Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Some remarks on retaining wall design under seismic conditions

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ABSTRACT: The design of earth retaining walls under seismic conditions is traditionally performed by means of pseudo-static methods, as generally suggested in present seismic codes. Alternative design methods are based on the evaluation of wall displacements induced by seismic motions. In the first part of the paper, the pseudo-static and the displacement methods are briefly reviewed. They are then applied to four typical walls and to a set of accelerometric data coming from the 1980 Irpinia earthquake. It is pointed out that walls with a very low pseudo-static safety factor can behave quite satisfactorily during such an earthquake, suffering small displacements. These results indicate that the adopted pseudo-static method overestimates the earthquake effects; simple design criteria are then suggested to decrease the overconservativeness of present Italian Seismic Code.

1 INTRODUCTION

In the last decades, significant advancements have been achieved in the analysis of the behaviour of earth retaining walls under seismic conditions. However, the results obtained are not yet fully accepted and need further experimental support; as a consequence the new procedures proposed in literature seem still far from being widely applied and codified. In fact, most regional and international codes and regulations on the seismic design of earth retaining walls are still based on the simple pseudo-static methods originally developed by Okabe (1926) and Mononobe (1929).

Research has been focused in two main directions:

- improvement of classical pseudo-static analysis by taking into account a number of factors related to the earthquake and to soil-structure configuration;
- development of methods for the prediction of permanent displacement of walls caused by seismic ground motion.

More recently, elastic analyses have been attempted for soil-structure systems undergoing small displacements; these methods will not be considered in this paper.

2 METHODS OF ANALYSIS

As it is well known, the pseudo-static methods of analysis of earth retaining wall are based on static equilibrium considerations; the dynamic loads originated by the earthquake are taken into account as equivalent additional inertia forces, proportional to the mass of the soil-structure system.

After Mononobe-Okabe, the research focused on the influence of factors such as hydraulic pressure, pressure distribution on the wall, and soil cohesion.

At present, most seismic codes and regulations rely on pseudo-static analyses; the values of the seimic coefficient K_{sism} to simulate, by a static force increment, the dynamic excitation are defined, and minimum values of the pseudo-static safety factors PSF are indicated.

Nevertheless, a proper definition of the seismic coefficient presents noticeable uncertainties, and the results of the analyses are significantly affected by the chosen values. A mere use of coefficients originally proposed for the design of other engineering structures, such as building frames, appears unappropriate.

Further uncertainties are connected to the values to be adopted for the safety factor. The Italian Seismic Code does not differentiate between static and seismic conditions, while many Authors (Seed and Whitman 1990, Prakash 1981) suggest to tolerate a lower value of the safety factor during an earthquake, accounting for the short duration of the seismic loading.

The first analysis of the permanent displacement induced by an earthquake has been carried out by Newmark (1965), referring to the simple case of a rigid block sliding on a plane surface subjected to an acceleration time history. The relative movements between the plane and the block starts every time the acceleration A(t) of the plane exceeds a limit value N·g, and stops when the velocities of the plane and the block become equal again.

Methods based on the Newmark model have been subsequently developed to analyse the displacements of slopes, earth dams and earth retaining structures subjected to realistic acceleration time histories.

The first contribution dealing with retaining walls was given by Richard and Elms (1979). Having determined the wall movements for a set of accelerometric data, they defined an upper bound curve for the expected displacement D, as a function of the wall limit acceleration factor N and of the maximum values of the acceleration A_{max} and of the velocity V_{max} of the input motion:

$$D = 0.087 \frac{V_{max}^2}{A_{max} g} \left(\frac{N}{A_{max}}\right)^{-4} \qquad (1)$$

Equation (1) can be used to predict the displacement of a given wall or alternatively as a design tool. In this case, given an allowable displacement the corresponding limit acceleration factor N can be derived; the wall can be then designed as a function of N and of the geometrical and mechanical characteristics of the soil-structure system. For the sake of safety in design, the Authors advised to increase the weight of the wall by a factor 1.5.

A more comprehensive model, developed by Zarrabi (1979), takes into account the vertical accelerations induced on the soil wedge behind the wall during the seismic motion; this implies that the limit acceleration factor N varies with the ground acceleration A(t).

Wong (1982) used the model by Zarrabi in a study of the displacement induced by a wide spectrum of homogeneous seismic motions, including 14 sets of accelerograms with $A_{max} > 0.15 \cdot g$, relative to 10 earthquakes with magnitude M > 6. Wong developed a procedure for the design of retaining walls consisting in the evaluation of the expected displacement

$$D = 37 \frac{V_{max}^2}{A_{max} g} e^{-9.4(N/A_{max})} R_v R_z \qquad (2)$$

where R_v is the coefficient for the vertical ground acceleration and R_z is the coefficient for the Zarrabi model, and in the use of a correlation function between the wall limit acceleration factor N and the limit displacement D_L

$$D_L = (3 + 5N)\, 37 \frac{V_{max}^2}{A_{max} g} e^{-9.4(N/A_{max})} \qquad (3)$$

Equation (3) implies a confidence level of 95% in the design.

The relationship among A_{max}, V_{max} and D developed by Wong (equation (2)) is represented in Figure 1 as a set of iso-displacement curves for a wall characterized by a limit acceleration $N \cdot g = 0.5 \cdot A_{max}$.

In a design procedure, A_{max} and V_{max} represent the maximum expected values at the site; their determination should be based on the available accelerometric records.

In the writers opinion the displacement methods should be preferred every time a reliable set of site specific seismic data is available.

3 APPLICATION TO THE IRPINIA REGION

The comparison between the pseudo-static and the displacement methods of analysis of retaining walls will be discussed with reference to the Irpinia region in South Italy, struck by an earthquake of magnitude M = 6.9 on November 23, 1980. The region had already been classified as seismically active, but after this earthquake the classification has been updated.

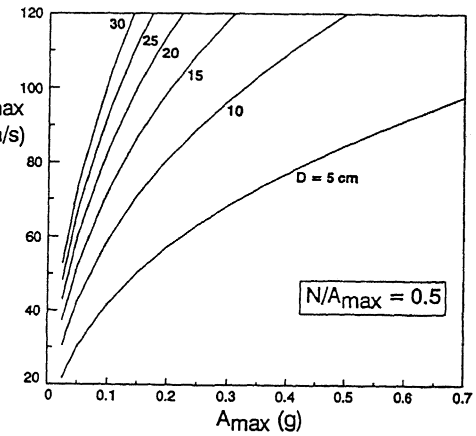


Figure 1 - Wong expected displacement curves vs. A_{max} and V_{max} ($N/A_{max} = 0.5$)

Seismic zones, seismicity levels and values of the seismic coefficients K_{sism} of the Italian Seismic Code are listed in Table 1.

During the 1980 earthquake, 15 accelerometric records were obtained at different sites of the region. Table 2 reports, for each site, the values of A_{max}, V_{max}, epicentral distance and seismic classification.

Table 1 - Italian seismic classification categories

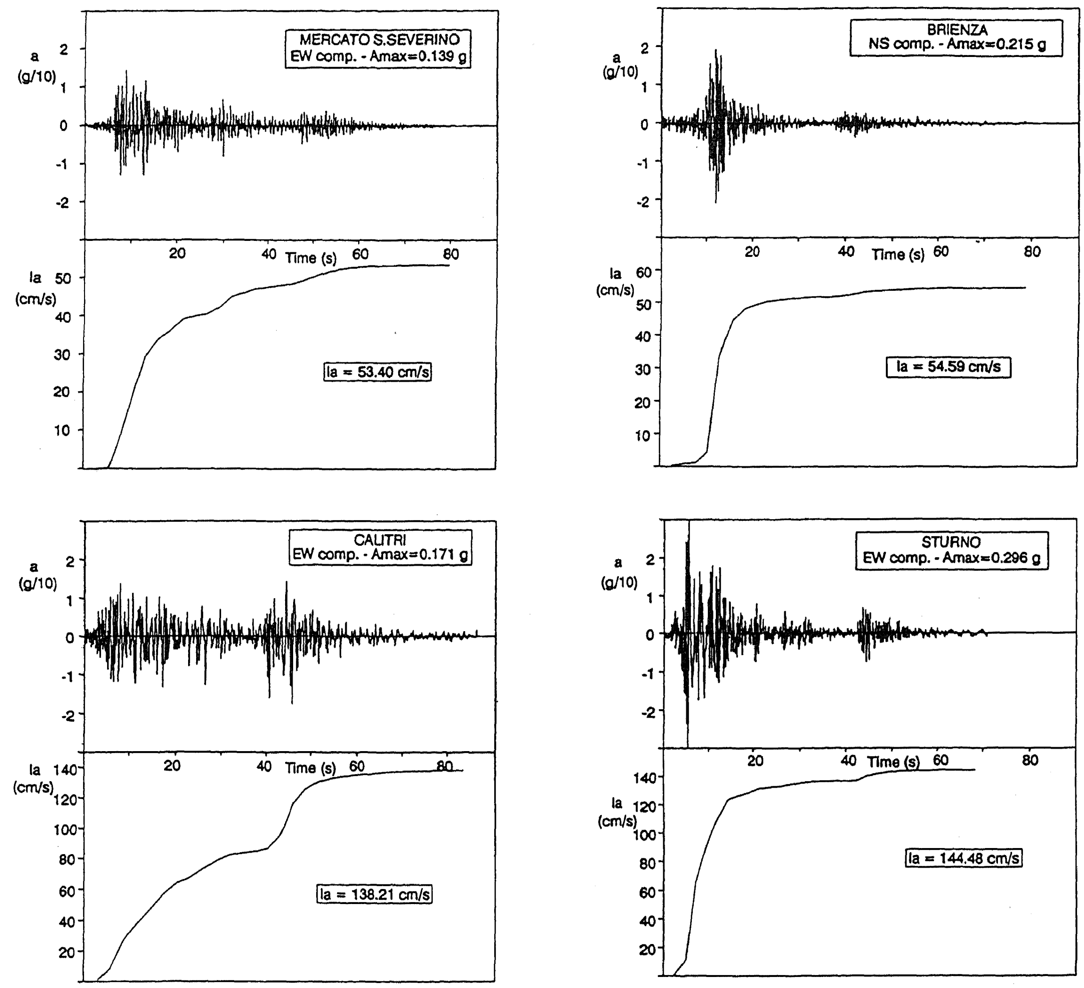
SEISMIC ZONE	S	Ksism
I	12	0.10
II	9	0.07
III	6	0.04

S : seismic level
Ksism : seismic coefficient

Table 2 - Recording sites: seismic classification and main ground motion characteristics

Id. no.	SITE	Seismic zone	Amax (g)	Vmax (cm/s)	D (Km)
1	S.Severo	II	0.025	2.3	105
2a	Vieste	II	0.036	2.4	146
2b	Arienzo	II	0.037	2.9	80
2c	Garigliano	II	0.039	8.2	138
3a	Bovino	I	0.047	3.6	58
3b	Tricarico	II	0.047	6.3	78
4	Auletta	II	0.059	5.6	31
5	Torre del Greco	II	0.061	5.4	81
6	Bisaccia	I	0.094	18.9	33
7	Rionero In Vulture	I	0.098	14.1	41
8	Mercato S.Severino	III	0.139	13.1	50
9	Calitri	II	0.171	28.4	26
10	Bagnoli Irpino	II	0.172	32.2	28
11	Brienza	II	0.215	11.2	38
12	Sturno	II	0.296	61.8	37

Id. no. : site identification number
D : distance from the focus



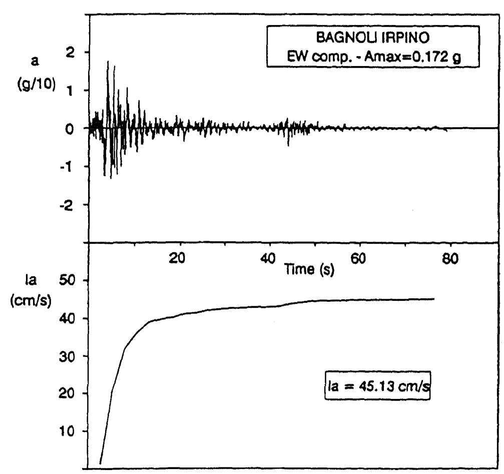


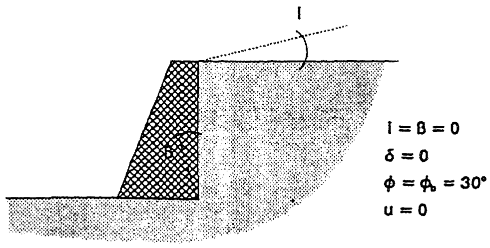
Figure 2 - Main recorded accelerograms and relative Arias intensity vs. time

All the sites belong to the II category zone, except three (Bovino, Bisaccia and Rionero in Vulture) belonging to the first one, and Mercato S.Severino which is classified in the third category seismic zone.

The highest values of A_{max}, ranging between 0.14·g and 0.30·g, have been recorded in five sites with epicentral distances smaller than 50 km. For each of these five sites the largest acceleration component and the Arias intensity I_A (Muzzi 1983) are plotted versus time in Figure 2.

It is noticed that the acceleration values recorded at Sturno are significantly higher than those at any other location; some doubts on the proper operation of the Sturno accelerometer have been raised.

Another relevant feature of the records is the exceptional duration of the ground motion, probably due to a sequence of at least two shocks occuring in succession; this is clearly evidentiated in the time



δ = wall - soil wedge friction angle

φ = soil friction angle

ϕ_b = soil - wall base friction angle

u = pore water pressure before and during dynamic excitation

Figure 3 - Soil-structure system

Table 3 - Main characteristics of the selected walls

WALL	w.w.f.	N (g)	PSF (Ksism=0.07)
A	0.958	0.146	1.3
B	0.877	0.124	1.2
C	0.716	0.070	1.0
D	0.635	0.040	0.9

histories of the accelerations and of the Arias intensity at Calitri (see Figure 2).

The dominant frequencies of the accelerograms are rather low, ranging generally between 2 and 3 Hz.

The expected permanent displacements of 4 different walls (A, B, C and D in Figure 3) have been calculated by the method of Wong (equation (2)) for the 15 accelerograms listed in Table 2.

The four walls are such that with a seismic coefficient of 0.07 (II category of seismic zone of Italian Code) they have a pseudo-static safety factor (PSF) in the range 1.3 to 0.9; the value 1.3 being the minimum required by the code against sliding of the wall.

Table 3 reports the main characteristics of the four walls, the PSF, the limit acceleration factor N, to which corresponds PSF = 1, and the wall weight factor

$$w.w.f. = \frac{W_w}{\frac{1}{2}\gamma H^2} \qquad (4)$$

where W_w is the weight of the wall, γ is the unit weight of the soil, H is the height of the wall.

The computed displacement values are reported in the upper part of Figure 4, plotted against the values of A_{max} of the input motions, whose identification numbers are reported on the same abscissa.

In the lower part of the same figure, the PSF values have been reported for the four walls calculated by assuming K_{sism} equal to the A_{max} value at each site. Obviously, when A_{max} is equal to 0.07·g the PSF values of the four walls are those relative to the II category seismic zone, listed in Table 3.

The pattern of the displacements against A_{max} in Figure 4 is somewhat irregular, due to the influence of V_{max}. As a matter of fact, the permanent displacement induced by an earthquake can not be correlated only to one or two parameters of its accelerogram; it can be shown, for instance, that the displacements can be strongly affected by the Arias intensity or by the duration of the ground motion. In the equation (2), only A_{max} and V_{max} appear explicitly, but the effects of other factors have been implicitly taken into account by Wong by considering many different waveforms scaled to A_{max} and V_{max} values.

With the exception of the Sturno site, it can be observed that 3 of the considered walls (A, B, C, with 1.3 ≥ PSF ≥ 1.0 in the II category seismic zone) exhibit displacements smaller than 5 cm, a value which is believed to be acceptable for earth retaining walls. This applies even to the sites 3, 6, and 7 belonging to the I category seismic zone.

On the contrary, an application of the Italian Seismic Code (K_{sism} from Table 1; PSF ≥ 1.3) brings to the conclusion that only wall A may be accepted, and only for the II and III category seismic zones. The differences between the displacement method and the pseudo-static analysis would be much greater if the PSF were evaluated assuming K_{sism} equal to A_{max} at each site; none of the considered walls could be accepted for most of the sites.

In conclusion, it may be stated that walls with low PSF values, and hence unacceptable according to the Italian Seismic Code, would probably have behaved

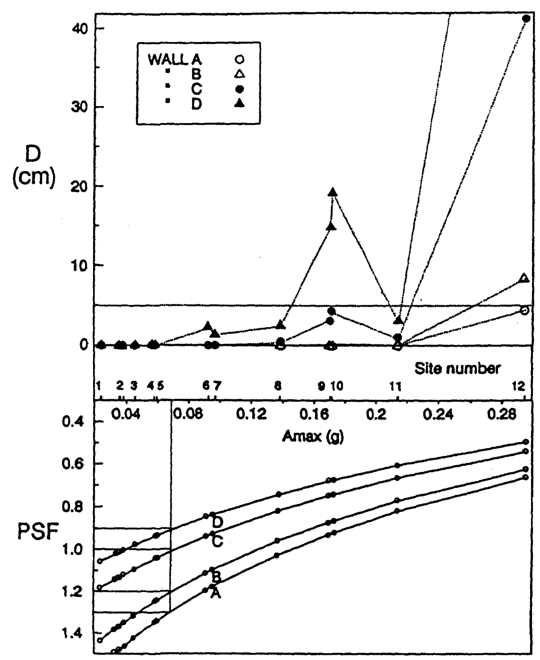
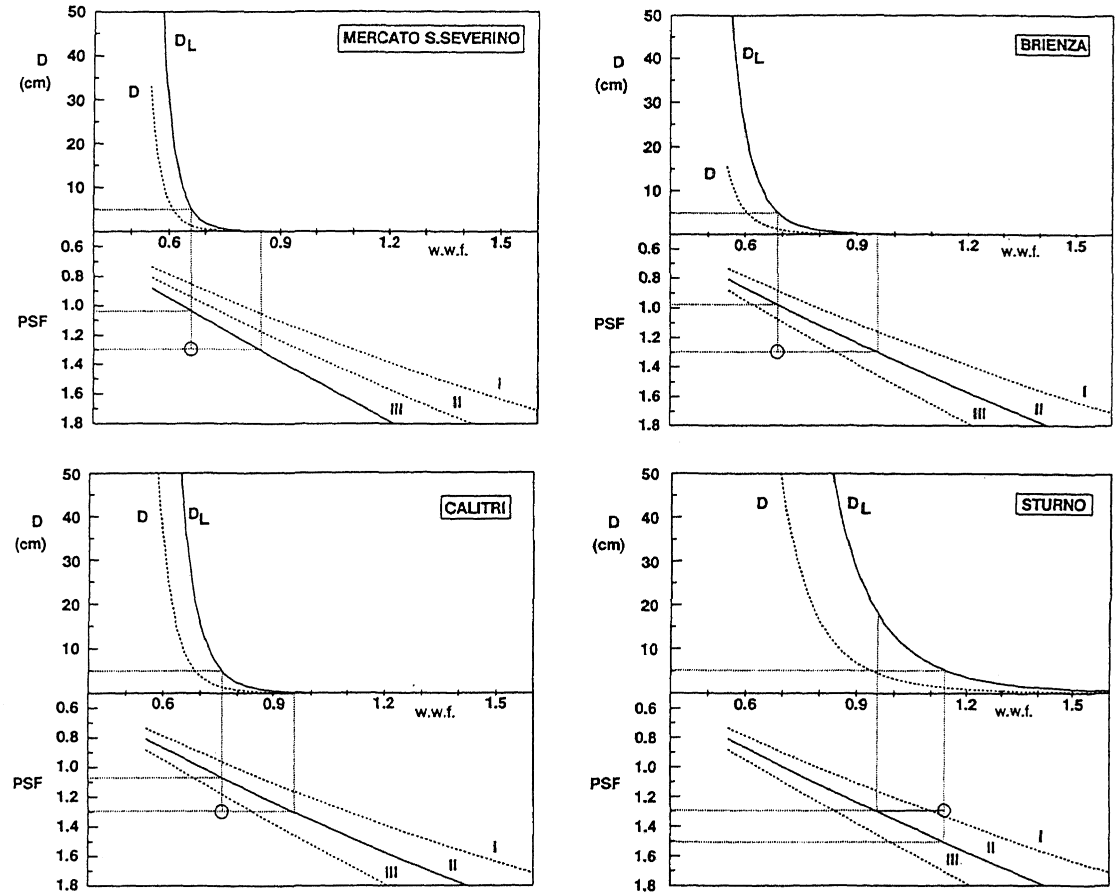


Figure 4 - Wall expected displacements and pseudostatic safety factors vs. site maximum accelerations



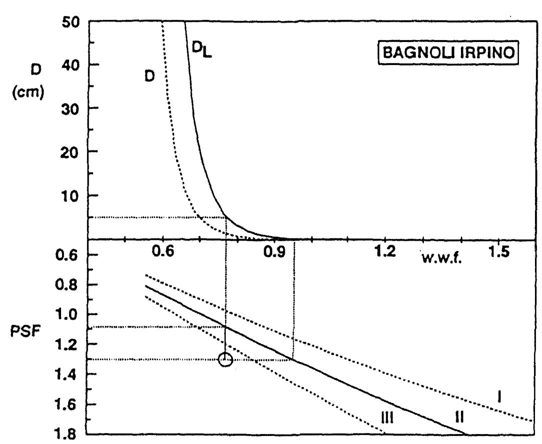


Figure 5 - Expected and limit displacements (D, D_L) and pseudo-static safety factors (PSF) for seismic categories (I, II, III) vs. wall weight factors w.w.f.

satisfactorily during the 1980 Irpinia earthquake, suffering small displacements.

4 DESIGN CRITERIA

A simple design procedure, accounting for the displacement analyses performed, but at the same time using the simpler and more familiar pseudo-static method, can be envisaged.

Assuming that the recorded values of A_{max} and V_{max} are the maximum expected values at each site, in the upper part of the diagrams in Figure 5, the expected and limit displacements calculated by the Wong method, are plotted against the wall weight factor. In the lower part of the same diagrams the values of PSF, calculated with the values of K_{sism} of the Italian Seismic Code, are reported.

The calculated displacement is larger than zero only when w.w.f. is so low that the corresponding N value is lower than the A_{max} at the site. For a further decrease of w.w.f., the displacement increases rapidly with an increasing gradient.

It can be observed that, with the only exception of Sturno, walls which would exhibit $D_L \leq 5$ cm have a PSF value (read on the proper category curve) much lower than the requested 1.3 value. Conversely, if a PSF = 1.3 is imposed, a much heavier wall, which would exhibit no displacement at all, would result.

Accordingly, the present Italian Seismic Code appears rather overconservative for the design of earth retaining walls.

A less conservative design could still be based on the classical pseudo-static approach, but either assuming a PSF < 1.3 or adopting smaller values of K_{sism}.

For instance, in the sites 9, 10 and 11 the wall design could be improved by changing the seismic classification from II to III category and mantaining the limit PSF ≥ 1.3.

Actually, the open circles in Figure 5 indicate that, in order to obtain PSF = 1.3 for the walls with D_L = 5 cm, K_{sism} < 0.04 (III category) should be adopted. Accordingly, the proposed category change would produce a more satisfactory, but still conservative design (0 ≤ D_L ≤ 5 cm).

For the site no. 8, even a III category classification appears overconservative.

On the contrary, only for the Sturno site, even the II category classification seems to be unconservative, giving rise to an expected displacement D = 4 cm and to a limit displacement of D_L = 18 cm. In this connection, however, the doubts on the representativity of this particular record are to be recalled.

As a final remark, it is underlined that the design criteria here presented are based on one set of accelerometric data, coming from just one earthquake; at present, it has to be considered as a preliminary suggestion, to be substantiated by further evidence.

In any case, a procedure based on the displacement method appears undoubtedly more rational and is to be preferred to the pseudo-static approach.

REFERENCES

Mononobe, N. 1929. Earthquake proof construction of masonry dams. *Proc. World Engineering Conference*, Vol.9

Muzzi, F. 1983. Risposta locale dei terreni durante passati terremoti. Analisi delle registrazioni accelerometriche mediante un nuovo operatore numerico. *Atti del XV Convegno Nazionale di Geotecnica*, Spoleto, Italy: 185-191

Newmark, N.M. 1965. Effect of earthquakes on dams and embankments. *Geotechnique*, 15: 139 - 159.

Okabe, S. 1926. General theory of earth pressure. *Japanese Society of Civil Engineers*, Vol.12, no.1

Prakash, S. 1981. Dynamic earth pressure and design of earth retaining structures. *Proc. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. St. Louis, Missouri, U.S.A.

Richards, R.,Jr. and Elms, D.G. 1979. Seismic behavior of gravity retaining walls. *Journal of the Geotech. Eng. Div. ASCE*, 105 (GT4): 449 - 464.

Seed, H.B., Whitman, R.V. 1970. Design of earth retaining structure for dynamic loads. *Proc. Specialty Conf. on Lateral Stresses in Ground and Design of Earth Retaining Structures, ASCE*, Cornell University, Ithaca: 103 - 147.

Wong, C.P. 1982. *Seismic analysis and an improved design procedure for gravity retaining walls*. M.S. Thesis. Dept. of Civ. Eng. MIT, Cambridge, USA.

Zarrabi-Kashani, K. 1979. *Sliding of gravity retaining walls during earthquakes considering vertical acceleration and changing inclination of failure surface*. M.S. Thesis. Dept. of Civ. Eng. MIT, Cambridge, USA .