3-D FINITE ELEMENT ANALYSIS OF SINGLE PILE UNDER INDUCED LATERAL SOIL MOVEMENT

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ABSTRACT: The paper presents a numerical study on the response of a single pile under induced lateral soil movements. The type of movements around the pile could be due to a landslide or those induced due to nearby excavations, due to surcharge loading on the adjacent area etc. A three-dimensional finite element model has been developed to investigate the influence of magnitude of soil movement, location of pile with reference to source of lateral movement, pile stiffness on the response of single pile. In the analysis, the pile is treated as linear elastic material and the soil as elastic-perfectly plastic based on Drucker-Prager constitutive model. Series of finite element analyses have been carried out by keeping the pile at different distances from the source of soil movement. The results obtained from the analyses are presented in terms of the lateral deflections along the length of pile and ultimate soil pressure on the pile due to induced lateral soil movement. Numerical results indicate that the response of the pile greatly depends on the parameters studied and there is a fairly good agreement of the current results with those from earlier published works.

Key words: Single Pile, Lateral soil movement, Deflection, Passive pressure, Finite element analysis, Drucker-Prager Constitutive model.

INTRODUCTION

A pile under induced soil movements is a highly complex soil-structure interaction phenomenon particularly with reference to lateral loads/movements. Lateral loading on piles may occur due to 'active loading' where external loads are applied to the pile head or due to 'passive loading' where the lateral movement of ambient soil induces additional stresses in the piles (Fig. 1). These additional stresses may cause increase in lateral deflections and bending moments, which may finally lead to distress of the structure and likely to create serviceability problems. Some examples of passive loading include the case of piles adjacent to deep excavations, piles supporting bridge abutments adjacent to approach embankments, piles used to stabilize slopes and tunnel operations etc. Although, the movement is possible in both vertical and lateral directions, lateral soil movement is more critical as piles are not often structurally designed to sustain significant lateral loads.

The failure of large number of piles at Kandla port during the recent Bhuj earthquake was attributed to passive loading resulting from excessive flow of soil, Raju (2001). The soil below the berthing structures at Kandla port consists of very soft marine clay having undrained cohesive strengths in the range of 5 to 15 kPa. The thickness of this soft clay layer is around 10 m. This soil was estimated to be naturally stable at a slope of 3 horizontal to 1 vertical. However, the actual slope provided at the site was 1.5 horizontal to 1 vertical. The number of piles installed at the site were assumed to provide for the stability of the steep soil slope. During the earthquake at the site, the entire soil slope failed and moved laterally, thus causing significant additional forces on the piles, for which these piles were not structurally designed, leading to their failure. Both vertical and raker piles have failed due to the soil movement.

Stewart et al. (1993) analyzed the response of pile groups to lateral soil movements from a nearby surface loading by a plane strain finite element analysis. Chen (1994) studied the behaviour of piles in soils undergoing lateral movements by a plane strain finite element analysis. These studies mainly focused on the ultimate soil pressures for a single pile and pile groups and the effects of a vertical cut or excavation on the ultimate soil pressures. Goh et al. (1997) carried out a 2-d finite element analysis on the behaviour of single piles to lateral movements with assumed soil displacement profiles.

Bransby & Springman (1999) studied the pile-soil interaction behaviour by 2-dimensional finite element analysis for a single rigid pile and for closely spaced pile rows and group under passive lateral loading from soil movements. A number of similar studies have been reported to assess the pile response to lateral soil movements [Stewart & Jewell (1993), Poulos and Chen (1996)], Figure 1.

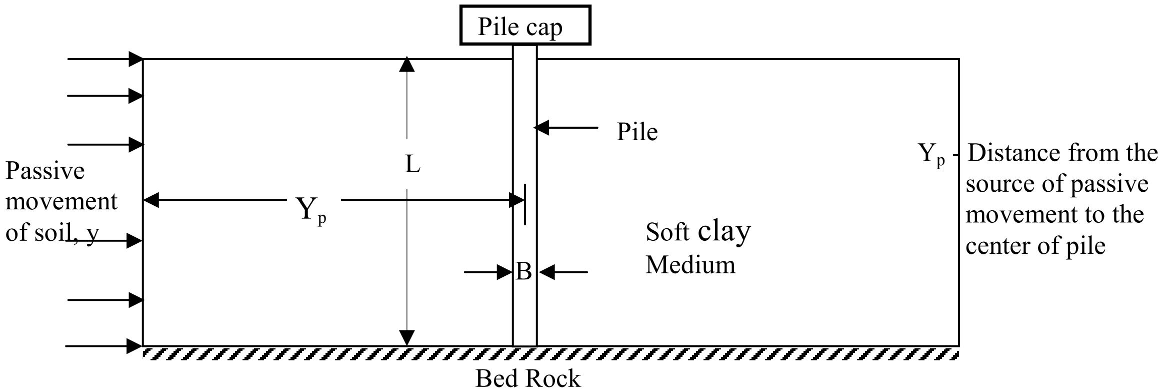

Figure 1. Schematic of single pile under induced lateral soil movement

Since, the pile-soil interaction under lateral movements is basically a three-dimensional phenomenon, a 2D analysis may not properly simulate the behaviour. Efforts have been made by a few investigators to analyze the response using 3-D finite element analysis [Chaoui & Magnan (1994); Pan et al. (2002)] assuming various soil movement profiles. In the similar lines, the present paper discusses the results of 3D finite element studies carried out to investigate the effect of various parameters, viz., pile stiffness, magnitude of soil movement and location of pile from source of movement etc. on the response of piles and its verification against some of the published works.

NUMERICAL MODELS

In the present analysis, the finite element program GEOFEM3D has been used to study the interaction between the pile and soils under lateral soil movements. Fig. 2 show the schematic finite element mesh used for the study which includes very fine mesh near the pile to simulate the possible slip/separation between pile and soil. All the nodes on the lateral and vertical boundaries are given smooth rigid boundary conditions with normal translation constrained. All the nodes on the bottom surface of the mesh are fixed from moving in all three directions, which represents a rough rigid base condition. The finite element mesh consisted of 5,460 nodes and 4,536 eight - noded isoparametric 3-dimensional brick elements.

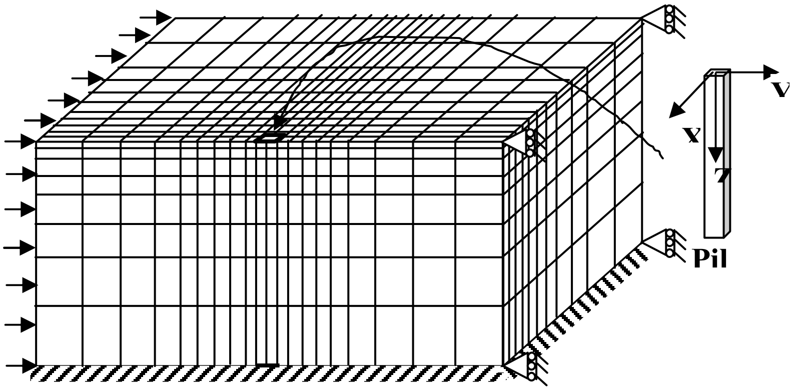

Fig. 2. Three-dimensional finite element mesh

Pile Model

The solid 8-node brick elements were used to model the pile. The pile was treated as linear elastic material and the length and breadth of square aluminum pile used for the analysis are 15 m and 1 m respectively. In the analysis, the Young's modulus of pile E_P was varied to change the relative stiffness factor K_r corresponding to a stiff ($E_P = 2.8\times10^7$ kPa) and a flexible pile ($E_P = 3.5\times10^6$ kPa), respectively. The Poisson's ratio μ of 0.32 was used. The relative stiffness between the pile and soil is defined using the factor K_r as follow:

$$K_r = E_p I_p / E_n L^4 \quad \text{------------------------} \ (1)$$

Where, E_pI_p is the flexural rigidity of the pile and E_n is the average normal soil modulus along the embedded length 'L'. A pile is considered as flexible if its relative stiffness factor K_r is less than about 0.01 (Poulos & Davis 1980).

Soil Model

The elastic-plastic stress-strain behaviour of soil has been idealized using the Druker-Prager constitutive model with associated flow rule. The Drucker-Prager model can be approximated to the well-known Coulomb criterion by a simple smooth function. The yield surface for this model has the form $F = \alpha J_1 + \sqrt{J_{2d}} - k$. Where J_1 is the first invariant of the total stress tensor, J_{2d} is the second invariant of the deviatoric stress tensor and α, k are the material constants related to the angle of internal friction (ϕ) and the cohesive strength of the materials (c) as follows:

$$\alpha = 2\sin\phi / \sqrt{3}(3+\sin\phi) \text{-------------------} \ (2)$$

$$k = 6c\cos\phi / \sqrt{3}(3+\sin\phi) \text{--------------------} (3)$$

During the plastic state, the constitutive matrix is first formed based on the current tangent modulus and Poisson's ratio for elastic state and then a correction is applied to obtain the elasto-plastic constitutive matrix. The soil is assumed to possess undrained cohesive strength of 50 kPa in all the analyses.

Analysis scheme

The analysis has been carried out in two parts. The first part was the application of self-weight of the soil with a given K_o condition. This K_o state was obtained by setting the Poisson's ratio to $K_o/(1-K_o)$ in the first part of the analysis. During this stage all elements (pile and soil) were assigned the same properties so as not to generate any shear stresses in the soil elements. All the displacements and strains were set to zero at the end of this stage. During the second stage of analysis, the pile elements were assigned a Young's modulus and Poisson's ratio corresponding to stiff and flexible piles as reported later. The nodes at the top of the piles were completely fixed from moving in all directions in order to account for the large stiffness arising from the combined action of the pile cap and the superstructure. Similarly all nodes at the bottom end of the piles were restrained to account for the stiff support given to the pile tip by the competent ground strata at the termination depth of the pile. The induced lateral soil movement was simulated by specifying uniform lateral displacement to all the nodes on the vertical boundary of the mesh as illustrated in Fig. 2 with arrows.

Three-dimensional finite element analyses have been carried out on stiff and flexible single piles under induced lateral soil movement. A uniform soil movement (δy) was applied incrementally to all the nodes on the left edge of the mesh. These displacements were applied in small increments of 1 mm per load step with a maximum of 50 iterations. The iterations were continued at each load step until the norms of out-of-balance force and incremental displacements decrease to less than 0.5% or until 50 iterations are completed.

The incremental finite element equilibrium equations used for the analysis are of the type shown in Equation 4 in which the load vector is expressed as the difference between the external load vector and the internal reaction force vector computed from the element stresses of the previous iteration.

$$[K]_t \{\Delta u_i\} = \{P\}_{exti} - \Sigma [B]^T \{\sigma_{i-1}\} \qquad (4)$$

In which the 1st term on the RHS is the applied force vector and the 2nd term on RHS is the internal nodal force vector (reaction force vector). This analysis scheme allows for carrying forward any error in the out-of-balance force to the next iteration (or next load step) thus satisfying the global equilibrium at all the load steps. The finite element solutions were iterated until the out-of-balance force norm is less than 0.5%.

RESULTS AND DISCUSSION

Effect of Magnitude of Induced Soil Movement

For the sake of initial trials, centre of the pile has been assumed to be located at a constant distance from the source of passive movement i.e. piles are kept constant at 9m from the source of ground movement. The results

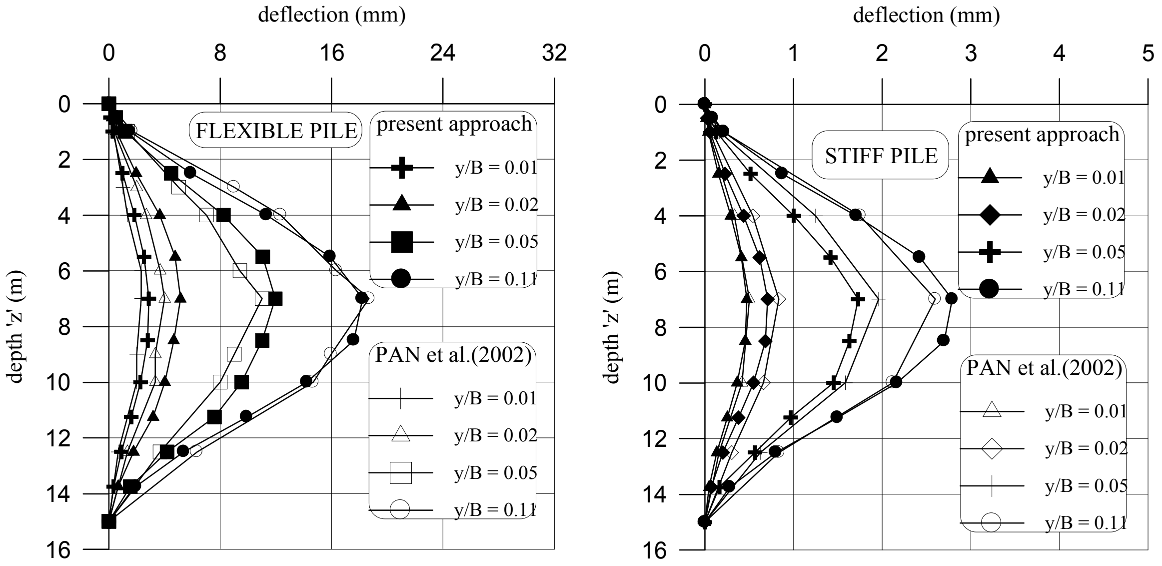

Figure 3. Deflection along the length of flexible and stiff piles

obtained from these analyses have been presented in the form of charts consisting of lateral deflection and passive pressures. Fig.3 shows the deflection profiles along the length of single flexible and stiff piles under various magnitudes of induced lateral soil movements in terms of y/B (y=magnitude of the soil movement; B = breadth of the pile). Generally the trend is same both for flexible and stiff piles, except that the deflections of the flexible pile was much greater than that of the stiff pile. Also, it is observed that the deflection

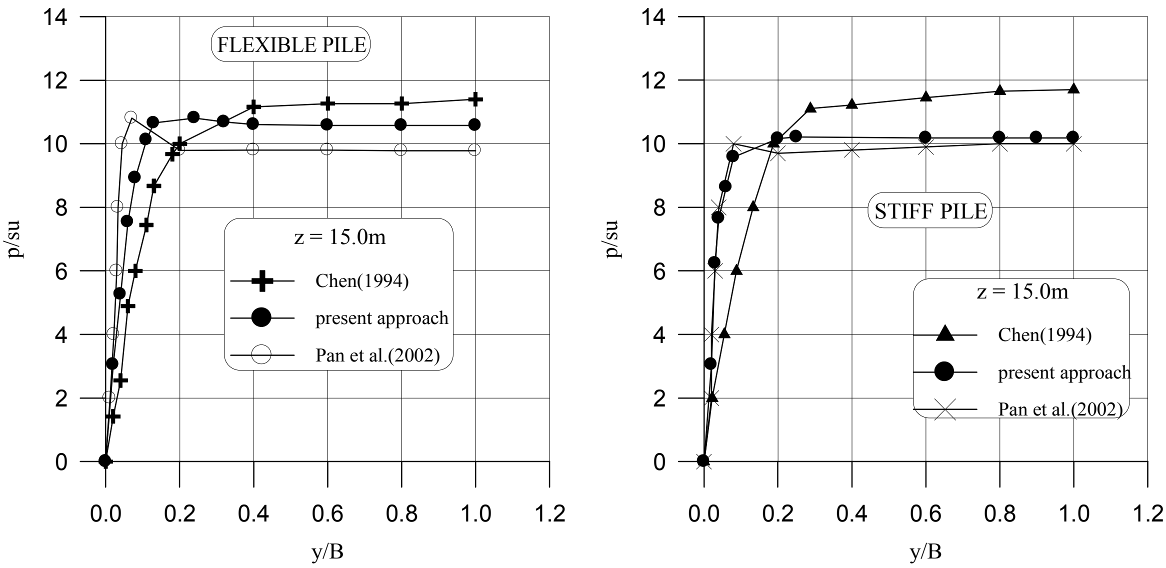

Figure 4. Normalized p-y curves for flexible and stiff piles

of the pile is more sensitive to the values of the magnitudes of soil movement (y/B) and it is observed similarly for both flexible and stiff piles. Further, the accuracy of the present finite element analysis scheme has been verified by back-predicting the results from published work of Pan et al (2002). The soil considered in this analysis is homogeneous and consists of a very soft uniform clay having modulus of elasticity and poisson's ratios of 4000kN/m^2 and 0.49 respectively. It can be seen from the plots that the deflections along the pile section predicted by the present approach are fairly in good agreement with those from Pan et al. (2002).

Figure 4 shows the normalized p-y curves for flexible and stiff piles. It can be observed that the passive pressure predicted by present approach is fairly comparable with those from Pan et al. (2002). The ultimate passive pressures computed by present approach were 10.21s_u for the stiff pile and 10.81s_u for the flexible pile, while those according to Pan et al. (2002) were 10s_u for stiff pile and 10.8s_u for flexible pile. Further, similar comparisons were also made against those reported by Chen (1994). The ultimate pressures by Chen (1994) were slightly higher side, i.e., 11.4s_u for stiff pile and 11.75s_u for flexible pile in view of 2D analysis. The computed ultimate passive pressures were generally noticed when the soil had translated approximately in the order of 0.22B to 0.25B. The percentage difference between the present FE analysis and published results is less than 10%. From these results, it can be concluded that the finite element model proposed in this investigation is capable of correctly representing the behaviour of piles under induced lateral soil movement.

Effect of Pile location from Source of Movement

Series of three-dimensional finite element analyses have been carried out on single flexible and stiff piles under induced lateral soil movement by keeping the pile in different locations. Three different pile locations were considered for the analyses, the distance from the source of lateral soil movement to the center of pile cap were kept as 3m, 6m and 9m.

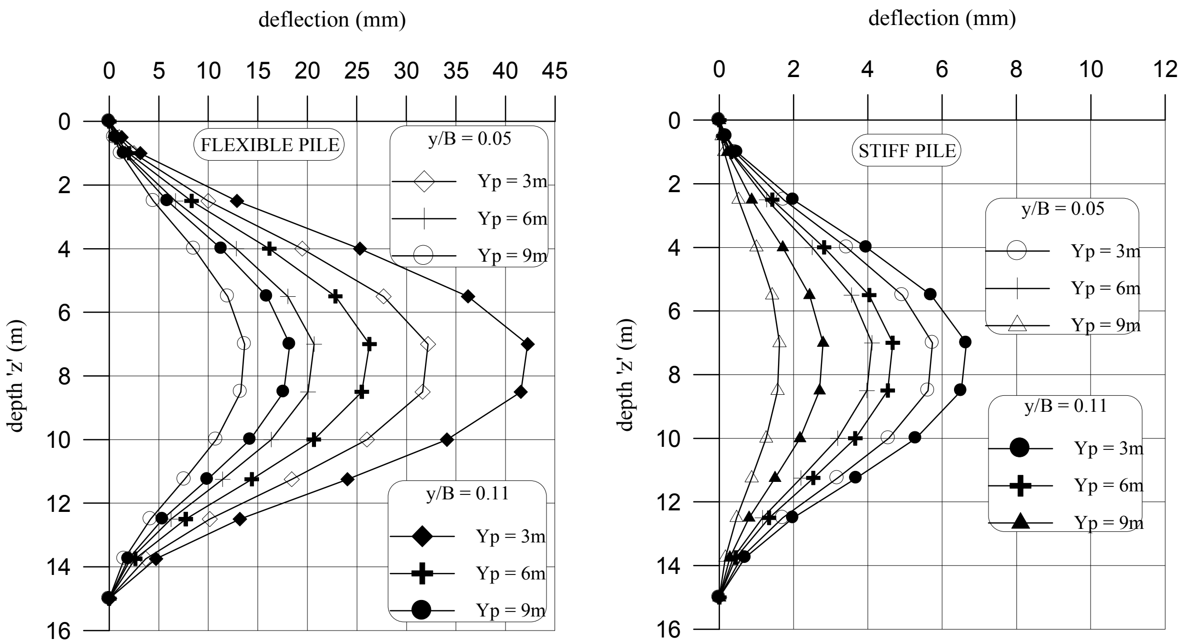

Figure 5. Deflection along the length of flexible and stiff piles

The results obtained from these analyses have been presented in the form of charts consisting of lateral deflection against the depth of piles with respect to various values of 'Yp' and for the specified values of passive movements of y/B = 0.05 and 0.11. Fig. 5 shows the pile deflections against the depth for flexible and stiff piles. It is observed that the maximum lateral deflections occurred at around mid-depth of the pile. This could be mainly due to the restraint at both top and bottom ends of the piles. Also, it is observed that the maximum deflection of the pile increases as the distance from the source of lateral soil movement to the center of the pile decreases. Further, the deflections along the length of stiff piles are much lesser than the flexible piles for all the values of 'Yp' and also for all the magnitudes of soil movements analyzed indicating the significance of pile stiffness on the behaviour.

The passive pressures developed on piles located at various distances i.e. 3m, 6m and 9m from the source of ground movement have also been studied and the results have been presented at two different positions along the pile section i.e. one on the pile bottom and another on the center of the pile where the maximum deflections occurred. Fig. 6 shows the relationship between normalized lateral soil movement (y/B) and normalized passive pressure (p/s_u) along the depth of flexible and stiff piles. The trends are almost same for both flexible and stiff piles. The maximum passive pressures computed for stiff pile were in the order of $7.26s_u$ to $10.87s_u$ and for flexible piles were in the order of $7.47s_u$ to $11.56s_u$. Further, it is observed that the maximum passive pressures were generally developed after the soil had translated in the order of 0.22B to 0.26B. It can also be seen from

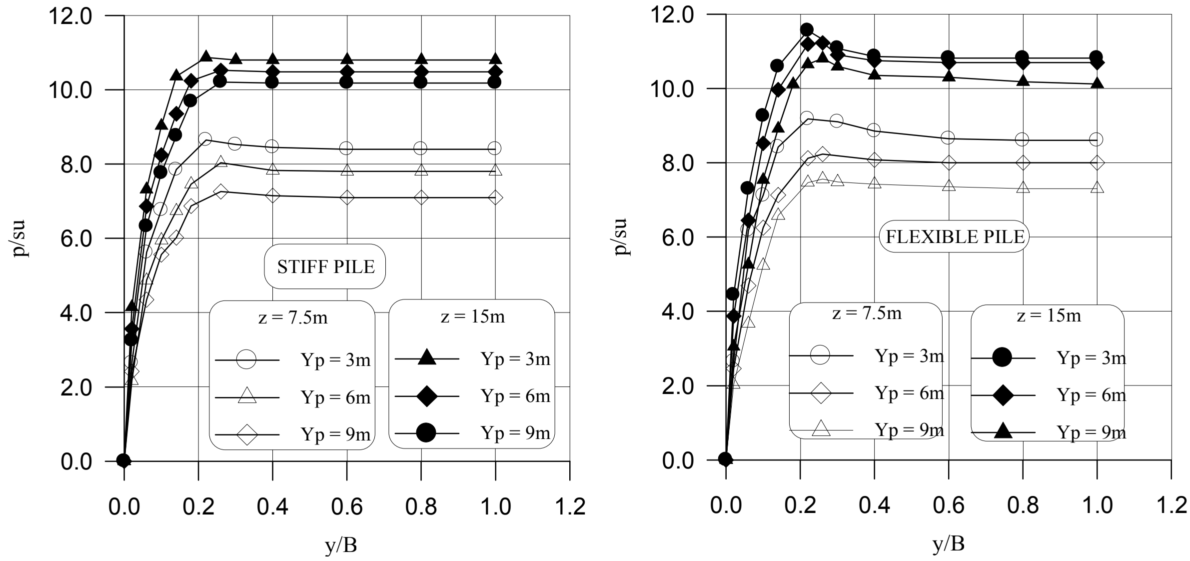

Figure 6. Normalized p-y curves for flexible and stiff piles.

the plots that the maximum passive pressures occur for the piles located closer to the source of soil movement indicating that the pile located closer to the source of soil movement is likely to be affected maximum and hence proper care shall be exercised while designing these piles taking into account of the additional stresses.

Effect pile location on the bending moment of piles

The bending moments in the pile section along the length of the pile were calculated using the well known flexural equation $f_y=(M/I)y$ in which f_y is the flexural stress and y is the distance from the neutral axis. The normal stress in the x direction is used in these calculations. Figure 7 shows the variation in bending moments along the pile depth for flexible and stiff piles at a normalized lateral soil deformation of 0.11. The soil pressures have attained their maximum values at this deformation. From the results presented, it can be noted that the bending moments are maximum at the pile head and reduce downwards and attain another peak towards the bottom end of the piles. This is mainly attributed to the fixity conditions at top and bottom ends of the piles. The pile located near to the source of ground movement (i.e. 'Yp' value is 3m) exhibited higher bending moments than the pile located away from the source of ground movement. The trends are almost the same for both flexible and stiff piles with higher bending moment in case of stiff piles.

CONCLUSIONS

A 3D finite element model to investigate the response of pile under induced lateral soil movement has been presented. The influence of pile stiffness, the magnitude of induced soil movement and the location of the pile from the source of movement have been studied in this paper. The lateral deflections as well as ultimate passive pressures along the depth of piles are more for flexible piles than for stiff piles irrespective of the magnitude of the induced lateral soil movements and pile locations.

The passive pressures and thereby lateral pile deflections are more in case of the pile located closer to the source of soil movement and hence proper care shall be taken while designing the piles adjacent to the source of any ground movement.

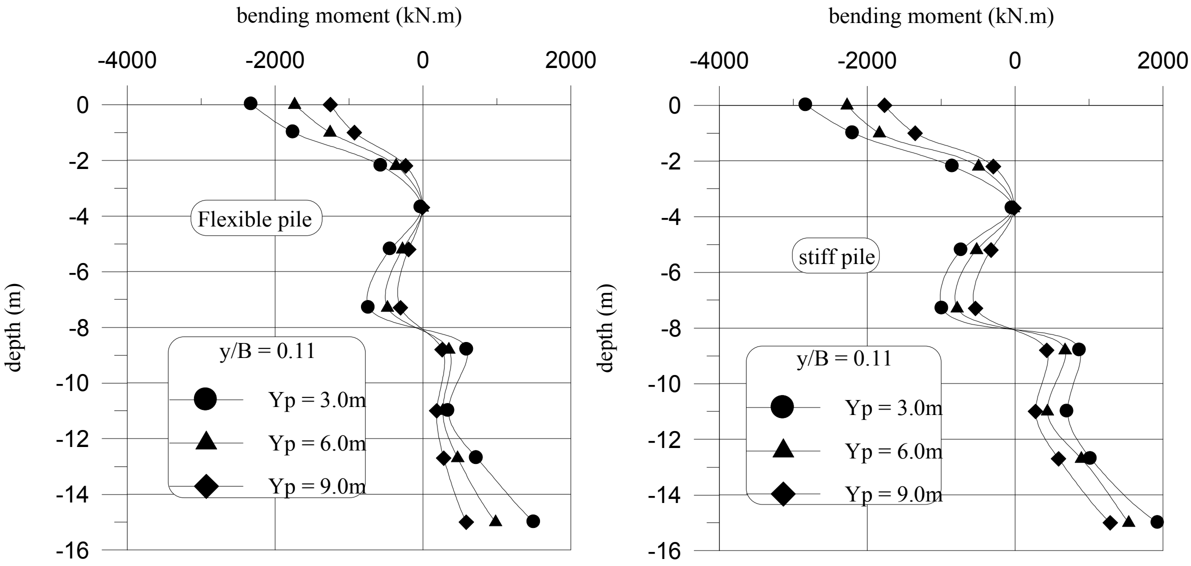

Figure 7 effect of pile location on the variation of bending moments of flexible and stiff piles

This paper has presented some quantitative results on the magnitudes of forces generated in the pile section due to ground movements. It is clear from these results that even as small a lateral ground movement as 0.2 times the pile size is sufficient for the soil pressures around the pile to increase to their peak values. The pressure on both flexible and stiff piles was found to be nearly equal. The peak pressure on flexible piles were observed to develop at a slightly larger deformations. The effect of lateral soil deformation around the pile is to increase the bending moments in the pile section. This increase in the bending moment (and the shear force) is dependent on the magnitude of the cohesive strength of the native soil. All the analyses in this case were performed with a c of 50 kPa corresponding to medium stiff clay. For actual designs, the analyses are to be performed with the observed cohesive strengths of the clay soils and the influence of the soil movements on the response of piles has to be properly analysed. The methodology of analysis is presented in this paper. The results have clearly demonstrated the considerable increase in forces in the pile section.

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