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Kinematic and Inertial Effects of Earthquakes on Rock Socketed Single Piles in a Two-Layered Medium

H. S. Thilakasiri

Abstract: The behaviour of piles in a two-layered soil medium subjected to earthquake ground accelerations are investigated using finite element method. The kinematic and inertial effects on rock socketed piles in a two-layered soil medium are investigated in this study considering the soil properties relevant to Sri Lanka. Hyperbolic nonlinear constitutive model is used for modelling the behaviour of the fully coupled soil medium. The effect of the earthquake was simulated by lateral ground acceleration applied to the bedrock and in this respect two earthquake records measured at a considerable distance away from the epicentre are used in the numerical simulation to take into account large epicentral distance to an anticipated earthquake that might affect Sri Lanka. The validity of the results of the proposed model was established by comparing with the trends observed in similar studies reported in the literature. A detailed parametric study of the kinematic bending moments developed in piles at the layer interface of the two-layered medium is carried out using the developed model. Furthermore, the effects of the inertial forces on the kinematic bending moment developed at the layer interfaces are investigated by varying the pile diameter and the effective masses at the pile head. Moreover, the variation of the bending moments, developed in the pile due to the combined effects of the kinematic and inertial responses of the pile-soil system, with the effective mass at the pile head for different pile diameters is also investigated.

Keywords: Rock socketed bored piles, earthquake, layered mediums, inertial forces

1.0 Introduction

Earthquakes are generally confined to certain zones in the world and these zones are concentrated along the active plate boundaries of the earth's crust. Fortunately, Sri Lanka is situated well away from the plate boundaries and it is believed that Sri Lanka is safer from the devastating effects of earthquakes. This is true to some extent but one should not be complacent and completely disregards the effects of earthquakes in the design of structures in Sri Lanka. There are few reasons for considering effects of a certain magnitude earthquake in designing structures in Sri Lanka:

- Some minor tremors are already felt in some parts of the country;
- During the design life of a structure possibility of experiencing a certain magnitude ground motion;
- Possibility of transmitting ground vibrations from a far away earthquake through the bedrock and affecting especially the structures on piles socketed to the bedrock; and
- The minor nature of the additional measures required to guard the structures against the effects of smaller magnitude earthquakes.

It is very important that engineers responsible for the design takes certain measures to safe guard the structures against the effects of a possible ground motion. Such ground motions, if ever happens, may have devastating effects on structures which are designed and constructed without considering the effects of such ground motion. However, one should not take this statement out of context and design the structures considering large magnitude earthquakes. The institutions responsible for developing design and construction guidelines in Sri Lanka should also take some meaningful actions to incorporate the effects of appropriate magnitude ground motion in the design and construction standards.

Experimental and theoretical research works related to dynamic forces on pile foundations due to ground motion are carried out especially in countries affected by earthquakes. There are large number of theoretical studies carried out to investigate the behaviour of single pile and pile groups in homogeneous soil mediums (Novak, 1991, Kuhlemeyer, 1979 and, Makris and Gazetas, 1992) by making varying

Eng. (Dr.) H. S. Thilakasiri, C. Eng., PEng.(SL). FIE(Sri Lanka), B.Sc. Eng. (Hons) (Moratuwa), M.Sc. (Lond), DIC, PhD(USF), Senior Lecturer, Department of Civil Engineering, University of Moratuwa, Sri Lanka.

assumptions regarding the excitation ground motion and idealization of the soil medium.

Other theoretical simulation researches (Gazetas and Mylonakis, 1998, and Gazetas and Dobrey, 1984) were also carried out to investigate the behaviour of piles in layered soil medium subjected to lateral ground motion. However, none of these researches were conducted considering the nonlinear coupled behaviour of the soil medium and the random nature of the natural earthquake excitations. Moreover, no research work is carried out considering the subsurface conditions and typical foundations in Sri Lanka to investigate the effects of a possible ground motion on local structures. Without the guidance from such research work, it is very difficult to improve the earthquake resistance of the foundations in Sri Lanka. Therefore, with that objective in mind a research programme was initiated to investigate the effects of earthquakes on rock socketed pile foundations in Sri Lanka.

Thilakasiri et al. (2009) presented kinematic effects of earthquakes on piles in layered soil mediums in Sri Lanka based on a numerical simulation using finite element method. This paper further investigates the development of kinematic forces in single piles and strengthens the findings presented in Thilakasiri et al. (2009). In addition, this paper also presents the results of the numerical simulation work carried out to investigate the combined effects of kinematic and inertial forces. It should be noted here that the behaviour of pile groups may be different from the behaviour of single piles due to the interaction between the piles in a group and should be considered separately.

1.1 Effects of Earthquakes on Pile Foundations in a layered soil medium

As previously mentioned, there is a possibility of transmitting the ground motion due to earthquakes along the basement rock to other regions of the earth crust well away from the epicenter. As a result, there is a possibility that the rock socketed end bearing bored piles may be subjected to the effects of such earthquakes due to the movement of the bedrock. Therefore, rock socketed bored piles, widely used in Sri Lanka, are considered in the present investigation. In most locations in Sri Lanka, soft alluvial soil deposits are present above the hard residual formations. Due to the above mentioned reasons, a pile socketed to the bedrock in a two layer soil medium with a soft alluvial deposit overlying a hard residual formation is considered in the present study.

A pile supporting a structure is subjected to two types of earthquake induced forces: *Inertial forces*; and *Kinematic forces*. In simple terms the inertial forces are developed due to the mass on the pile head and the kinematic forces are developed due to the difference of the rigidity of the surrounding soil medium and that of the pile.

It is typically found that when a structure is supported on a pile, the motion of the pile is transferred to the structure and the structure is forced to oscillate. The oscillatory motion of the mass of the structure generates inertial forces that in turn is applied on the pile and hence on the soil. The deformation of the pile due to the inertial forces may further change the inertial forces in the superstructure. This is referred to as the *inertial response*.

Generally the effects of the inertial forces are concentrated within very shallow depths (less than about ten times the pile diameter below the ground surface). However, Mizuno (1978) observed failures of piles at depths below the levels generally attributed to inertial effects. After similar other observations, the research work was focused to find the cause of such failures. Based on the evidence of numerical and experimental studies, such failures were attributed to discontinuities in the subsurface due to sudden variations in the soil stiffness and such effects were termed as *kinematic effects* of the earthquake on piles. Furthermore, some research work using centrifugal model tests (Boulanger et al., 1999) using soft clay layer overlying a dense sand layer showed an increase in the peak bending moment near the interface between the two layers. A brief description of the way kinematic forces are developed in a pile embedded in a layered medium is given below.

The soil response at a given site without any structural element is referred to as the 'free field' motion of the site. Due to the variations of the stiffness of the soil layers, the lateral motion of the layers due to the horizontal ground acceleration created by the earthquake may considerably vary. Now consider a pile embedded in a layered soil medium. Due to the high inertial effects of the surrounding soil, the pile is forced to follow the movement of the surrounding soil medium. However, due its high rigidity the piles resist such forced movement and reflect the incident stress waves in the process. This is referred to as the wave scattering and as a results, the ground motion near the pile considerably differs from the free field motion.

As a result of this forced oscillation, the pile may develop curvature and hence, the development of bending moments and shear forces in the pile. This is referred to as the *kinematic response* of the pile. When the pile is in a layered soil medium, the curvature near the layer interface may be higher as the difference in displacement pattern of the layers due to the non-uniform stiffness of the adjacent layers. The magnitudes of such kinematic forces, developed in piles, mainly depend on the contrast between the layers in the subsurface and have maximum effects near the boundaries between the layers in the subsurface (Gazetas and Mylonakis, 1998).

The present codes of practice take into account only the inertial forces. There are mainly two calculation procedures used in most of the design codes. For example Indian code of practice for design seismic forces for buildings, elevated liquid storage tanks, stacks, concrete and masonry dams, embankments, bridges, and retaining walls (IS:1893, 1984) specifies the use of two procedures for the estimation of lateral forces on buildings:

i. Seismic Coefficient method; and
ii. Response Spectrum Method.

For the use of the code provisions, India is divided into five seismic zones I to V with the associated Modified Mercalli Intensity (MMI) V (or less), VI, VII, VIII, and (IX (and above) respectively. In seismic coefficient and response spectrum methods, due consideration is given to the seismic zone where the structure is located, importance of the structure, soil-foundation system, ductility of constructions, flexibility of the structure, and weight of the building. The estimated lateral force is applied as a static base shear force on the piles and the bending moments and shear forces generated in the pile are estimated. It is proved that the dynamic loading due to the superstructure inertial effects in piles is confined to a shallow length, termed active length, below the ground surface.

The bending moment developed in a 1.2m diameter 20m long pile, supporting a five storey office building with a plan area of 50m x 50m, is estimated assuming the conditions relevant to Zone II in India. It is assumed that the pile is loaded to an axial stress equivalent to 5000 kPa and the seismic coefficient method is used to estimate the lateral force on the pile. Then, the bending moment developed in the pile is estimated using the theory of laterally loaded piles and the developed bending moment diagram is shown in Figure 1.

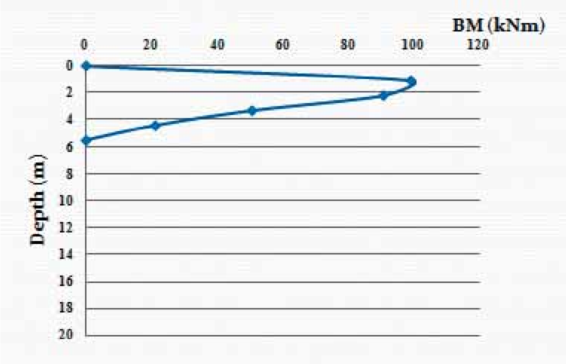

Figure 1 – Bending moment diagram of a 1.2m diameter 20m long pile due to inertial effects.

It is clear from the above discussion that the inertial forces for a given earthquake excitation depend on the effective mass oscillating with the pile at the pile head. The effective mass relevant to a pile head depends on many factors such as the mass of the superstructure, distribution of the mass within the superstructure and the stiffness of different elements of the structure. On the other hand, the magnitude of the kinematic forces for a given earthquake excitation depends on the rigidity of the pile, stiffness and the variation of the stiffness of the surrounding soil medium along the pile shaft. Even though the total forces on the pile is the summation of the inertial and the kinematic forces, the relative magnitude of the individual component depends on many factors as mentioned above. Therefore, it is very important that for design purposes the effects of both the components be considered to take into account the total forces developed in the pile.

In this study, it is intended to investigate the combined effects of both the kinematic and inertial effects on a single rock socketed pile in a layered nonlinear two-phase soil medium. Considering the economy and the feasibility, numerical simulation with finite element method is used for the present investigation.

2.0 Investigation Methodology

2.1 Introduction

Finite Element Computer software, named Imperial College Finite Element Program (ICFEP), developed at the Soil Mechanics section of the Department of Civil and Environmental Engineering at Imperial College, London, UK is used for the present study. ICFEP is specially developed to solve problems related to geotechnical engineering and has been successfully utilized for solving large number of complex geotechnical engineering problems. ICFEP possesses the capability of solving problems related to soil dynamics with the availability of suitable soil constitutive models and the capability of the applying dynamic boundary conditions (Kontoe, 2006).

2.2 Soil Constitutive Relationship

The ability of the soil constitutive relationship to model the accurate behaviour of the soil under dynamic loading is a major factor affecting the accuracy of any finite element model used in soil dynamics. For dynamic shearing problems, loading and unloading occur simultaneously. Since the soil does not behave elastically, the unloading and reloading paths do not generally follow the previous loading paths giving rise to hysteretic behaviour of soil. Hyperbolic nonlinear constitutive model is capable of numerically simulating this soil behaviour, when subjected to dynamic forces. In addition, it has the added advantage of well established correlations between the simple soil parameters and the damping ratio curves and stiffness decay curves (Guerreiro, 2008). According to the hyperbolic nonlinear constitutive model, the variation of the shear stress (τ) vs. shear strain(γ) of a soil element is shown in Figure 2.

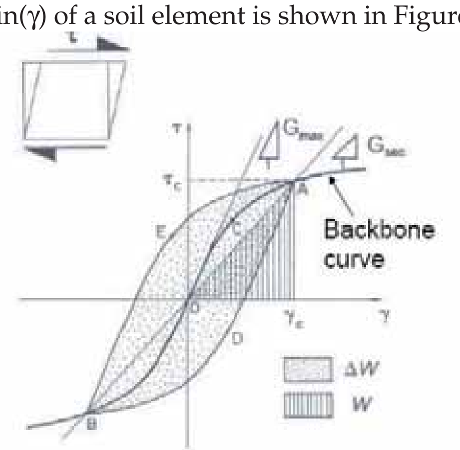

Figure 2 – Monotonic loading curve and hysterisis loop of hyperbolic nonlinear constitutive relationship during cyclic shearing.

In the present model, hyperbolic nonlinear constitutive model is used for the soil with the empirical correlation proposed by Darendali (2001). Material damping represents the energy dissipation due to several mechanisms such as internal friction, plastic deformation and heat generation. The relevance of each mechanism changes with the strain amplitude. Area under the curve, ΔW in Figure 2, represents the energy dissipation due to material damping. Material damping ratio ξ is expressed as the ratio between the dissipated energy of the hysteresis loop (ΔW) and the stored elastic energy (W) as shown in Figure 2. The damping ratio is expressed by $\xi=(\Delta W/(4\pi W)$. The damping ratio of the soil vs. shear strain for the soil in Layer 1 of the developed model is shown in Figure 3.

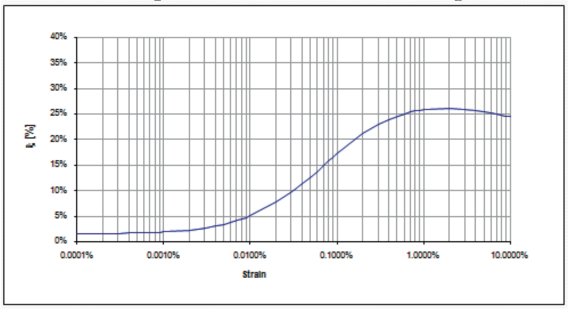

Figure 3 – Material damping ratio for soil in Layer 1 of the model.

2.3 Pile-Soil Model

A relatively soft alluvial deposit overlying a hard residual formation, typically found in most of the piling sites in Sri Lanka, is considered in the numerical simulation, as shown in Figure 4.

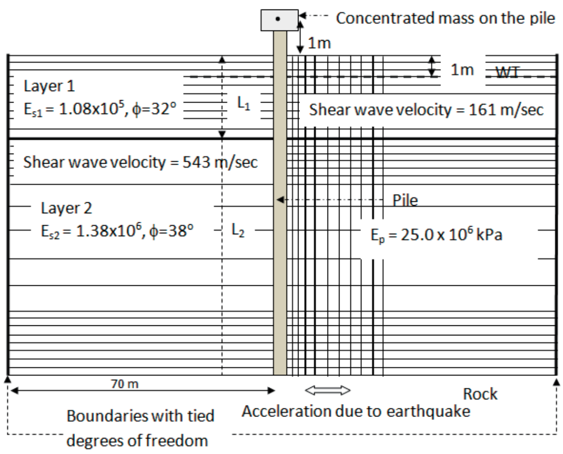

Figure 4 – Finite element model representing the pile-soil system.

The thickness of the top layer is taken as 5m and 8m while the overall thickness of the subsurface soil is kept constant at 20m. The initial elastic modulus, angle of internal friction, Poisson ratio of the top layer (Layer 1) are assumed to be 1.08x10^5 kN/m^2, 32^o and 0.2 respectively while the same properties of the bottom layer (Layer 2) soil are assumed to be 1.38x10^6 kN/m^2, 38^o and 0.2 respectively. The water table is located at 1m below the ground surface and initial hydrostatic pressure distribution is assumed.

Even though the behaviour of a pile is best modelled under three dimensional strain, considering the economy of the solution process plane strain condition was assumed in the model. The pile diameter is varied from 1200mm to 600mm and assumed to behave in a linear elastic manner with an elastic modulus of 25 x 10^6 kPa and Poisson ratio of 0.2. Only for the study of the inertial effects, the effective mass of the structure is considered by placing a mass equivalent to a certain percentage of the design load at a height of 1m above the ground surface, as shown in Figure 4.

In the present study, two horizontal ground acceleration records, shown in Figures 5 and 6, were used to get the ground excitation for the numerical simulation. It is assumed that the pile-soil system is subjected to ground acceleration only in one direction at a given time. Both the horizontal ground acceleration records considered in this study were measured more than about 200 km away from the epicentre, to take into the effects of large epicentral distance to Sri Lanka from an anticipated earthquake. The predominant frequency of the selected earthquake records are well away from the resonance frequency of the soil medium. This was done purposely as the kinematic effects on the pile are predominant under such conditions. Further, the maximum peak ground acceleration of both the earthquake records are less than 0.05g as an anticipated earthquake may be of low magnitude.

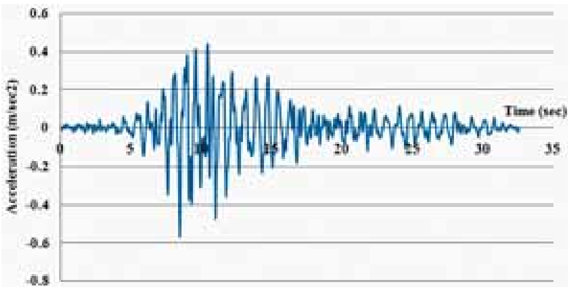

Figure 5 – Earthquake record 1.

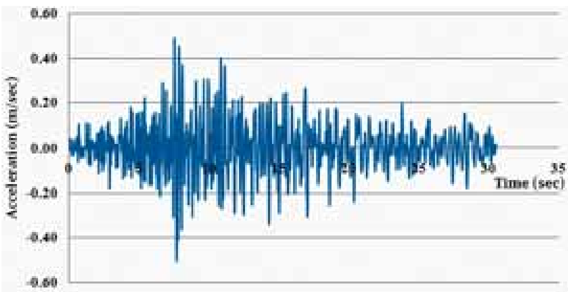

Figure 6 – Earthquake record 2.

Zienkiewicz et al. (1988) introduced a boundary condition, in which the degrees of freedom at the lateral boundaries are tied. Thus the boundary nodes at the same elevation move in an identical fashion. This method can perfectly model the one dimensional soil response but it cannot absorb any waves radiating away from the structural element resulting wave trapping inside the mesh. Kontoe (2004) observed that the tied degrees of freedom boundary conditions at the mesh boundaries are suitable when the wave radiating away from the structure is negligible. Since there is no measure of the amount of wave radiating away from the pile, the boundary response of the pile soil system with tied degrees of freedom were compared with the response of the corresponding positions of the system without the pile ('free field' motion) subjected to the same excitation ground motion. The difference between the two systems was brought to acceptable limits by increasing the distance from the pile to the lateral boundary. In this case the material damping of the cyclic soil constitutive behaviour attenuates the wave so that the wave reflected at the boundary becomes insignificant.

Potts and Zdravkovic et al. (1988) showed that the results of finite element simulation depend on how the behaviour of the boundaries between different mediums are modelled. In this regards, the modelling of the interface between the pile modelled, with linear elastic material properties, and the surrounding soil, modelled with hyperbolic nonlinear constitutive relationship, is extremely important. The pile-soil interface was modelled with Mohr-Coulomb elasto-plastic behaviour with normal and shear stiffness. The normal and shear stiffness of the pile-soil interface elements are selected based on a sensitivity analysis of the maximum bending moment developed in the pile for different pile-soil interface shear and normal stiffness. The variation of the maximum bending moment developed in a fixed head pile for different pile-soil interface stiffness values for the top layer thicknesses 5m and 8m are shown in Figures 7 and 8.

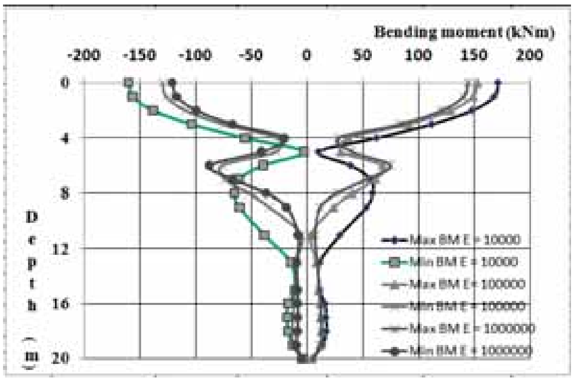

Figure 7 – Variation of the maximum and minimum BM with the pile-soil interface stiffness for top layer thickness 5m.

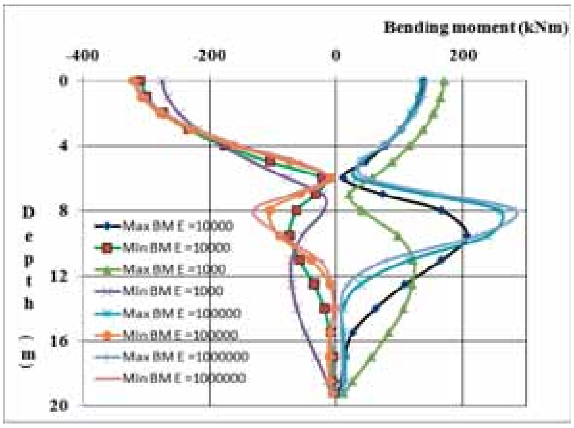

Figure 8 – Variation of the maximum and minimum BM with the pile-soil interface stiffness for top layer thickness 8m.

It is evident from the maximum bending moment variations shown in Figures 7 and 8 that the bending moment profiles does not vary significantly as the pile-soil interface stiffness is varied from 10^{05} to 10^{06}. Therefore, based on the results of the sensitivity analysis, the interface stiffness of 10^{05} is used in the present study as shown in Potts and Zdravkovic et al. (1988). Furthermore, the mesh configuration and the size were selected based on the results of a sensitivity analysis of the results with respect to different mesh configurations.

3.0 Results of the Numerical Simulation

Thilakasiri et al. (2009) presented the results of a similar analysis carried out to investigate the kinematic forces developed in single pile socketed to bedrock. Thilakasiri et al. (2009) used the earthquake effects given by the horizontal ground acceleration shown in Figure 5. Based on the results of that analysis, it was concluded that:

i. Basic trends observed by other experimental and simplified theoretical studies are observed;

ii. Significant bending moment is developed in the pile near the layer interface;

iii. The active length, L_a given by Equation [1], proposed by Gazetas and Mylonakis (1998) based on their study assuming linear elastic soil medium, is an important parameter in determining the behaviour of a pile in a two layer soil medium.

$$L_a = 1.5d\left(\frac{E_p}{E_{s1}}\right)^{0.25} \qquad [1]$$

Where

d -	Pile diameter
E_p -	Elastic modulus of the pile material
E_{s1}–	Initial elastic modulus of the top layer

iv. The stiffness decay of the soil layers increases the actual active length more than the active length estimated assuming initial elastic modulus of the top layer as given in Equation [1];

v. The kinematic bending moment developed near the layer interface increases with the diameter of the pile;

vi. The fixity at the pile head increases the bending moment at the pile head and slightly reduces the bending moment in the pile near the layer interface;

vii. The BM at the pile top and at the interface for the fixed head condition are significantly different when the top layer thickness is less than the active length;

viii. If the bottom layer is below the active length, its stiffness does not have a significant effect on the kinematic force developed in the pile;

ix. A defect present near the layer interface reduces the kinematic bending moment developed. However, even with a defect near the layer interface, a kinematic bending moment of significant magnitude is developed.

3.1 Results of the Present Analysis

A fully coupled finite element simulation is carried out by first applying the working load on the pile and subsequently applying the horizontal ground acceleration to the bedrock. Figure 9 shows the shear stress vs. shear strain behaviour of an element close to the pile during initial axial loading and subsequent shearing.

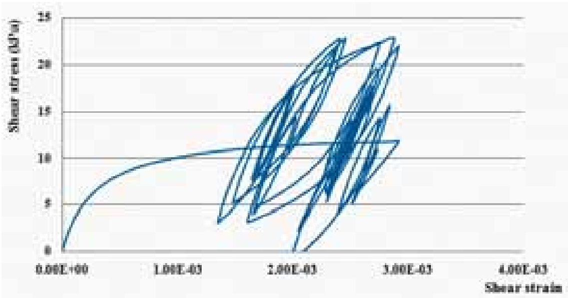

Figure 9 – Shear stress vs. shear strain of a soil element close to the pile during axial loading of the pile and lateral movement due to the earthquake.

The force developed at any level in the pile with an engineering significance is commonly considered to be the maximum bending moment developed at that level. Generally, the maximum bending moment along the entire pile shaft occurs when the relative horizontal displacement in the pile shaft is the maximum. Therefore, following the published research of similar studies, the maximum bending moment developed at each section during the ground motion is presented in this paper.

3.1.1 Kinematic Bending Moment

The maximum kinematic bending moments developed in the pile are further studied in the present paper to strengthen the findings of Thilakasiri et al. (2009) and to investigate the accuracy of the model developed by comparing with the already observed trends reported in the literature.

The variation of the maximum bending moment near the layer interface with different pile diameters are determined for the top layer thickness of 5m, as shown in Figure 10. Figure 11 shows the variations of the maximum bending moment developed at the pile top and at the layer interface for the active lengths of different pile diameters. It should be noted here that the active length is estimated from Equation [1] using the initial elastic modulus of the top layer soil.

The general trend observed from previous studies using linear elastic soil properties is that when the active length is more than the top layer thickness, the bending moment developed in the pile at the soil layer interface is less than the bending moment developed at the pile top. This trend is observed in Figure 11. However, it is interesting to note in Figure 11 that the pile top bending moment becomes greater than the interface bending moment even when the active length, estimated using the initial elastic modulus of the soil, is less than the top layer thickness (5m). The reason for this is the stiffness degradation of the soil with the shear strain. Therefore, the effective elastic modulus is smaller than the initial elastic modulus of the soil and hence, the actual effective length may be higher than the effective lengths shown in Figure 11. This observation is very much in agreement with the findings of the Gazetas and Mylonakis (1998) using linear elastic soil medium.

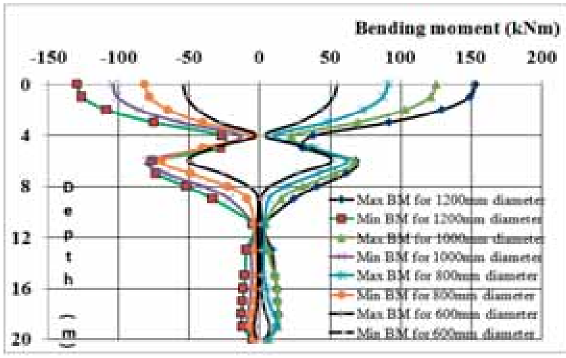

Figure 10 – Variation of the maximum and minimum bending moments along the pile shaft for different diameter piles with top layer thickness 5m.

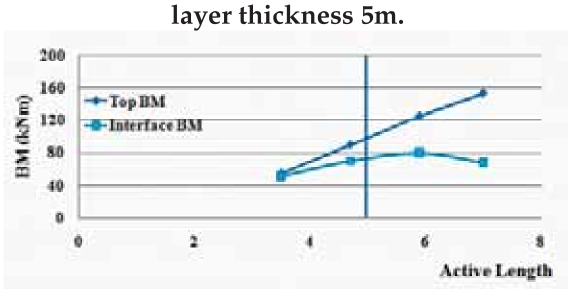

Figure 11 – Bending moment at the interface and top of the pile for fix-headed piles of different diameter in a soil medium with top layer thickness of 5m.

A different earthquake record is used to check the validity of the findings of Thilakasiri et al. (2009). For this purpose, earthquake ground acceleration record 2 given in Figure 6 is used with the top layer thickness of 8m. The obtained maximum and minimum bending moments along the pile shaft are shown in Figure 12. Figure 13 shows the variations of the pile top bending moment and the bending moment developed at the layer interface with the active length of the piles.

Similar to the Figure 11, the pile top bending moment becomes greater than the interface bending moment for active lengths less than the top layer thickness. The reason for such deviation is the degradation of the elastic modulus with the shear strain as explained earlier. Therefore, this may be taken as a further verification of the developed model.

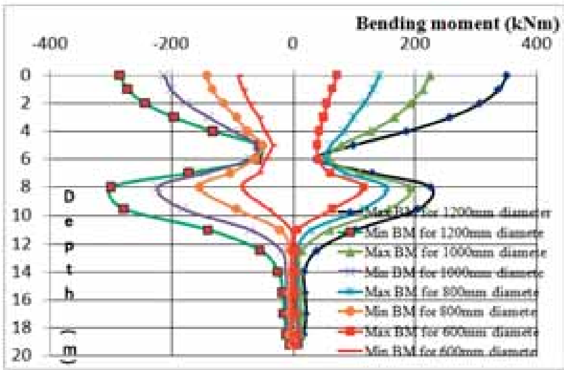

Figure 12 – Variation of the maximum and minimum bending moments along the pile shaft, obtained for the acceleration record 2, for different diameter piles with top layer thickness 8m.

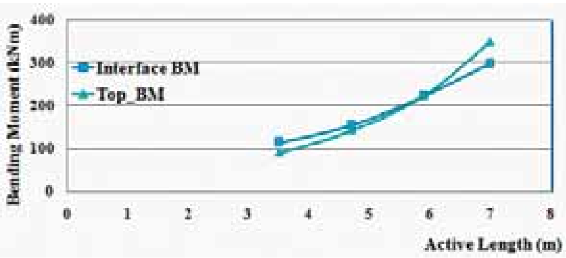

Figure 13 – Bending moment at the interface and top of the pile, obtained from acceleration record 2, for fix-headed different diameter piles in a soil medium with top layer thickness of 8m.

The above findings are very much in agreement with the general trends that were observed in similar analysis. Therefore, based on the above findings one could conclude that the results obtained from the model is reasonably accurate. However, a true verification of model predictions may be confirmed only by comparing with the field or laboratory measured forces developed in piles subjected to earthquake ground motion. The findings of this study are in excellent agreement with the previous observations made by Thilakasiri et al. (2009). Therefore, the findings of the present study strengthen the conclusions made by Thilakasiri et al. (2009) related to the kinematic forces developed in piles subjected to earthquake ground motion.

3.1.2 Combined effects of Inertial and Kinematic Effects

The main aim of this study is to investigate the combined effects of the inertial and kinematic forces on a single rock socketed pile. To simulate the mass of the structure on the pile, a weight was kept on the pile at 1m above the ground surface. The weight that was kept on the pile was varied to one-tenth of the working load and one-fourth of the working load. A certain mass of the structure may be directly on the pile and may oscillate with the pile. The mass that moves with a single degree of freedom assumed in this simulation may be relatively smaller in a structure such as a building consisting of distributed mass. In such cases only the mass of the pile cap, portion of the capping beam and the columns directly attached to the pile may contribute to the inertial effects on the pile. However, in short bridge piers the assumption of single degree of freedom system with a relatively high percentage of weight on the pile head may be realistic. Therefore, in such structures both the inertial and kinematic forces should be considered.
Figure 14 shows the maximum and minimum bending moments generated in a 1200mm diameter pile without mass, mass equivalent to one-tenth of the working load and one-fourth of the working load kept 1m above the pile head as shown in Figure 4.

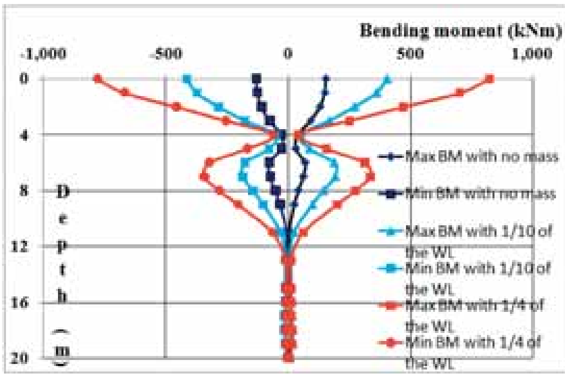

Figure 14 – Maximum and minimum BM in 1200mm diameter pile with different mass on the pile head for 5m thick top layer.

The developed bending moment in the pile clearly indicts that the interface bending moments are also increased with the mass on the pile head. However, the increase in the pile top bending moment takes place at a higher rate than the interface bending moment. It should be noted here that the active length of the pile is more than the thickness of the top layer.

The maximum and minimum bending moments developed in different diameter piles with a mass equivalent to one-fourth of the design load and one-tenth of the design load placed at the pile head are shown in Figures 15 and 16 respectively.

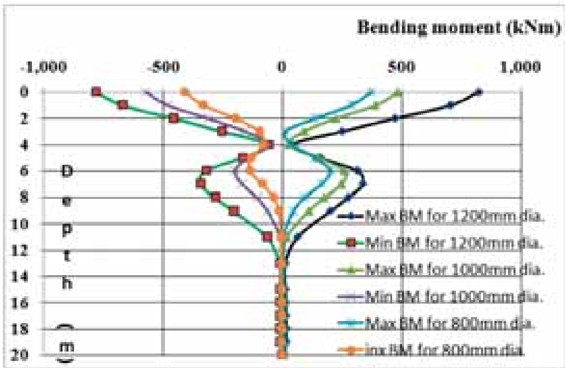

Figure 15 - Maximum and minimum BM with 1/4th of the working load on the pile head for different diameter piles for 5m thick top layer.

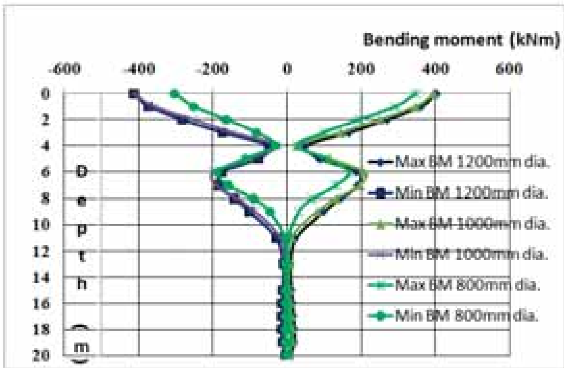

Figure 16 - Maximum and minimum BM with 1/10th the working load on the pile head for different diameter piles for 5m thick top layer.

The variation of the pile top and interface bending moments with the mass at the pile head for different pile diameters are shown in Figure 17.

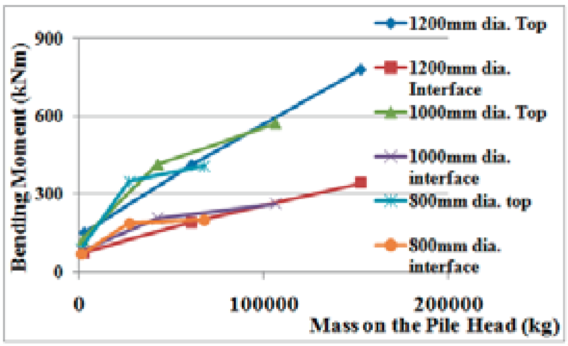

Figure 17 – Variation of the pile top and Interface BMs with the mass at the pile head for different pile diameters.

Both the pile top bending moment and the bending moment at the layer interface increases with the increase in the mass placed at the pile head. It seems that the pile top bending moment increase at a faster rate than the interface bending moment. Rate of increase in both the top and the interface bending moments seems to decrease with the increasing in the mass placed at the pile head.

The increase in the pile head bending moment with the mass on the pile head is clearly visible in Figure 17. However, the variation of the pile top and interface bending moment with the mass at the pile head should be investigated further to quantify the effects of different parameters on the variation of the bending moments. Damage to large number of flyover bridges during earthquakes may be due to the large effective mass oscillating with the head of the pier head and the resulting large bending moments developed in the bridge piers.
The interface bending moment developed due to the kinetic effects are increased due to the inertial effects of the effective mass at the pile head. Therefore, higher kinetic effects should be expected if the mass directly attached to the pile head is higher.

4.0 Conclusions

The importance of the active length in relation to the top layer thickness for the development of the bending moment in a pile subjected to earthquake effects is further verified by the present study. However, it is shown by the present study that the stiffness degradation of the soil with the shear strain should be considered in the estimation of the active length. The active length estimated using the initial elastic modulus of the soil may yield the active length less than the actual effective active length.

The effects of the mass oscillating with the pile are investigated in the present study. It is shown that considerably high bending moments are developed at the pile head due to the inertial effects. The developed bending moment in the pile clearly indicts that the interface bending moments are also increased with the mass on the pile head. Further, the increase in the pile top bending moment takes place at a higher rate than the interface bending moment. However, the variation of the pile top and interface bending moment with the mass at the pile head should be investigated further to quantify the effects of different parameters on the variation of the bending moments. The results of the present study explain the reasons for failure of large number of flyover bridges during earthquakes as the effective mass on the pier head is considerably high for such structures.

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