The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.

Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

Seismic behavior of strip footings on slopes

Comportement sismique des semelles filantes sur les pentes

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ABSTRACT: In past, the seismic behavior of slopes and shallow foundations on flat ground has been studied separately. Recently few researchers have studied the seismic behavior of shallow foundations resting on slopes by pseudo-static analysis. The seismic behavior of buildings or foundations on hill slopes are not much reported in the literature. In the present research work, seismic behavior of strip footing placed on slopes is studied. The effect of different slope angles and footing loads on seismic response of a strip footing is investigated. A two dimensional finite element based numerical analysis has been carried out to investigate the failure mechanism and displacement of strip footing on soil slopes. The response of slope-footing system is obtained in terms of displacement when strip footing is located at the centre of slope face for given earthquake excitation. From the results, it is observed that with the increase in slope angle, the amplification of the slope-footing system increases and remain almost constant at toe. The vertical displacement at the center of the slope and beneath the footing significantly increases with the increase in footing loads.

RÉSUMÉ : Dans le passé, la réponse sismique des pentes et des fondations peu profondes sur un sol plat a été étudiée séparément. Récemment, peu de chercheurs ont examiné la réponse sismique de fondations peu profondes reposant sur des pentes par analyse pseudo-statique. Le comportement sismique des bâtiments ou des fondations sur les pentes des collines n'est pas beaucoup rapporté dans la littérature. Dans la présente étude, la réponse sismique d'une fondation peu profonde reposant sur une pente est étudiée. L'influence des différents angles de pente et des charges de semelle sur la réponse sismique d'une semelle en bande est étudiée. Une analyse numérique bidimensionnelle basée sur les éléments finis a été réalisée pour étudier le mécanisme de rupture et le déplacement des semelles filantes sur les pentes du sol. La réponse du système de semelle de talus est obtenue en termes de déplacement lorsque la semelle filante est située au centre de la face de talus pour une excitation sismique donnée. D'après les résultats, on observe qu'avec l'augmentation de l'angle de pente, l'amplification du système de talus-semelle augmente et reste presque constante au pied. Le déplacement vertical au centre de la pente et sous la semelle augmente significativement avec l'augmentation des charges de la semelle.

KEYWORDS: Slope-Footing System; Earthquake; Displacement; Finite Element Analysis

1 INTRODUCTION

The general purpose of footing is to transmit the superstructure loads into the subsoil within a permissible settlement and safe bearing pressure. The footing need to perform satisfactory under inconsistency in the ground conditions which may come across the site. When footings are placed in the vicinity of sloping surface, it is highly desirable that the Slope-Footing-Structure (SFS) work together as a collective system. In particular, during earthquake events soil-footing system play an appropriate role in bringing the level of performance.

Past studies have reported that the bearing capacity of strip footing on slopes decreases due to sloping surface and different pressure distribution than the horizontal surface (Meyerhof 1957). Mainly two types of failure (global and local) of a slope has been observed when footings are located on slopes (Paul and Kumar, 1997) with the reduction in Factor of Safety (FOS). Recently, using pseudo-static method, researchers proposed design charts for seismic bearing capacity of footing in slopes. Some of them have considered the footing at the top of the slope. Whether footing is located on the face or at the top of slope, a significant reduction of bearing capacity of footing has been witnessed due to seismic forces (Sarma and Iossifelis, 1990; Sawada et al., 1994; Kumar and Mohan Rao, 2003; Choudhury and Subba Rao, 2006). There are many approaches of analyses e.g. using upper-bound solutions (Richards et al., 1993; Soubra, 1999; Kumar and Ghosh, 2006; Yamamoto, 2010) and methods of stress characteristics (Casablanca et al., 2016), or numerical analyses (Charkraborty and Kumar, 2015; Cinicioglu and Erkli, 2018). However, only the advanced numerical method gives the displacement for each time step of the given seismic excitation (Kourkoulis et al., 2010; Azzam, 2015). Fatahi et al., (2019) investigated the seismic behavior slope-building system with real earthquake motion. They reported that the rocking and deflection of building increases at nearest distance of building from the slopes. Huang (2019) studied experimentally, the seismic bearing capacity of fixed and free rotating square footings near the slope. A critical failure mechanism of two footings was reported in his study. However, more study or research work is needed to make proper understanding of design of footing on top or near the slopes under earthquake events. The bearing capacity of strip footing on the face of the slope under real earthquake motion has not been explored much.

In the present study, the seismic response of footing has been examined using two dimensional (2D) finite element (FE) analyses under the real earthquake event. First, the results obtained from the present FE analysis are compared with one dimensional ground response analysis and thus validated. Next effect of increase in slope angle on the seismic response of slope at three different locations (crest, center and toe) are examined. Finally, the effect of surcharge load (q) on both horizontal and vertical displacements of footing located at the centre of slope is investigated.

2 FEM MODELING

A strip footing of 4m width embedded on the face of the slope ($\beta = 0^0$, 20^0 and 30^0) has been adopted in this numerical analysis. 2-D Finite Element Analysis (FEA) with 15-noded triangular elements (Figure 1) has been performed to examine the seismic behavior of strip footing on slopes in plain-strain condition using PLAXIS 2D. Height of soil slope (h_s) varies according to slope angle and thus the total height (H) also varies. While slope width (b_s) and total base width (W) are kept constant as 50 m and 150 m, respectively. The slope is subjected to surface load (q) equal to 0kPa, 100kpa and 300kPa.

The elasto-plastic Mohr-Coulomb (MC) soil model with yield failure criteria has been adopted. The material parameters of the soil have been collected from the database of the sand properties given by Zhang et al., (2010) and presented in Table 1. The strip footing has been considered as an elastic beam element. The average dimension of the elements *l* in the PLAXIS 2D has been taken by satisfying the condition in (Eq. 1). It means that the size of the finite elements, Δl, must be smaller than approximately 1/10 to 1/8 of the minimum wavelength (λ_{min}) related with the maximum frequency content (f_{max}) of the input excitation, (Kuhlmeyer and Lysmer, 1973) i.e.

$$\Delta l \leq \frac{\lambda_{min}}{8-10} \quad (1)$$

In the dynamic analysis, the free-field boundaries at the lateral sides of the model has been adopted. While the boundary condition at the bottom of the FE model has been kept as fixed in both horizontal and vertical directions. The input ground motion is applied at the bottom nodes as vertically propagating shear waves having particle motion in the horizontal direction. The details of geometry, meshing and boundary conditions are shown in Figure 1. The input ground motion applied at the base of the FE model is 45^0 component of the recorded outcrop motion of 1999 Chamoli earthquake at Gopeshwar station in Chamoli district (Uttarakhand, India) as recorded in the seismological observatory of IIT Roorkee. The acceleration-time history of this motion indicates a Peak Ground Acceleration (PGA) of 0.37g (Fig. 2a) and the Fourier spectrum shows a predominant frequency of 1.66 Hz (Fig. 2b).

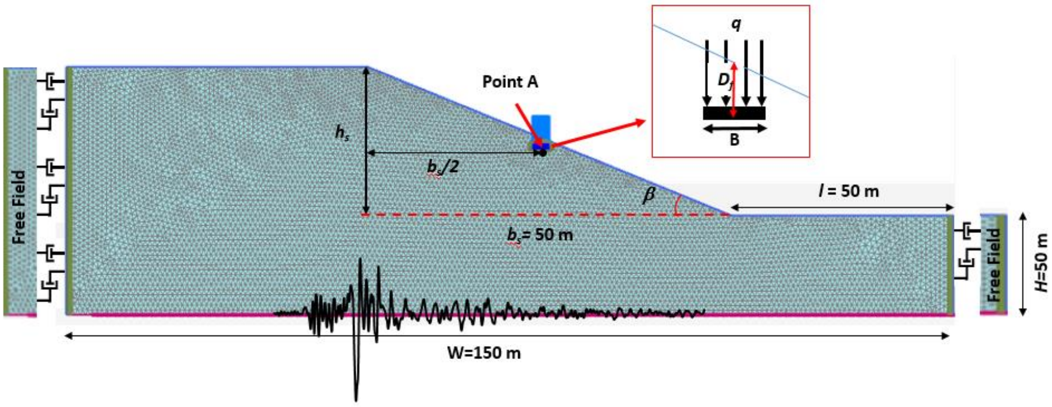


Figure 1. Geometry and boundary conditions of slope footing system where footing width (B)=4m and embedment depth (D_f)=2m.

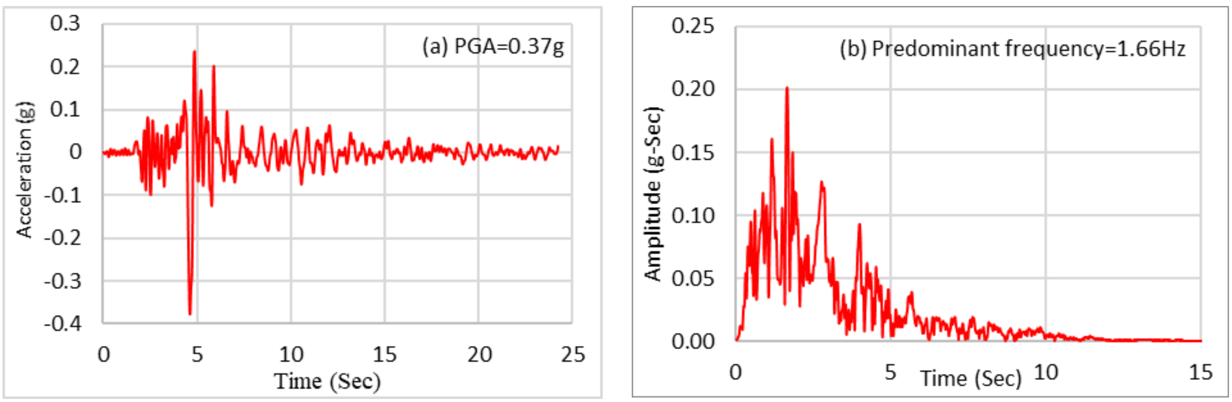


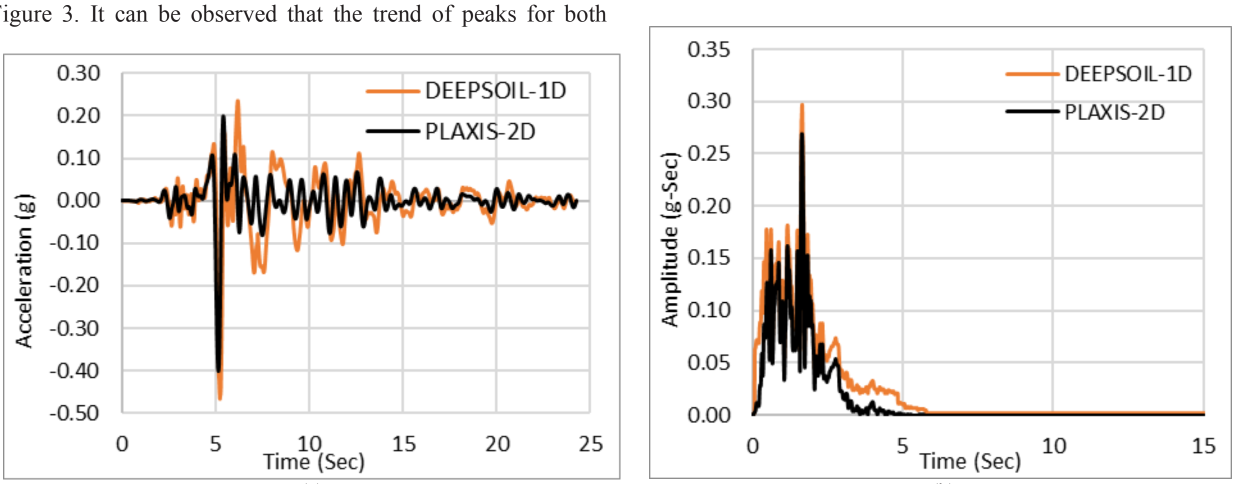
Figure 2. Recorded outcrop motion at IIT Roorkee: Gopeshwar station in Uttarakahnd, India during 1999 Chamoli earthquake (a) Acceleration-time history (PGA=0.37g) (b) Fourier spectrum (Predominant frequency=1.66Hz)

Table 1. Material properties of soil (Toyoura sand) and footing used in FE analyses

Materials	Parameter	Value
Soil	Unit weight, γ (kN/m^3)	16.3
	Modulus of elasticity, E (MPa)	40
	Poisson's ratio, ν	0.30
	Shear wave velocity, V_s (m/s)	96
	Damping Ratio (ξ)	0.10
Footing	Unit weight, γ (kN/m^3)	25
	Modulus of elasticity, E (GPa)	30
	Poisson's ratio, ν	0.2
	Depth of footing, D_f, (m)	2
	Thickness of footing, t_f (m)	0.05

3 VALIDATION

It is important to validate the results obtained from the present FEA. For this, a comparison of acceleration-time history and Fourier amplitude spectrum obtained using 2D FE Analysis (PLAXIS 2D) and 1D Analysis (DEEPSOIL) for horizontal ground (β=0) with no surcharge (q=0) for linear elastic soil is carried out. The results obtained for horizontal ground motion at the surface using DEEPSOIL and PLAXIS 2D are shown in Figure 3. It can be observed that the trend of peaks for both acceleration-time history (Fig. 3a) and Fourier spectrum (Fig. 3b) are similar using two different analyses. However, there is difference in peak values. The peak values using 2D analyses are slightly lower than that obtained using 1D analysis. This is attributed to the fact that release of energy flux is bit higher in two-dimensional domain. Thus, the results from 2D FEA are as expected and this validates computation tool used.



(a) (b)

Figure 3. Comparison of surface ground motion in free field condition for horizontal ground (a) Acceleration time history and (b) Fourier spectrum

4 RESULTS OF FEA AND DISCUSSIONS

The behavior of soil has been considered using MC Soil model in FEA performed using PLAXIS 2D. The results are presented in following three subsections. First free-field response is examined, followed by influence of slope angle and location of footing on the seismic response of footing. Finally, the seismic displacement of footing on slope has also been examined under increasing surface loads (q=0kPa, 100kPa & 300kPa).

4.1 *Free field response*

The seismic excitation is assigned at the base of the horizontal ground and the free field response is recorded at the top surface. The acceleration-time history and Fourier spectra of surface ground motion are shown in Figure 3. The peak values are listed in Table 2, it can be observed that for 2D analysis there is a small amplification in PGA from 0.37g to 0.40g. Similarly, the Fourier amplitude increases from 0.20g-sec to 0.26g-sec at predominate frequency 1.66Hz. This can be explained with the fact that the fundamental frequency of soil layer built-in-base (Fig. 1) is 0.48 Hz (= V_s/4H) which is quite lower than the predominant frequency of earthquake excitation, therefore, a large amplification is not expected for 10% damping ratio of soil.

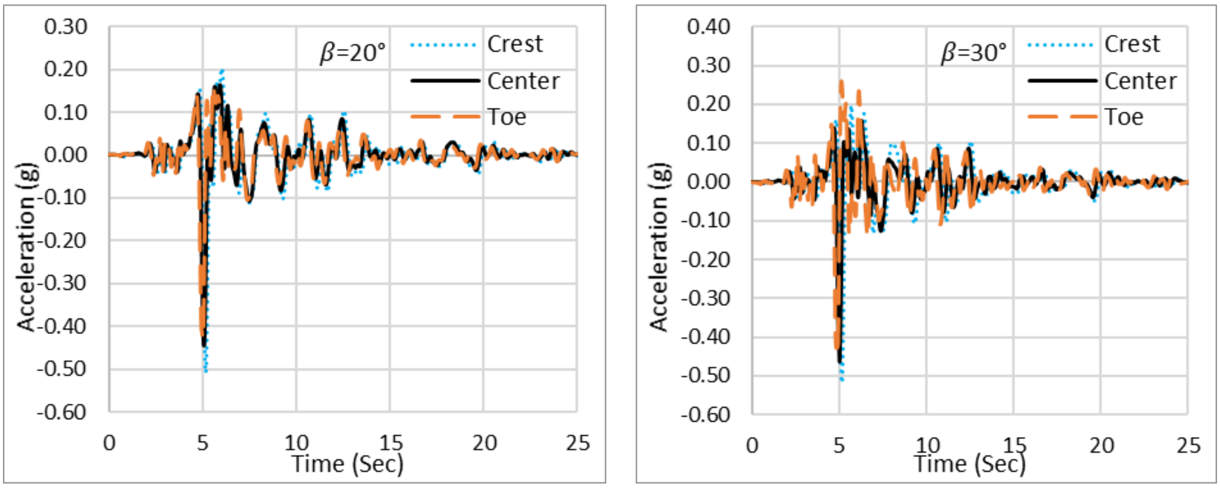
4.2 *Influence of slope angle*

Figure 4a and 4b present acceleration time history at crest, center and toe for slope angle 20^0 and 30^0, respectively. The variation of acceleration with time is observed to be similar for different locations along the slope but the maximum PGA has been found at the crest. However, some amplifications can also be observed at the center and toe of the slopes. This observation holds good for both slope angles 20^0 and 30^0. The PGA of acceleration at crest, centre and toe of the slopes has been recorded and given in Table. 3. It can be noted that as compared to horizontal ground (β=0), values at all locations are amplified with respect to 0.40g. Further, for slope 20^0, the change of PGA from toe to center is 7% and from toe to crest is 19%. Similarly, for slope 30^0, the change of PGA from toe to center is 11% and from toe to crest is 24%. Thus for both slope angles, the largest amplification is at the crest and smallest is at toe.

Further, as slope angle increases, the PGA and Fourier amplitude at the centre of the slope also increases, however, the effect of slope angle is not evident at toe (Table 3). The variation of the PGA and Fourier amplitude at the center of the slope for angles β = 0^0, 20^0 and 30^0 are presented in Fig. 5. It can be observed from, Fig. 5a, that the PGA increases by a margin of 13% as slope angle increases from 0 to 20^0 and by a margin of 18% as slope angle increases 0 to 30^0. Similarly, the Fourier amplitude increases by a margin of 23% and 31%, respectively due to increase of slope angle from 0^0 to 20^0 and from 0 to 30^0 respectively. Thus higher the slope angle, higher the amplification at the same location. This was as expected as slope angle increases, the height of slope also increases and greater amplification may be expected for higher depths of soil layers.

Table 2. Comparison of PGA and Fourier amplitude in free field condition with input motion

Condition	**PGA (g)**	**Fourier amplitude (g-Sec)**
Input motion	0.37	0.20
Free field motion (PLAXIS-2D)	0.40	0.26
Free field motion (DEEPSOIL-1D)	0.46	0.29



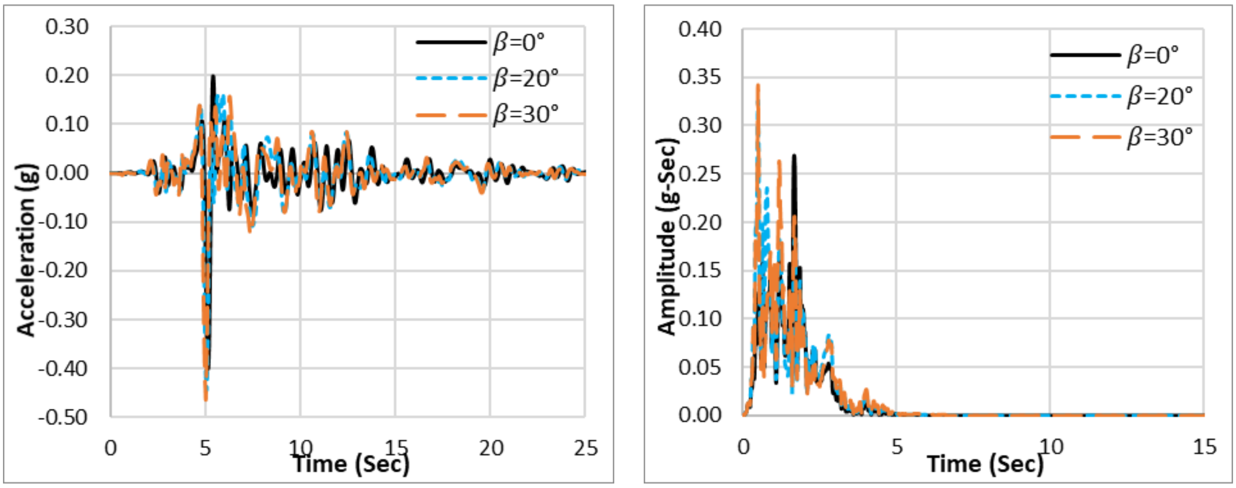
(a) (b)

Figure 4. Computed acceleration time histories at the crest, center and toe of the slopes for unloaded slopes for (a) $\beta = 20^0$ (b) $\beta = 30^0$

Table 3. The PGA at the crest, center and toe of slopes

Slope angle (β)	PGA in g		
	Crest	Center	Toe
β=0°	0.40	0.40	0.40
β=20°	0.50	0.45	0.42
β=30°	0.52	0.47	0.42

Therefore, the effect of slope angle is found significant in ground motion amplification (13% to 18% for slopes considered). The amplification has been found maximum at crest and decreases towards the toe of the slopes. The amplification at toe has been found almost constant due to constant height irrespective of the slope angle.



(a) (b)

Figure 5. Seismic response at center of slope (without footing) for $\beta = 0^0$, 20^0 and 30^0 (a) Acceleration time history (b) Fourier spectrum

4.3 *Effect of surface loads on seismic displacement*

In general, the load of the superstructure is transmitted by the footing into the soil. In the present study, an attempt has been made to know the influence to surface load on seismic displacement of footing on slopes, at point 'A'. A footing of 4m width has been placed on the face of the slope under surface load (q= 0kPa, 100kPa and 300kPa) subjected to earthquake motion.

The seismic displacements of footing on horizontal ground under surface loads (q) in lateral direction and vertical direction have been recorded and presented in Fig. 6. Further, Figures 7 and 8 present these results for □ = 20^0 and 30^0, respectively. It can be observed that there is no effect of surface load on lateral displacements though values increase with the slope angle. However, there is a significant effect of applied vertical load (q) on vertical displacements at all the slope angles. Where the values of vertical displacements are increased suddenly as q increases. Due to application of q, the lateral displacement remain constant because of the direction of the applied surface load is vertical. In Fig. 6b, vertical displacement at q=0kpa initially follows zero displacement with zigzag pattern after time 5sec due to increase in values of the excitation. This trend also holds for other two slope angles (Figs. 7b and 8b).

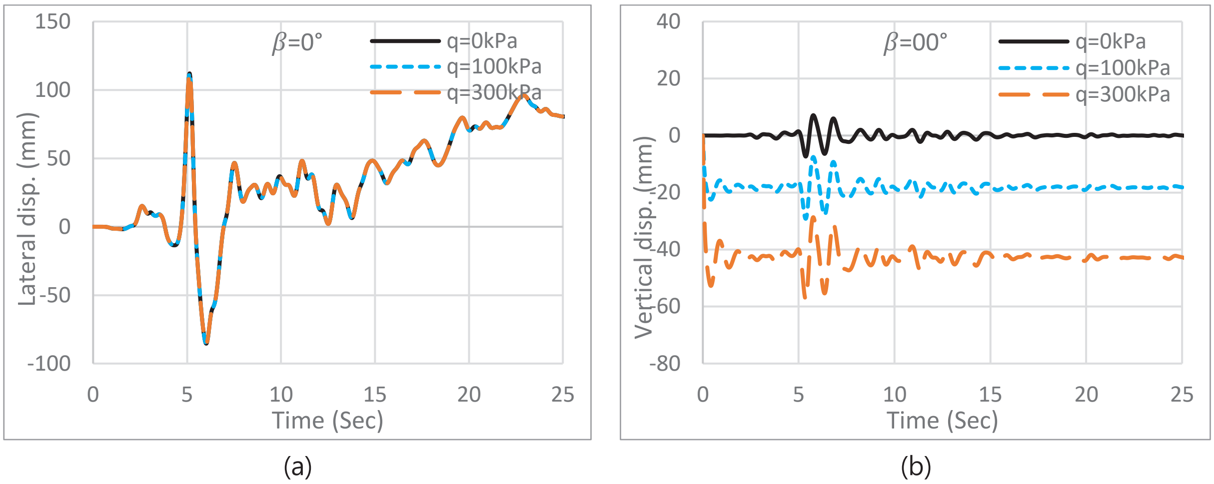


Figure 6. Influence of footing loading (q) at the centre of slope for horizontal ground (a) Lateral displacement (b) Vertical displacement

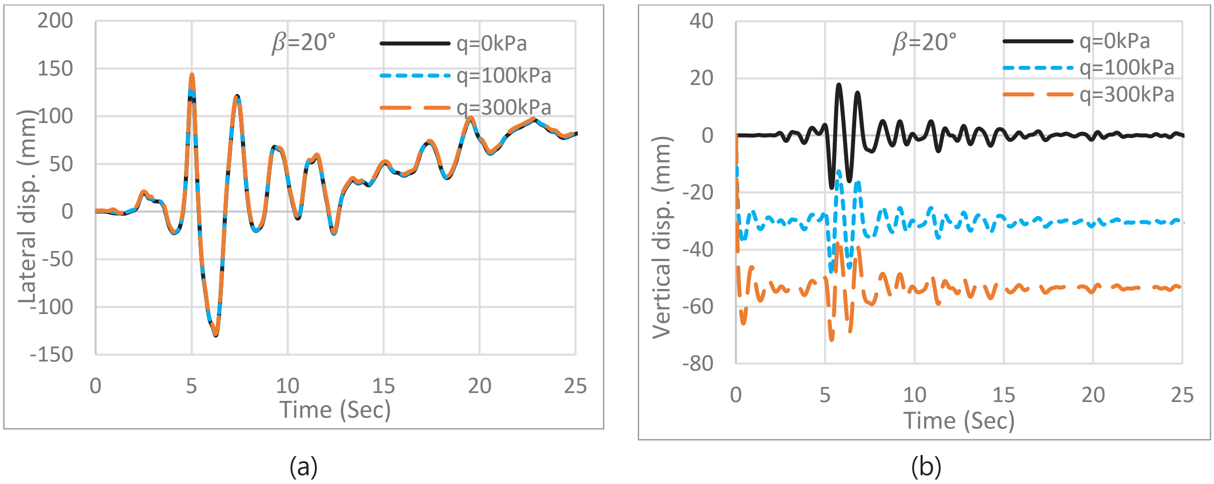


Figure 7. Influence of footing loading (q) on seismic displacement at center of slope for 20^0 slope (a) lateral displacement (b) Vertical displacement

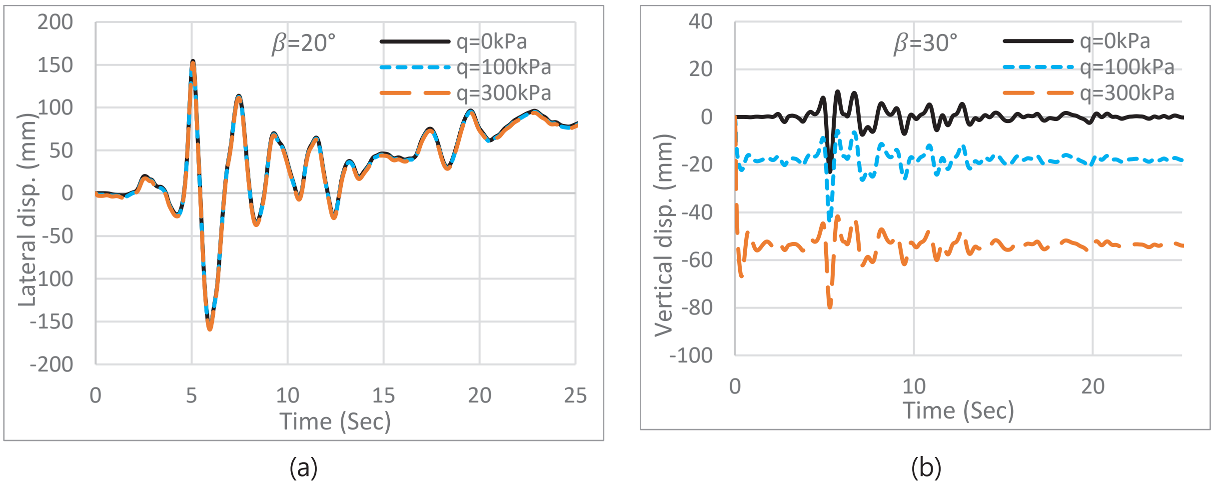


Figure 8. Influence of footing loading (q) on seismic displacement at centre of slope for 30^0 slope (a) lateral displacement (b) Vertical displacement

5 CONCLUSIONS

The present results of FE analyses indicate the following:

- A comparison of seismic response (acceleration time history and the Fourier spectra) has been performed using PLAXIS-2D and DEEPSOIL-1D. The acceleration and amplitudes obtained from PLAXIS 2D are found less compare to DEEPSOIL due to maximum release of energy but the trends of the response are similar.
- The slope amplification increases as slope angle increase and the maximum amplification has been found at the crest and smaller at center of the slopes. The slight amplification has been observed at the toe which is not significantly influenced by the slope angles.
- For a constant surface load q, as slope angle increases the both lateral and vertical seismic displacement increases. However, an initial vertical displacement has been observed due to presence of static vertical load and with the increase of surface load q, the vertical displacement increases. While, the lateral increase displacement has been found insignificant under increment of surface loads.

6 ACKNOWLEDGEMENT

Author wants to thank and appreciate the help of his PhD student Mr. Sukanta Das in preparing this manuscript.

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