Effect of Vertical Seismic Coefficient in Slope Stability Analysis

Sukanta Das and B. K. Maheshwari

Abstract From the major earthquakes in hilly areas, the researchers have focused on the need of consideration of vertical seismic acceleration component in seismic slope stability analysis. The conventional pseudo-static method is quite common because of its simplicity. The earthquake force is considered as an equivalent static force (two seismic acceleration components) within the soil mass. The horizontal seismic acceleration coefficient is always considered acting away from the slope and the criticality of the direction of vertical seismic acceleration coefficient depends on the soil properties. The conventional pseudo-static method is considered in this study. The variation of factor of safety due to change in direction of vertical seismic coefficient for different soil properties is examined. Moreover, the critical direction of vertical seismic coefficient (k_v) for different types of soil has been investigated throughout this study.

Keywords Factor of safety · Pseudo-static method · Seismic slope stability · Type of soil

1 Introduction

The earthquake induced ground shaking may lead slopes to fail which are marginally stable before shaking. Although, stability of a natural or man-made slope depends on material properties, geometry and geological conditions of the slope [1]. Several methods have been adopted for stability analysis of slopes. Limit equilibrium is the method where the factor of safety (FS) can be estimated but no information is obtained regarding slope deformations. The stress deformation method gives the information about factor of safety as well as deformation. In pseudo-static method, to check the seismic stability of slopes, the earthquake force is considered as equivalent static force acting within the soil mass. Newmark Sliding block method is also adopted for seismic slope stability and permanent displacement assessment for seismic condition

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[2]. The horizontal seismic acceleration component (k_h) significantly reduces the FS of a slope. The recent earthquake damages in hilly areas have influenced researchers to focus on the vertical seismic coefficient (k_v) for the stability analysis of slopes. The vertical seismic coefficient is quite strong enough to influence the conventional stability analysis [3–5]. Sarma [6] determined the critical acceleration taking into account both seismic components for different soil conditions. Many researches have been conducted to check the effect of 'k_v' on slope stability analysis but those are mostly based on a particular soil type [7, 8].

No study has been found which directly suggests for considering the direction of 'k_v' for different types of soil in a common platform. In the present study, the effect of vertical seismic coefficient 'k_v' on conventional pseudo-static method for different types of soil has been discussed through analytical expressions and graphically. The effect of direction of 'k_v' on slope stability analysis for all types of soil has been summarized in the present work.

2 Pseudo-static Method

In Fig. 1, a typical planer failure surface has been presented and forces acting on the plane are shown with the as per direction. FS is a ratio of resisting force to the disturbing force acting on the failure plane. F_v and F_h are the seismic forces in vertical and horizontal directions, respectively, W is weight of the soil mass and N is the reaction force acting on the soil mass. General equation for FS can be obtained by resolving all the forces acting on the failure plane.

2.1 Factor of Safety

After resolving force acting along the failure surface of the slope, the equations for FS is obtained to evaluate the FS for c-Ø, pure cohesionless and cohesive soil. The c and ϕ are cohesion and internal friction of the soil is used as in conventional method

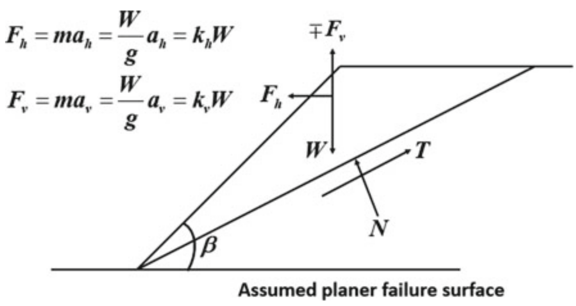

Fig. 1 Assumed failure surface in pseudo-static method

of pseudo-static analysis. Where W is weight of the soil, T is resisting force acting along the plane, N is reaction force acting perpendicular to the plane and β is slope angle. The direction of vertical seismic coefficient is positive in downward direction and negative in upward direction.

FS for c-Ø soil

$$\mathrm{FS} = \frac{\mathrm{CL} + [(W \mp F_V)\mathrm{Cos}\beta - F_h \mathrm{Sin}\beta]\tan\phi}{(W \mp F_V)\mathrm{Sin}\beta + F_h \mathrm{Cos}\beta} \tag{1}$$

In Eq. 1, the FS depends on soil strength parameters, slope angle and seismic forces. The Cosβ, term is effected by direction of (k_V) thus the FS is also effected. For c-ϕ soil, in normalized form is given in Eq. 2.

$$\mathrm{FS} = \frac{\frac{\mathrm{CL}}{W} + [(1 \mp K_V)\mathrm{Cos}\beta - K_h \mathrm{Sin}\beta]\tan\phi}{(1 \mp K_V)\mathrm{Sin}\beta + K_h \mathrm{Cos}\beta} \tag{2}$$

FS is strongly influenced by cohesion in Eq. 3. The 'Sinβ' denominator term is effected by direction of 'k_V' and the FS is also influenced.

FS for $\phi = 0$ soil

$$\mathrm{FS} = \frac{\frac{\mathrm{CL}}{W}}{(1 \mp K_V)\mathrm{Sin}\beta + K_h \mathrm{Cos}\beta} \tag{3}$$

In Eq. 4, numerator and denominator both are influenced by the FS but the numerator is influenced much because of its 'cos' component.

FS for $c = 0$ soil

$$\mathrm{FS} = \frac{[(1 \mp K_\mathrm{V})\mathrm{Cos}\beta - K_\mathrm{h}\mathrm{Sin}\beta]\tan\phi}{(1 \mp K_\mathrm{V})\mathrm{Sin}\beta + K_\mathrm{h}\mathrm{Cos}\beta} \tag{4}$$

3 Results and Discussion

In this present study, FS of slopes is obtained using commercial tool *Geostudio*, 2012. The ordinary slice method has been considered and the critical slip circle is obtained by several trial. The Mohr-Column failure criteria is considered and FS for different types of soil has been examined. The variation of FS with the change of direction of k_v for different soils has been presented subsequently.

3.1 *For Cohesionless Soil (c = 0)*

In this study, the value of vertical seismic coefficient is assumed as half of the horizontal seismic coefficient. Thus, Indian standard code 1893 [9] suggests that the value of '$k_{\rm v}$' should be taken as half or two third of the '$k_{\rm h}$'. The Fig. 2a, d shows the effect of vertical seismic coefficient on factor of safety for cohesionless soil with different value of angle of internal frictions. It can be observed that when '$k_{\rm v}$' is acting upward, the FS decrease with increase in value of '$k_{\rm v}$'. While when '$k_{\rm v}$' is acting downward, the FS increase with increase in value of '$k_{\rm v}$'. Thus, there is a clear effect of direction of '$k_{\rm v}$' and the difference in FS (for '$k_{\rm v}$' upward and for '$k_{\rm v}$' download cases) increase with increase in '$k_{\rm v}$'. As expected, with the increase in '$k_{\rm v}$' the difference of FS also increases and this phenomenon becomes strong when Ø value increases. The critical FS is observed when the '$k_{\rm v}$' acts against the gravity. The change of critical FS is much stronger at higher value of the vertical seismic

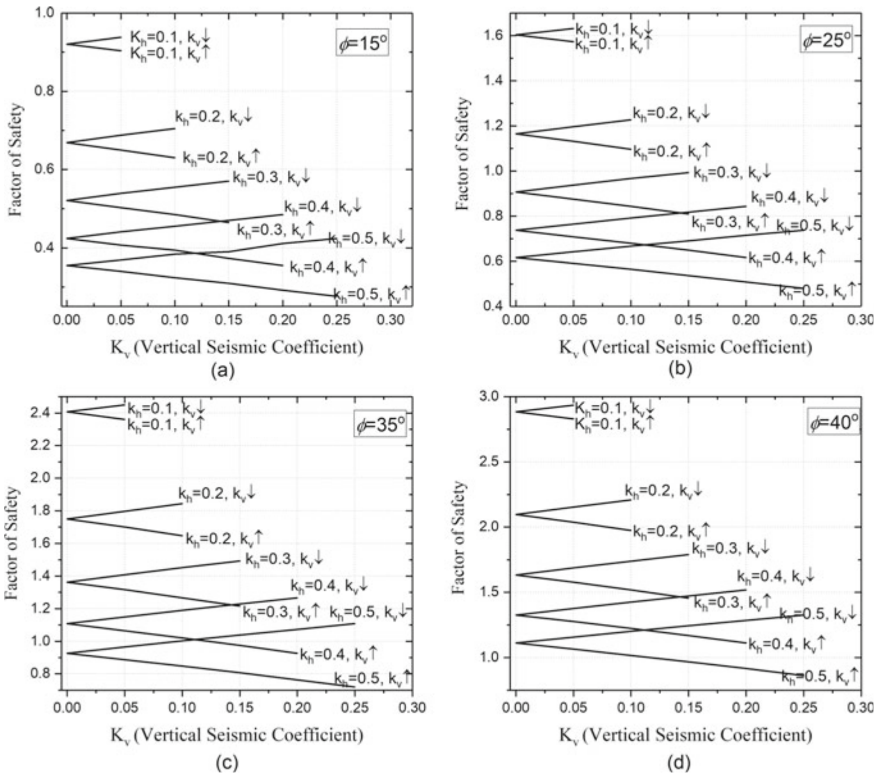

Fig. 2 Variation of factor of safety (FS) with vertical seismic coefficient ($k_{\rm v}$) towards ↓ and against ↑ the direction of gravity for cohesionless soil and for $c = 0$, $\gamma = 17$ kN/m^3, $\beta = 26°$, **a** $\phi = 15°$, **b** $\phi = 25°$, **c** $\phi = 35°$, **d** $\phi = 40°$

coefficient. Therefore, 'k_v' should be considered in upward direction or against the gravity for estimating of minimum or critical FS for cohesionless soil.

3.2 For Cohesive Soil ($\phi = 0$)

The variation of FS with the direction of 'k_v' for pure cohesive soil has been shown in Fig. 3. For pure cohesive soil, the critical FS has been found when the direction of 'k_v' is the that of the gravity. The trend of the results for cohesive soil are opposite to that of cohesionless soil. Similar phenomena has been observed throughout the graph with the increase of cohesion the FS increasing.

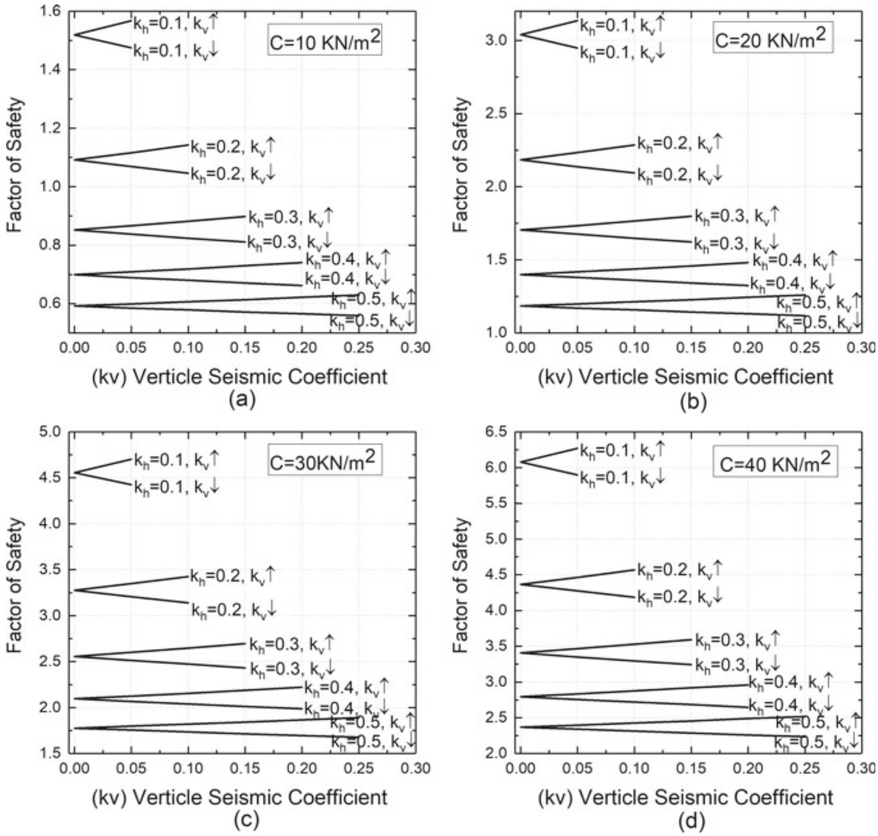

Fig. 3 Variation of factor of safety (FS) with vertical seismic coefficient (k_v) towards ↓ and against ↑ the direction of gravity for cohesive soil and for $= \phi 0$, $= \gamma 26$ kN/m^3, $= \beta 26°$, **a** $c = 10$ kN/m^2, **b** $c = 20$ kN/m^2, **c** $c = 30$ kN/m^2, **d** $c = 40$ kN/m^2

3.3 For c-ϕ Soil

The change of FS with different slope angles for '*c*-Ø' soil is shown in the Fig. 4a, d. From Fig. 4a, the variation of FS increases due to change of direction of 'k_v' with the increase of 'k_h'. The upward direction of 'k_v' is giving critical factor of safety in most of the cases for lower value of β. However, with the increase of slope angle the critical FS has been observed in downward direction of 'k_v' at a certain value of 'k_h' and after that upward direction of 'k_v' gives the critical FS.

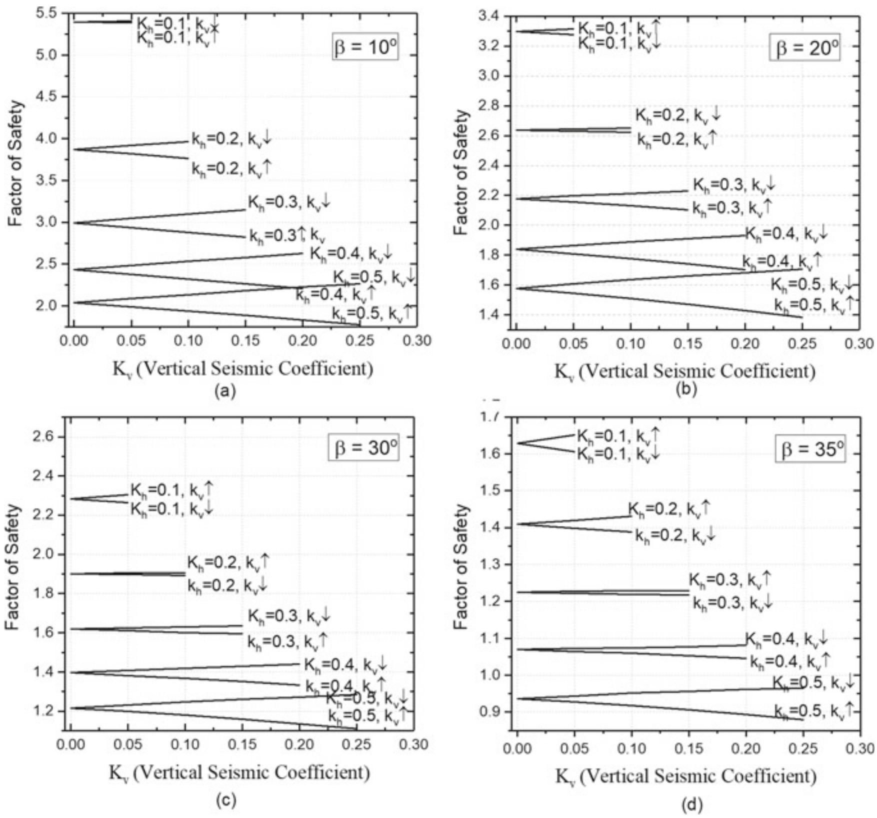

Fig. 4 Variation of factor of safety (FS) with vertical seismic coefficient (k_v) towards ↓ and against ↑ the direction of gravity for *c*-Ø soil and for $c = 10$ kN/m^2, $= \gamma 17$ kN/m^3 and $= \phi 40°$, **a** $= \beta 10°$, **b** $= \beta 20°$, **c** $= \beta 30°$, **d** $= \beta 35°$

4 Conclusions

From the above study the following conclusions can be drawn:

For a given cohesionless soil slope, the critical direction of vertical seismic coefficient is upward direction or against the gravity which gives the minimum factor of safety. While the minimum FS is observed in the downward direction of vertical seismic coefficient for cohesive soil slope.

In case of '*c*-Ø' soil slope, the critical direction of vertical seismic coefficient depends on the domination parameter between *c* and Ø. However, the critical direction of vertical seismic coefficient depends on the slope angle for a constant *c*-Ø value.

References

1. Kramer SL (1996) Geotechnical earthquake engineering. Prentice Hall, Upper Saddle River NJ
2. Newmark NM (1965) Effects of earthquakes on dams and embankments. Geotechnique 15(2):139–160
3. Chopra AK (1966) The importance of vertical component of earthquake motion. Bull Seismol Soc Am 56(5):1163–1175
4. Jibson RW (2011) Methods for assessing the stability of slopes during earthquakes—a retrospective. Eng Geol 122(1):43–50
5. Leschinsky D, Ling HI, Wang JP (2009) Equivalent seismic coefficient in geocell retention systems. Geotext Geomembr 27(I):9–18
6. Sarma SK (1999) Seismic slope stability—the critical acceleration. In: Proceedings of the second international conference on earthquake geotechnical engineering. Balkema, Lisbon. pp 1077–1082 Standard (BIS). New Delhi, India
7. Sahoo PP, Shukla SK, Mohyeddin A (2018) Analytical expressions for determining the stability of cohesionless soil slope under generalized seismic conditions J Mountain Sci 15(3)
8. Malla S (2017) Consistent application of horizontal and vertical earthquake components in analysis of a block sliding down an inclined plane. Soil Dyn Earthq Eng 101:176–181
9. IS: 1983 (2016) Indian standards criteria for earthquake resistant design of structures. Part 1, Bureau of Indian