



Effect of vertical earthquake shaking on displacement of earth retaining structures

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ABSTRACT: Seismic design of large, reliable, economic retaining structures can be achieved by allowing limited displacement, provided their likely displacement performance during earthquakes is known. Design is commonly based on pseudo-static methods using horizontal peak ground accelerations, with no consideration given to vertical ground motions.

The research examined the effect of significant vertical earthquake motions on the displacement of retaining structures. Numerical time history analyses using a finite-difference program FLAC were carried out for a typical reinforced soil wall. Four earthquake records with different characteristics were used, and the results are presented.

The research showed that peak ground accelerations are a poor parameter for the prediction of wall displacements. The sum of the power spectral density, representing energy content, correlated better with the displacements calculated. Vertical shaking and the frequency content of the earthquakes had a significant effect on wall displacements. The results led to a hypothesis that vertical shaking increases the flexibility of the retaining structure, modifying its natural period, and where this shifts the period to a frequency with significant earthquake energy, resonance and larger displacements result.

The research confirmed the importance of energy, frequency content and vertical shaking of earthquakes to the displacement performance of retaining structures, particularly in near-field areas with significant vertical shaking.

1 INTRODUCTION

Earthquake design of earth retaining structures is commonly based on limit equilibrium methods with a pseudo-static approach using horizontal peak ground accelerations. Vertical ground motions are not taken into consideration. In near-field situations close to earthquake sources, there is often a potential for a significant vertical component of ground shaking, and the authors considered that the conventional designs could lead to unacceptable displacement performance of important structures in large earthquake events. Displacement based design would lead to more economical earth retaining structures, than the traditional strength based design, provided structures supported by the wall can tolerate the limited ground deformations. This requires a reliable understanding of the likely displacement performance of retaining structures, under both horizontal and vertical shaking.

Use of displacement-based design in the seismic design of Reinforced Earth walls was incorporated into the guidelines published by the Road Research Unit of the National Roads Board of New Zealand (Wood and Elms, 1990). Its use is limited to important structures in New Zealand.

Research to explore the theoretical displacement performance of retaining structures was carried out during 1999-2000 by Opus International Consultants (2000) with funding from the Research Foundation of the Earthquake Commission (EQC) of New Zealand.

2 REVIEW OF PREVIOUS RESEARCH

It is understood that a combination of horizontal and vertical ground motions led to severe damage to earth structures during the 1923 Kanto earthquake in Japan, and in 1924 Mononobe highlighted the importance of vertical ground motions for the design and performance of retaining structures. However, little attention has been given to vertical ground shaking until very recently.

Seed and Whitman (1970) considered the effect of vertical accelerations to be insignificant in the analyses of retaining walls, based on the assumption that vertical accelerations are generally small. Wolfe et al (1978) studied the effect of vertical accelerations using shaking table tests, for $\pm 0.2g$ horizontal and vertical accelerations, and concluded that the displacements were not appreciably greater than with horizontal accelerations alone, and vertical motions could be disregarded in the assessment of the displacement of walls. Elms and Richards (1979) showed that even modest vertical accelerations of up to $0.2g$ have an important effect on the earthquake forces on the wall, but the effects of the vertical accelerations were relatively minor when the horizontal accelerations were less than $0.2g$. However, they did not consider the effect of vertical shaking in their method for assessment of the displacement of walls. Elms and Richards (1990) considered that the effect of vertical accelerations on wall displacement would be negligible as they considered that there would be little correlation between the vertical and horizontal components of shaking, and the effects of upward and downward vertical accelerations would cancel each other.

Siddharthan et al (1992) found that vertical accelerations can have a significant effect on the displacement of gravity walls, considering both sliding and tilting. Siddharthan et al (1991) assessed likely displacements using records from five earthquakes, considering both vertical and horizontal accelerations. They found that the displacements varied considerably even though the horizontal accelerations were all scaled to $0.3g$, and attributed this to the frequency content of the records. But, this could also be due to different levels of concurrency between vertical and horizontal motions.

Cai and Bathurst (1996) assessed modular block faced geosynthetic-reinforced soil retaining walls and showed that high vertical accelerations would give a lower critical horizontal acceleration, which would imply a larger displacement. Ling and Leshchinsky (1998) used pseudo-static limit equilibrium analyses to carry out a parametric study and suggested that vertical accelerations would be significant where the horizontal acceleration is greater than $0.2g$. They also presented a case study of a 6 m high geosynthetic-reinforced wall that displaced 100 mm at the base during the 1995 Hyogoken-Nanbu earthquake, and attributed the displacement to the vertical ground shaking recorded in the area.

3 REASON FOR RESEARCH

It has been observed in recent earthquakes that the vertical and horizontal components of shaking can be large, particularly in near-field situations close to earthquake sources. It was recognised that intuitively vertical ground motions can have an important effect of retaining wall performance, where the resistance to displacement is derived from gravity loads, particularly in the near-field, where there is a higher likelihood of coincidence between vertical and horizontal motions. Recent research has indicated that vertical shaking can indeed have an important effect on retaining wall performance.

In high seismicity areas, it is difficult and uneconomic to design retaining structures to withstand the full earthquake loads derived from pseudo-static approaches using peak ground accelerations assessed from seismicity studies. Displacement performance based design allowing for limited displacement is a very important aspect in the practical design of retaining structures. This research studied the displacement of retaining structures, considering vertical and horizontal earthquake shaking.

4 MODEL ANALYSES

4.1 Numerical Modelling

Numerical modelling was chosen for this study as this would be independent of the previous analytical research, and would enable better representation of the soil and earthquake shaking characteristics.

The finite difference program, FLAC (Fast Lagrangian Analyses of Continua) was chosen because of its capability to accommodate large displacements, its successful use by other researchers for assessing earthquake behaviour of reinforced soil retaining walls and its availability and familiarity. FLAC is a two-dimensional explicit finite difference code, which simulates the behaviour of structures built of materials that may undergo plastic flow when their yield limit is reached (Itasca Consulting Group, 1993). Version 3.23 of FLAC was used with the associated dynamic analysis module.

The model used consisted of a 7.5 m high reinforced earth wall with 7.5 m long steel strips as shown in Figure 1. To overcome difficulties experienced during modelling due to different lateral boundary heights, a slope was modelled well away from the front face of the wall. The model was built in stages to represent the construction sequence. Gravel backfill and a dense gravel foundation were modelled to minimise foundation deformations, so that the wall displacement could be studied.

A reinforced earth retaining wall was chosen because the reinforced earth block will displace mainly by sliding (no tilting), and its common use in New Zealand, where walls of significant heights (greater than 3 m) are required to support important structures.

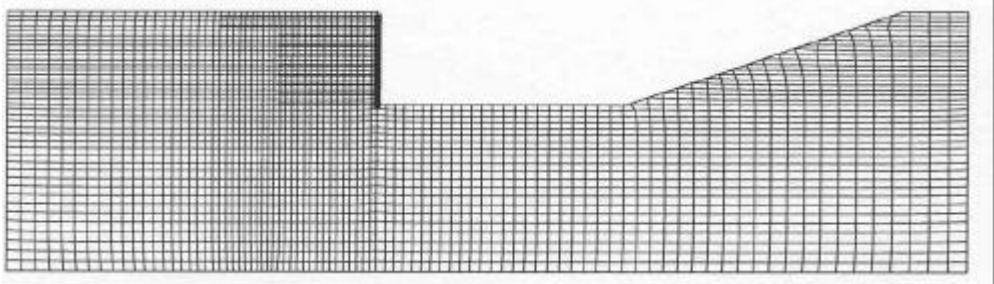


Figure 1 – FLAC Model of Reinforced Earth Wall

FLAC’s implementation of free field and quiet (viscous) boundaries was used for the lateral boundaries to simulate unlimited lateral extent, and to avoid reflection of outward radiating waves from the model boundaries. A non-reflecting quiet boundary was used for the base of the model.

4.2 Earthquake inputs

Earthquake time histories with significant peak vertical and horizontal accelerations were chosen from records within 20 km of the epicentre of earthquakes with a magnitude greater than 6.5. The characteristics of the four Californian earthquake records chosen are presented in Table 1.

Table 1. Characteristics of earthquake records

Earthquake Record	Magnitude	Hypocentral Distance	Peak Acceleration	
			Component	PGA (g)
Landers, Jun 28, 1992 at Joshua Tree Fire Station	$M_S = 7.5$ $M_W = 7.4$	9 km	90 Deg	0.28
			0 Deg	0.27
			Up	0.18
Big Bear, Jun 28, 1992 at Big Bear Lake – Civic Center Grounds	$M_L = 6.6$	7 km	270 Deg	0.48
			360 Deg	0.54
			Up	0.19
Northridge, Jan 17 1994 at Castaic Old Ridge Route	$M_L = 6.6$ $M_W = 6.7$	18 km	360 Deg	0.51
			90 Deg	0.56
			Up	0.22
Loma Prieta, Oct 17, 1989 at Corralitos Eureka Canyon Rd, Santa Cruz Mtns	$M_L = 7.0$ $M_S = 7.1$	18 km	90 Deg	0.48
			0 Deg	0.63
			Up	0.44

The records were baseline corrected for use in the analyses (that is, the displacement, velocity and acceleration were adjusted using long period sine waves so that they are zero at the start and end of the record). Their amplitudes were scaled to produce peak accelerations at the wall foundation level that were close to those recorded in the field (that is to overcome the attenuation of the shaking applied at the base of the model as it passes through the foundation layers of the model). Because the Landers Earthquake record had relatively smaller horizontal accelerations, the horizontal and vertical time histories were scaled to obtain peak horizontal accelerations of about 0.55g, comparable in size to the other earthquakes.

Scaling was also used to derive synthetic earthquake records with the same frequency characteristics as the original records but with different amplitudes (and hence energy content) of vertical and horizontal shaking.

Two groups of earthquake shaking were used in the numerical analyses. Group I had accelerations and also energy inputs similar to the earthquake records. Group II earthquake inputs were obtained by scaling the Group I records to have larger horizontal and vertical accelerations and also have larger energy contents. The Group II records are consistent with earthquake shaking (magnitudes and maximum peak ground accelerations) reported from earthquakes, although suitable earthquake time histories could not be readily sourced for this study.

The following earthquake load combinations were used in the numerical analyses, for each group :

- horizontal earthquake record only
- horizontal and vertical earthquake records
- horizontal and scaled ($\frac{1}{2}$ and 2 times earthquake record) vertical earthquake records.

The vertical records were scaled by a factor of up to 2 to enable comparison of the effect of different levels of vertical shaking on the displacement of walls.

4.3 Analyses

The model was analysed by running FLAC with the earthquake input at the base of the model. Displacements were measured at various points in the model during the analyses, particularly at the top, middle and bottom of the wall face. The net displacements were calculated as the difference between the displacements recorded at selected points and the displacement recorded at a node within the foundation well below the wall base. The earthquake parameters used in the assessment were derived from accelerations recorded at the base of the wall during the numerical analyses.

4.4 Results

Pull-out of the upper strips was observed and affected the results of the displacement at the top of the wall. The pull out is considered to be due to the lack of confining stress at the top of the wall. In practice, the upper strips are bent down to a lower level to attract a higher confinement stress, but this complication was avoided in the numerical model. To minimise the pull-out of the strips at the top of the wall, longer strips were instead modelled as shown in Figure 1.

The displacements of the lower wall under all combinations of horizontal and vertical motions were :

- less than 25 mm in the Group I earthquake analyses,
- less than 200 mm in the Group II earthquake analyses.

The maximum displacement of the lower half of the wall was only 23 mm when only horizontal shaking was applied for both Group I and Group II earthquakes. This illustrates the important effect of vertical earthquake motions.

The limited displacements of the wall modelled are consistent with the well-designed wall with an aspect ratio (strip length to height) of one, and the design for a peak ground acceleration of 0.42g.

5 APPRAISAL OF THE RESULTS

5.1 Energy and Frequency Content

The power spectral density (PSD) of an earthquake record is a representation of the energy against frequency in an earthquake. It is calculated from the square of the Fourier amplitude spectrum. The power spectral density for the input motions at the base of the walls was calculated to represent the frequency and power content of the earthquake inputs, and is presented in Figure 2. By summing the power in all frequency bins of the earthquake record for each component, a representation of the total energy content of the component was obtained.

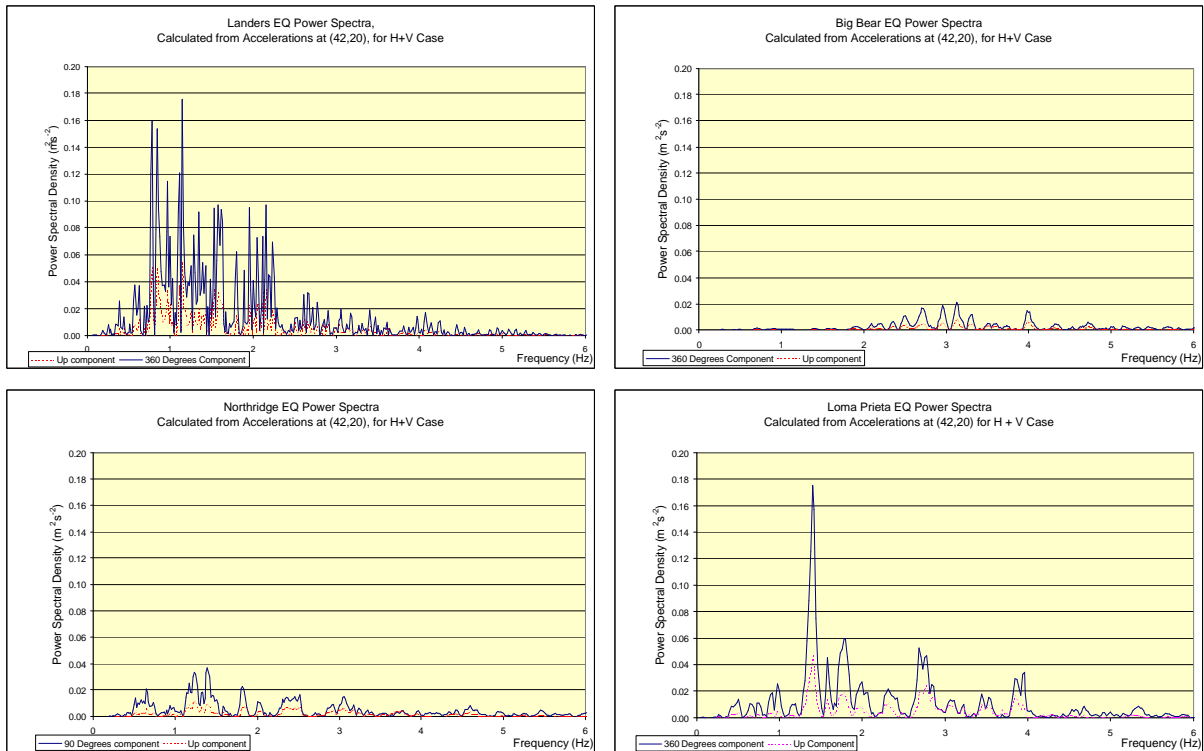


Figure 2. Power Spectral Density – Frequency for Input Motions

5.2 Horizontal shaking alone

The displacements for the top of the wall from the model analyses with the application of horizontal motions alone are shown on Figure 3.

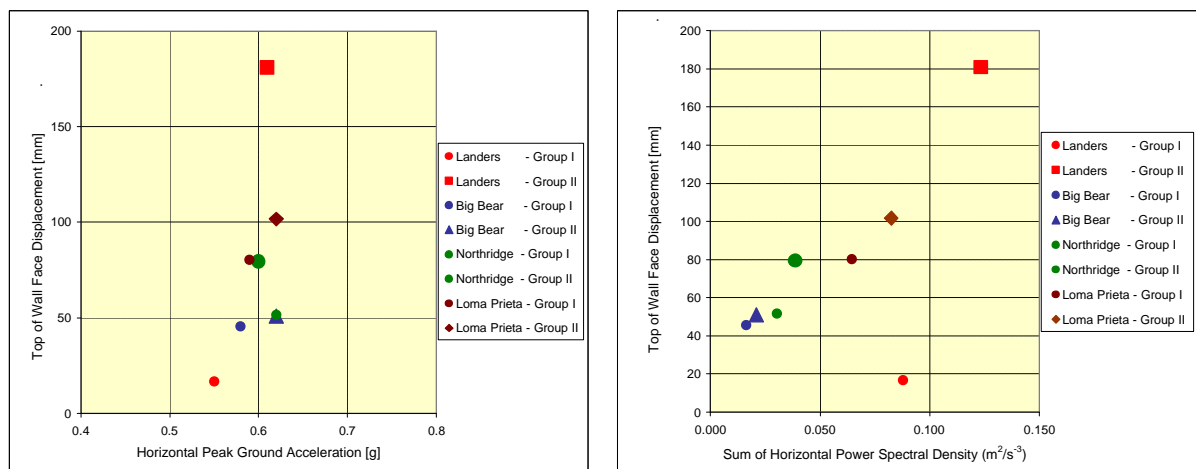


Figure 3. Wall displacement v Peak horizontal acceleration and Sum of power spectral density

The figure illustrates how the displacements can vary significantly for earthquakes with a similar peak horizontal acceleration of 0.55g to 0.62g, which suggests that the peak horizontal acceleration is a poor parameter for use in assessing wall displacements. It can be seen from the other chart presented on Figure 3 that the displacements are larger for earthquakes with higher sums of the power spectral density, a measure of the energy content of the earthquake. The sum of the power spectral density may therefore be a better parameter for use in the assessment of wall displacements.

5.3 Horizontal and vertical shaking

The results of the analyses using simultaneous horizontal and vertical motion inputs are presented in terms of displacement ratio. The displacement ratio (DR) is the ratio of displacement with vertical and horizontal shaking to that with horizontal shaking alone.

$$DR = \frac{\text{Displacement of the Wall with Vertical and Horizontal Accelerations}}{\text{Displacement of the Wall with Horizontal Acceleration Only}}$$

For the inputs associated with each of the earthquake records, the application of vertical motions leads to larger displacements than with horizontal motions alone, and for increasing vertical motions (zero, half, one and twice the actual vertical record) the displacements also increase, see Figure 4. The larger the sum of the horizontal PSD, the larger the displacements when vertical shaking is applied.

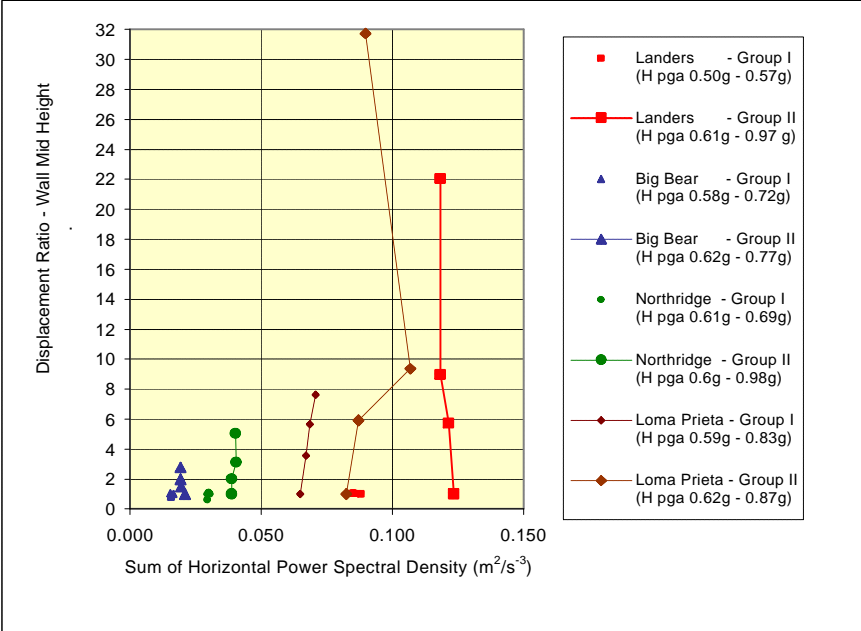


Figure 4. Displacement Ratio v Horizontal Power Spectral Density, for varying vertical motions

The effect of the vertical motions on the wall displacements is shown in the dimensionless plot of the displacement ratio against the ratio of the sums of the vertical and horizontal power spectral density, see Figure 5.

The results of the analyses with vertical shaking indicate that :

- (a) The magnitude of the displacements depends on the energy content of both vertical and horizontal components of shaking.
- (b) The vertical shaking has a very significant effect on wall displacements when the energy content of the earthquakes is large (Group II inputs).
- (c) The effect of the vertical shaking is very small for the smaller energy Group I shaking inputs, except for the Loma Prieta earthquake input.

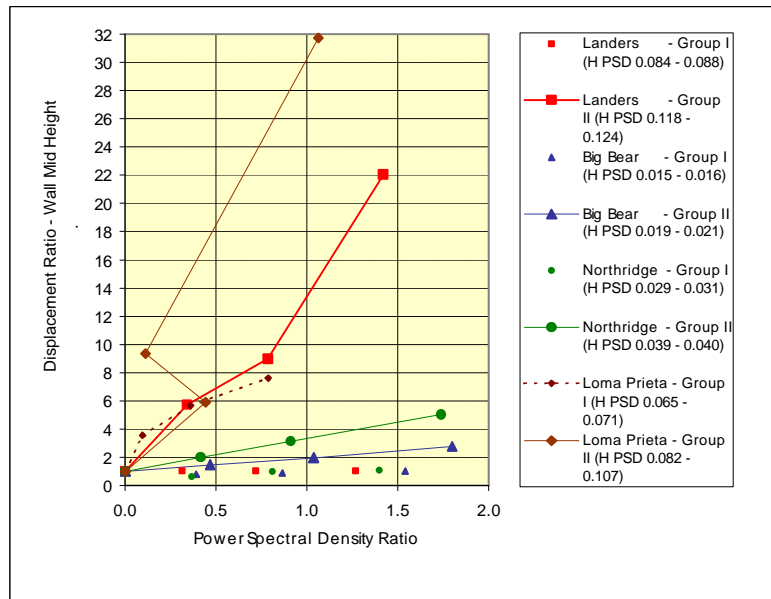


Figure 5. Variation of Displacement Ratio with Power Spectral Density Ratio

For a commonly assumed ratio of two-thirds between peak vertical and peak horizontal shaking, the analyses indicate a displacement of about twice that with horizontal shaking alone, based on the larger energy Group II inputs scaled from the Big Bear and Northridge records. Considering the Group II Landers and Loma Prieta records, the displacement could be much larger. For near-field areas where the proportion of the vertical shaking to horizontal shaking can be larger than two-thirds and even greater than one, a correspondingly larger displacement can be expected.

5.4 Influence of Frequency Content

The large difference in displacements between the different earthquakes and between the Group I and Group II earthquake shaking may not be solely explained by the differences in energy contents, which are not very large. The frequency of the energy contents of the earthquakes is also very different as shown in Figure 2. The vertical and horizontal components of each of the earthquakes are indicated to have similar frequency distributions.

The reinforced earth retaining structure modelled probably has a short first mode response period of less than $\frac{1}{4}$ second (or a frequency of 4 Hz to 5 Hz). The energy content of the earthquake records used is small at these frequencies, and therefore resonance effects are not likely. An exception is the Loma Prieta earthquake, which had a significant energy pulse at 4 Hz, leading to some resonance, which may explain the unusually large displacements with Group I Loma Prieta earthquake input. Landers and Loma Prieta records gave smaller displacements than the Big Bear and Northridge records with horizontal shaking alone, but gave larger displacements with vertical shaking included.

When vertical shaking is applied, it is possible that the period of the structure changes as the flexibility of the wall is temporarily increased. This may arise from a temporarily increased flexibility of the soil-wall system due to a reduced friction between the strips and the soil during the downward vertical accelerations associated with earthquake shaking.

Such a change in the first-mode period of response could have a profound effect on the behaviour of the structure and hence the displacement, if this period of response becomes similar to a frequency at which the earthquake has a large energy content. This could lead to resonance and large displacements. It is worth noting that Siddharthan et al (1991) also attributed the wide differences in the calculated displacements for various earthquake records to their frequency contents.

Further research is recommended to explore this hypothesis in detail and hence confirm its importance for design of wall structures.

6 CONCLUSIONS

- (a) The energy content, the frequency content and the vertical shaking characteristics of earthquakes have an important effect on the displacement performance of retaining structures.
- (b) Peak ground acceleration reflects the amplitude of a single pulse, and does not represent strong motion duration, energy and frequency content of earthquake shaking. It is shown to be a poor parameter for the assessment of the displacement of retaining structures.
- (c) Power spectral density represents the energy content of earthquake shaking, and is a better parameter for the assessment of wall displacement performance during earthquakes.
- (d) Vertical shaking of earthquakes having a significant energy content had a significant effect on the displacement of the model retaining wall. The power spectral density of the vertical motions was a better parameter to assess wall displacements than peak vertical acceleration.
- (e) Vertical shaking generally had a small effect on wall displacements when the earthquake shaking only had modest energy and peak ground acceleration, and when the energy content of the earthquake at a frequency similar to the first-mode period of response of the wall was low.
- (f) Retaining walls can undergo large displacements due to resonance, when exposed to earthquakes with significant energy content at frequencies similar to their first-mode of response, even when the total energy content of the earthquake is not large.
- (g) It is hypothesised that vertical shaking increases the flexibility of reinforced earth retaining structures and hence its period, and if the earthquake has a large energy content at this modified frequency, then resonance and significantly greater displacements could result.
- (h) Design methods should be modified to take into consideration the energy, frequency content and the vertical shaking of earthquakes, particularly for walls that support important structures.

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