundation soil
E_s : Young's modulus of the filling soil
H : Height of the retaining wall
h : Application point of total active soil thrust from the wall base
i : Angle of filling soil slope
K_{as} : Static active soil pressure coefficient
K_{at} : Total active soil pressure coefficient
K_{pt} : Total passive soil pressure coefficient
P_{as} : Static active lateral soil thrust per unit length
P_{ad} : Dynamic active lateral soil thrust per unit length
P_{at} : Total active lateral soil thrust per unit length
P_{ws} : Static water force
P_{wd} : Hydrodynamic water force
r : Coefficient for design ground acceleration
S : Soil factor defined in EN 1998-1:2004
W_d : Soil wedge weight
λ : Angle of earthquake acceleration
υ_c : Poisson ratio of the retaining wall
υ_f : Poisson ratio of the foundation soil
υ_s : Poisson ratio of the filling soil
φ : Angle of soil friction
φ' : Angle of shearing resistance in terms of effective stress
ψ : Inclination angles of the back of the wall
α : Angle of the wall back surface to vertical
α' : Ratio of the design ground acceleration on type A ground, a_g, to the acceleration of gravity g
δ : Friction angle between the wall and filling soil
γ : Unit weight of filling soil
γ_c : Unit weight of retaining wall
γ_d : Dry unit weight of soil
γ_s : Saturated unit weight of soil
γ_w : Unit weight of water
γ_φ : The partial factors for material properties
θ_h : Angle of the soil wedge to horizontal