Effect of Transmitting Boundary on Soil – Slope - Foundation Interaction

Vijay Kumar, Surbhi Rani, Akash Priyadarshee, Ashish Kumar, Atul Kumar Rahul

Abstract*: In recent years, extensive research has been performed when the foundation is placed on the crest of slope. Besides of so many researches less number of researches has been done for foundation is placed on slope considering Soil-Structure Interaction (SSI) effect. Construction on slopes poses more challenges especially under seismic load due to an earthquake in addition to the forces of sliding slope itself. The failure of slope not only affects any structure but also has damaging consequences on the environment in general. Therefore, transmitting boundaries should be adequate to absorb the seismic energy at the boundaries. In this paper, effect of transmitting boundary on soil-slope-foundation interaction (SSFI) is studied. Two cases have analysed for SSFI when foundation is placed at various position on the crest and slope itself. El-Centro earthquake (1940) with three different PGA viz. 0.25g, 0.5g and 1g is applied as input motion for both the cases. It is observed that the foundation placed near the slope is more susceptible to damage. Responses of slope (acceleration and displacement) have also been observed at three different nodal points on slope. Results show that the amplification in soil mass leads to settlement of foundation. Shear stress and equivalent plastic strain distribution for SSFI is discussed for different load conditions. It is found that the slope-foundation system shows the local and global failure. Further Post earthquake peak settlement for foundation is plotted and it shows the true behavior of soil.

Keywords: SSFI, Seismic loading, slope, Transmitting Boundary, Post earthquake, slope stability.

I. INTRODUCTION

The important structures like high rise buildings, long span bridges, nuclear power plants, dam etc. must be cost effective and safe. To achieve these goals responses of the structures to various types of loading must be known very accurately. Loadings are may be dynamic in nature. There are so many factors that affect response of the system. Past studies confirm that, dynamic interaction between soil and the structures is very important [1].

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Hence, dynamic behaviours of the systems cannot be accurately predicted without considering the SSI. Past studies show that the structural design methods neglect the SSI effects; results inaccurate solution of soil-foundation system. Therefore, effect of SSI becomes important for structures situated on relatively soft soils. Many researchers [2–4] confirm that Kobe, 1995 earthquake highlighted the seismic behaviour of a superstructure as well as substructure.The transmitting boundaries can be typically classified into two important arrangements [5]; local (viscous) and consistent boundaries. Local boundary conditions are commonly used in engineering practice because the radiation condition is satisfied approximately at the artificial boundary, as the solution is local in space and time. On the other hand, consistent boundaries [6] and [7] have mathematically complex formulations and satisfy exactly the radiation condition at the artificial boundary. [8] recommended a system of dashpots (independent of wave frequency) known as viscous boundary, positioned at an artificial boundary, which are able to absorb both harmonic and non-harmonic scattering waves effectively. [6] proposed a transmitting boundary (dependent on the frequency) which is intended to absorb body waves and surface waves on the lateral infinite boundary. [9] proposed the technique which absorb radiating wave from the interior region to outward on the absorbing region around about an interior region. Dirichlet and the Neumann boundary conditions for mathematical modeling was proposed by [10]. For elastic wave propagation problem Perfectly Matched Layer (PML) method was introduced by Berenger [11]. Further some mixed method was used with increasing damping along the wave propagation path by Liu and Jerry [12]. A serious limitation of this approach is that for low frequency excitations it leads to permanent displacements even in elastic systems. Various modifications of the standard viscous boundary have been introduced that overcome this shortcoming: boundaries based on Kelvin elements by Novak et al. [13] and Novak and Mitwally [14], the doubly asymptotic multi-directional boundary of Wolf and Song [15] and cone boundary of Kellezi [16]. Among above discussed boundary some of the boundary has been used in the present study for analysing the dynamic soil–slope-foundation interaction. The available literature on stability analysis of soil–slope-foundation interaction deals the failure mechanism caused by shear strength reduction method but very less number of literatures are available based on strain localization failure in slope mass. Past studies [17–26] have used failure caused by shear strength reduction mechanism in both the cases of static and dynamic.

SSI consideration is important in the behaviour of structure as well as soil under static or dynamic loading.
The analysis accurately predicts the structural behaviour. Improvement occurs in the safety of structures under seismic loading by considering SSI. Since soil-foundation behaviour is predominantly nonlinear, therefore, it makes the problem complex. In a soil-foundation interaction effect it is necessary to account on soil properties, foundation material, foundation width, loading type and bed slope of ground. The overall understanding of SSI is depicted in Fig. 1.

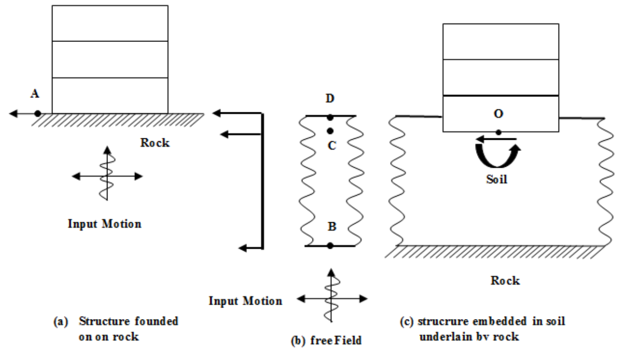


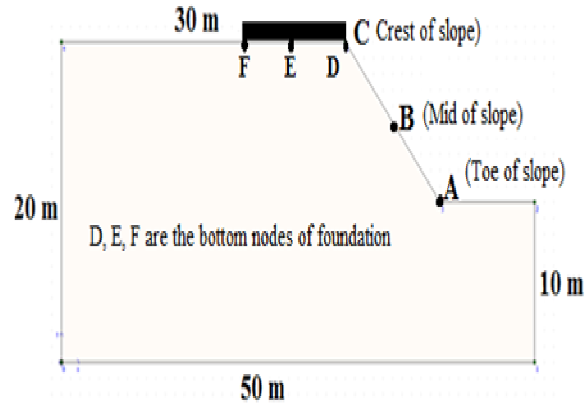
Figure 1: Seismic Response of structure with interaction effect {after Wolf, 1994}

In this paper effect of transmitting boundary on soil-slope-foundation interaction (SSFI) is studied with finite element method (FEM). Two cases have analyzed for SSFI when foundation is placed at various position on the crest and slope itself. El-Centro earthquake (1940) is applied as input motion at the base of Soil-Foundation system in both the cases. Analysis has been performed to assure the damage susceptibility in the slope. Acceleration and displacement response at various nodal points on slope-foundation have been calculated. For different load conditions shear stress and equivalent plastic strain distribution for SSFI is Further Post earthquake peak settlement for foundation is plotted.

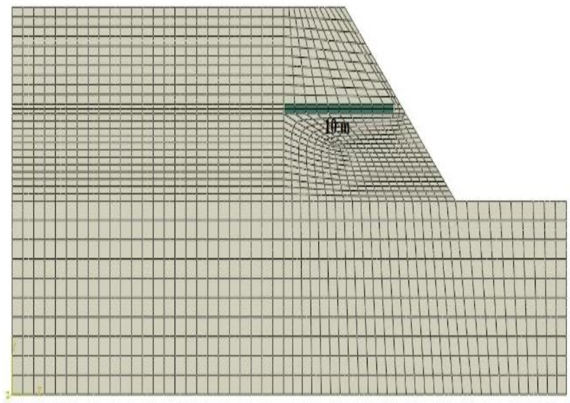
II. STATEMENT OF PROBLEMS

For the analysis of soil–slope-foundation interaction (SSFI) a slope geometry of 45 degree inclination is considered which is shown in Fig. 2. The geometry is modelled with non-linear finite element (FE) plain strain model. The model is analysed with the Lysmer and Kuhlemeyer [8] boundary condition in PLAXIS. Further results have been compared with three transmitting boundary conditions viz. Lysmer and Kuhlemeyer [8], Novak and Mitwally [14] and (Bettess 1977) Infinite element boundaries in ABAQUS. The three boundary conditions will be called further as BC-1, BC-2 and BC-3 corresponding to Lysmer and Kuhlemeyer, 1969 (abbreviated as, L-K), Novak and Mitwally, 1988 (abbreviated as, N-M) and Bettess, 1977 (abbreviated as, Bettess), respectively. The 15-node finite triangular element is used in PLAXIS and 8 noded quadrilateral element is used in ABAQUS. Two cases have analysed for SSFI when foundation is placed at:

1. Near the crest of slope (Fig. 2a) and
2. On the slope itself (Fig. 2b).



(a)



(b)

Figure 2: Geometry of Slope Model

In this analysis foundation is palced near to crest, 10 m away from crest and slope itself. The width of foundation is considered as 10 m. The damping in soil and foundation are assumed as 15% and 5% respectively. The 5 kN, 10 kN, 15 kN, 20 kN and 25 kN along with self weight are applied on the foundation for the analysis.
The stress distribution for all load case is discussed in further section. Factor of Safety (FOS) and response of slope-foundation system in terms of acceleration and displacement have been observed at three various nodal points as shown in Figure 2a. Further responses have been observed at the nodal points D, E amd F of the foundation. Finer and coarser mesh have compared for getting the percentage of accuracy of solutions. For input motion El-Centro earthquake (1940) with three different PGA such as 0.25g, 0.5g and 1g is applied for 30 seconds at the base of the system. Acceleration time history for 0.5g PGA is shown in Fig. 3.

III. ANALYSIS OF RESULTS

For analysis, Mohr-Coulomb material model is used. The results has been observed for two different approach using PLAXIS and ABAQUS.

The frequency analysis of the soil foundation system has been performed. On the basis of obtained frequency the Rayleigh damping co-efficient α and β has calculated. The material properties for soil and foundation are shown in Table-1.

Table 1. Slope-Foundation Parameters

Properties of Soil-Slope	
Modulus of Elasticity	40 x 10^6 N/m^2
Poisson's ratio	0.35
Density of Soil	2040 kg/m^3
Damping in soil	15%
Rayleigh damping Co-efficient α and β	0.2805 & 0.1212
Dilation angle	0.1
Shear Modulus	250 x 10^6 N/m^2
Cohesion	5 x 10^6 N/m^2
Friction angle	18^0
Slope angle	45^0
Properties of Foundation	
Thickness of foundation	0.5 m
Width of foundation	10 m
Density of concrete	2500 kg/m^3
Damping in concrete	5%
Normal stiffness	25 x 10^6 N/m
Flexure rigidity	9 x 10^6 Nm^2/m
Poisson's ratio	0.1
* Density corresponding to the 25 kN/m load on a beam.	

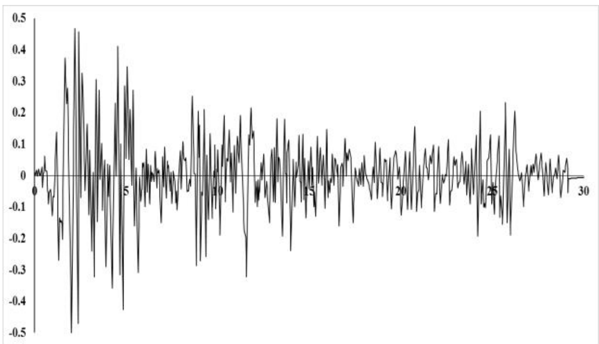


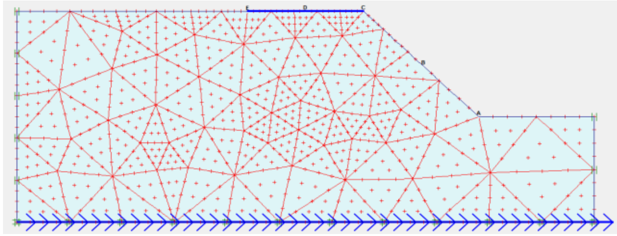
Figure 3: Peak ground acceleration-time history (EL-Centro, 1940) with 0.5g

Table 2. Time Period of system (sec.)

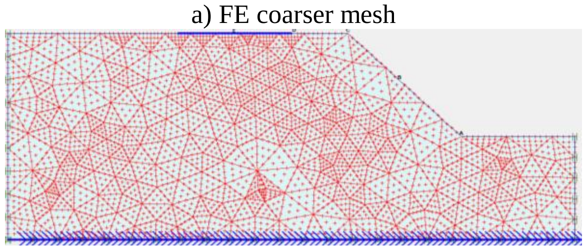
Modes	Without foundation	With foundation on crest	With foundation on slope
1	0.183	0.716	0.947
2	0.116	0.352	0.528
3	0.078	0.268	0.478

IV. EFFECT OF POSITION OF FOUNDATION ON SLOPE STABILITY

In order to study the slope stability foundation is placed near the crest of slope and 10 m away from the crest as shown in Figure 4.



a) FE coarser mesh



(b) FE finer mesh

Figure 4: FE mesh of geometry model

The slope stability criterion has set up for the stability of slope. The stability of slope is tabulated in Table 2.

Table 3. Effect of position of foundation

Slope stability criteria	Near the crest: Coarser mesh	Near the crest: Medium mesh	Near the crest: Finer mesh	10 m away from crest: Coarser mesh	10 m away from crest: Medium mesh	10 m away from crest: Finer mesh
FOS	1.39	1.40	1.44	1.57	1.61	1.65
Computational time	30 mins.	36 mins.	45 mins.	27 mins.	31 mins.	38.5 mins.

Table 3 shows the variation of FOS with mesh size. It has been observed that, finer mesh is increasing the FOS from 2.78 % to 3.47 % with respect to medium and coarser mesh.

V. EFFECT OF PGA ON SLOPE

The enactment of position of foundation on slope has been evaluated in terms of displacement and acceleration response at various points as shown in Figure 2. First slope-foundation system analysis has performed in PLAXIS with Lysmer and Kuhlemeyer boundaries. Again, results have been compared in ABAQUS with three transmitting boundaries as BC-1 (L-K), BC-2 (N-M) and BC-3 (Bettess). Response has been calculated for three nodes of the foundation with three different PGA with various boundary conditions and tabulated in Table 3.

Table 3. Max displacement and acceleration response at toe of slope corresponding to different PGA

PGA	PLAXIS (L-K)	BC-1 (L-K)	BC-2 (N-M)	BC-3 (Bettess)
	Max Displacement (cm)			
0.25g	1.23	1.22	1.17	1.03
0.5g	1.42	1.42	1.39	1.28
1g	5.1	5.1	4.8	4.6
	Max Acceleration (g)			
0.25g	0.45	0.45	0.38	0.325

0.5g	0.62	0.62	0.57	0.52
1g	1.4	1.4	1.37	1.3

Table 4. Max displacement and acceleration response at mid of slope corresponding to different PGA

PGA	PLAXIS (L-K)	BC-1 (L-K)	BC-2 (N-M)	BC-3 (Bettess)
	Max Displacement (cm)			
0.25g	1.43	1.42	1.39	1.31
0.5g	2.2	2.21	2.15	1.9
1g	6.0	6.1	5.8	5.1
	Max Acceleration (g)			
0.25g	0.55	0.55	0.48	0.42
0.5g	0.74	0.74	0.70	0.63
1g	1.495	1.5	1.47	1.38

Table 5. Max displacement and acceleration response at crest of Slope corresponding to different PGA

PGA	PLAXIS (L-K)	BC-1 (L-K)	BC-2 (N-M)	BC-3 (Bettess)
	Max Displacement (cm)			
0.25g	2.5	2.5	2.44	2.3
0.5g	5.2	5.2	5.01	4.8
1g	8.7	8.7	7.9	7.0
	Max Acceleration (g)			
0.25g	0.64	0.64	0.58	0.53
0.5g	0.8	0.8	0.76	0.69
1g	1.6	1.6	1.51	1.48

VI. RESPONSE ANALYSIS FOR SOIL SLOPE-FOUNDATION-INTERACTION (SSFI)

Maximum response for foundation interaction has been observed at nodal points (D, E and F). The corresponding responses have shown for PGA of 0.5g in Table 6. The deformed shape for the different mesh size has been observed after the complete action of seismic load and depicted in Figure 5-6.

Table 6. Max Response for SSFI corresponding to PGA=0.5g

Response Points	PLAXIS (L-K)	BC-1 (L-K)	BC-2 (N-M)	BC-3 (Bettess)
	Max Acceleration (g)			
C	0.8	0.8	0.76	0.69
D*	0.56	0.55	0.49	0.41
E	0.56	0.55	0.49	0.41
F	0.56	0.55	0.49	0.41
	Max Displacement (cm)			
C	5.2	5.2	5.01	4.8
D*	3.8	3.79	3.1	2.67
E	3.7	3.7	3.6	2.6
F	3.61	3.61	3.5	2.54

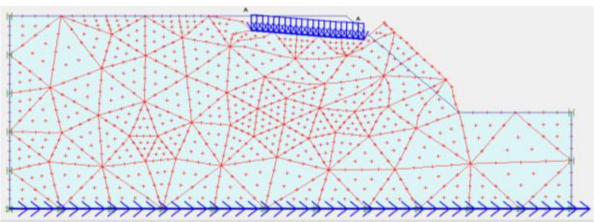


Figure 5: Deformed mesh (case a)

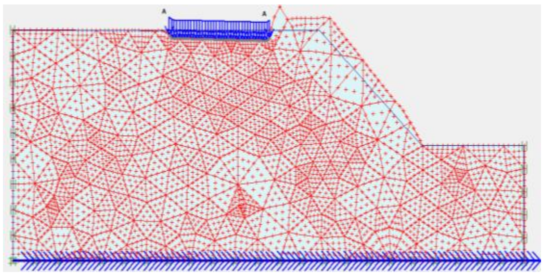
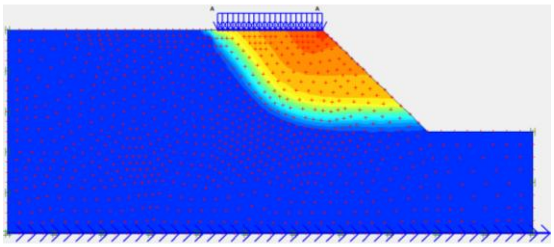


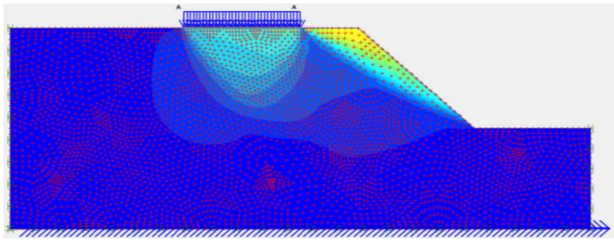
Figure 6: Deformed mesh (case b)

VII. STRESS DISTRIBUTION ANALYSIS

The stress distribution for foundation when it is placed near the crest and away from the crest has been observed in Figure 7. It is clearly observed from the Figure 7 the maximum stress is concentrated near the crest region and stresses are completely distributed in entire slope. When the foundation is placed away from the crest the stress is very low and localised in very narrow zone.



(a) Stress distribution (case a)



(b) Stress distribution (case b)

VIII. EFFECT OF SSFI WHEN FOUNDATION IS PLACED ON THE SLOPE

In the previous section effect of SSFI has analysed when foundation was placed on crest of slope. The same analysis has been performed when the foundation is placed on slope itself. In this analysis the foundation is subjected to different load conditions. The shear stress contours and equivalent principal plastic strain are plotted to study the stability of slope. For this, load condition such as 5 kN, 10 kN, 15 kN, 20 kN and 25 kN are applied to the foundation.

IX. ANALYSIS OF SHEAR STRESS

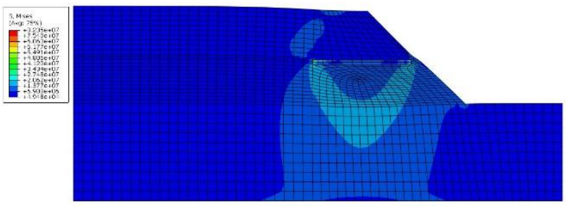
Figure 8 shows the shear stress contours for different load conditions. The each load conditions are applied at the system and at the end of earthquake excitation the shear stress contours are plotted. Fig. 8(a) shows the shear stress distribution corresponding to 5 kN load at the foundation and it can be observed the stress is maximum at the centre of foundation and occurred very insignificant deformations of crest as well as slope.

Fig. 8(b) shows the shear stress contour when the foundation is subjected to 10 kN. It can be observed that the deformation of crest and slope are increased as load increased. The shear stress is more concentrated in foundation vicinity with load increment. It can be concluded that the slope-foundation system has insignificant local failure in slope mass.

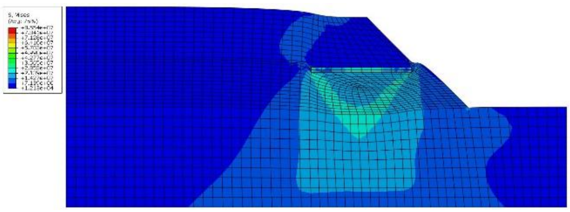
Fig. 8(c) shows the shear stress variation with 15 kN load condition. Here shear stress is more localized near the foundation. The intensity of stress is very significant as load increased to 15 kN. Also the crest and slope deformation are comparable with other load condition.

Fig. 8(d) shows the shear stress distribution corresponding to 20 kN load at foundation. The whole area below the foundation is deeply intensifies as further increment in load. A very significant deformation can be observed in the slope in this condition. It can also be observed the system has started global failure at this load condition.

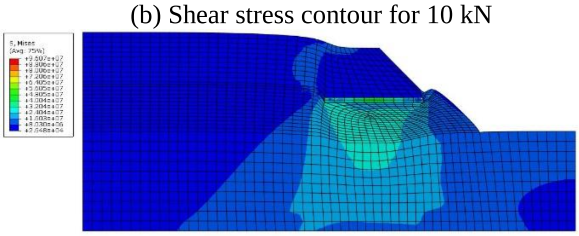
Fig. 8(e) is shows the shear stress profile when foundation is subjected to 25 kN. Here it can be observed the large deformation occurred in the slope mass. The shear stress has increased very significantly as comparison of 20 kN and it can be concluded that the slope is almost at verge of failure.



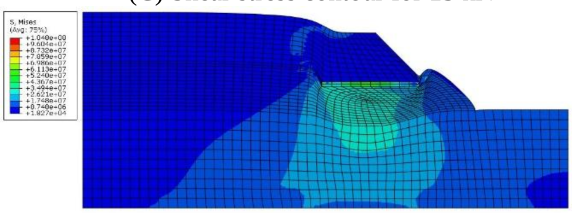
(a) Shear stress contour for 5 kN



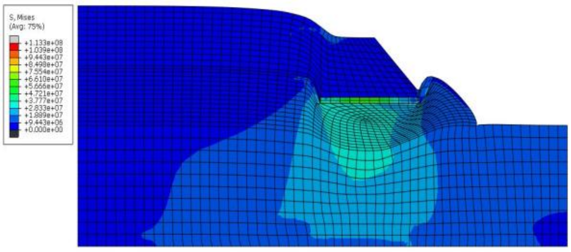
(b) Shear stress contour for 10 kN



(C) Shear stress contour for 15 kN



(d) Shear stress contour for 20 kN



(e) Shear stress contour for 25 kN

Figure 8: Shear Stress contours for different load conditions

X. ANALYSIS OF EQUIVALENT PRINCIPAL PLASTIC STRAIN

The equivalent principal strain is calculated for different load conditions and corresponding accumulation of strain is observed in Figure 9.

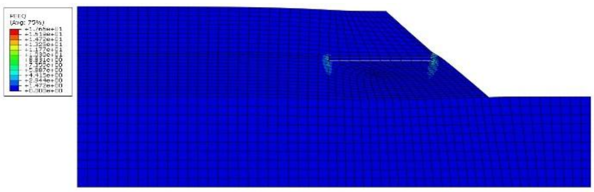
Fig. 9(a) shows the propagation of equivalent plastic shear strain when foundation is subjected to 5 kN. It is observed that the strain is intensifies in the both ends of foundation. Very less amount of deformation in slope mass can be observed.

Fig. 9(b) shows the accumulation of shear strain due to 10 kN load condition. The shear strain accumulation is start to propogate in downward direction. It shows the start of local failure in slope-foundation system.

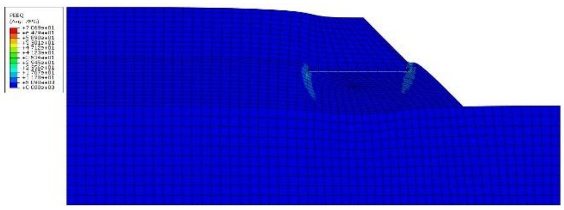
Fig. 9(c) shows the variation plastic equivalent shear strain when foundation is subjected to 15 kN. It can be observed the strain accumulation is more intensify near the right edge of foundation. Deformation of crest is significantly in this load condition. The behavior of propagation of failure in slope may start near the right edge of the foundation.

Fig. 9(d) shows the accumulation of shear strain for 20 kN load. The strain is significantly increased by amount of 66.48 %. It is assumed as very large increment in shear strain. It shows the occuring of global failure in the slope mass.

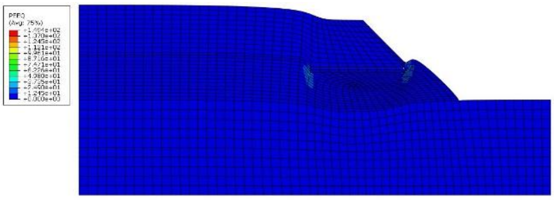
Fig. 9(e) shows the equivalent plastic strain contour for 25 kN load. It is observed thet the shear strain is completely accumulated near the right edge of foundation. It can be concluded that the slope-foundation has global failure.



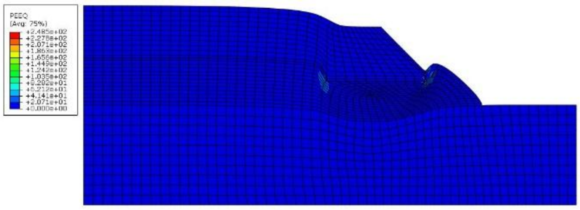
(a) Accumulation of shear strain for 5 kN



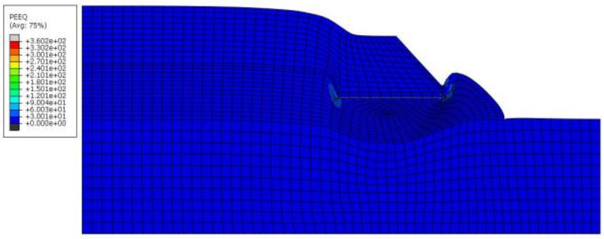
(b) Accumulation of shear strain for 10 kN



© Accumulation of shear strain for 15 kN



(d) Accumulation of shear strain for 20 kN



(e) Accumulation of shear strain for 25 kN

Figure 9: Shear Strain accumulation for different load conditions

XI. POST-EARTHQUAKE PEAK SETTLEMENT PROFILE

The evolution of maximum settlement underneath the foundation at various nodes has been observed as shown in Figure 10. Three characteristics locations at the two edges (nodes D and F), and at the middle of the foundation (node E). Zeroing of the nodes along foundation denotes loss of contact between the footing and the ground. While at the middle of the foundation (node B) support is somehow disturb through the whole duration of seismic shaking, while substantial loss of support can be observed at the two edges (nodes D and F).

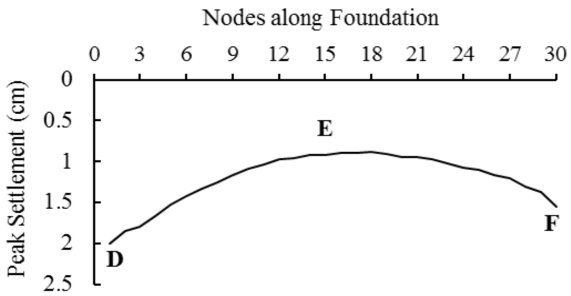


Figure 10: Post earthquake peak settlement profile for foundation

XII. CONCLUSIONS

Two cases have analyzed for SSFI when foundation is placed at and near the crest of slope and slope itself. The following conclusions are observed:

1. While increase the acceleration response along the depth of soil slope mass shows amplification in soil mass.
2. Amplification in soil mass leads to settlement of foundation to an extent.
3. As moved the foundation away from the crest, factor of safety increased; which shows that foundation placed near the slope is more susceptible to damages.
4. More Factor of Safety (FOS) has calculated with the foundation when it is placed away from the crest of slope.
5. The F.O.S increases by 14.65% and total displacement decreases when the foundation is moving away from the crest of the slope.
6. It is seen that in both cases slope is stable because, the value of FOS is found to be greater than one.
7. The shear stress contour and shear strain accumulation have analysed for the different load conditions and it was found that the slope-foundation system behaves local failure as well as global failure.
8. The equivalent plastic shear strain accumulation is increased as load increased.

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