Behaviour of Batter Piles under Dynamic Loads

Comportement des pieux inclinés sous charges dynamiques

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ABSTRACT: Batter piles have performed quite well in some cases and also quite badly in some cases over the past earthquakes there by arising credibility issues in their performance under dynamic loads. To address this problem, a comprehensive 3D finite element studies were carried out on 2x1 pile groups embedded in clay using ABAQUS. The dynamic analysis was carried out on the following configuration of the pile groups:(a) both vertical piles, (b) one vertical and another batter pile, and (c) both batter piles. The angle of inclination of batter piles is taken as 20º . The following soil profiles are considered: linearly increasing stiffness with depth and non uniform variation (varied profile I and II). The pile is modelled as a beam element and soil as solid brick elements. The soil is characterized with drucker prager cap model and pile with linear elasticity material model. The sinusoidal loading was applied at the pile head with frequency varying between 1 to 25 Hz. The analysis is run using dynamic implicit scheme. The finite element results are validated using the experimental studies on batter piles reported in literature. The results are presented in terms of frequency displacement response and bending curves. It is found that the batter pile groups shown 50% reduction of displacements than the vertical pile group, at frequencies lesser than their resonant frequency.

RÉSUMÉ : Pieux inclinés ont effectué très bien dans certains cas, et aussi très mal dans certains cas au cours des séismes par découlant des problèmes de crédibilité dans leur performance sous des charges dynamiques. Pour résoudre ce problème, un ensemble complet d'éléments finis 3D Des études ont été réalisées sur 2x1 groupes de pieux ancrés dans l'argile à l'aide d'ABAQUS. L'analyse dynamique a été réalisée sur la configuration suivante de la pile des groupes :(a) les deux pieux verticales, (b) l'une verticale et une autre pieu incliné, et (c) les deux pieux inclinés. The angle of inclination of the inclined pile is taken as 20º. Les profils de sols suivants sont considérés : augmentation de la rigidité linéairement avec la profondeur et la variation non uniforme (profil varié I et II). Le pieu est modélisé comme élément de poutre et le sol comme élément de brique. Le sol est caractérisé avec drucker prager modèle pac et tas avec l'élasticité linéaire modèle materiel. Le chargement sinusoïdal a été appliqué à la tête du pieu avec la fréquence variant de 1 à 25 Hz. L'analyse est effectuée à l'aide de schéma implicite dynamique. Les résultats d'éléments finis sont validées au moyen d'études expérimentales sur des pieux inclinés rapportés dans la literature. Les résultats sont présentés en termes de fréquence des courbes de flexion et courbes de déplacement. Il est constaté que les groupes de pieux inclinés montré 50 % de réduction des déplacements que de la verticale groupe de pieux, à une fréquence moindre que leur fréquence de résonance.

KEYWORDS: batter piles, inclined piles, finite element, dynamic.

1 INTRODUCTION

Piles are subjected to lateral dynamic loads during earthquakes. When lateral loads are dominant it is wise to use batter piles. They were a viable option in the yesteryears but at present they are not given importance by engineers because of their recent poor show in the series of earthquakes. Some structures in which they were found failed under seismic events includes a collapse of a bridge in the Port of Los Angeles in the 1994 Northridge earthquake (Mw = 6.7), a wharf in the Port of Oakland in the 1989 Loma Prieta earthquake (Mw = 6.9), etc. (Kavazanjian, 2006). Some of the reasons for the failures of batter piles were found to be poor reinforcement provision in the joints between cap and pile, improper design, inferior grade of concrete to the cap when compared to the pile etc (Mitchell et al., 1991; Priestley et al., 1991). But there are cases where even the vertical piles have failed abruptly upon taking seismic loads. Some typical cases of vertical pile failures includes the collapsed Rio Bananito Bridge near Limon, Costa Rica, in 1991CalTrans earthquake (M=7.6), Sheared Hollow Tube Pile under Warehouse in1995 Kobe earthquake (M=6.7), Struve Slough Bridge (Calif.), 1989Loma Prieta earthquake, (M=7.1) etc (The Earthquake Engineering Online Archive, NISEE). From above phrase it is understood that more research is needed on the behavior of batter piles in comparative terms with the vertical piles under different soil conditions. Also some recent numerical studies (Sheikhbahaei et al, 2009 and Ginnanokou et al 2010)on dynamic behavior of batter piles are encouraging and emphasis the need to do further studies.

In this view a comprehensive dynamic finite element studies were carried out on 2 x 1 batter pile groups under different soil conditions.

2 FINITE ELEMENT MODELLING

3D Finite element studies were carried out using the finite element code ABAQUS. The piles used in this study are assumed to have a diameter of 1000 mm and length of 14.85 m in which 12.375 m is embedded in predominantly clayey strata. These dimensions simulate some common piling length for bridges. Three different pile configurations are used in this study (Figure 1): both piles vertical piles (B0B0), one vertical and one batter piles (B20B0) and two symmetrical batter piles (B20B20). The batter angle of the battered pile is 20º. The young's modulus and Poisson's ratio of the piles are taken as 26.8 GPa and 0. 2 respectively. The piles were discritized using B31 beam elements connected to a rigid cap through a constraint. The pile groups are embedded into three type idealized soil profiles (Figure 2): (a) linearly increasing soil profile, (b) varied profile I and (c) Varied profile II. Varied profile I is characterized by an initial medium stiff layer

followed by a soft layer and again a higher stiff layer. Varied profile II is characterized by a top high stiff layer followed by low stiff layer and then by a medium stiff layer.
The clay was modelled with an undrained shear strength varying between 47 to 134 kPa according to the description of the soil profile. The undrained behavior of clay was characterized by modified drucker prager cap model which was defined by d, the undrained cohesion which is 1.73 times Cu (Helwany, 2007) and a poison ratio of 0.49. The elastic modulus (E_s) was defined using equation,

$$E_s = KS_u \qquad (1)$$

Where K is defined as

$$K = 4200\text{-}142.54I_p + 1.73I^2_p - 0.0071I^3_p \qquad (2)$$

I_p – plasticity index in percent

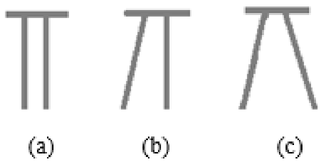

Figure 1 Pile configurations – (a) B0B0, (b) B20B0, and (c) B20B20

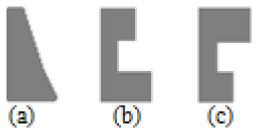

Figure 2 Different soil profiles considered (a) linearly increasing profile (b) Varied profile I and (c) Varied profile II

Bigger soil matrix corresponding to 100 times the diameter of the pile in loading direction and 50 times in the perpendicular direction of loading was used. The soil matrix was partitioned effectively (Figure 3) so as to produce structured meshing and for increasing the computational efficiency. The meshes were discretized with C3D8R elements and made finer surrounding the pile in order to predict the response more precisely. At both ends of loading direction the mesh were discretized with infinite elements so as to act as quiet boundaries thus creating a free field condition. On other sides of soil matrix standard boundary conditions were provided. The pile soil contact was established using a tie constraint. The analysis was carried out in two steps: geostatic and dynamic implicit load step. In the geostatic step all the in-situ conditions were defined. The sinusoidal excitation force was applied at the pile cap as a frequency sweep in the dynamic step. The load and top deflection at cap and bending strain along pile length were measured.

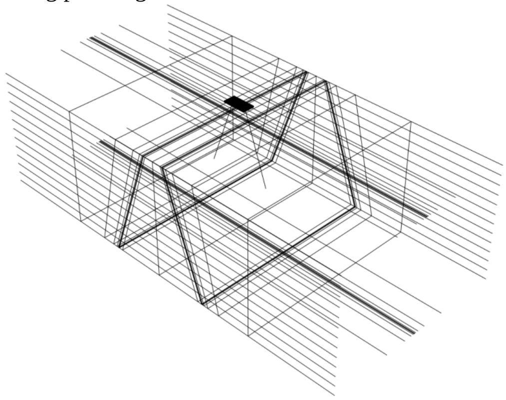

Figure 3. Wireframe view of discritized mesh

3 DYNAMIC LATERAL LOAD

It is found from literature (Finn 2005; Liyanapathirana et al 2011, Chowdhury &Dasgupta 2012) that during earthquakes piles at its head are subjected to load in range of 100 kN to 1000 kN. The displacement at pile head are in range of 10 mm to even about 200 mm. In this study the 2x1 pile groups were subjected to sinusoidal excitations of magnitude 270 kN (Low) and 540 kN (High) with frequencies 1 Hz to 25 Hz.

4 RESULTS AND DISCUSSIONS

4.1 *Frequency response*

4.1.1 *Typical frequency response*

The typical frequency displacement curve of symmetrical batter pile group (B20B20) embedded in different soil profiles is shown in Figure 4. It is seen that for all the cases there is only a single peak indicating the pile soil system behaves as a single degree of freedom system. It is also noticed as expected where that the top soil is relatively soft the pile experiences more displacement.

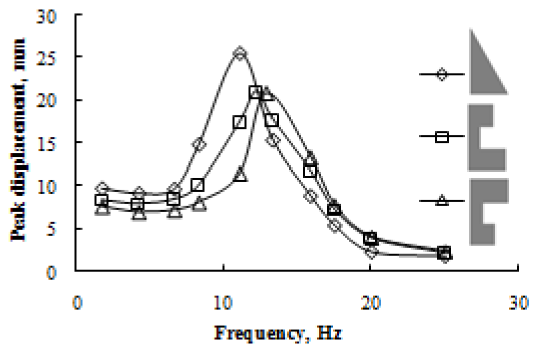

Figure 4. Frequency displacement response of symmetrical batter pile (B20B20) group

4.1.2 *Effect of batter piles*

The normalized displacement response is presented in Figure 5 to Figure 7 for different soil profiles at an applied force magnitude of 270 kN. The displacement is normalized by dividing the actual displacement amplitude (U) to the peak displacement of vertical pile group (UV_{max}). The frequency is normalized by dividing the actual frequency (f) by the resonant frequency of the vertical pile group (f_{nv}). For the case of linearly varying soil profile (Figure 5) it shall be noted that for the frequencies upto resonance the displacement amplitude of batter piles is lesser than vertical piles. The resonant frequency of batter piles is also larger than vertical piles indicating the increase in stiffness of the batter pile group.

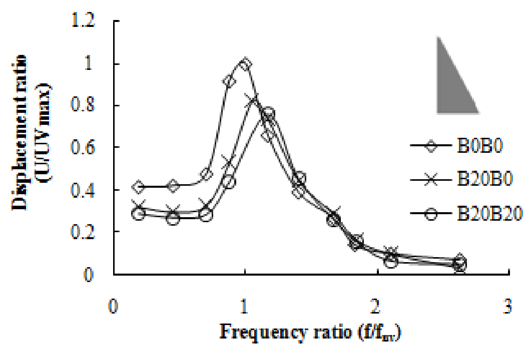

Figure 5. Normalized frequency displacement response of pile group in linearly increasing soil profile

The normalized response of varied soil profile I and II (Figure 6 and Figure 7) also show a similar trend like that for linearly increasing profile. However it may be inferred that when top layer is relatively stiffer, then the margin of reduction of displacement between vertical and batter pile at resonance reduces (Figure 7).

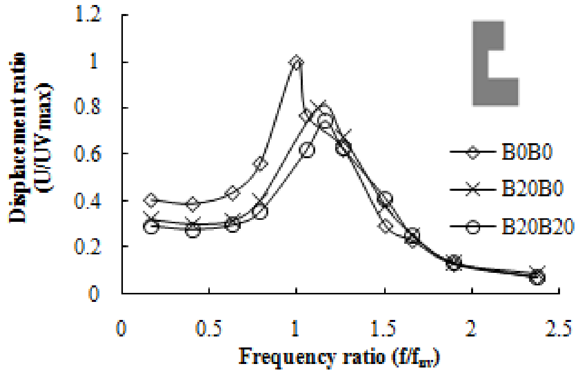

Figure 6. Normalized frequency displacement response of pile group in varied soil profile I

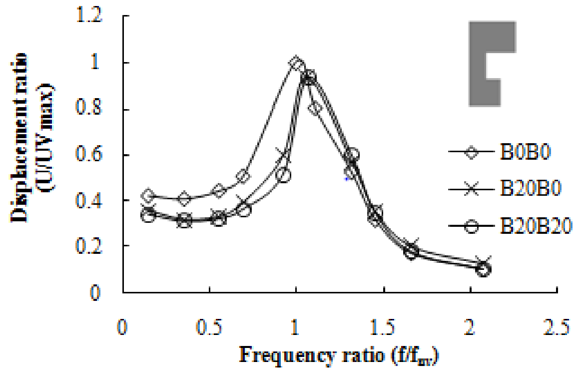

Figure 7. Normalized frequency displacement response of pile group in varied soil profile II

It is also observed from Figures 5 to 7 that the benefit of deamplification of displacement by use of batter piles is frequency dependent. It can be seen just before resonance of vertical piles the displacement difference is large. The normalized peak displacement (displacement of batter pile divided by displacement of vertical pile group) at about lower frequency and 80 % of resonant frequency is shown in Figure 8. The Figure 8 indicates that with symmetrical batter piles the reduction in displacement is as high as 50%.

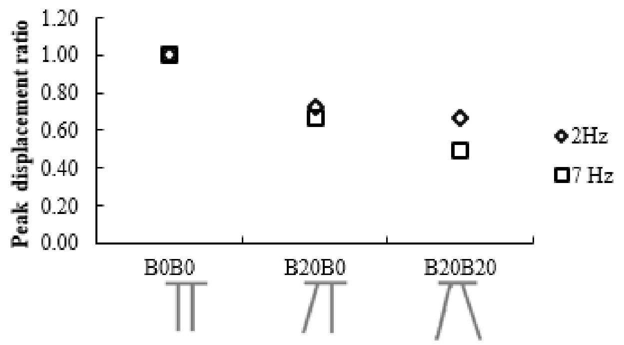

Figure 8. Normalized peak displacement at frequencies before resonance

4.1.3 *Effect of magnitude of load*

The normalized response curves for varied soil profile I for a load of 570 kN is shown in Figure 9. It shall be noticed that as compared to lower magnitude force (Figure 6) the difference in displacement amplitude increases between batter and vertical piles with increase of force. This is due to the larger mobilization of axial force in case of batter piles with increase of lateral dynamic load.

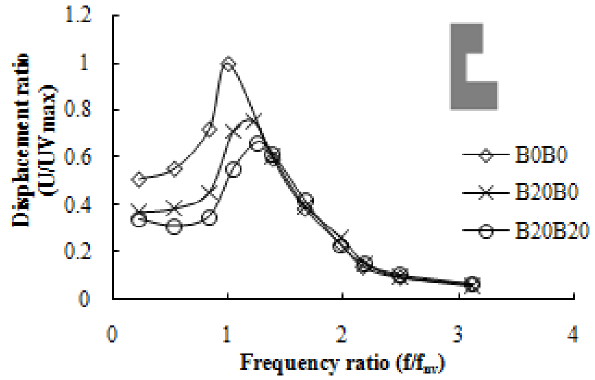

Figure 9. Normalized frequency displacement response of pile group in hetrogeneous soil profile I for higher magnitude of load

4.2 *Bending response*

4.2.1 Typical bending response

Typical bending response of symmetrical batter pile group (B20B20) is shown in Figure 10. It is inferred that though the maximum bending strain does not differ in amplitude in three soil profiles but the depth of occurrence of peak bending strain varies. For profiles with top soft soil the maximum bending strain occurs slightly at deeper depth indicating transfer of load to deeper depth.

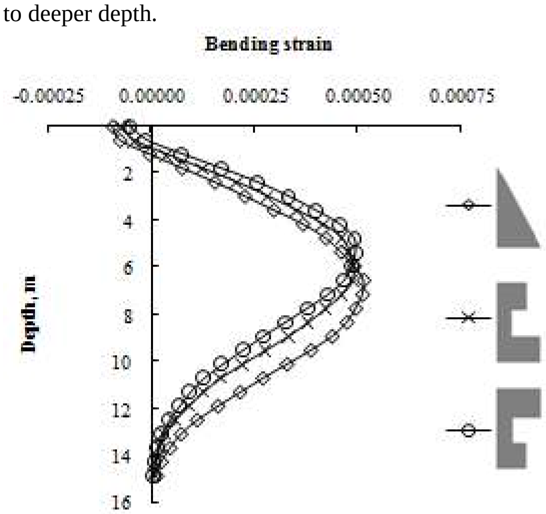

Figure 10. Typical bending strain of B20B20 pile group

4.2.2 *Effect of batter pile*

The normalized bending strain ratio is shown in Figure 11. The bending strain is normalized by dividing the bending strain (BM) to the peak bending strain of vertical pile (BM_{Vmax}). It shall be noticed that overall bending strain reduces with batter piles as some load of batter piles is transferred as axial capacity and is found to be a function of number of batter piles in group.

Likewise displacement, the beneficial role of batter piles in case of bending strain is also a function of load. The normalized maximum bending strain at resonance for pile in tension and pile in compression at low and high magnitude of load is shown in Figure 12 and Figure 13 respectively. It may be inferred that bending strain reduction is more in compression piles and is about 30% with symmetrical batter piles. It is because here the batter pile in compression transfers more of its load in axial compression thereby less straining the pile in lateral direction.

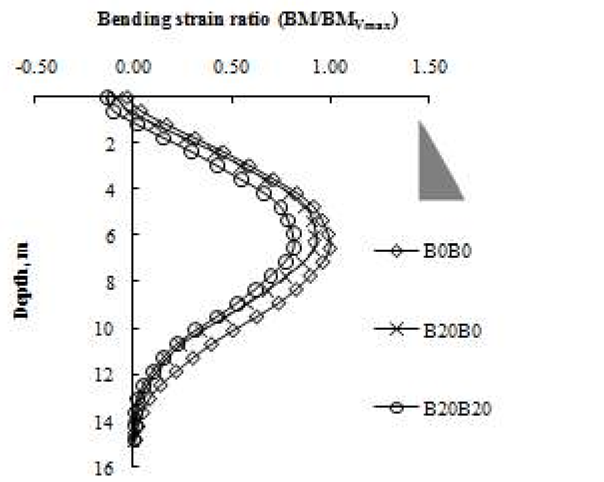

Figure 11. Bending strain ratio

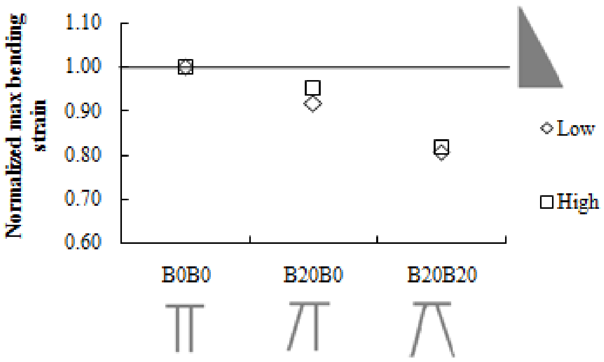

Figure 12. Peak bending strain ratio for piles in tension

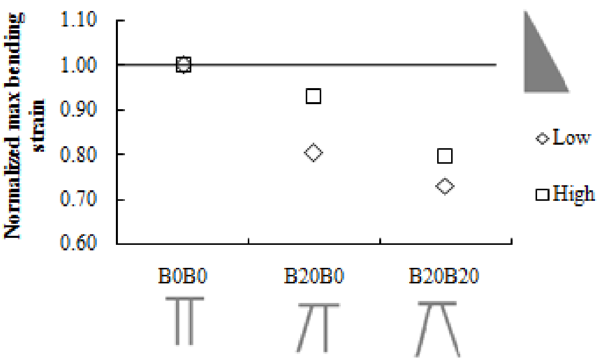

Figure 13. Peak bending strain ratio for piles in compression

4.3. *Comparison with experimental studies*

The finite element model in this study is based on the model tests carried out on batter piles presented in Subramanian and Boominathan (2016). The pile dimensions and soil parameters were based on the prototype dimensions presented in the paper arrived using the dynamic similitude by Woods et al (2004). The resonant frequency and peak displacement for B20B20 pile group at a force of 60 N (comparable to 270 kN at prototype scale) are about 43 Hz and 1.5 mm respectively. To convert these values to prototype scale the frequency has to be divided by 4.062 and displacement multiplied by 16.5 as in Subramanian and Boominathan (2016). Hence the prototype values are 10.58 Hz and 24.75 mm which are in closer agreement to the values presented for symmetrical batter piles embedded in different soil profile (Figure 4).

5. CONCLUSIONS

1. In all the soil profiles considered the pile head displacement of batter piles is found to be less than the vertical piles upto the resonant frequency of the vertical piles. The peak displacement of batter piles even reduces to half of the vertical pile displacement.
2. The introduction of batter piles in the group increases natural frequency of the group indicating increase in overall stiffness of the soil-pile system.
3. The batter piles have less bending strain than vertical piles and the bending strain reduction is more predominant for piles in compression than in tension.

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