Dynamic Study of Batter Pile Groups under Seismic Excitations through Finite Element Method

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***Abstract*—**This paper presents a study on the behavior of batter pile groups under seismic excitations. Using 3D Finite Element Method a model has been developed to investigate dynamic response of batter pile groups. The governing constitutive model behavior for analysis is a Hardening Drucker-Prager behavior. In order to implement boundary conditions to soil medium series of Dashpot Elements are attached to the media so that absorbing boundary conditions have been taken into account. The pile group model has been affected by seismic excitations and the analysis has been performed using Rayleigh damping through dynamic explicit method. The group pile studied in the present work consists of four frictional piles which different model groups have been created during parametric study.

The present research aims to study the effect of pile inclination angle on the performance of batter pile groups under seismic motions. Moreover, the influences of slenderness and spacing ratios on performance of group piles have been also considered.

***Keywords*—**Batter Pile Groups, Finite Element Analysis, Dynamic Explicit method, Seismic Excitations.

I. INTRODUCTION

PILE Foundations have been extensively used in variety of civil and geotechnical engineering purposes. The forces on these structures are axial loads due to self weight of a superstructure; stockpiled materials and traffic from trucks, cranes, impact loads from ships, and wave loads that are cyclic in nature. Numerous studies have been performed concerning determination of lateral bearing capacity of pile foundations under seismic motions. Some of analytical studies proposed by Kausel and Kaynia (1982) [1], Sen et al. (1985) [2] , Dobry and Gazetas (1992) [3] and many other researchers have been developed to investigate dynamic response of pile group assuming linear behavior of soil. Konagai and Nogami (1986,1988) [4],[5] considered dynamic response of pile group using Winkler-theorem. Nogami et al. (1992) , [6] investigated pile group behavior by defining separated elements of soil-mass, spring and damper and using non-linear behavior of soil. While El-Neggar and Novak (1995, 1996) [7], performed a non-linear time history analysis for pile group under lateral loading using winkler-theorem. All of these studies indicate that soil non-linear behavior has significant influence on dynamic response of pile groups. Throchanis et al. (1991), [8] also investigated behavior of pile groups using a three dimensional model of vertical pile embedded in clay assuming an elastic-perfectly-plastic soil behavior. Brown and Shie (1991), [9] used finite difference method to model the pile as a beam element and soil mass as non-linear springs connected to pile. The non-linear springs was defined through specified lengths of pile using P-Y curves.

The application of batter pile groups has been increased in recent years due to its considerable resistance against lateral loading condition. Actually batter pile groups are more appropriate choice to resist lateral forces due to seismic excitations and inertial forces, that’s because vertical pile group perform much weaker while seismic motions affect these structures. Nevertheless the application of these pile groups is effectively restricted in seismic districts so that some of designer engineers do not recommend using batter pile groups in these areas. That’s mostly because of large forces developed in cap which makes it more insecure for other further constructions. Based upon Gazetas and Mylonakis studies (1998), [12] investigations have shown that in particular cases application of batter pile groups is very helpful and advantageous for pile group and other structures over them. For example field evidence from the 1995 Mw 6.9 Kobe earthquake reveals that one of the few quay-walls that survived in a Kobe harbor was a composite wall supported by batter piles, while nearby walls built on vertical piles suffered very severe damage. Also Juran et al. (2001) conducted a series of centrifuge tests and pseudo static analysis on batter pile and micropile groups and concluded that increase of pile inclination angle up to a specified value will cause to significant reduction of both deflection and bending moment in cap-pile connection region.

Attention in the present study is mostly focused on effect of pile inclination angle on performance of batter pile groups under earthquake loading. Therefore a three dimensional finite element model considering soil non-linear cyclic behavior has been developed and dynamic response of batter pile group under seismic excitations has been investigated. Also a series of parametric studies have been conducted to understand influences of crucial parameters on the behavior of structure.

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II. PROBLEM DEFINITION

Piles are commonly used in groups. The behavior of pile groups relies on variety of factors such as pile distance, pile slenderness ratio as well as pile inclination in case of batter pile groups. This paper aims to understand dynamic behavior of Batter Pile Groups under lateral loading which are mostly due to seismic motions. Therefore, having better perception of these structures, behavior of a frictional group pile has been considered. These group piles consist of four concrete rounded piles with section diameter of 50 centimeters and length of 9 meter. The piles are entirely embedded in soil mass. Properties for both soil and concrete material used for piles are presented in table 1. A cap has been used to make four piles connected to each other and its thickness is assumed to be about 60 centimeters with length and width equal to 3 meters. One of the crucial parameters contributing to performance of batter pile groups is pile inclination angle. Accordingly, to investigate influence of pile inclination angle, four different models with different pile inclination angles of 0,10,20,25 have been developed and effect of this parameter is evaluated. Soil medium surrounding piles is also has to be modeled properly. Considering wave transmission conditions to permit wave propagate inside soil an optimized dimensions for soil medium around the piles is presumed. As a result, this medium has been modeled with dimensions in global x, y, z coordinate directions equal to 25, 25, 20 meters respectively (Fig. 4). To conduct dynamic analysis, bottom of developed model is subjected to acceleration component of Naghan earthquake (1977) in southwestern Iran with peak acceleration response of 0.72g. The horizontal acceleration history of Naghan earthquake is depicted in Fig. 1. In order to take into account superstructure circumstances an equivalent uniform load is placed over the cap.

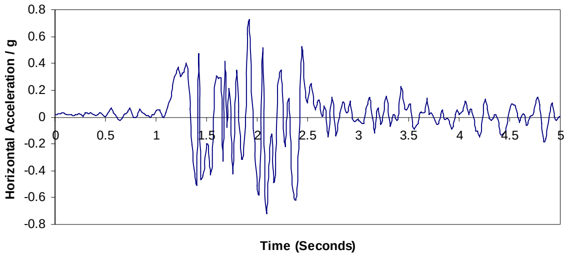


Fig. 1 Horizontal Acceleration History of Naghan 1977 earthquake in southwest Iran

Effects of pile slenderness ratio and pile spacing were also considered for pile groups. To investigate effects of these parameters a number of batter pile group with 20 inclination degree and different slenderness ratio and pile spacing were simulated. It's remarkable that the direction of which piles are inclined is x global coordinate direction. Geometric properties of pile section and cap are illustrated in Fig. 2.

III. FINITE ELEMENT SIMULATION

The general purpose code ABAQUS version 6.5 [16] was utilized for all analyses. To perform finite element analysis of batter pile group two different type of elements were employed.

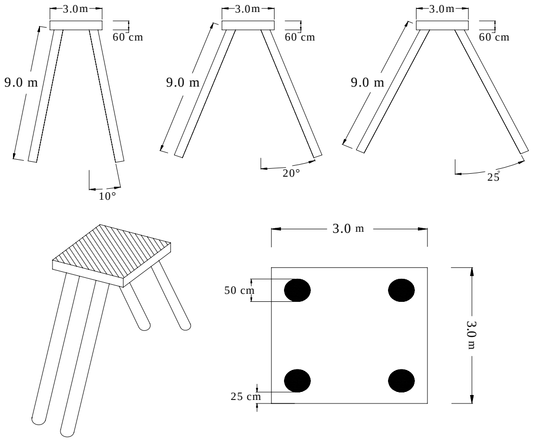


Fig. 2 Geometric properties of batter pile groups and cap section

TABLE I
SOIL AND CONCRETE PILE CHARACTERISTICS USED IN FEM ANALYSES

Properties	Soil	Concrete
ν	0.3	0.25
E (MPa)	4.32×10^5	2.1×10^6
V_s (m/s)	100	-
ξ	1%	2.5%
ρ (kg/m^3)	1800	24.5
φ	30 °	-
C (kPa)	0	-

Tetrahedral elements were used to mesh piles while hexahedral elements were employed to compose medium far from piles. It is remarkable that for those medium elements close to piles, tetrahedral elements were employed. That's mainly due to intensive variations of stress and also considering plasticity features of soil. A finer mesh was used for regions near piles. The geometry of in use elements are shown in Fig. 3 (a). Each node includes three degrees of translational freedom in x, y, z directions. Numerical distortion of propagating wave can take place in a dynamic analysis as a function of modeling conditions. It should be noted that both the frequency content of the input wave and the wave velocity characteristics of the system will influence accuracy of wave transmission. Kuhlemeyer and Lysmer (1973) show that for accurate representation of wave transmission through a model, the spatial element size , Δl must be smaller than approximately one-tenth of the wavelength associated with the highest frequency component of the input wave –i.e ;

$$\Delta l \leq \frac{\lambda}{10} \tag{1}$$

Hence in order to simulate semi-finite soil medium, spring-damper elements (Kelvin elements) were utilized so that absorbing boundary conditions have been taken into account [Fig. 3 (b)]. These elements were spread in three directions attached to mesh boundaries along some specific pre-defined points.

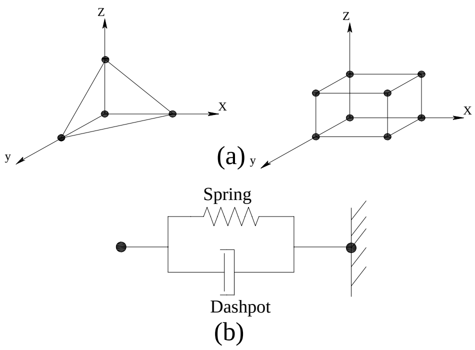
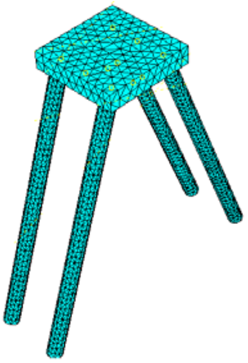


Fig. 3 a) Tetrahedral and Hexahedral elements used for simulation of piles and medium b) Spring-Dashpot elements



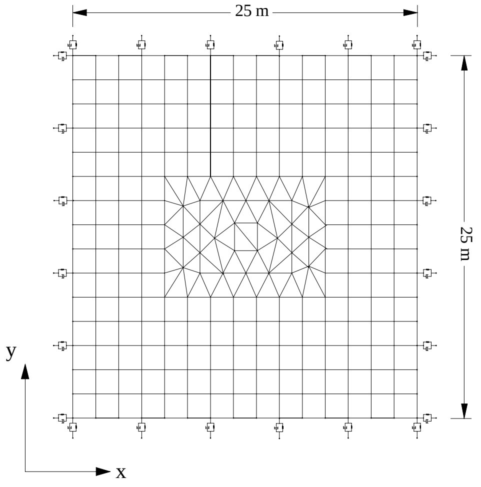


Fig. 4 Mesh elements used to simulate batter pile group and surrounding soil medium

IV. SOIL CONSTITUTIVE LAW

In order to have a better prediction of soil behavior under cyclic loading conditions an elastic-perfectly-plastic model behavior is assumed to represent both elastic and plastic behavior of soil. An isotropic elastic assumption for soil elastic behavior is considered and to predict soil plastic behavior a Hardening Drucker-Prager model is presumed. Two type of interaction property have been considered during this research. One is concerned with tangential interaction mechanism between pile circumferential surface and surrounding soil, another is attributed as normal (or axial) interaction mechanism which deals with that kind of interaction where happens between pile end and soil around.

V. GOVERNING EQUATIONS AND SOLUTION

The equations governed motion at time is as below:

[M] EMBED Equation.DSMT4 $^{t+\Delta t}$ + [C] EMBED Equation.DSMT4 $^{t+\Delta t}$ + [K] EMBED Equation.DSMT4 $^{t+\Delta t}$ = $[R]^{t+\Delta t}$ (2)

Where, [M] is diagonal mass matrix (due to lumped mass assumption); [C] is damping matrix including both material (hysteretic) and geometric damping (dashpots along boundary) and [K] is symmetric stiffness damping. $[R]^{t+\Delta t}$ represents the external load at time step ,are relative nodal acceleration, velocity and displacement respectively at time .

To incorporate damping of system, both material and geometry damping has to be taken into account. Basically damping includes two terms as below:

$$C = C_r + C_m \tag{3}$$

which C_r represents geometry damping including a diagonal matrix having non-zero terms at nodes which are placed at boundaries and C_m will correspond to material damping of system. To consider soil hysteretic behavior under cyclic loading conditions, Rayleigh damping is utilized as a method to assume material damping conditions. If [c] is assumed as damping matrix then it is a linear combination of diagonal mass matrix and stiffness matrix like below:

$$[C] = \alpha[M] + \beta[K] \tag{4}$$

Where α, β are constants representing damping in proportion with mass and stiffness matrixes. Damping ratio varies in relation with natural frequency of system at i*th* mode according to following equation:

$$\xi_i = \frac{\alpha}{2\omega_j} + \frac{\beta\omega_j}{2} \tag{5}$$

Having both shear wave velocity and two natural frequency of soil, the unknown variables are obtained as below:

$$\alpha = \xi \frac{2\omega_i\omega_j}{\omega_i + \omega_j} \quad , \quad \beta = \xi \frac{2}{\omega_i + \omega_j} \tag{6}$$

where, ω_i, ω_j are featured as frequencies at i*th* and j*th* modes.

For low frequencies β coefficient is supposed to undertake damping role of system while for high frequencies α is crucial component concerning damping of system. Therefore for materials with low level of frequency it is recommended to use damping coefficient in proportion with mass matrix, i.e. α. For the present research, damping coefficient regarding mass matrix (α) is assumed to be 0.2 and another damping coefficient related to stiffness matrix is equal to zero.

The bottom of model is restrained by roller as well as side boundaries. To prevent reflection of waves, viscous dampers as a sort of artificial boundary are commonly used as an appropriate tool to represent a transmitting boundary for propagated waves. Accordingly, equations below results in damping coefficients in both normal and tangential direction:

$$\sigma = \rho v_p \dot{w} \quad \Rightarrow \quad C_p = \rho A v_p \tag{7}$$

$$\tau = \rho v_s \dot{u} \quad \Rightarrow \quad C_s = \rho A v_s \tag{8}$$

VI. SOLUTION ALGORITHM AND EQUATIONS

Algorithm utilized in the present study is explicit solution method which is based upon the implementation of an explicit integration rule together with use of diagonal or lumped element mass matrixes. This method is an appropriate tool for minute timesteps and the equations of motion for the body are integrated using explicit central difference integration rule:

$$\dot{u}^N_{i+\frac{1}{2}} = \dot{u}^N_{i-\frac{1}{2}} + \frac{\Delta t_{i+1} + \Delta t_i}{2} \ddot{u}^N_i \tag{9}$$

$$u^N_{i+1} = u^N_i + \Delta t_{i+1} \dot{u}^N_{i+\frac{1}{2}} \tag{10}$$

which u^N_i, represents displacement or rotation vector, $\dot{u}^N_i$ velocity vector, $\ddot{u}^N_i$, acceleration vector. The superscript i refers to the increment number and $i-\frac{1}{2}$ and $i+\frac{1}{2}$ refer to midincrement values. The central difference integration operator is explicit in that the kinematic state can be advanced using known values of $\dot{u}_{i-\frac{1}{2}}$ and $\ddot{u}_i$ from the previous increment. The explicit integration rule is quite simple but by itself does not provide the computational frequency associated with the explicit dynamics procedures.

Special treatment of the mean velocities is required for initial conditions, certain constraints and presentation of results. For presentation of results, the state velocities are stored as a linear interpolation of the mean velocities:

$$\dot{u}^N_{i+1} = \dot{u}^N_{i+\frac{1}{2}} + \frac{\Delta t_{i+1}}{2} \ddot{u}^N_{i+1} \tag{11}$$

The central difference operator is not self-starting because the value of the mean velocity $\dot{u}_{-\frac{1}{2}}$ needs to be defined. The initial values (at time t=0) of velocity and acceleration are set to zero unless they are specified by the user. We assert the following equation:

$$\dot{u}^N_{+\frac{1}{2}} = \dot{u}^N_0 + \frac{\Delta t_0}{2} \ddot{u}^N_0 \tag{12}$$

Substituting this expression into the update expression for $\dot{u}^N_{i+\frac{1}{2}}$ yields the following definition of $\dot{u}^N_{-\frac{1}{2}}$:

$$\dot{u}^N_{-\frac{1}{2}} = \dot{u}^N_0 - \frac{\Delta t_0}{2} \ddot{u}^N_0 \tag{13}$$

And the acceleration for substitution at the first timestep for above equation is defined as below:

$$\ddot{u}^N_i = M^{NJ} (P^J_i - I^J_i) \tag{14}$$

where M^{NJ}, is the diagonal lumped mass matrix, P^J_i is the applied load vector, and I^J_i is the internal force vector. It is worth mentioning that the explicit procedure will not require any iterations as well as stiffness matrix [16].

VII. RESULTS OF PARAMETRIC STUDY

Numerous parameters affect the performance of batter pile groups while some of these parameters such as pile inclination angle, pile relative spacing and pile slenderness ratio are much more crucial. Other factors like damping, stiffness and interaction mechanism between cap and underneath soil and pile-soil stiffness ratio contribute on performance of these structures as well. But this paper intends to have better perception of influence of parameters like pile inclination angle, pile slenderness ratio and pile relative spacing on behavior of structure.

A. Pile Inclination angle

Effect of pile inclination angle was considered in this section. Three models of batter pile groups with different inclination angles were made by software in addition to vertical pile group. The horizontal displacement response of pile head is demonstrated in Fig. 5. According to this figure it can be seen that as the pile inclination angle increases, the pile head displacements diminishes. Fig. 6 also depicts effect of different pile inclination angle on normal stress distribution developed in pile head. It can be deduced that while pile inclination angle increases, the whole batter pile group stiffness will increase and it can improve pile performance to enhance its resistance against lateral loading conditions. As a result, shear stresses along pile will decrease as pile inclination increases and subsequently pile head displacements reduce.

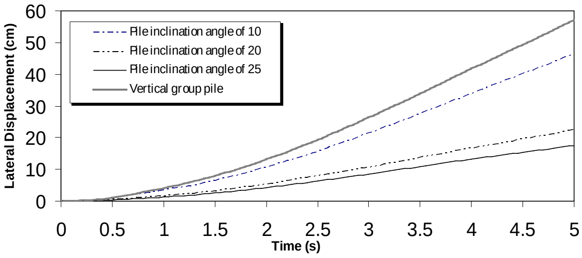


Fig. 5 Time History of horizontal displacement at pile head for different pile inclination angles

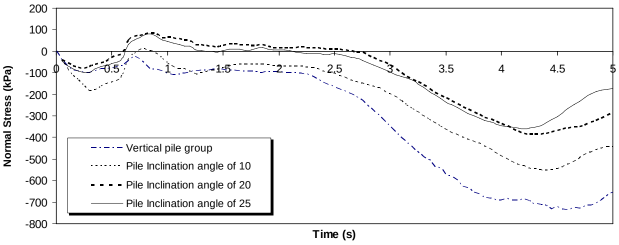


Fig. 6 Time History of normal stress at pile head for different pile inclination angles

Figs. 7 and 8 display distribution of maximum bending moment along standard pile length for both right and left-sided piles. It indicates that with increase in pile angle inclination the developed bending moment along pile standard length will diminish. Fig. 9 shows distribution of shear stresses along standard pile length for different pile inclination angles. Accordingly it can be understood that increase in pile inclination angle will result in reduction in developed shear forces along pile length. Fig. 10 also displays history of normal stress developed in cap for different pile inclination angles and it can be observed that pile inclination angle will result in increase in developed axial stresses inside cap.

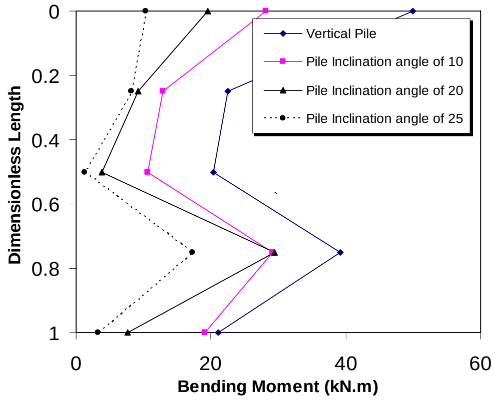


Fig. 7 Maximum bending moment for group pile with different pile inclination angle (Right Piles)

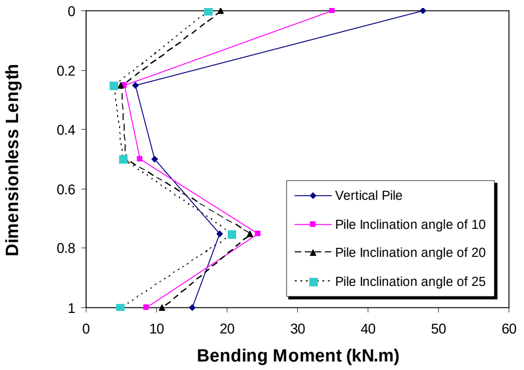


Fig. 8 Maximum bending moment along standard length of pile for different pile inclination angle (Left Piles)

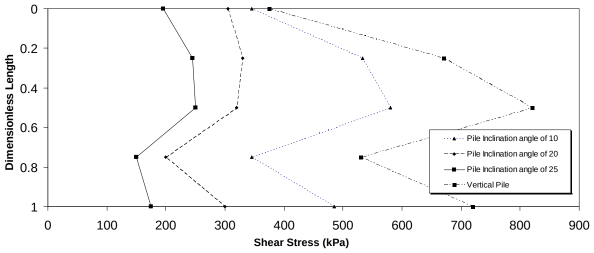


Fig. 9 Shear stress along standard length of pile for different pile inclination angle

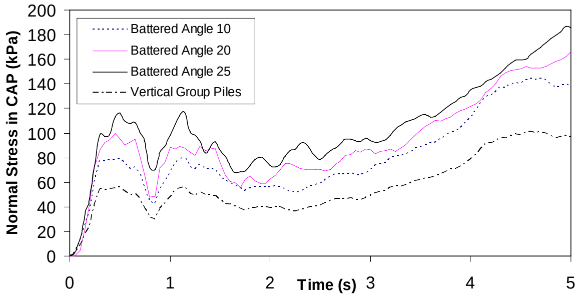


Fig. 10 Time History of normal stress head for different pile inclination angle

A. *Slenderness ratio*

To investigate effect of slenderness ratio on batter pile group performance two different slenderness ratios have been considered. It has been assumed that all other parameters are not varying during these analyses.

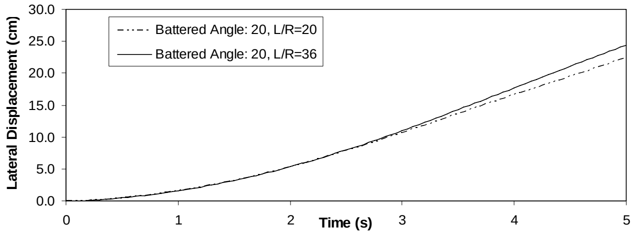


Fig. 11 Time History of horizontal displacement at pile head for different pile slenderness ratios

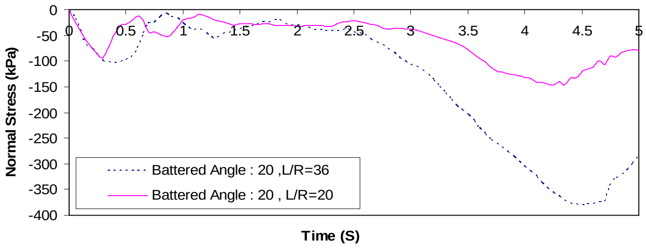


Fig. 12 Time History of normal stress at pile head for different pile slenderness ratios

Fig. 11 illustrates history of horizontal displacements in pile head and it can be observed that since slenderness ratio decreases, there is a slight decrease in pile head horizontal displacement. This is mainly due to insignificant influence of increase of slenderness ratio to values beyond 25. Because increase of pile slenderness beyond 25 will not affect on impedance functions and then both stiffness and damping functions remain unchanged. It can be inferred that one of the major causes of slight decrease in pile head horizontal displacements might be due to trivial effect of pile slenderness ratio on influencing impendence function for ratios beyond 25. Fig. 12 displays history of normal stresses developed at pile head and it can be concluded that pile slenderness ratio is a crucial factor contributing development of stress at pile head and it is also of interest to know that during design process of these structures pile slenderness ratio is fundamental factor determining pile performance under lateral loading conditions. Figs. 13 and 14 depict distribution of maximum bending moment and shear stress along standard length of pile for two different pile slenderness ratios.

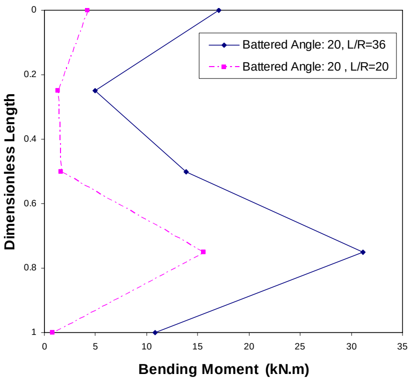


Fig. 13 Maximum bending moment along standard length of pile for different pile slenderness ratios

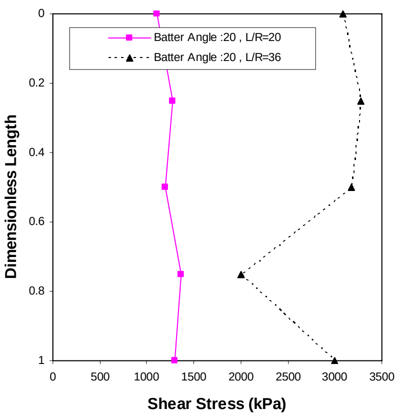


Fig. 14 Shear stress along standard length of pile for different pile slenderness ratios

A. *Pile Spacing*

To understand effect of pile spacing on behavior of batter pile groups three different spacing ratios for pile groups have been considered. Figs. 15 and 16 display history of lateral displacement of pile head and normal stress at pile head for batter pile group with inclination angle of 20 and different spacing ratios. It can be seen that as spacing ratio increases, axial stresses in pile head would decrease.

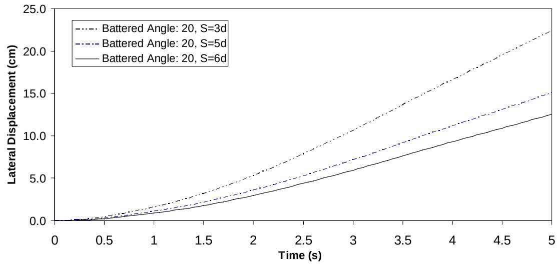


Fig. 15 Time History of horizontal displacement at pile head for different pile spacing ratios

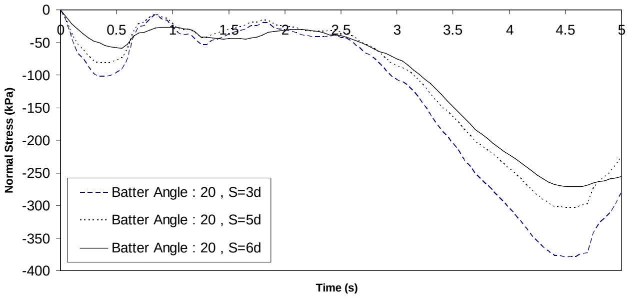


Fig. 16 Time History of normal stress at pile head for different pile spacing ratios

It can be concluded as pile spacing increases the intensity of developed stress in pile head decreases due to weakened mutual pile interaction on each other. Figs. 17 and 18 present maximum bending moment and shear forces distribution along pile standard length and it can be observed that increased pile spacing ratio will result in reduction of both bending moment and shear forces along pile length. It was observed that pile spacing ratio would not affect cap horizontal and vertical displacements while it causes reduction in both horizontal and vertical displacements of pile head.

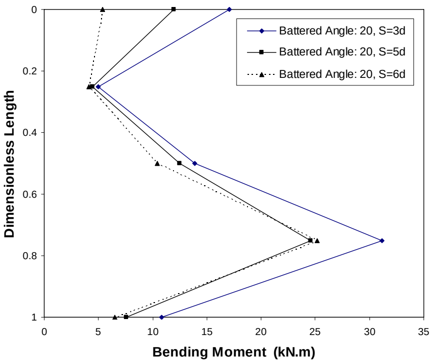


Fig. 17 Maximum bending moment along standard length of pile for different pile spacing ratios

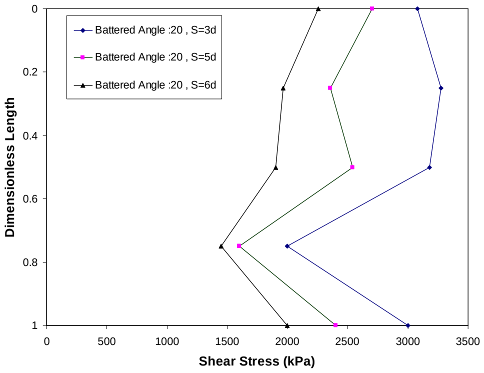


Fig. 18 Shear stress along standard length of pile for different pile spacing ratios

VIII. CONCLUSION

Present research focuses on understanding behavior of batter pile groups under seismic excitations. Numerous finite element models developed using code ABAQUS v.6.5-1. Taking into account boundary conditions, spring-dashpot elements were employ in order to consider absorbing boundary condition. The method used for solution of the problem was dynamic explicit method besides using Rayleigh damping. A parametric study conducted considering influence of three crucial factor like, pile inclination angle, pile spacing ratio, pile slenderness ratio. Some of results obtained through analyses are indicate briefly.

1) While pile inclination angle increases, the horizontal displacement occurred at pile head reduces. This is because improved lateral stiffness of structure so that provides enhanced resistance against lateral loading. Furthermore normal stress at pile head will decrease since pile inclination angle increases. Improved performance of batter pile groups during earthquakes is mainly due to enhanced lateral stiffness and consequently it results in reduction in pile shear stress and bending moments.
2) Due to weakened effect of mutual interaction mechanism of piles on each other it can be concluded that both horizontal displacement and normal stress at pile head decreases as pile spacing increases. Despite of signifant reduction of horizontal displacement at pile with increased pile spacing ratio it was also deduced that this parameter will not influence on horizontal and vertical displacements of cap.
3) Once pile slenderness ratio decreases, normal stresses developed at pile head will decrease. Similar behavior was observed for maximum bending moment developed along piles with lesser slenderness ratio. However, slenderness ratio would not influence both horizontal and vertical displacements of pile head as well as horizontal and vertical displacements of cap. Due to flexibility features of piles in horizontal direction, impendence functions are independent of slenderness ratio and as a result it would not influence pile head displacements significantly.
4) Pile inclination angle is an effective parameter contributing cap performance so that as pile inclination angle increase, it results in increase in normal stresses developed in cap.

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