Displacement-Based Design Criteria for Gravity Retaining Walls in Light of Recent Earthquakes

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ABSTRACT

In the last 20 years many large earthquakes have occurred giving the geotechnical community an abundance of data available for analysis. Richards and Elms (1979) developed a design method for gravity retaining walls based on finite displacements, in accordance with the Newmark (1965) sliding block analysis and the Franklin and Chang (1977) earthquake records analysis. Richards and Elms approximated an upper bound to Franklin and Chang's curves with an expression that permits a designer to choose an allowable displacement to determine the required wall weight for a particular peak ground acceleration and peak ground velocity. A preliminary investigation of digitized records from the Loma Prieta, Northridge, and Kobe earthquakes shows that the upper bound suggested by the Richards and Elms procedure significantly under predicts the displacement that would occur during these recent earthquakes. Consequently, walls designed with the suggested upper bound may be subject to excessive displacement. Comparisons are made between the Whitman and Liao (1985) method and the Richards and Elms procedure. An upper bound developed from the Northridge data results in as much as a 25% increase in the required wall weight. This paper analyzes the records of recent earthquakes and discusses the implications of raising the upper bound of the Richards and Elms limited displacement design approach. The combined consideration of recent earthquakes suggests that the normalizing parameters of peak velocity and peak acceleration (as suggested by Richards and Elms) may not be sufficient to develop an upper bound without significant scatter.

INTRODUCTION

The design of gravity type retaining walls for earthquake induced loads is commonly accomplished by using the Richards and Elms (1979) limited displacement design procedure. Gravity type retaining walls are those that derive their stability from their weight and these can include mechanically stabilized earth structures. Whitman and Liao (1985) proposed a modification to the Richards and Elms procedure to account for the uncertainty in the determination of soil properties, uncertainty in the modeling assumptions, and uncertainty in the nature of the expected ground motions. Both of these design methods are evaluated herein using data from recent earthquakes (Loma Prieta, Northridge, and Kobe) and the results and their implications upon current design practice are discussed.

CURRENT DESIGN PROCEDURES AND ANALYSIS

Mononobe/Okabe Analysis

Richards and Elms and Whitman and Liao both assume a Mononobe/Okabe (M/O) pseudo-static analysis for the determination of the active earth pressure during the earthquake. The major assumption associated with the M/O analysis is that the soil wedge behind the wall acts as a rigid body with a maximum shear stress mobilized along the sliding surface (Mononobe and Matsuo, 1929 and Okabe, 1926). The maximum interaction force between the wall and the backfill is assumed to occur when the maximum D'Alembert "inertial force" of the soil wedge is directed outwards. In other words, when the ground acceleration is at a positive maximum towards the backfill.

Newmark Sliding Block Analysis

Newmark (1965) proposed a sliding block analysis to estimate the relative displacement between a rigid body and a planar surface upon which it is resting. The rigid block and the planar surface (ground) will move together until the ground acceleration exceeds a cutoff acceleration of the block/plane interface. At this point, the block will move at the constant cutoff acceleration and the ground will continue to follow the motion of the earthquake. The difference in acceleration between the block and the ground causes a relative velocity and relative displacement. The relative displacement continues until the ground velocity and block velocity are equal, and they both move together again. The analysis is performed in the time domain as an integration of the relative velocity between the rigid block and the planar surface. The cutoff acceleration (dependent upon the sliding strength of the block/plane interface) is used to establish the threshold at which this relative sliding initiates. Richards and Elms (1979) reasoned that a gravity type retaining wall is synonymous with the sliding block and that during sliding the M/O force would be acting upon it.

Richard and Elms Design Procedure

The Richard and Elms design procedure is based upon selecting an allowable displacement and choosing a wall mass that would experience that displacement for a given peak ground velocity and peak ground acceleration. The Richards and Elms procedure was developed by creating an expression to approximate the upper bound of standardized maximum displacement charts developed by Newmark and later enhanced by Franklin and Chang. Considering a particular displacement d, their expression for the cutoff block acceleration N (from their upper bound equation), is as follows (Richards and Elms, 1979):

N = A[0.087*V^2/(A*G*d)]^.25 (1)

Where A is the peak ground acceleration and V is the peak ground velocity, in units of g and in/sec, respectively. The acceleration due to gravity G, is in units of in/sec^2. The maximum transmittable acceleration (N), also known as the cutoff acceleration, is used to estimate the earthforce that would be acting between the wall and backfill soils with the M/O equation. The wall weight is then determined from a pseudo-static sliding equilibrium analysis using the M/O force and a sliding coefficient of friction. The Richards-Elms procedure can be summarized in four steps: 1) with known values of V and A expected for the area of interest, and an allowable displacement d solve equation (1) for N; 2) determine the earth force P_{AE} by the use of the M/O analysis and taking N as the horizontal acceleration in the soil wedge; 3) solve for the required wall weight based upon a pseudo-static sliding equilibrium analysis of the wall; and 4) apply a safety factor to the estimated wall weight (Richard and Elms suggest 1.5).

Whitman and Liao Design Procedure

Whitman and Liao (1985) recognized that while the Richards and Elms procedure is relatively simple, it has large sources of uncertainty arising from the determination of the actual soil properties, from assumptions in the modeling, and from the nature of the expected ground motions. They noted that it may be too conservative under certain circumstances and they proposed alternative design equations based upon the probability of non-exceedance of a chosen allowable displacement. They proposed the following equations with a 95% and 90% probability of non-exceedance.

N = A[0.66+ln(V^2/(A*G*d))/9.4] (95%) (2a)

N = A[0.61+ln(V^2/(A*G*d))/9.4] (90%) (2b)

Additionally, they proposed that if using the Richards and Elms procedure, a safety factor of 1.1 to 1.2 on the wall weight, rather than the 1.5 suggested by Richards and Elms, should be sufficient for a probability of non-exceedance of 95%.

EVALUATION OF THE WHITMAN AND LIAO PROCEDURE

All comparative analyses performed herein use the soil properties and wall geometry of the design example employed by Richards and Elms (1979). The wall geometry is shown in Fig. 1.

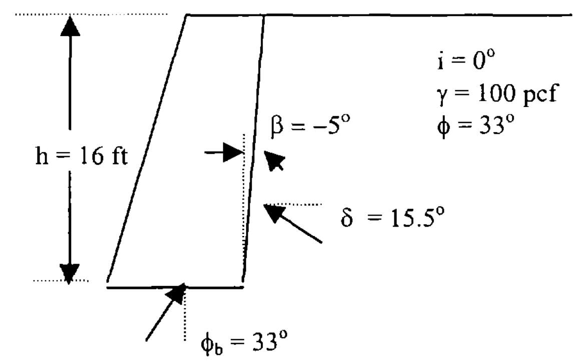

Fig. 1. The wall geometry used in the design example.

The wall has a height h of 16ft and has a wall batter β, taken from the vertical, of −5° (all angles are positive in a counter-clockwise sense). The backfill and foundation soil are dry and cohesionless with an inclination i of 0°. The soil has a dry unit weight γ equaling 100 pcf. The internal friction angle ϕ of the soil is equal to the soil/wall base friction angle ϕ_b, which equals 33°. The soil/wall interface friction angle δ is equal to 15.5°. The peak ground acceleration A and the peak ground velocity are equal to 0.2g and 6in/sec, respectively.

For this design case, both the Whitman and Liao and Richards and Elms procedures were used to calculate the required wall weight at different allowable displacements. Figure 2 shows that the Whitman and Liao procedure is less conservative than would be expected using the Richards and Elms procedure at safety factors of 1.1, 1.2, and 1.3.

Whitman and Liao (1985) state: "for walls designed by the Richards and Elms approach, with a safety factor of 1.1 to 1.2 on wall weight, there is at least 95% probability that the limiting displacement will not be exceeded." Figure 2, shows that the Richards and Elms approach, with safety factors of 1.1, 1.2, and 1.3, are all more conservative than Whitman and Liao's 95% non-exceedance line, hence it supports their statement.

However, if the maximum ground acceleration and maximum ground velocity were changed from 0.2g and 6in/sec (given for the design example) to 0.44g and 23.54in/sec, respectively, for Northridge earthquake data, this statement no longer holds. Figure 3 shows that a safety factor of at least 1.3 on wall weight for the Richards and Elms approach is required to have at least a 95% probability of non-exceedance using the Whitman and Liao equation

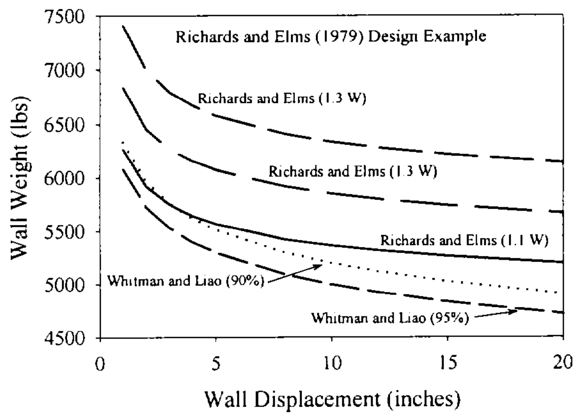

Fig. 2. Comparison of the Whitman and Liao procedure with the Richard and Elms procedure for the design example.

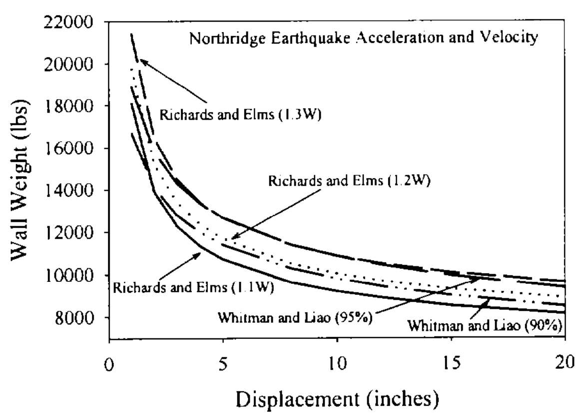

Fig. 3. Comparison of the Whitman and Liao procedure with the Richard and Elms procedure for Northridge data.

It should also be noted that the wall weight increases much more rapidly with decreasing allowable displacement from Fig. 2 to Fig. 3. Therefore, for regions in which large accelerations and velocities are expected, the required wall weight is much more sensitive to decreasing the allowable displacement for both design approaches.

EVALUATION OF THE RICHARDS AND ELMS PROCEDURE

Newmark's sliding block analysis was used to estimate relative displacements between the wall and the ground. Digitized records of Loma Prieta, Northridge, and Kobe were analyzed.

Equation (1), developed by Richards and Elms is based upon the upper bound to Franklin and Chang's curves and can be used to plot a line representing the upper bound of displacement for different input values of peak ground acceleration and peak ground velocity. Using the peak ground acceleration and peak ground velocity taken from the Northridge earthquake data as summarized in Table 1, the Richards and Elms upper bound is depicted on Fig. 4. As expected, the line plots as a straight line for different allowable displacements. For comparison, the Newmark sliding block analysis was performed on the Northridge digitized earthquake record for varying cutoff acceleration coefficients N, in order to determine the relative displacements. Figure 4 shows that the relative displacement expected for a gravity retaining wall during the Northridge earthquake using the Newmark analysis is greater than what would be expected using the upper bound Richards and Elms equation. Additionally, both Loma Prieta and Kobe earthquake records (refer to Table 1) evaluated in the manner just described plotted above the upper bound line suggested by Richards and Elms. Figures 5 and 6 show these results for the Loma Prieta and Kobe earthquakes, respectively.

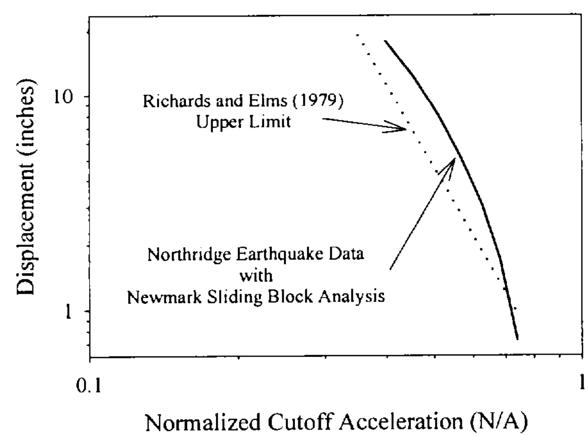

Fig. 4. Displacement versus normalized acceleration coefficient for the Northridge EQ and for the Richards and Elms Approach.

The Landers and Cape Mendocino earthquakes were also analyzed as described above, but both plotted below the upper limit suggested by the Richards and Elms approach. Hence, if a gravity type retaining wall were designed for the Loma Prieta, Northridge, and Kobe earthquakes using the peak ground acceleration and peak ground velocity from the records selected and in accordance with the Richards and Elms approach, excessive relative displacements might be expected

The Richards and Elms upper bound was modified based upon the Northridge earthquake data for comparative reasons. This new equation is not proposed as a new design equation but rather, to show the sensitivity of raising the upper bound of the Richards and Elms procedure on the required wall weight. Equation (1) was modified as follows:

$$N = A[0.12*V^2/(A*G*d)]^{.22} \quad (3)$$

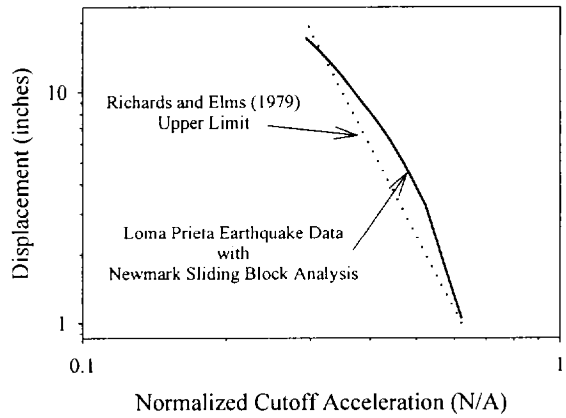

Fig. 5. Displacement versus normalized acceleration coefficient for the Loma Prieta EQ and for the Richards and Elms Approach

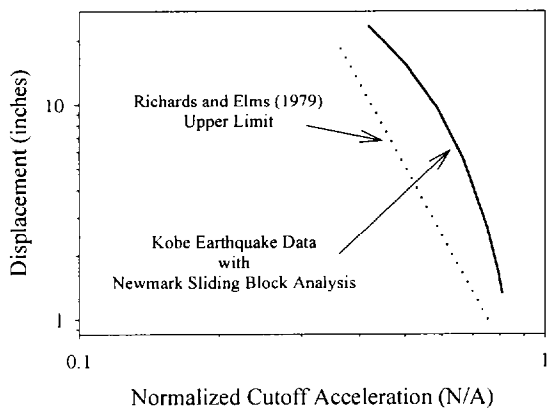

Fig. 6. Displacement versus normalized acceleration coefficient for the Kobe EQ and for the Richards and Elms Approach.

This equation was then used to plot a new upper bound as is shown in Fig. 7. It should be noted that if this equation were used for the Kobe earthquake data, it would still be unconservative. The new equation plots tangent to the Northridge data for allowable displacements between 3in and 10in.

The required wall weight was then calculated based upon Richards and Elms procedure equation and compared to what would be required with the use of the new equation. The same design example proposed by Richards and Elms (1979) was used for this comparison, except that the input peak ground acceleration and peak ground velocity were those of the Northridge earthquake time history previously identified. Figure 8 shows the increase in required wall weight using the new equation versus the Richards and Elms equation. The required weight plotted in Fig. 8 does not have a safety factor applied to it. The required weight increases from 15%-25% with the use of the new equation. As an example, for an allowable displacement of 4 inches, the Richards and Elms approach predicts a required weight of 10,288lb/ft (without a safety factor), while the new equation predicts a required weight of 12,258lb/ft. This represents an increase in required wall weight of 19%.

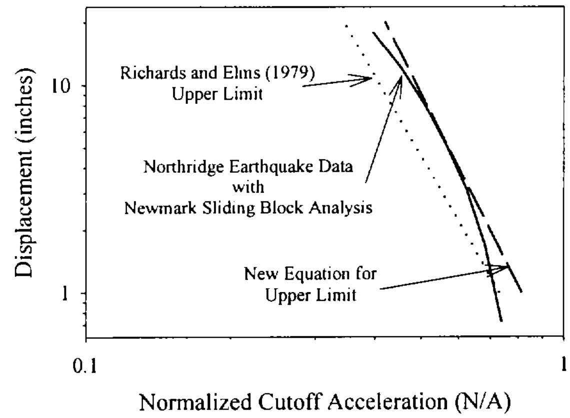

Fig. 7. Displacement versus normalized acceleration coefficient for the Northridge EQ , for the Richards and Elms Approach, and new equation.

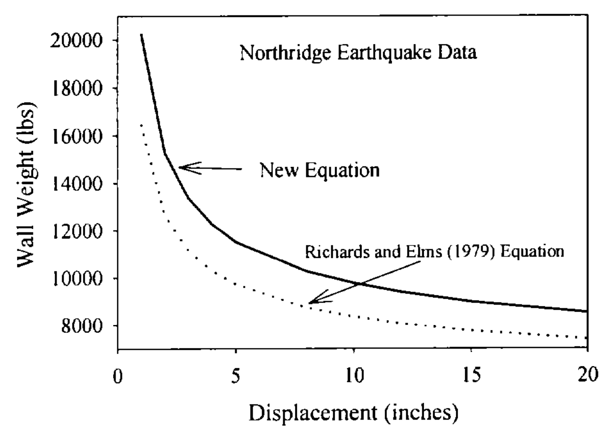

Fig. 8. Required wall weight for design example in Northridge earthquake using the Richards and Elms approach and the new equation.

OTHER POSSIBLE DESIGN PARAMETERS

The Richards and Elms procedure requires the selection of a peak ground acceleration and a peak ground velocity that would be expected over the lifetime of the structure. Other normalizing parameters may be needed to more accurately predict the amount of relative displacement. The duration of the loading may have a significant influence on the predicted displacement. The Northridge data plotted in Fig. 4 have a peak ground acceleration and peak ground velocity of 0.44g and 23.54in/sec, respectively. The duration of the digitized record was 60.21sec. As shown previously, the Northridge data plotted above what would be expected by using the Richards and Elms approach. However, the Cape Mendocino earthquake record (refer to Table 1) was also plotted and compared to the Richards and Elms approach. The Cape Mendocino record had a peak ground acceleration of 1.497g; a peak ground velocity of 50.157in/sec, but only had a duration of 30sec. Even though the peak acceleration for the Cape Mendocino record was more than 3 times as great and the peak velocity is more than double that of the Northridge earthquake data, the relative displacement for the Cape Mendocino time history plotted below what would be expected from the Richards and Elms approach.

One of the conclusions of the Franklin and Chang (1977) analysis states:

"standardized maximum displacement was found to be proportional to the duration of shaking, and consequently to be positively correlated with magnitude, but the trend is weak and with considerable scatter."

In this analysis there was considerable scatter using only peak ground acceleration and peak ground velocity as normalizing factors. Since the duration of shaking may have a significant influence on displacement, perhaps it should also be included as a normalizing parameter in future design equations.

SUMMARY AND CONCLUSIONS

With new data available from recent earthquakes, it is possible to reevaluate the state of practice in engineering design for the seismic analysis of structures. This brief analysis has indicated that more research is needed to predict the relative displacement of type gravity retaining walls under seismic conditions.

The Richards and Elms procedure using a limited displacement design approach for gravity type retaining walls in seismic conditions, is employed in common practice. In creating their method, they developed an expression that approximated the upper bound of standardized earthquakes evaluated by Newmark and Franklin and Chang. Richards and Elms suggest applying a safety factor of 1.5 to the required wall weight. Recognizing that this safety factor may be too conservative, Whitman and Liao proposed a modified method of design that takes into account the probability that the allowable displacement may be exceeded over the life of the structure. Whitman and Liao also recommended that if the Richards and Elms method is used, a smaller safety factor on the wall weight of 1.1 to 1.2 would yield a displacement that would have at least a 95% probability of non-exceedance over the life of the structure. This assumption apparently holds for small to moderate seismic environments, as was shown in Fig. 2 for the design case of A = 0.2g and V = 6in/sec. Indeed, a safety factor of 1.1 correlated well with Whitman and Liao's recommended 95% non-exceedance equation. However, for more severe seismic conditions, as what occurred during the Northridge earthquake, a more conservative safety factor of 1.3, on wall weight applied to the Richards and Elms approach, was required to correlate with a 95% non-exceedance criterion developed by Whitman and Liao.

These analyses suggest the possibility that the Richards and Elms procedure may not adequately describe a seismically loaded wall (especially in severe seismic environments). Indeed, the more recent larger earthquakes of Loma Prieta, Northridge, and Kobe all predict larger displacements, with the use of Newmark's sliding wedge analogy, than what the Richards and Elms procedure would predict.

The question might be posed why more gravity type retaining walls didn't fail during the Loma Prieta, Northridge, and Kobe earthquakes if the Richards and Elms approach does not adequately predict displacement behavior during seismic shaking. Obviously, there could be many different reasons for this, but perhaps the most influential are:

- Designers continue to apply a safety factor of 1.5 to the calculated required wall weight, which potentially overcompensates for the possible inadequacies of the Richards and Elms procedure.
- Designers generally use conservative estimates of soil properties.
- Passive resistance, which may be neglected during the design, may actually occur due to embedment effects or with the addition of a key at the wall base.
- The importance of many gravity type retaining walls to the infrastructure may be considered to be so low that larger than expected displacements have not been classified as "excessive".

The Richards and Elms equation was modified to create a new upper bound based upon the Northridge earthquake data and to determine the influence of this upper bound on the required weight. An increase of 15%-25% in wall weight was calculated for the design example.

Additional analysis has demonstrated that the normalized parameters of peak ground acceleration and peak ground velocity may not be sufficient to accurately predict displacement of gravity retaining walls under seismic conditions. Additional studies with recent earthquakes should be performed to either raise the upper bound of the Richards and Elms procedure, or develop a new procedure based upon additional normalizing parameters. A more rational selection of a safety factor for wall weight could then be obtained.

Also Whitman and Liao concluded that the use of a sliding block analysis may only be marginally appropriate for the design of gravity retaining walls. Additional physical modeling studies with realistic ground motions and models capable of fully characterizing the soil structure interaction behavior will be necessary to validate this conclusion.

EARTHQUAKE DATA

All the earthquake records used for analysis were taken from the internet web sites that are listed in the reference list. The Northridge data was taken from the University of Southern California web page, while the Loma Prieta, Kobe, and Cape Mendocino earthquake data were taken from the University of

California, Berkeley web page. Table 1 below lists the station, record, and component of each earthquake data record used.

Table 1: Earthquake Record Information

Earthquake	Station	Record	Comp
Northridge	17645 Saticoy St.	V2X0300_USC	S00E, S90E
Loma Prieta	57007 Corralitos	LOMAP	CLS000, CLS090
Kobe	0 KJMA	KOBE	KJM000, KJM090
Cape Mendocino	89005 Cape Mendocino	CAPEMEND	CPM000, CPM090

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http://peer.berkeley.edu/smcat/search.html

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