Seismic stability of tailings dam by using pseudo-dynamic method

Stabilité sismique d'une digue de retenue de résidus miniers examinée par une méthode pseudo-dynamique

Deepankar Choudhury
Department of Civil Engineering, Indian Institute of Technology (IIT) Bombay, Mumbai 400 076, India. Email: dc@civil.iitb.ac.in

Sanjay Nimbalkar
Faculty of Engineering, University of Wollongong, New South Wales 2522, Australia. And former Lecturer, Department of Civil Engineering, Government College of Engineering, Karad, Maharashtra, India. Email: sanjay_nimbalkar@yahoo.com

ABSTRACT

Seismic stability of tailings dams and embankments is an important topic which needs the special assessments by the researchers as it is mainly governed by the safety concerns. Several researchers in the past had attempted to investigate the seismic stability of earthen dams and embankments by using conventional pseudo-static method of analysis. However, the crude estimate of finding the approximate seismic acceleration makes the pseudo-static approach too conservative to adopt in the stability assessment. Although a few researchers in the recent past highlighted the limitations and drawbacks of the pseudo-static approach, there are very limited studies being reported worldwide for the seismic stability assessment of earthen dams and embankments by using alternative methods of analysis. In this paper, a recently developed and modified pseudo-dynamic method of analysis is used to compute the seismic inertia forces acting on the sliding wedge of the tailings dam by considering the effects of time of seismic accelerations, phase differences in the propagating shear and primary waves in the soil during an earthquake, frequency of earthquake excitation etc. with the horizontal and vertical seismic accelerations. The factor of safety decreases with increase in the seismic accelerations and phase difference in body waves. Influence of various parameters such as seismic acceleration coefficients, period of lateral shaking on seismic stability of tailings dam are studied under harmonic seismic loading conditions for both empty and full water cases. Present results are compared with the pseudo-static based solutions to validate the findings of the pseudo-dynamic method of analysis.

RÉSUMÉ

La stabilité sismique des digues de retenue de résidus miniers et des remblais est un sujet important qui nécessite une attention particulière des chercheurs puisqu'elle est principalement régie par des soucis de sécurité. Dans le passé, nombreux chercheurs ont essayé d'examiner la stabilité sismique des digues de retenue de résidus miniers et des remblais en utilisant la méthode d'analyse pseudo-statique conventionnelle. Cependant, l'évaluation grossière pour déterminer l'accélération sismique approchée rend cette approche trop conservatrice pour satisfaire l'évaluation de la stabilité. De plus, récemment, quelques chercheurs ont mis en évidence les limitations et les inconvénients de l'approche pseudo-statique. Toutefois il existe au jour d'aujourd'hui très peu d'études au niveau mondial permettant d'évaluer la stabilité sismique des digues de retenue de résidus miniers et des remblais en utilisant des méthodes d'analyse alternatives. Dans ce papier, une méthode pseudo-dynamique récemment développée et modifiée est utilisée pour calculer les forces d'inertie sismiques agissantes sur la cale coulissante de la digue. En particulier, les effets de temps des accélérations sismiques, les différences de phase dans la propagation du cisaillement et des ondes primaires souterraines durant le tremblement de terre, et la fréquence d'excitation de ce dernier ont été considérés tout en prenant en compte les accélérations sismique horizontales et verticales. Le facteur de sécurité diminue avec l'augmentation des accélérations sismiques et la différence de phase dans le corp ondulatoire. Les influences de divers paramètres tels que les coefficients d'accélération sismiques et l'effet de la période du tremblement latéral sur la stabilité sismique de la digue de retenue de résidus miniers sont étudiés dans des conditions de charge sismiques harmoniques pour les cas sans eau et remplis d'eau. Les résultats présents sont comparés aux solutions déduites de la méthode pseudo-statique afin de valider les observations faites à partir de la méthode d'analyse pseudo-dynamique.

Keywords : pseudo-dynamic, horizontal slice method, stability, earthquake, dam

1 INTRODUCTION

Seismic stability of tailings dams and embankments is an important topic which needs the special treatment by researchers as it is mainly governed by the safety concerns. Many researchers in the past have attempted to investigate the seismic stability of dams and embankments by using pseudo-static method of analysis. Semi empirical stability charts (Sarma 1975; Makdisi & Seed 1978) are often used to obtain a preliminary estimate of the permanent, earthquake induced deformation of earth dams and embankments.

Considering the fact that Permanent down slope movement depends on the shape of the acceleration pulse, i.e., whether the pulse is rectangular, sinusoidal or triangular, and the predominant frequency of the earthquake ground motion, closed form solutions were obtained (Sarma 1975) for the permanent displacements for simple periodic ground motion with rectangular sinusoidal and triangular wave forms. Similar studies was reported (Makdisi & Seed 1978) to relate empirically the permanent deformation of a sliding block to the ratio of yield acceleration to peak horizontal ground acceleration at the elevation of the toe of the dam considering a suite of earthquake accelerograms. However all these investigations were based on pseudo-static method of analysis, which didn’t consider the actual dynamic effect with variation of time and propagation of shear and primary wave velocities through the medium.

Although several researchers in the past highlighted the limitations and drawbacks of the pseudo-static approach, there are very limited studies being reported worldwide for the seismic stability assessment of dams and embankments. To Rectify the shortcomings of the pseudo-static approach, a pseudo-dynamic method has been recently developed to address this problem (Steedman & Zeng 1990; Choudhury & Nimbalkar 2005, 2006, 2008; Nimbalkar & Choudhury, 2008).

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-1542

Recently, Horizontal Slice Method (HSM) has been formulated (Shahgholi et al. 2001; Fakher et al. 2002) to analyse the seismic stability of reinforced slopes and walls based on pseudo-static apprach. Considering the non-linear variation of pseudo-dynamic inertia forces, horizontal slice method method is extended (Nimbalkar et al. 2006; Choudhury et al. 2007) to investigate the stability of reinforced soil wall.

In this paper, a complete study has been carried out to obtain the practical design values of the seismic stability of the tailings dam by using horizontal slice method considering pseudo-dynamic inertia forces along with other seismic input parameters.

2 PROPOSED ANALYTICAL MODEL

The tailings dam, of height H, supporting the compacted tailings overlaid by tailings pond is shown in Fig. 1a. Similar to the pseudo-dynamic approach (Choudhury & Nimbalkar 2005, 2006), the finite shear wave velocity (V_s) and primary wave velocity (V_p) are considered in the present analysis. The phase of both the horizontal and vertical seismic accelerations are varying along the depth of the dam. In the present analysis, $V_p/V_s = 1.87$ for $\nu_s = 0.3$ is used. Period of lateral shaking, $T = 2\pi/\omega$ is considered in the analysis.

To obtain the critical design values of horizontal and vertical seismic inertia forces acting within the body of tailings dam, it is assumed that both the horizontal and vertical vibrations start at exactly the same time without any phase shift between these two vibrations, which is the worst possible combination of earthquake loading. The horizontal and the vertical acceleration at any depth z and time t, below the top of the dam can be expressed as,

$$a_h(z,\ t) = a_h \sin\omega\left[t - \frac{H-z}{V_s}\right] \tag{1}$$

$$a_v(z,\ t) = a_v \sin\omega\left[t - \frac{H-z}{V_p}\right] \tag{2}$$

The total horizontal inertia force $q_{hi}(t)$ acting on the i^{th} slice can be expressed as,

$$q_{hi}(z,\ t) = m_i(z).a_h(z,\ t) \tag{3}$$

Again, the total vertical inertia force (q_{vi}) acting on the i^{th} slice can be expressed as,

$$q_{vi}(z,\ t) = m_i(z).a_v(z,\ t) \tag{4}$$

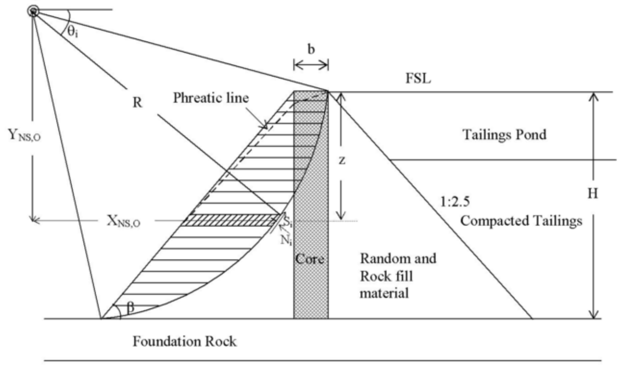

Figure 1(a). Tailings dam section considered in the analysis

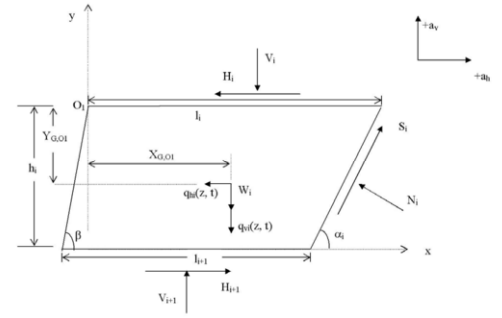

Figure 1(b). Pseudo-dynamic forces acting on elemental slice

Only the critical directions of $q_{hi}(t)$ and $q_{vi}(t)$ acting on elemental slice are considered as shown in Figure 1b. Detailed mathematical treatment of $q_{hi}(t)$ and $q_{vi}(t)$ can be found elsewhere (Nimbalkar et al. 2006; Chodhury et al. 2007). Similar to the 2N+1 formulation (Fakher et al. 2002), equilibrium equations can be written as

$\sum F_y = 0$ (for each slice) gives

$$V_{i+1} - V_i - W_i - q_{vi} + S_i\sin\alpha_i + N_i\cos\alpha_i = 0 \tag{5}$$

where, V_i and V_{i+1} are vertical inter-slice forces calculated by integration of overburden pressures on horizontal border of slice (Shahgholi et al. 2001; Nimbalkar et al. 2006).

Again, $\tau_r = \dfrac{\tau_f}{FS}$ (for each slice) yields

$$S_i = \frac{1}{FS}\left(cb_i + N_i\tan\phi\right) \tag{6}$$

Substituting for S_i from equation (6) into equation (5),

$$N_i = \frac{V_i - V_{i+1} + W_i + q_{vi}(z,t) - \dfrac{cb_i}{FS}\sin\alpha_i}{\dfrac{\tan\phi}{FS}\sin\alpha_i + \cos\alpha_i} \tag{7}$$

$\sum M_O = 0$ (for the whole wedge)

$$\sum_{i=1}^{m}\left[\begin{array}{l} q_{hi}(z,t)\left(Y_{G,Oi} + R\sin\theta_i\right) \\ -\left(W_i + q_{vi}(z,t)\right)\left(X_{G,Oi} + R\cos\theta_i - l_i\right) \\ -\left(S_i\sin\alpha_i + N_i\cos\alpha_i\right)\left(X_{NS,O}\right) \\ -\left(S_i\cos\alpha_i - N_i\sin\alpha_i\right)\left(Y_{NS,O}\right) \end{array}\right] = 0 \tag{8}$$

Here, the assumption is made that the normal (N_i) and shear (S_i) forces act at the mid-point of base of each slice and thus,

$$\left.\begin{array}{l} X_{NS,O} = R\cos\theta_i - \dfrac{h_i}{2\tan\alpha_i} \\ Y_{NS,O} = R\sin\theta_i + \dfrac{h_i}{2} \end{array}\right\} \tag{9}$$

Substitute S_i and N_i in equation (8) to obtain the factor of safety (FS). If $q_{vi}(t)$ and $q_{hi}(t)$ are replaced by constant pseudo-static inertia forces such as k_vW_i and k_hW_i respectively, the expression (8) reduces to the pseudo-static formulation originally proposed (Fakher et al. 2002) using moment equilibrium condition. The slip circle is assumed as circular in this analysis for the sake of simplicity.

3 RESULTS AND DISCUSSIONS

Results are presented in the form of tables and graphs. Variations of parameters considered in the present analyses are as follows:

k_h = 0.0, 0.1, 0.2, 0.3
k_v = 0.0, 0.5k_h and 1.0k_h
T = 0.2, 0.3, 0.4 s
V_s = 100 m/s, V_p = 187 m/s.

The input properties used in the analysis presented in this paper are given in Table 1. The values of factor of safety for tailings dam are reported for both the tailings pond empty and full water conditions.

Table 1. Input properties for the tailings dam.

Sr. No.	Particulars	Input Parameter
1	Random	Unit weight (γ) = 18.30 kN/m^3 Angle of internal friction (ϕ) = 28 Cohesion (c) = 3.125 kN/m^2
2	Impervious core	Unit weight (γ) = 16.40 kN/m^3 Angle of internal friction (ϕ) = 28 Cohesion (c) = 35 kN/m^2
3	Tailings pond	Unit weight (γ) = 19.00 kN/m^3. Angle of internal friction (ϕ) = 12 Cohesion (c) = 14.7 kN/m^2
4	Compacted Tailings	Unit weight (γ) = 19.00 kN/m^3. Angle of internal friction (ϕ) = 15.2 Cohesion (c) = 14.7 kN/m^2
5	Foundation	Unit weight (γ) = 18.30 kN/m^3. Angle of internal friction (ϕ) = 28 Cohesion (c) = 3.125 kN/m^2
6	Height of dam crest, H	= 44 m
7	Width of crest, b	= 4 m
8	Length of the crest	= 655 m
9	Slope of dam, n	= 1: 2.5
10	Slope of phreatic line	= 4:1 (Random section) = 2:1 (Core section)
11	Water table depth	= 3.5 m below ground level
12	Ground level	Base of the dam

3.1 *Effect of seismic acceleration coefficients (k_h and k_v) on factor of safety (FS)*

Fig. 2 shows the effects of both horizontal and vertical seismic acceleration coefficients (k_h and k_v) on factor of safety (FS) for tailings dam empty and full water condition respectively. It is evident from Fig. 2 that, the required value of FS shows significant decrease with increase in horizontal and vertical seismic acceleration coefficients (k_h and k_v).

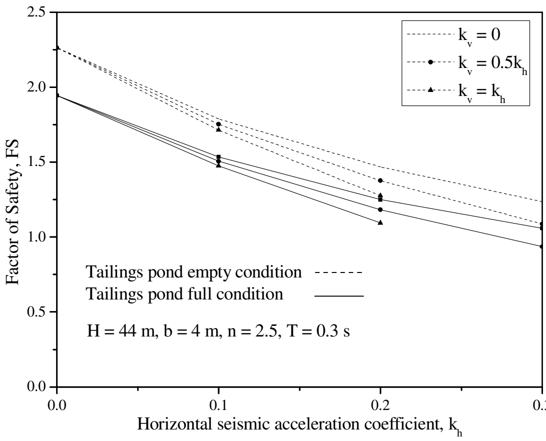

Figure 2. Effect of horizontal and vertical seismic acceleration coefficients on factor of safety, FS

Referring to the tailings dam empty condition, for k_v = 0.5k_h, when k_h changes from 0 to 0.1, required factor of safety (FS) of decreases by about 22.6%. Also when k_h changes from 0.1 to 0.2, required factor of safety (FS) decreases by about 21.5%. Similarly when k_h changes from 0.2 to 0.3, required factor of safety (FS) decreases by about 21%. Also for k_h = 0.2, when k_v changes from 0 to 0.5k_h, the required factor of safety (FS) decreases by about 6.2% and when k_v changes from 0.5k_h to 1.0k_h, required factor of safety (FS) decreases by about 8%.

Similar trend is observed for the tailing dam full water condition. Thus, effects of both horizontal and vertical seismic acceleration coefficients (k_h and k_v) are significant in the computation of stability of the tailings dam.

3.2 *Effect of period of lateral shaking (T) on required factor of safety (FS)*

Fig. 3 shows the effect of period of lateral shaking (T) on the required factor of safety (FS) with k_v = 0.5k_h for tailings dam empty and full water condition respectively. From the plot it is seen that for k_h = 0.2, the value of FS required to maintain stability of the tailings dam, when completely filled, corresponding to T = 0.2s is 21%, 33% and 53% larger than that corresponding to T = 0.3s and 0.4s respectively.

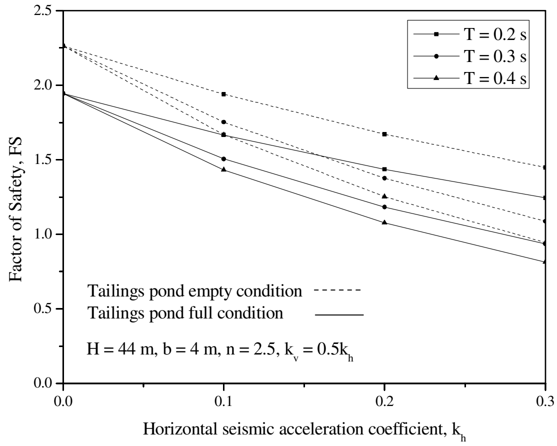

Figure 3. Effect of period of lateral shaking (T) on factor of safety, FS with k_v = 0.5k_h

Almost similar trend is observed for the effect of period of lateral shaking (T) while investigating the stability of the tailings dam in an empty state. Thus it is evident from the plot that, as the period of lateral shaking increases, seismic stability of the tailings dam decreases. For most geotechnical structures, T = 0.3s is a reasonable value (Prakash 1981). Hence, for all other results reported in this paper, T = 0.3s is used.

4 COMPARISON OF RESULTS

The pseudo-dynamic method of analysis (Steedman & Zeng 1990; Choudhury & Nimbalkar 2005, 2006) is quite established for the seismic design of rigid retaining walls. However, this robust pseudo-dynamic method of analysis is not yet been applied to investigate the stability of dams and embankments. Hence present results cannot be compared due to scarcity of results in literature. However, for the sake of completeness, the results reported in the present paper are compared with the pseudo static based slope stability analysis of the tailings dam.

Figure 4 shows such a comparison of the results of slope stability analysis using both of these methods of analysis for the case of tailings pond empty and full water condition respectively. It is evident that for the static case, both the methods report similar results.

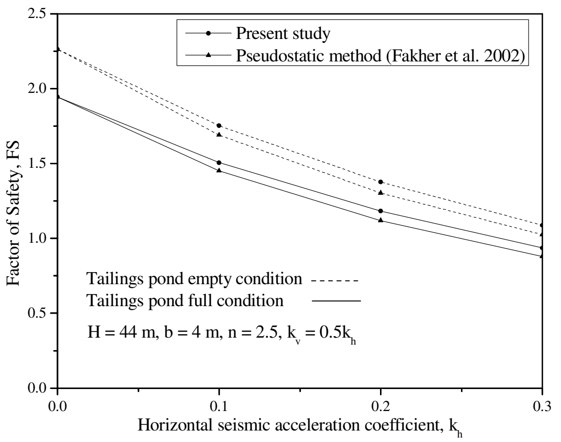

Figure 4. Comparison of factor of safety (FS) obtained by pseudo-dynamic results with those by pseudo-static results (Fakher et al. 2002) with $k_v = 0.5k_h$.

For finite values of k_h and k_v, factor of safety (FS) computed by pseudo-dynamic method of analysis is more than that by pseudo-static method. The pseudo-static based approach seriously underestimates the stability of dam due to conservative use of constant seismic accelerations throughout the height of dam. Also as the seismic increases, the results computed by using pseudo-dynamic method of analysis deviates more from those of pseudo-static method of analysis.

5 CONCLUSIONS

Considering the effect of time duration and phase differences in body waves propagating through the tailings dam during an earthquake, seismic inertia forces acting on the tailings dam are obtained using the pseudo-dynamic method. Present results show more appropriate consideration of real earthquake motion parameters as compared to the conventional pseudo-static methods. The study reveals that along with the seismic accelerations, the combined effect of time duration and the phase difference in body waves propagating through the tailings dam significantly changes the stability of the dam. The Factor of safety decreases significantly with increase in the seismic accelerations and phase differences in body waves.

The results of this study also indicate that, the pseudo-static based procedures conventionally used may underestimate sometimes the stability of tailings dams and embankments under seismic conditions. By using the pseudo-dynamic method, a more rational approach can be adopted for the seismic stability assessment based on correct estimation of dynamic soil properties and accurate prediction of ground motion parameters.

6 NOTATIONS

$a(z, t)$ = acceleration at depth z, time t
a_h, a_v = amplitude of horizontal and vertical seismic acceleration
g = acceleration due to gravity
G = shear modulus of the soil
k_h, k_v = seismic acceleration coefficient in the horizontal and vertical direction
$q_{hi}(t)$, $q_{vi}(t)$ = horizontal and vertical inertia force due to seismic acceleration acting on slice
t = time
T = period of lateral shaking (s)
V_s = shear wave velocity (m/s)
V_p = primary wave velocity (m/s)
l_i = length of top of i^{th} slice
V_i = vertical interslice force for i^{th} slice
c = cohesion of soil
FS = factor of safety
S_i = shear force acting on the base of each slice
N_i = normal force acting on the base of each slice
W_i = weight of i^{th} slice
H = height of the tailings dam
b = width of the crest of dam
R = radius of circular slip circle
h_i = thickness of elemental i^{th} slice
l_i = length of top side of elemental i^{th} slice
$m_i(z)$ = mass of elemental i^{th} slice
$X_{NS,O}$, $Y_{NS,O}$ = coordinates of the point where N_i and S_i act on the base of the slice with respect to centre of slip circle
$X_{G,O1}$, $Y_{G,O1}$ = coordinates of the centre of mass of the slice with respect to O_1 (the left corner point of the slice)
O = centre of the most critical slip circle
α_i = angle of base of elemental i^{th} slice
β = slope angle
m = number of slices
γ = unit weight of the soil
ϕ = soil friction angle
ω = angular frequency of base shaking
ρ = density of soil
ζ = $t - H/V_s$
ψ = $t - H/V_p$

ACKNOWLEDGEMENT

Authors appreciate financial support received from the sponsored project no. AERB/CSRP/31/07 by Atomic Energy Regulatory Board, Mumbai, India for carrying out this research.

REFERENCES

Choudhury, D. & Nimbalkar, S.S., 2005. Seismic passive resistance by pseudo-dynamic method. *Geotechnique* 55(9): 699-702.

Choudhury, D. & Nimbalkar, S.S. 2006. Pseudo-dynamic approach of seismic active earth pressure behind retaining wall. *Geotechnical and Geological Engineering* Springer, 24(5): 1103-1113.

Choudhury, D. & Nimbalkar, S.S. 2008. Seismic rotational displacement of gravity walls by pseudo-dynamic method. *International Journal of Geomechanics* ASCE, USA, 8(3): 169-175.

Choudhury, D. Nimbalkar, S.S. & Mandal, J.N. 2007. External stability of reinforced soil-walls under seismic conditions. *Geosynthetics International* The Institution of Civil Engineers, London, U.K. 14(4): 1-8.

Fakher, A. Nouri, H. & Shahgholi, M. 2002. Limit equilibrium in reinforced soil walls subjected to seismic loads. *In: Proceedings of the Third Iranian International Conference on Geotechnical Engineering and Soil Mechanics*, Tehran, vol. 3: 281-286.

Makdisi, F.I. & Seed, H.B., 1978. Simplified procedure for estimating dam and embankment earthquake-induced deformations. *Journal of Geotechnical Engineering* ASCE 104: 849–867.

Nimbalkar, S.S. & Choudhury, D. 2008. Effects of body waves and soil amplification on seismic earth pressures. *Journal of Earthquake and Tsunami*, World Scientific Publishing Company, Singapore, 2(1): 33-52.

Nimbalkar, S.S. Choudhury, D. & Mandal, J.N. 2006. Seismic stability of reinforced soil-wall by pseudo-dynamic method. *Geosynthetics International* The Institution of Civil Engineers, London, U.K., 13(3): 111-119.

Prakash, S. 1981. *Soil dynamics*, McGraw Hill, Inc., USA.

Sarma, S.K. 1975. Seismic stability of earth dams and embankments. *Geotechnique* 25: 743–761.

Shahgholi, M. Fakher, A. & Jones, C.J.F.P. 2001. Horizontal Slice Method of Analysis. *Geotechnique* 51 (10): 881-885.

Steedman/, R.S. & Zeng, X. 1990. The influence of phase on the calculation of pseudo-static earth pressure on a retaining wall. *Geotechnique*, 40(1): 103-112.