LATERAL DISPLACEMENTS OF COMMONLY FOUND GRAVITY RETAINING WALLS IN SRI LANKA DUE TO SEISMIC ACTION

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Abstract

Gravity type retaining walls have been widely used to retain soil in Sri Lanka. However, it was reported that the performance of gravity type retaining walls during earthquake is poor. In view of the above, it was attempted in this study to develop a methodology to estimate the possible displacements of commonly found gravity retaining walls in Sri Lanka due to expected earthquakes. In addition, it was attempted to recommend an optimum shape for gravity retaining walls to minimize the possible displacements.

This work was backed by Mononobe-Okabe theory and Newmark's sliding wedge analysis. Using Mononobe-Okabe analysis, threshold acceleration that would cause a relative displacement between retaining wall and soil, was found for different types of retaining walls. Using Newmark's method, an analytical model was developed to predict lateral displacements during seismic loadings. Then different acceleration-time histories of earthquakes, which are similar to those observed near Sri Lanka recently, were fed to the developed analytical model and the lateral displacements were found.

Gravity retaining walls with a sloping back is found to give the least displacements, compared to the other types such as vertical and battered type gravity retaining walls for same acceleration-time history and to the same ground slope behind the retaining wall.

Keywords: Gravity retaining wall, Lateral Displacements, Earthquake, Mononobe-Okabe analysis, Newmark's Sliding Block Model, Threshold acceleration, Acceleration-time history.

1. Introduction

The possibility of new plate boundary about 400-500 km away from southern coast of Sri Lanka as expressed by some scientists and frequent tremors observed in and around the country have made Sri Lanka a “moderate earthquake prone country” [Dissanayake, P.B.R. et al (2004), Dissanayake, C.B. (2005 & 2012) & Peiris, L.M.N. (2008)]. Moreover, following the 2004 December Tsunami, various local and international bodies demanded the buildings and other newly built structures to be designed considering the seismic loads. In line with this, retaining walls are no exception to the above and care is needed to prevent retaining wall failures during anticipated seismic actions.

Gravity retaining walls are the commonly found retaining walls in Sri Lanka and the past experience suggests that their performance during earthquakes is not satisfactory. Despite many publications on earthquake resistant practices for buildings and other structures [Society of Structural Engineers Sri Lanka (2005 & 2006), Renuka, I.H.S. & Lewangamage, C.S. (2011), Dias W.P.S., & Bandara, K.M.K (2012)], a less effort has been made on seismic performance of gravity type retaining walls by the Sri Lankan engineering fraternity. Hence, this study attempted to quantify the possible lateral displacements of gravity type retaining walls during different magnitudes of earthquakes.

During earthquakes, gravity retaining walls are likely to fail due to the changing pressures and displacements and the likely modes of failures are sliding away from the backfill, combined effect of sliding and rotation and lateral spreading and associated settlement. The above failure modes may cause the gravity retaining walls to permanently displace by several centimetres or even few metres, depending on the magnitude of the earthquake. Thus in addition to calculating the factor of safety against failure in bearing, sliding and overturning under static conditions, care should be taken of the likely displacements of the gravity retaining walls during strong earthquakes.

Many researchers conducted experimental and theoretical studies in order to develop and improve seismic design methods for these structures. Among them, there are four major analytical methods available in the published literature to predict the dynamic earth pressure and the behaviour of retaining structures. These four major analytical methods can be listed as follows: Linear Elasticity Theory, which is based on assumptions and does not represent the realistic situations; Plastic Limit Solutions which is based on Mononobe – Okabe’s Quasi Static Theory; The other two methods are Elastic Plastic Solution and Non – Linear Elastic Solution; Both of which are not successful due to lack of reasonable representation of interface behaviour between soil and wall.

In addition to the above analytical methods, experimental studies were also conducted using physical models and they can be listed as follows: Shaking Table tests under gravitational field of earth [Prasad S.K (2004), *Iai, S.(1999) & Koga, Y.(1990)*] and

Centrifuge devises tests under higher gravitational field [Takemura, J et al (2003) & Porbaha, A et al (1996)].

In view of the above, this study was carried out using Mononobe and Matsuo (1929) and Okabe (1924) analysis, which was used to estimate the acceleration, above which the relative movement starts to occur (threshold acceleration between wall and soil). In addition Newmark's Sliding Block analysis (1965) was used to estimate of earthquake-induced accumulated displacements.

2. Research Methodology

Firstly it was intended to find the acceleration above which, earthquake induced displacements start to accumulate using Mononobe and Matsuo (1929) and Okabe (1924) analysis which is simply referred to as Mononobe-Okabe Analysis. Then an analytical tool was developed in line with Newmark's model to estimate the earthquake induced displacements for the earthquakes which are similar to those observed near Sri Lanka recently. Finally, it was intended to compare the cumulative lateral displacements of the selected geometric shapes. The dimensions of the commonly found geometric shapes of mass concrete gravity retaining walls as shown in Figure 1, were selected in such a way that the cross sectional area of all three geometric shapes are equal.

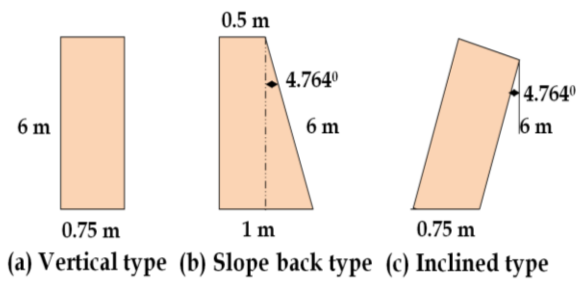


Figure 1*: Selected geometric shapes of mass concrete gravity retaining walls*

3. Mononobe-Okabe Analysis to find threshold acceleration

This paper makes use of the Mononobe-Okabe analysis, which was known to be the earliest method to determine the combined static and dynamic earth pressures on a retaining wall. The Mononobe-Okabe analysis was an extension of the Coulomb-Rankine Sliding wedge theory. According to the studies conducted by YAu-Yeung, Y.S et all. (1994) & Rowland Richards, J.M, David, G.E (1979), the effect of earthquake motion can be represented as inertial forces K_hW_s and K_vW_s, acting at the centre of gravity of the mass as shown in

Figure 2, whereas the K_h, K_v are coefficients of horizontal and vertical, accelerations respectively and W_s is the weight of the soil wedge. However, the scope of the present paper is limited to cohesionless and dry (no water table) backfill.

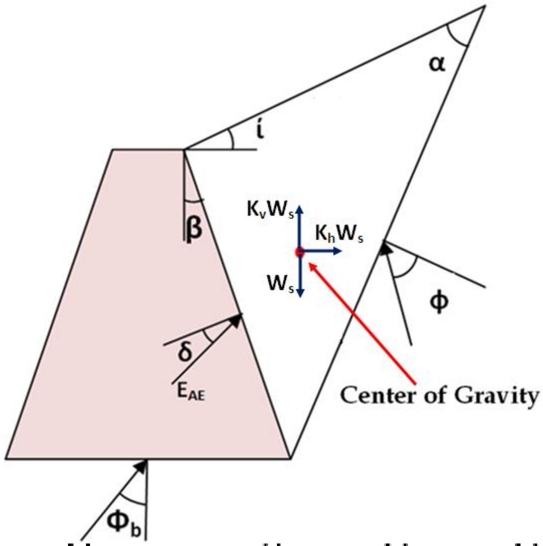


Figure .

Where,

Backfill angle

Friction angle between wall and

Soil friction angle

Slope of the wall to the vertical

Coefficients of Vertical, horizon

Inclination of resultant inertial fo

whereas coefficient of vertical a

Hence,

The combined dynamic factor F for the effects of soil pressure ar follows:

$$Fw = \frac{W_w}{W} = F_T \times F_I \qquad (1)$$

Where,

W_w - Weight of the wall

W - Weight of the wall required for static equilibrium

Thus soil thrust factor F_T can be expressed as follows:

$$F_T = \frac{(1-K_V)K_{AE}}{K_A}$$

It is assumed in the present study that the coefficient of vertical acceleration K_V =0;

Hence, $$F_T = \frac{K_{AE}}{K_A} \qquad (2)$$

where pseudo-static earth pressure co-efficient

$$K_{AE} = \frac{Cos^2(\Phi - \theta - \beta)}{Cos\,\theta \times Cos^2\beta \times Cos(\delta+\beta+\theta)\left[1+\sqrt{\frac{Sin(\Phi+\delta)\times Sin(\Phi-\theta-i)}{Cos(\delta+\beta+\theta)\times Cos(i-\beta)}}\right]^2} \qquad (2a)$$

Static active earth pressure

$$K_A = \frac{Cos^2(\theta - \beta)}{Cos^2\beta \times Cos(\delta+\beta)\left[1+\sqrt{\frac{Sin(\Phi+\delta)\times Sin(\Phi-i)}{Cos(\delta+\beta)\times Cos(\beta-i)}}\right]^2} \qquad (2b)$$

Similarly, wall inertia factor F_I could be expressed as follows:

$$F_I = \frac{C_{IE}}{C_I} \qquad (3)$$

$F_I = \frac{C_{IE}}{C_I}$ Where $C_{IE} = \frac{\cos(\delta+\beta)-\sin(\delta+\beta)\tan\Phi_b}{(1-k_v)(\tan\Phi_b-\tan\theta)}$

$$C_{IE} = \frac{Cos(\delta+\beta) - Sin(\delta+\beta)\times\tan\,\Phi_b}{(1-k_v)(tan\Phi_b - tan\theta)}$$

Since vertical acceleration Kv =0,

$$C_{IE} = \frac{Cos(\delta+\beta) - Sin(\delta+\beta)\times\tan\,\Phi_b}{(tan\Phi_b - tan\theta)} \qquad (3a)$$

and, $$C_I = \frac{Cos(\delta+\beta) - Sin(\delta+\beta)\times\tan\,\Phi_b}{tan\Phi_b} \qquad (3b)$$

Thus, $$F_I = \frac{C_{IE}}{C_I} = \frac{tan\Phi_b}{tan\Phi_b - tan\theta} \qquad (3c)$$

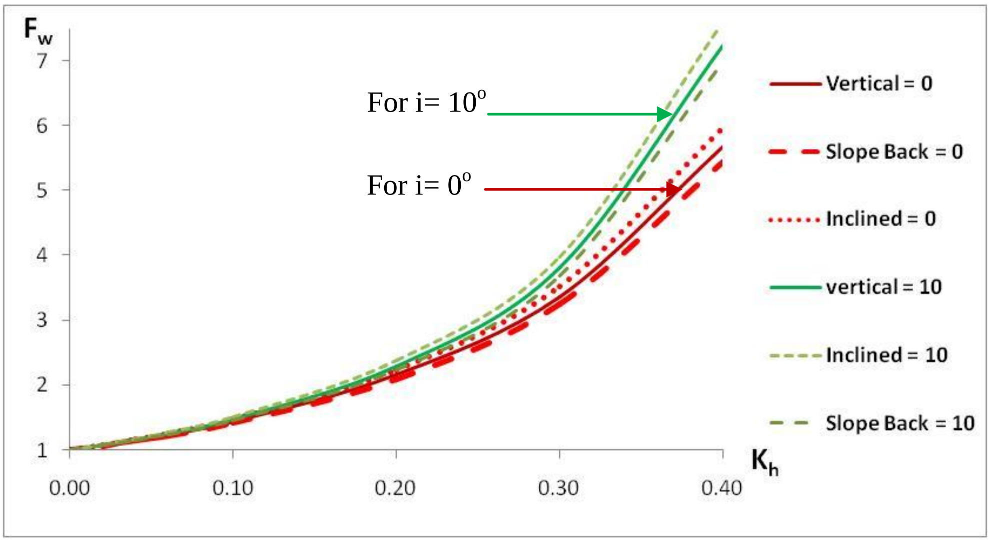


Figure 3: *Dynamic factor (F_w) with horizontal acceleration coefficient (K_h) for vertical, slope back and inclined type gravity retaining walls for backfill angle $i=0^0$ & $i=10^0$*

The Figure 3 shows the variation of dynamic factor F_w with horizontal ground acceleration co-efficient k_h. Where the graphical variations were obtained using soil parameters such as ί = 10°, δ = 17.5°, ϕ = 35°, β = 4.764°, ϕ_b = 35. The above properties correspond to the strength parameters of commonly found backfill material in Sri Lanka.

Coefficient of horizontal acceleration (K_h) was obtained by keeping combined dynamic factor (F_W) as 1.2 for the three types of gravity retaining walls using the relationship between K_h and F_w as shown in Figure 3. For the vertical back gravity retaining wall (with $i=0^0$), for combined dynamic factor of 1.2, the K_h is found to be 0.05 using the relationship between Dynamic factor (F_w) and horizontal acceleration coefficient (K_h) as shown in Figure 3. Hence the threshold acceleration is found to be 49.05 cm/s^2 (0.05×100×9.81) for vertical back gravity retaining wall with $i=0^0$. For the three types of gravity retaining walls for both $i=0^0$ and 10 ^{0}, the threshold accelerations were found in a similar manner and are tabulated in Table 1.

Table 1: Threshold acceleration values for different geometric shapes of wall

	Geometric Shape	Threshold Acceleration (cm/s^2)
ί=0^0	Vertical	49.050
	Sloping Back	51.503
	Inclined	49.050
ί=10^0	Vertical	45.919
	Sloping Back	51.012
	Inclined	43.731

4. Estimation of earthquake-induced displacements by using Newmark's sliding block theory

Newmark (1965) first proposed the sliding block model for estimating the dynamic wall displacements. By computing the ground acceleration at which the movement starts to begin (when the threshold acceleration is exceeded) and by summing up the displacements during the period of instability, the final cumulative displacement of the sliding mass can be evaluated.

The above methodology was used to estimate displacements of gravity retaining walls due to expected earthquakes in Sri Lanka. Newmark's sliding block can be graphically illustrated as shown in Figure 4.

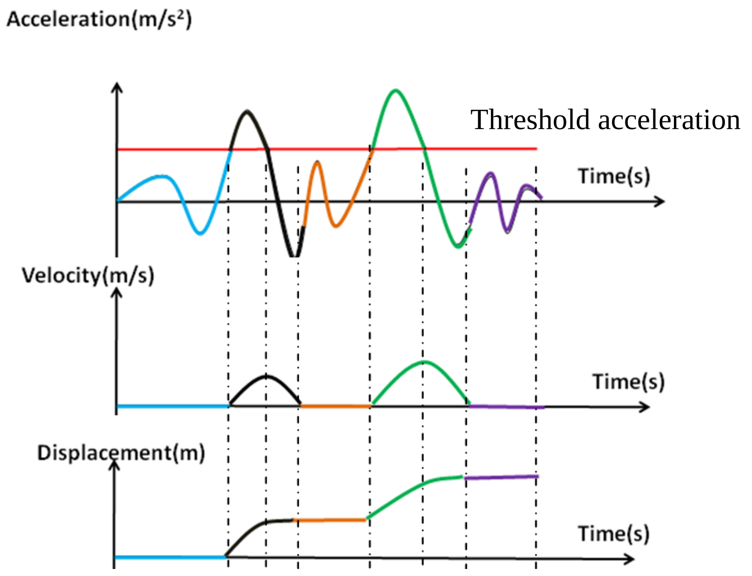


***Figure 4**: Relationships between acceleration and corresponding velocity and displacement diagrammes with time.*

Development of velocity time diagram by numerically integrating acceleration diagram is shown in Figure 5(a). Developing Displacement time diagram by integrating velocity diagram is shown in Figure 5(b).

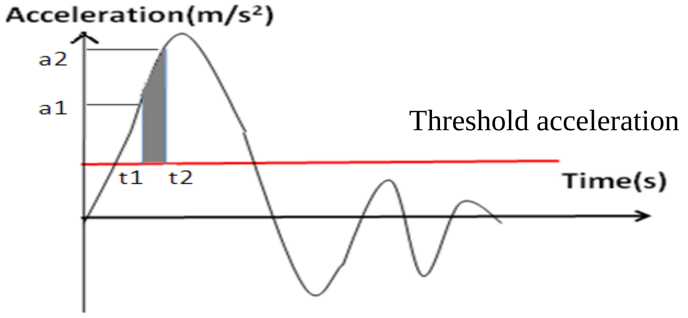


***Figure 5(a):** Numerical integration of acceleration versus time graph*

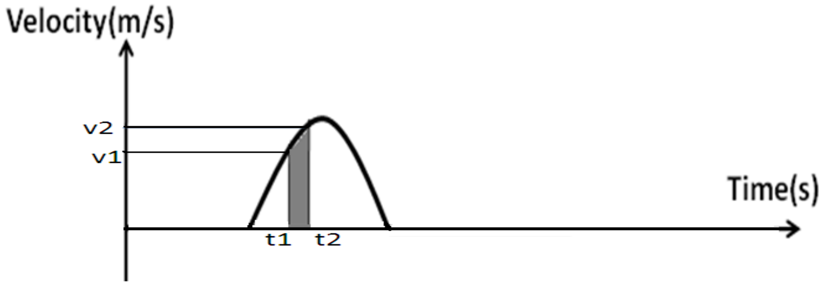


Figure 5(b): *Numerical integration of velocity versus time graph*

4.1 Selected Earthquakes Acceleration Time History

Six different earthquakes, covering Richter scale ranging from 4 to 9, were considered in the analysis and their acceleration time histories are shown in the Figure 6, which were obtained from strong motion [www.strongmotioncentre.org].

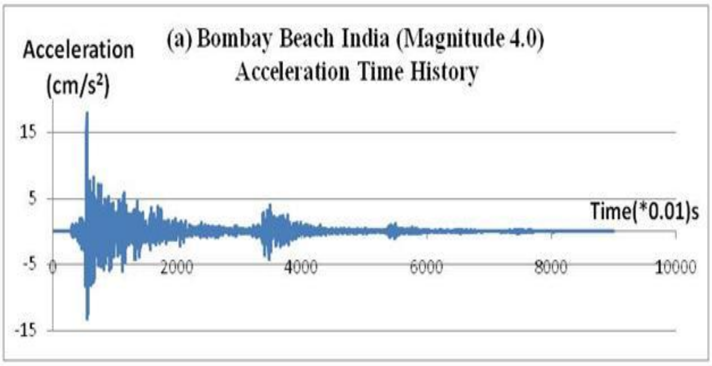


Figure 6(a) : *Bombay Beach India Magnitude 4.0 which occurred in 25th March 2009, Time 8:25:21 PM PDT, Latitude 33.293, Longitude -115.722*

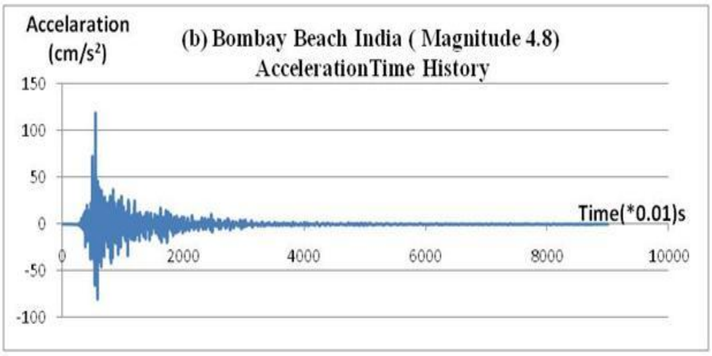


Figure 6(b): Bombay Beach India Magnitude 4.8 which occurred in 24th March 2009, Time 4:55:43 AM PDT, Latitude 33.318, Longitude -115.728

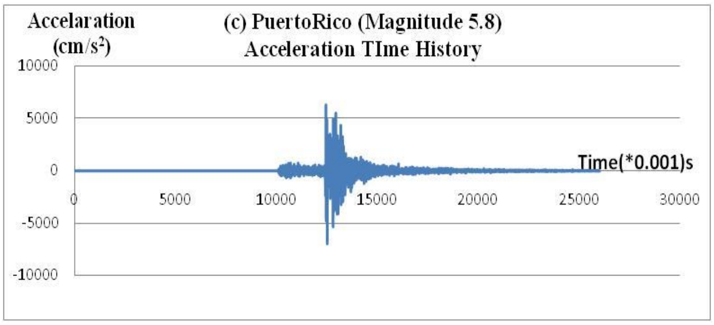


Figure 6(c) : *Puerto Rico Magnitude 5.8 which occurred in 16th May 2010, Time 05:16:10 UTC, Latitude 18.400,Longitude -67.07*

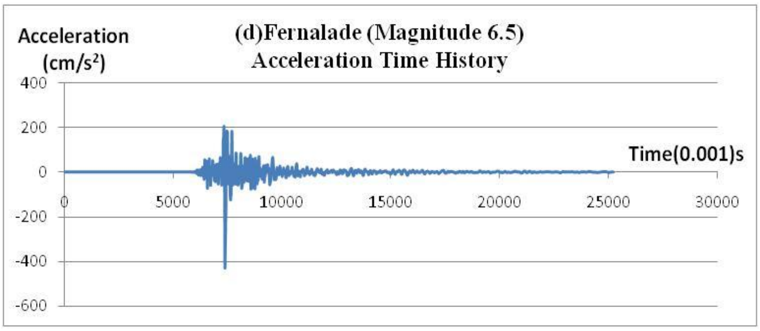


Figure 6(d) *: Ferndale Magnitude 6.5 which occurred in 09th January 2010: Time 4:27:38 PM PST, Latitude 40.645, Longitude -124.763*

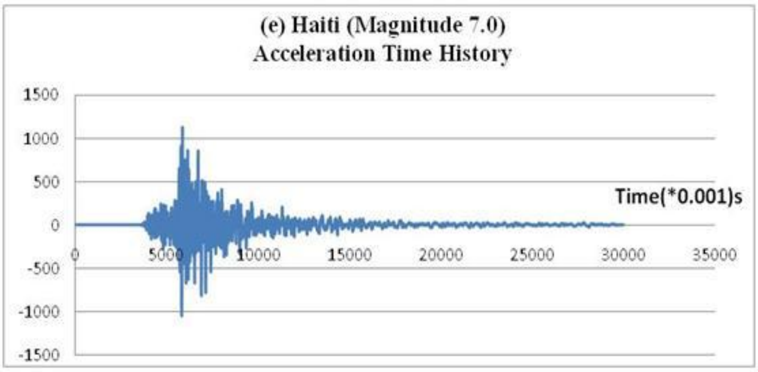


Figure 6(e) : *Haiti Magnitude 7.0 which occurred in 12th January 2010: Time 12:21:53 UTC, Latitude 18.457, Longitude -72.533*

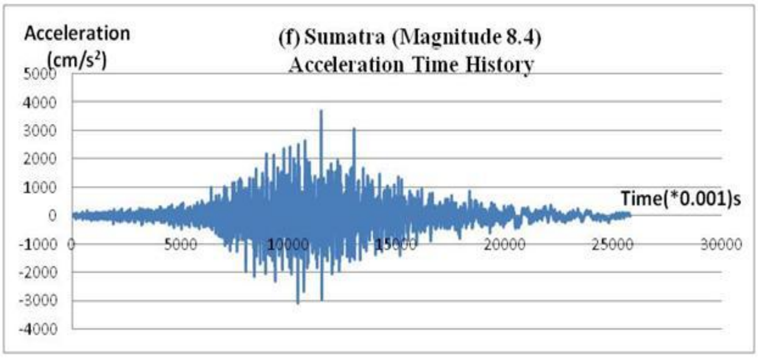


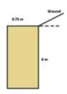
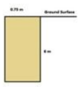
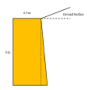
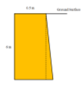
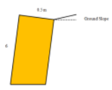
Figure 6(f) : *Sumatra Magnitude 8.4 which occurred in 12th September 2007: Time* 11:10:26 GMT , Latitude -4.520, Longitude 101.374

Figure 6*: Selected earthquakes and their corresponding acceleration time history*

5. Results and Discussions

The above mentioned methodology was employed to estimate the earthquake induced displacements of the three types of most commonly found gravity retaining wall types in Sri Lanka and are tabulated in Table 2.

Table 2: Cumulative lateral displacements of different types of gravity retaining walls due to the considered earthquakes

Place	Magnitude	Gravity Retaining Walls Lateral Displacement(cm)					
		Vertical Type		Sloping Back Type		Inclined Type	
		back fill angle of i=10°	back fill angle of i=0°	back fill angle of i=10°	back fill angle of i=0°	back fill angle of i=10°	back fill angle of i=0°
							
		cross sectional areas were kept same for comparison purpose					
Bombay	4.0	0.00	0.00	0.00	0.00	0.00	0.00
Bombay	4.8	1.56	1.23	1.10	1.07	1.81	1.46
Puerto Rico	5.8	3.87	3.74	3.66	3.64	3.97	3.83
Ferndale	6.5	13.59	12.60	11.95	11.80	14.35	13.27
Haiti	7.0	23.09	21.80	21.12	20.95	24.06	22.69
Sumatra	8.4	33.51	32.32	31.62	33.15	34.40	33.15

According to the analysis, slope back type gives lesser displacement compared to both vertical back and inclined back for same acceleration-time history and to the same ground slope (i^0) behind the retaining wall. In sloping back gravity retaining walls, mass per unit depth increases with the depth, thereby inertia and lateral resistance against sliding during earthquake increases. Thus sloping back walls give lesser displacements compared to the vertical, inclined type gravity retaining walls.

6. Conclusions

It can be concluded from this study that among the commonly found gravity retaining walls, sloping back gravity retaining wall gives the least lateral displacement during seismic activity, compared to vertical and inclined type gravity retaining walls for same acceleration-time history and to the same ground slope behind the retaining wall.

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