Effect of Soil Amplification on the Seismic Stability of Reinforced-soil Wall for Cohesive Backfill with Uniform Surcharge

Ashish Gupta[1[0000-0003-2379-8265]], V. A. Sawant[2[0000-0002-6730-4311]] and B. S. Khati[3[0000-0002-0200-7770]]

[1] Assistant Professor, Department of Civil Engineering, BIET Jhansi, Jhansi 284128, India
[2] Associate Professor, Department of Civil Engineering, IIT Roorkee, Roorkee 247667, India
[3] Assistant Professor, Department of Civil Engineering, GBPIET Pauri, Pauri 246194, India
[1]shi_g2000@rediffmail.com; [2]sawntfce@iitr.ac.in; [3]bhishmkhati007@gmail.com

Abstract. The design of reinforced-soil wall is very crucial under seismic condition, in which the soil amplification is a very important factor. Most of the researchers had analysed the reinforced-soil wall considering the effect of soil amplification for non-cohesive soils using the pseudo-dynamic approach. Very few researchers had analysed the reinforced-soil wall with a cohesive backfill along with the effect of soil amplification. In this paper, the pseudo-dynamic approach has been used to find out the seismic stability of reinforced-soil wall considering the effect of soil amplification for cohesive soil backfill with uniform surcharge. The effect of shear strength parameters, soil-wall adhesion, number and length of reinforcement layers and seismic coefficients of ground accelerations on the stability of reinforced-soil wall is critically examined. Variation in mobilized pullout resistance of reinforcement layers and factor of safety with time is also considered. For cohesionless backfill without soil amplification factor, numerical predictions are in good agreement when compared with available studies in literature for validation purpose.

Keywords: Reinforced-soil Wall, Pseudo-dynamic Approach, Soil Amplification, Surcharge, Factor of Safety

1 Introduction

Design of a retaining wall under the seismic condition necessitates the value of seismic earth pressure. From the earlier predicted earthquakes, it can be concluded that the reinforced soil walls perform well when compared to conventional retaining walls. The pioneer work for calculating the seismic earth pressure, Okabe (1926) and Mononobe and Matsuo (1929) designed the retaining walls using the pseudo-static method. Afterwards, this method is known as Mononobe and Okabe (M-O) method (Kramer 1996). The seismic stability analysis showing the effect of reinforcement and backfill properties of reinforced soil walls were performed using the pseudo-static method (Reddy et al. 2008; Chandaluri et al. 2015; Gupta and Sawant 2018d).

A new technique to analyse the retaining wall under seismic condition known as time dependent pseudo-dynamic approach was established by Steedman and Zeng (1990). The only drawback of this study was the consideration of finite shear waves in soil backfill. Nimbalkar et al. (2006) and Choudhury et al. (2007) extended this approach to analyse the seismic stability of reinforced soil wall. Soil amplification effect was introduced by Nimbalkar and Choudhury (2008) for calculating the seismic earth pressure distribution for cohesionless backfill behind a vertical retaining wall and introduced by Ghosh (2008) for inclined retaining wall. For inclined retaining wall considering the inclined backfill, the seismic stability analysis was performed by Gupta and Sawant (2018b) for cohesionless soil backfill and Gupta and Sawant (2018c) for cohesive soil backfill.

For pseudo-dynamic forces, Shekarian and Ghanbari (2008) analysed the retaining walls with and without reinforcement under seismic condition using horizontal slice method. Using pseudo-dynamic approach, Reddy et al. (2009) studied the seismic stability of reinforced soil wall. Ghanbari and Ahmadabadi (2010) proposed a pseudo-dynamic approach for reinforced retaining walls having c-ϕ soil backfill based on the limit equilibrium method and horizontal slice method. Effect of soil amplification for the case of reinforced soil wall for c-ϕ soil backfill was reported by Gupta and Sawant (2018a and 2019). The seismic study for the design of reinforced soil walls considering soil amplification are very limited for c-ϕ soil backfill with uniform surcharge. In the present study, the detailed formulation by using a simplified limit equilibrium method is used for the analysis of reinforced soil walls using pseudo-dynamic method for c-ϕ soil backfill with uniform surcharge.

2 Methodology

A vertical reinforced soil wall system ABC of height H retaining the soil backfill having unit weight γ, cohesion c and soil friction angle ϕ is shown in Fig. 1. The wall is having n number of planar reinforcement of length L_r with uniform spacing $S_v = H/n$. The top and bottom reinforcements are at vertical distance of $0.5S_v$ from its position. The effect of propagation of shear and primary waves is considered along with the effect of soil amplification with soil amplification factor, f_a in the present analysis. The present analysis is assuming linear variation in input ground acceleration with depth. The amplitudes of seismic accelerations in horizontal and vertical direction on the base of wall are $a_h = k_h.g$ and $a_v = k_v.g$. k_h and k_v are the seismic coefficients in the horizontal and vertical directions. The soil amplification effect in the seismic condition is assumed to act within the soil media. In the present analysis, AB is the failure plane making an angle, α, with the horizontal (Fig. 2). Force F is the resultant force of the shear and normal force acting on the failure plane of reinforced soil. Under seismic condition the shear and primary wave velocity, V_s and V_p, are assumed to act within the reinforced soil wall. The period of lateral shaking is $T = 2\pi/\mu$, where ω is the angular frequency.

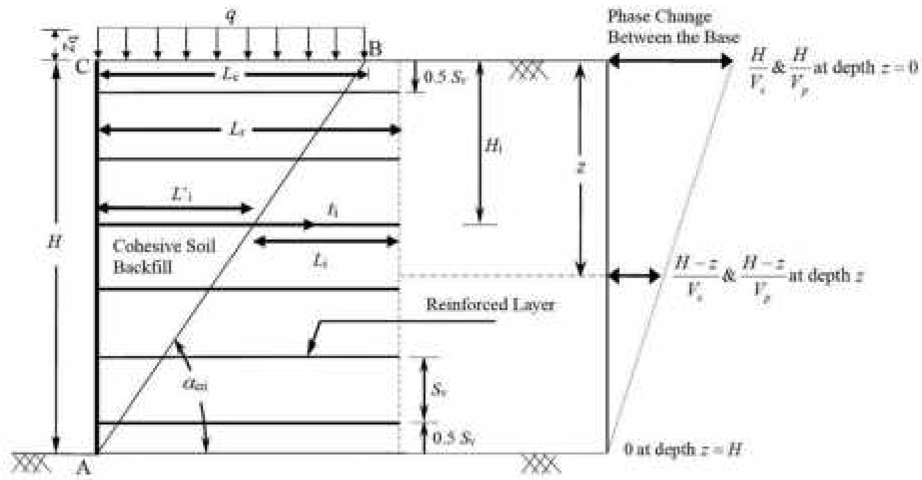

Fig. 1. Reinforced soil wall system.

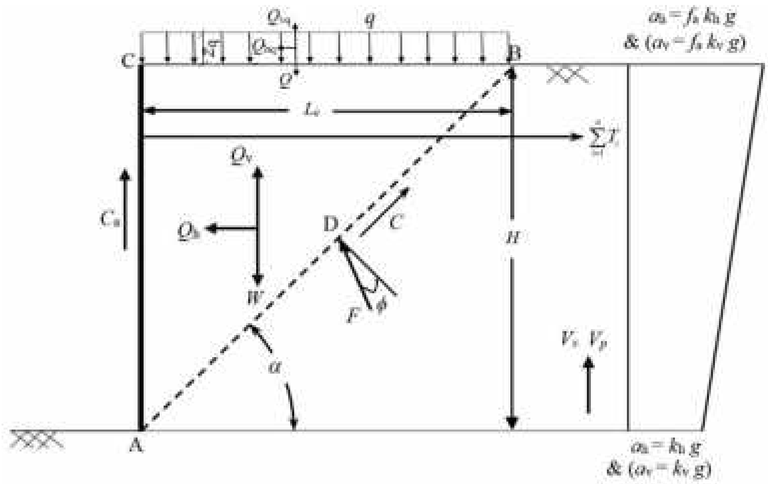

Fig. 2. Forces acting on the reinforced soil wall system under seismic condition.

Considering the dynamic equilibrium of forces on reinforced soil wall system in horizontal and vertical directions, total tensile force generated in the reinforcement, $T_{\text{Total}} = \sum_{i=1}^{n} T_i$ can be obtained as:

$$T_{Total} = \begin{bmatrix} \{W + Q - Q_v - Q_{vq}\}\tan(\sim - ¤) + Q_h + Q_{hq} \\ -cH\{\tan(\sim - ¤) + \cot\sim\} - c_a H \tan(\sim - ¤) \end{bmatrix} \tag{1}$$

The required strength of reinforcement (K) can be expressed as:

$$K = \begin{bmatrix} -\left\{ \dfrac{Q_v + Q_{vq}}{0.5\text{¥} H^2} \right\} \tan\left(\sim - \text{¤} \right) + \left\{ \dfrac{Q_h + Q_{hq}}{0.5\text{¥} H^2} \right\} - c^* \cot \sim \\ + \tan\left(\sim - \text{¤} \right) \left\{ \cot \sim + q^* \right\} - c^* \left(1 - a_f \right) \tan\left(\sim - \text{¤} \right) \end{bmatrix} \tag{2}$$

Where,

$$K = \frac{T_{Total}}{0.5\text{¥} H^2};\ q^* = \frac{2q}{\text{¥} H} \text{ and } c^* = \frac{2c}{\text{¥} H}$$

At depth z and time t, the seismic accelerations in horizontal (taken x as h and $V = V_s$) and vertical (taken x as v and $V = V_p$) direction due to soil backfill and due to surcharge load can be written as Eqs. (3) and (4):

$$a_x\left(z,t \right) = \left\{ 1 + \frac{H-z}{H}\left(f_a - 1 \right) \right\} k_x\ g \sin \mu \left(t - \frac{H-z}{V} \right) \tag{3}$$

$$a_{xq}\left(z,t \right) = \left\{ 1 + \frac{H + z_q - z}{H}\left(f_a - 1 \right) \right\} k_x\ g \sin \mu \left(t - \frac{H + z_q - z}{V} \right) \tag{4}$$

Using, mass of the small shaded part of thickness dz at depth z; the total inertia force in the horizontal and vertical direction due to soil backfill, Q_h and Q_v and due to surcharge load, Q_{hq} and Q_{vq} can be obtained as:

$$Q_h = \begin{bmatrix} \dfrac{\text{¥}\, k_h H f_a}{2\text{®}}\left(TV_s \right) \cot \sim \cos \dfrac{2\text{®}}{T}\left(t - \dfrac{H}{V_s} \right) \\ + \dfrac{\text{¥}\, k_h}{4\text{®}^2}\left(TV_s \right)^2 \cot \sim \left\{ \left(2 f_a - 1 \right) \sin \dfrac{2\text{®}}{T}\left(t - \dfrac{H}{V_s} \right) - \sin 2\text{®}\, \dfrac{t}{T} \right\} \\ + \dfrac{\text{¥}\, k_h\left(f_a - 1 \right)}{4\text{®}^3 H}\left(TV_s \right)^3 \cot \sim \left\{ \cos 2\text{®}\, \dfrac{t}{T} - \cos \dfrac{2\text{®}}{T}\left(t - \dfrac{H}{V_s} \right) \right\} \end{bmatrix} \tag{5a}$$

$$Q_v = \begin{bmatrix} \dfrac{\text{¥}\, k_v H f_a}{2\text{®}}\left(TV_p \right) \cot \sim \cos \dfrac{2\text{®}}{T}\left(t - \dfrac{H}{V_p} \right) \\ + \dfrac{\text{¥}\, k_v}{4\text{®}^2}\left(TV_p \right)^2 \cot \sim \left\{ \left(2 f_a - 1 \right) \sin \dfrac{2\text{®}}{T}\left(t - \dfrac{H}{V_p} \right) - \sin 2\text{®}\, \dfrac{t}{T} \right\} \\ + \dfrac{\text{¥}\, k_v\left(f_a - 1 \right)}{4\text{®}^3 H}\left(TV_p \right)^3 \cot \sim \left\{ \cos 2\text{®}\, \dfrac{t}{T} - \cos \dfrac{2\text{®}}{T}\left(t - \dfrac{H}{V_p} \right) \right\} \end{bmatrix} \tag{5b}$$

$$Q_{hq} = \left(\frac{qH\cot\sim k_h TV_s}{2® z_q}\right)\left[\begin{array}{l} \left\{f_a+\frac{z_q}{H}(f_a-1)\right\}\cos\frac{2®}{T}\left(t-\frac{H+z_q}{V_s}\right)-f_a\cos\frac{2®}{T}\left(t-\frac{H}{V_s}\right) \\ -\left(\frac{f_a-1}{H}\right)\left(\frac{TV_s}{2®}\right)\left\{\sin\frac{2®}{T}\left(t-\frac{H}{V_s}\right)-\sin\frac{2®}{T}\left(t-\frac{H+z_q}{V_s}\right)\right\} \end{array}\right] \quad (6a)$$

$$Q_{hq} = \left(\frac{qH\cot\sim k_h TV_p}{2® z_q}\right)\left[\begin{array}{l} \left\{f_a+\frac{z_q}{H}(f_a-1)\right\}\cos\frac{2®}{T}\left(t-\frac{H+z_q}{V_p}\right)-f_a\cos\frac{2®}{T}\left(t-\frac{H}{V_p}\right) \\ -\left(\frac{f_a-1}{H}\right)\left(\frac{TV_s}{2®}\right)\left\{\sin\frac{2®}{T}\left(t-\frac{H}{V_p}\right)-\sin\frac{2®}{T}\left(t-\frac{H+z_q}{V_p}\right)\right\} \end{array}\right] \quad (6b)$$

On applying the load in the reinforced soil wall system, the axial pullout of reinforcement causes the shear resistance. The tension fully mobilized in the reinforcement layers over the effective length of reinforcement. Hence, $t_{\text{Total}} = \sum_{i=1}^{n} t_i$ can obtain by the following expression:

$$t_{Total} = ¥ S_v \tan ¤_r \left(1+k_v\right)\left[n^2\left(L_r - H\cot\sim_{cri}\right)+\cot\sim_{cri} S_v \left\{\left(4n^3-n\right)/6\right\}\right] \quad (7)$$

The factor of safety, *FOS* is the ratio of the total mobilized bond resistance (t_{Total}), to the maximum tensile force generated in the reinforcement layers (T_{Total}).

3 Results and Discussion

A parametric study is showing the effect of surcharge along with the effect of soil amplification on the required strength of total reinforcement, critical inclination of failure angle and the factor of safety against pull out. Variation of parameters considered in the present study is reported in Table 1.

Table 1. Variation of parameters considered in the present study.

Description	Values are taken
Unit weight of soil backfill (¥)	18 kN/m^3
Height of retaining wall (H)	5 m
Shear wave velocity (V_s)	100 m/s
Primary wave velocity (V_p)	187 m/s
The time period of lateral shaking (T)	0.3 s
Soil cohesion (c)	0 and10 kPa
Soil friction angle (ϕ)	30º
Uniform Surcharge (q)	5 and 10 kPa
Horizontal seismic coefficient (k_h)	0.0, 0.1 and 0.2
Vertical seismic coefficient (k_v)	0.0 and 0.5 k_h
Soil amplification factor (f_a)	1.0 and 1.4
Number of reinforcement layer (n)	5
Length of reinforcement layer (L_r/H)	0.8

The variation of required strength of total reinforcement (K_{max}), variation of critical inclination of failure angle (α_{cri} in ^{o}) and the variation of the factor of safety (*FOS*) is shown in Table 2, Table 3, Table 4, Table 5 and Table 6 respectively for k_v = 0, 0.5 k_h and ϕ = 30^{o} for Case 1 (c = 0, q = 5 and f_a = 1.0), Case 2 (c = 0, q = 5 and f_a = 1.4), Case 3 (c = 10, q = 5 and f_a = 1.0), Case 4 (c = 10, q = 5 and f_a = 1.4) and Case 5 (c = 10, q = 10 and f_a = 1.4). From the Tables, it can be clearly observed the effect of soil cohesion, uniform surcharge, horizontal and vertical seismic coefficients and effect of soil amplification on the values of K_{max}, α_{cri} and *FOS*. For both the cases with and without considering the soil amplification factor, the value of K_{max} increases and *FOS* decreases significantly when the horizontal and vertical seismic coefficients increases. On comparing Table 5 with Table 6, the considerable effect of uniform surcharge can be quantified. The effect of soil cohesion for both the cases, with and without considering the effect of soil amplification can be also quantified. From Tables 2 to 6, it can be concluded that the value of α_{cri} decreases or the arear of failure wedge increases on considering the effect of soil amplification. The same for the value of α_{cri} can be noticed when the value of horizontal seismic coefficient increases. For example, at k_h = 0.2, k_v = 0.0 and q = 5 kPa, the value of K_{max} decreases 55.9% (when c increases from 0 to 10 kPa for f_a = 1.0) and 55% (when c increases from 0 to 10 kPa for f_a = 1.4). The example shows the significant effect of soil cohesion for both the cases, with and without consideration of soil amplification. For the same value of k_h = 0.2, k_v = 0.0 and q = 5 kPa, the percentage increase of *FOS* is 140.9 and 177.4 respectively; which shows the significant effect of soil amplification along with the effect of soil cohesion. On increasing the uniform surcharge from 5 kPa to 10 kPa, for c = 10 kPa and f_a = 1.4, the value of K_{max} substantially increases by 27.5%, which is showing the effect of surcharge loading along with the effect of soil cohesion.

Table 2. Values of K_{max}, $\sim_{cri}$ and *FOS* for k_h (c = 0, q = 5, ϕ = 30^{o} and f_a = 1.0).

Results	k_h = 0.0		k_h = 0.1		k_h = 0.2	
	k_v = 0.0	k_v = 0.5 k_h	k_v = 0.0	k_v = 0.5 k_h	k_v = 0.0	k_v = 0.5 k_h
K_{max}	0.404	0.404	0.427	0.443	0.467	0.497
$\sim_{cri}$ (^{o})	65.28	65.28	60.25	60.32	51.51	52.98
FS	5.79	5.79	5.16	4.73	4.13	3.58

Table 3. Values of K_{max}, $\sim_{cri}$ and *FOS* for k_h (c = 0, q = 5, ϕ = 30^{o} and f_a = 1.4).

Results	k_h = 0.0		k_h = 0.1		k_h = 0.2	
	k_v = 0.0	k_v = 0.5 k_h	k_v = 0.0	k_v = 0.5 k_h	k_v = 0.0	k_v = 0.5 k_h
K_{max}	0.404	0.404	0.431	0.450	0.500	0.528
$\sim_{cri}$ (^{o})	65.28	65.28	58.25	58.51	41.74	45.92
FS	5.79	5.79	4.97	4.55	3.05	2.92

Table 4. Values of K_{max}, $\sim_{cri}$ and FOS for k_h (c = 10, q = 5, ϕ = 30^o and f_a = 1.0).

Results	k_h = 0.0		k_h = 0.1		k_h = 0.2	
	k_v = 0.0	k_v = 0.5 k_h	k_v = 0.0	k_v = 0.5 k_h	k_v = 0.0	k_v = 0.5 k_h
K_{max}	0.146	0.146	0.170	0.187	0.206	0.237
$\sim_{cri}$ (^{o})	63.71	63.71	60.16	60.21	55.12	55.69
FS	15.79	15.79	12.91	11.22	9.95	7.84

Table 5. Values of K_{max}, $\sim_{cri}$ and FOS for k_h (c = 10, q = 5, ϕ = 30^o and f_a = 1.4).

Results	k_h = 0.0		k_h = 0.1		k_h = 0.2	
	k_v = 0.0	k_v = 0.5 k_h	k_v = 0.0	k_v = 0.5 k_h	k_v = 0.0	k_v = 0.5 k_h
K_{max}	0.146	0.146	0.175	0.193	0.225	0.260
$\sim_{cri}$ (^{o})	63.71	63.71	58.90	59.04	50.86	52.14
FS	15.79	15.79	12.40	10.66	8.46	6.75

Table 6. Values of K_{max}, $\sim_{cri}$ and FOS for k_h (c = 10, q = 10, ϕ = 30^o and f_a = 1.4).

Results	k_h = 0.0		k_h = 0.1		k_h = 0.2	
	k_v = 0.0	k_v = 0.5 k_h	k_v = 0.0	k_v = 0.5 k_h	k_v = 0.0	k_v = 0.5 k_h
K_{max}	0.226	0.226	0.246	0.265	0.287	0.323
$\sim_{cri}$ (^{o})	68.01	68.01	63.29	63.22	54.32	55.37
FS	10.68	10.68	9.30	8.21	7.04	5.73

4 Conclusion

In the present work, the formulations for computing the required strength of reinforcements, critical inclination of failure angle and factor of safety against pull out for c-ϕ soil backfill for the case of reinforced soil wall for cohesive backfill with uniform surcharge is derived using the pseudo-dynamic approach. The effect of soil cohesion and horizontal and vertical seismic coefficients of ground accelerations on the stability of reinforced-soil wall is significant. The effect of surcharge is 27% more on the required strength of reinforcements when the effect of soil amplification is considered.

References

1. Chandaluri, V. K., Sawant, V. A., Shukla, S. K.: Seismic stability analysis of reinforced soil wall using Horizontal Slice method. International Journal of Geosynthetics and Ground Engineering 1:23 (3), 1–10 (2015).
2. Choudhury, D., Nimbalkar, S. S., Mandal, J. N.: External stability of reinforced soil walls under seismic conditions. Geosynthetics International 14 (4), 211–218 (2007).

3. Ghanbari, A., Ahmadabadi, M.: New analytical procedure for seismic analysis of reinforced retaining wall with cohesive-frictional backfill. Geosynthetics International 17 (6), 364–379 (2010).
4. Ghosh, P.: Seismic active earth pressure behind a non-vertical retaining wall using pseudo-dynamic analysis. Canadian Geotechnical Journal 45, 117–123 (2008).
5. Gupta, A., Sawant, V. A.: Effect of soil amplification on seismic earth pressure using pseudo-dynamic approach. International Journal of Geotechnical Engineering, (2018b). doi: 10.1080/19386362.2018.1476803.
6. Gupta, A., Sawant, V. A.: Pseudo-dynamic approach to analyse the effect of soil amplification in the calculation of seismic active earth pressure distribution behind the inclined retaining wall for inclined c-ϕ soil backfill. Sustainable Civil Infrastructures, Springer, pp. 87–100 (2018c). doi: 10.1007/978-3-030-01920-4.
7. Gupta, A., Sawant, V. A.: Pseudo-dynamic approach to analyze the seismic stability of reinforced soil wall for c-ϕ soil backfill. Indian Geotechnical Journal, (2019). doi: 10.1007/s40098-019-0349-3.
8. Gupta, A., Sawant, V. A.: Seismic behaviour of reinforced retaining walls using the pseudo-dynamic approach for c-ϕ soil backfill. In: 2nd International Conference Proceedings on Advances in Concrete, Structural & Structural Engineering (ACSGE2018), pp. 118–123. BITS Pilani, India, February 26-28 (2018a).
9. Gupta, A., Sawant, V.A.: Simplified solution to analyze seismic stability of reinforced soil wall. International Journal of Geotechnical Engineering, (2018d). doi: 10.1080 /19386362.2018.1558759.
10. Kramer, S. L.: Geotechnical earthquake engineering. Prentice-Hall, Englewood Cliffs (1996).
11. Mononobe, N., Matsuo, H.: On the determination of earth pressures during earthquakes. In: World engineering congress Proceedings, Vol. 9, pp. 179–187. Tokyo, Japan (1929).
12. Nimbalkar, S. S., Choudhury, D., Mandal, J. N.: Seismic stability of reinforced soil wall by pseudo-dynamic method. Geosynthetics International 13 (3), 111–119 (2006).
13. Nimbalkar, S. S., Choudhury, D.: Effects of body waves and soil amplification on seismic earth pressures. Journal of Earthquake and Tsunami 2 (1), 33–52 (2008).
14. Okabe, S.: General theory of earth pressure and seismic stability of retaining wall and dam. Journal of Japan Society of Civil Engineers 10 (6), 1277–1323 (1926).
15. Reddy, G. V. N., Choudhury, D., Madhav, M. R.: Pseudo-dynamic analysis of reinforced soil wall subjected to oblique displacement. Geosynthetics International 16 (2), 61–70 (2009).
16. Reddy, G. V. N., Madhav, M. R., Reddy, E. S.: Pseudo-static seismic analysis of reinforced soil wall: Effect of oblique displacement. Geotextiles and Geomembranes 26 (5), 393–403 (2008).
17. Shekarian, S., Ghanbari, A.: A Pseudo-dynamic method to analyze retaining wall with reinforced and unreinforced backfill. Journal of Seismology and Earthquake Engineering: Spring 10 (1), 41–47 (2008).
18. Steedman, R. S., Zeng, X.: The influence of phase on the calculation of pseudo-static earth pressure on a retaining wall. Geotechnique 40 (1),103–112 (1990).