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Three-Dimensional Dynamic Behaviour of Batter Pile Groups

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***Abstract:** To a practicing foundation engineer, the performance of batter piles under seismic conditions still remains a questionable prospect. The contradictory findings reported by various investigators with regard to the performance of batter piles add to this dilemma. This calls for a rigorous three-dimensional investigation to evaluate seismic behaviour of batter pile groups. In this study, a comparative assessment of three-dimensional seismic behaviour of 2 x 2 vertical and batter pile groups (batter angle 150) was carried out in Finite Element (FE) software package ANSYS. The effects of centre to centre spacing of piles and soil modulus values were investigated. Idealized soil profiles having constant and triangular variation of soil modulus were adopted for the study. Results of analyses for both vertical and batter pile groups are presented in terms of dynamic stiffness and kinematic interaction factors. Results suggest that the horizontal dynamic stiffness of the batter pile groups is higher in comparison to the vertical pile groups in most of the cases considered in the present study. However, vertical dynamic stiffness of batter pile groups is slightly lesser in comparison to the vertical pile groups. Moreover kinematic interaction factors for the batter pile groups for various cases are either comparable or smaller to that of the vertical pile groups. This indicates better seismic performance of batter pile groups in comparison to that of the vertical pile groups.To demonstrate the importance of the findings, a five-storied portal frame structure supported separately on vertical and batter pile group was considered. Time history record of N-S component of El-Centro earthquake (1940) was adopted for the study. The effects of dynamic stiffness and kinematic interaction factors for different configurations of vertical and batter pile groups on the seismic response of the superstructure are highlighted.*
***Keywords:** Foundation, Pile Foundation, Batter Pile Foundation*

I. INTRODUCTION TO PILE FOUNDATION

Pile foundations are commonly used deep foundation, used to support and transfer the load of the structure to the bearing ground. Piles transfer the load to deeper soil or rock of high bearing capacity avoiding shallow soil of low bearing capacity. When bedrock is not encountered at a reasonable depth below the ground surface, piles are used to transmit the structural load to the soil gradually by friction. In such situation, the resistance to the applied structural load is derived mainly from the frictional resistance developed at the soil-pile interface. Pile foundations are generally provided in group and the main components are the pile cap and the piles. The common types of materials used for piles are wood, steel and concrete. Piles made from these materials may be driven, drilled or jacked into the ground and connected to pile caps. In addition to vertical loads from the superstructure, piles are also subjected to the lateral loads from earthquakes, wind etc. It is observed that recent earthquakes have caused the collapse of important massive structures such as power plants, bridges, dams, offshore structures and heavy oil tanks owing to the failure of pile foundations. The dominating mechanism of failure was bending failure of piles under lateral loading conditions. However, it may be noted that in majority of the cases, vertical piles were used.

A. Advantages of Batter Piles over Vertical Piles

Batter piles, also known as *inclined piles* or *raked piles*, can generally carry additional lateral loads in comparison to vertical piles. There are various sources of high lateral loads to which the structure may be subjected. Some of the common sources are seismic loads, wind loads, blasts, impact loads from ships (berthing, pier collision etc), ocean wave forces etc. Depending on the magnitude of the lateral load, the degree of batter may be varied up to 30^0. In vertical piles, the total applied lateral load is transferred to soil media only. However, for batter piles, only a component of the lateral load gets transferred to the soil reducing the bending moment developed along the pile. Hence batter piles, if used judiciously, are expected to have a greater lateral load carrying capacity and smaller deformations than vertical piles of the same dimensions and material. However, the performance of batter pile under seismic conditions still remains a questionable prospect to a practicing foundation engineer. The contradictory findings reported by various investigators with regard to the performance of batter piles add to this dilemma. This calls for a rigorous three-dimensional investigation to evaluate seismic behaviour of batter pile groups.

B. *Types of Batter Piles*

There are two types of batter piles depending on the formation of slip surfaces.

1) Negative batter pile
2) Positive batter pile

C. *Negative Batter Pile*

When slip surface deflects downwards, the batter piles are known as negative batter piles. Negative batter piles are also known as *in-batter piles.* In this case lateral load acts in the direction of batter.

D. *Positive Batter Pile*

When slip surface deflects upwards, batter piles are known as positive batter piles. Positive batter piles are also known as *out-batter piles*. In this case lateral load acts in opposite to that of the direction of batter.

E. *Applications of Batter Piles*

Batter piles are generally employed for carrying large lateral loads. In case of large unsupported length, or presence of weak layers at the top, batter piles are beneficial. Though at present the applications of batter piles are limited to bridge abutments, wharf structures and some port and harbor structures, batter piles may have promising prospect in other common structures as well.
It may also be noted with caution that batter piles may not be efficient when the soil through which the pile is driven may settle causing additional loads and bending moments along the entire length of the pile.

F. *Details of Portal Frame Considered*

A five-storied portal frame is considered in the study as shown in Fig. 1.1. The structure consists of a single bay having plan dimensions of 6m x 6m and storey height 3.5 m. Each of the columns is assumed to be supported on 2 x 2 vertical and batter pile groups separately.

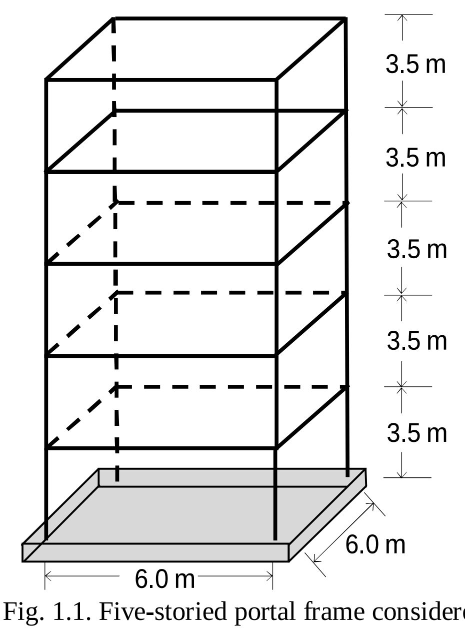

Fig. 1.1. Five-storied portal frame considered in the study

A two-node beam element with six degrees of freedom at each node is considered and the portal frame is modeled in software package SAP 2000 (*Version 14.0*). It is assumed that the portal frame is made of concrete and the properties are the same as that used for the pile material. The cross-sections of all beams and columns for the portal frame are assumed to be identical and are taken as 300mm × 300mm. The mass of the infill, mass of the slab and imposed load is also considered. Following values are used for this purpose. Unit weight of slab = 25 kN/m^3; Unit weight of infill = 20 kN/m^3; Imposed load = 3.5 kN/m^2 (IS: 875 (Part-2)-1987). Here it may be noted that the imposed load on the roof is not considered.

G. Details of Soil-Pile System

For the study with superstructure, E_p/E_s ratio 1408 is considered. The dynamic stiffness of both the vertical and batter pile groups are obtained from the charts presented in the previous chapters corresponding to the frequency of excitation. The stiffness is then incorporated at the bottom node of the columns as springs in the relevant degrees of freedom.

H. Earthquake Time History Considered

The N-S component of El Centro earthquake (1940) time history with PGA value 0.32g and predominant frequency 1.83 Hz is considered as the bed rock motion. This time history is shown in Fig. 1.2. The time history is then modified considering kinematic effects of the soil-pile system as obtained from the charts presented in *Chapter 5* of Kinematic Interaction Factor corresponding to the dominant frequency. Both original and modified time histories are then adopted as the base motion of the structure with springs and analyzed to obtain the roof displacement and base shear for different configurations of pile groups.

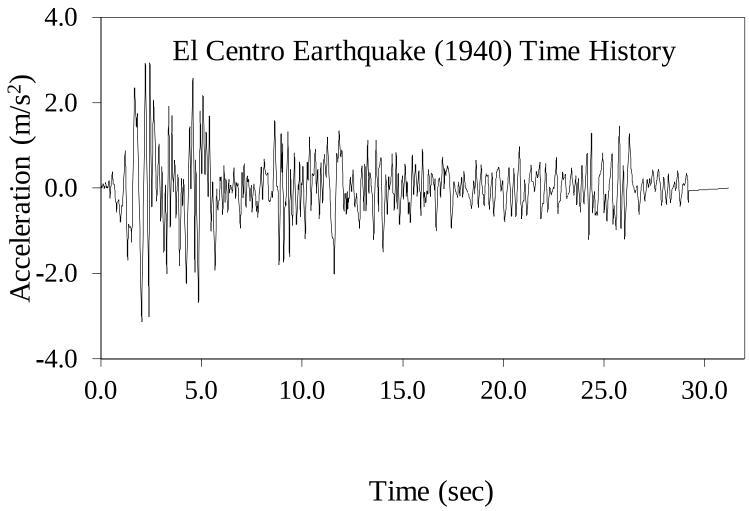

Fig. 1.2. El Centro earthquake time history

I. Response of Superstructure

Response histories of the structure subjected to the both original and modified earthquake time history are evaluated and compared in terms of roof displacement and base shear. Following three cases are considered for the analyses of superstructure.

1) Fixed base
2) Flexible base without kinematic interaction factor
3) Flexible base with kinematic interaction factor

J. Fixed Base Condition

For this case, base of superstructure is considered to be fixed. No soil-structure interaction effect is taken into consideration. Response of superstructure in terms of roof displacement and base shear is shown in Fig. 1.3. Values of maximum base shear and roof displacement are 1864 KN and 21.7 mm respectively.

K. Flexible Base Condition

For the known predominant frequency of input earthquake time history, dimensionless quantity (a_0), horizontal and vertical non-dimensional stiffness (normalized by single pile) is obtained from the charts presented earlier. The horizontal and vertical stiffness for the pile groups are then evaluated by multiplying single pile static stiffness and number of piles with the real part of the dynamic stiffness. These stiffness values are then incorporated at the bottom node of the columns as springs in the relevant degrees of freedom. The response of superstructure in terms of roof displacement and base shear are then evaluated and compared for the structure supported separately on vertical and batter pile groups considering uniform and triangular variation of soil modulus.

L. Response of superstructure considering uniform soil modulus

The response of the superstructure supported separately on vertical and batter pile groups with uniform soil modulus and flexible base has been presented in terms of roof displacement and base shear in Fig. 1.4(a) and Fig. 1.4(b) respectively.

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A comparison of Fig. 1.3 and Fig. 1.4 clearly highlights the effect of soil-structure interaction (flexible base condition) on the response of the superstructure. It is observed that under flexible base conditions, an increase in roof displacement and base shear occurs in comparison to fixed base conditions. However, another prominent observation is with regard to the better performance of batter pile groups with flexible base conditions. It has been noted that the roof displacement and base shear is lower for superstructure supported on batter pile groups in comparison to vertical pile groups under flexible base conditions.

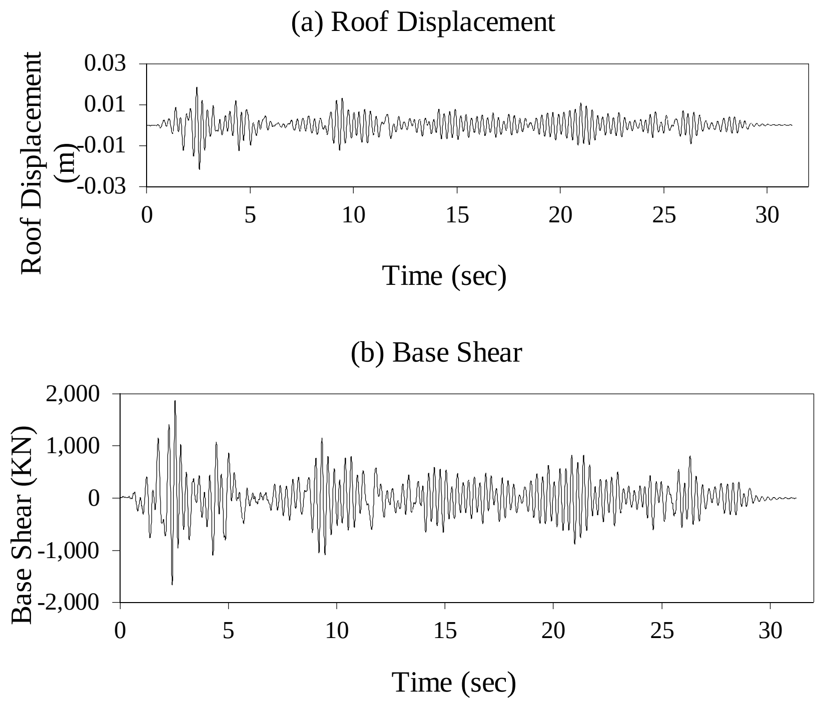
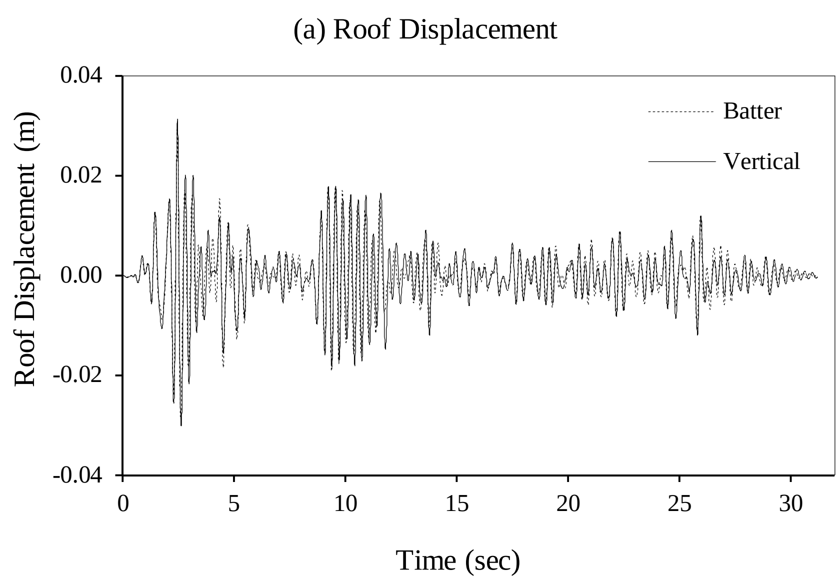


Fig. 1.3. Response of superstructure for fixed base condition (a) Roof displacement (b) Base shear



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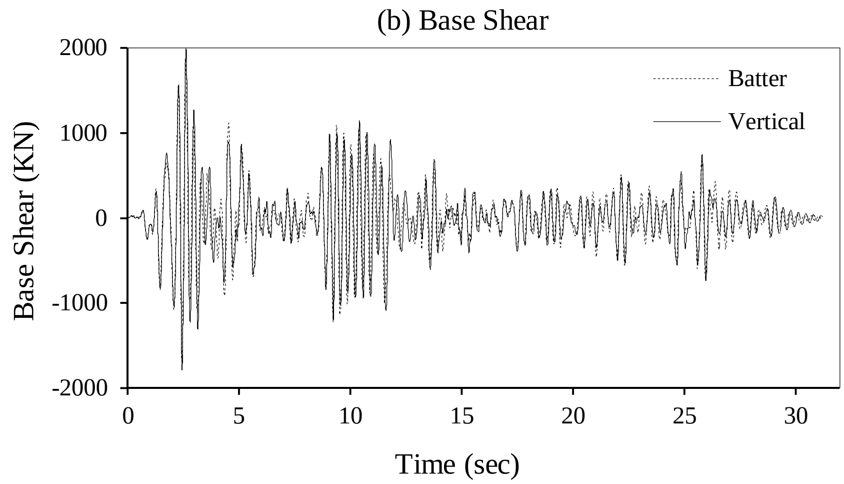

Fig. 1.4. Response of superstructure for flexible base condition considering uniform soil modulus (a) Roof displacement (b) Base shear

M. Response Of Superstructure Considering Triangular Variation Of Soil Modulus

Roof displacement and base shear of superstructure supported separately on vertical and batter pile groups with flexible base condition considering triangular variation of soil modulus is shown in Fig. 1.5(a) and Fig. 1.5(b) respectively.

From Fig. 1.4 and Fig. 1.5, it can be stated that consideration of idealized non-linear soil behavior results in an increase in base shear and roof displacement.

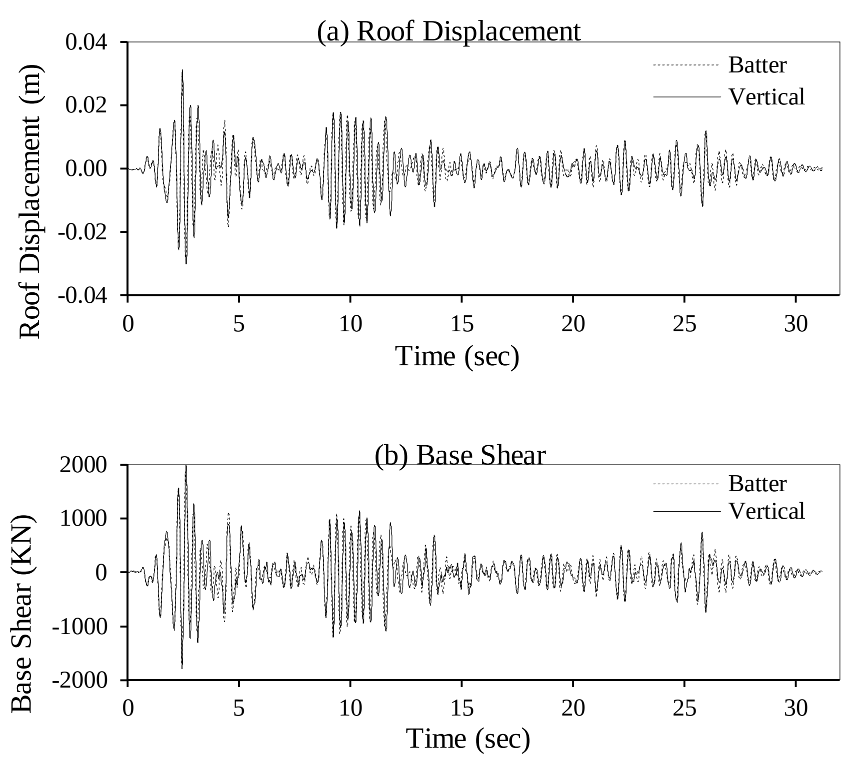

Fig. 1.5. Response of superstructure for flexible base condition considering triangular varying soil modulus (a) Roof displacement (b) Base shear

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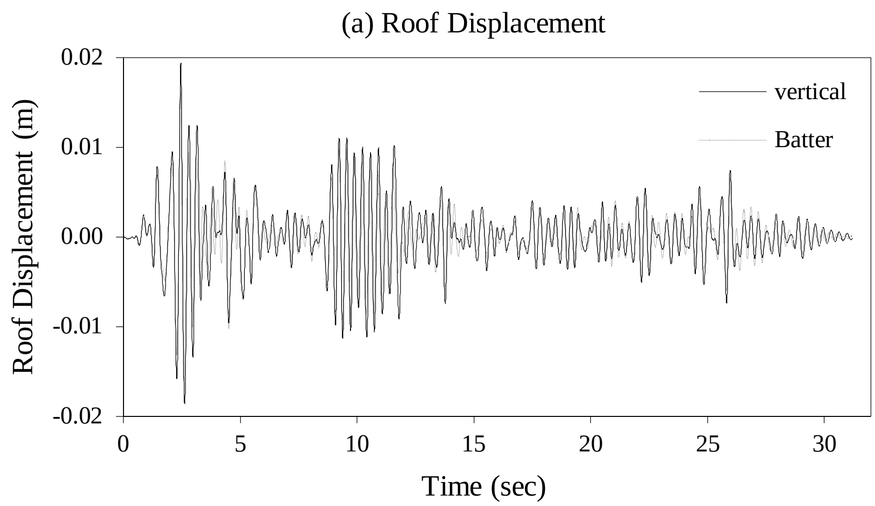
N. Response Of Superstructure Considering Uniform Soil Modulus

Fig. 1.6 presents the response of the superstructure considering the KIF for uniform soil modulus condition. Comparison of Fig. 1.6 with Fig 1.4 clearly shows that incorporation of KIF results in a decrease in the response of the superstructure for both vertical and batter pile groups under uniform soil modulus condition.



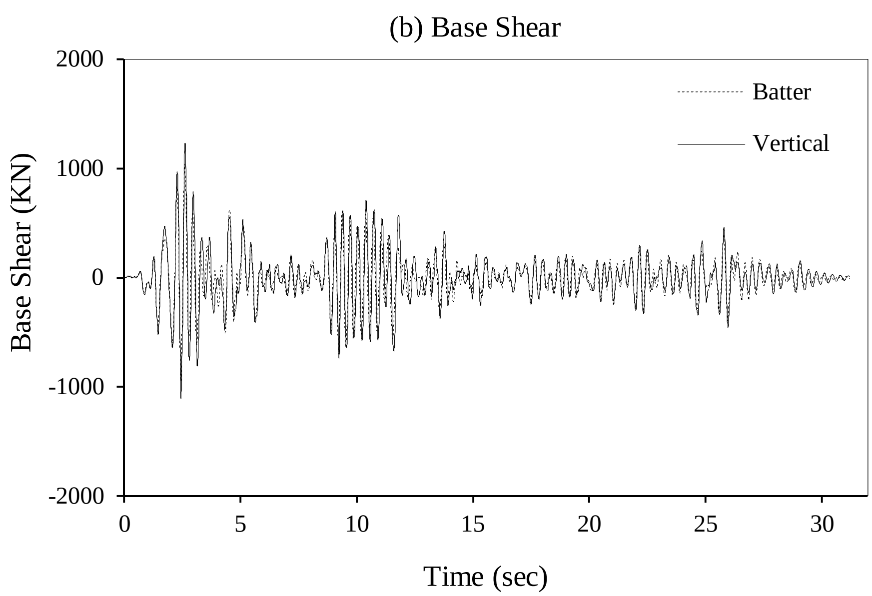


Fig. 1.6. Response of superstructure for flexible base condition with KIF considering uniform soil modulus (a) Roof displacement (b) Base shear

O. Response Of Superstructure Considering Triangular Variation Of Soil Modulus

Fig. 1.7 presents the response of the superstructure considering KIF for triangular variation of soil modulus with depth. Comparison of Fig. 1.7 with Fig. 1.6 clearly shows that an increase in response of the superstructure in terms of roof displacement and base shear on consideration of the idealized non-linear soil behavior. On comparison of Fig. 1.5 and Fig. 1.7, it has also been observed that KIF reduces the base shear and roof displacement values of the superstructure considering the flexible base condition.

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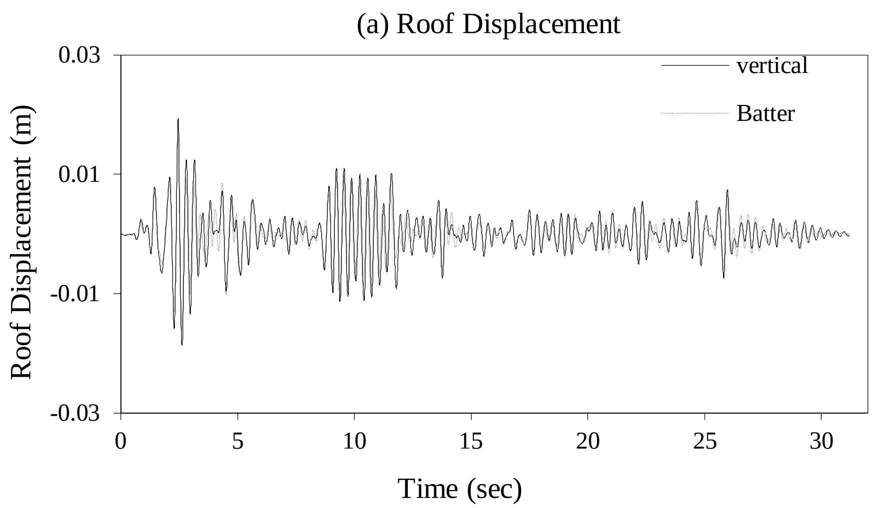


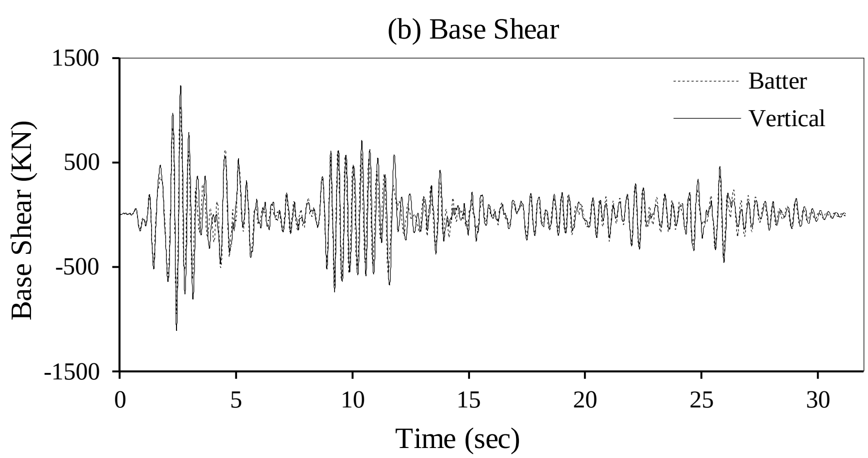


Fig. 1.7. Response of superstructure for flexible base condition with KIF considering triangular varying soil modulus (a) Roof displacement (b) Base shear

P. Summary of Response of Superstructure

Summary of responses of superstructure supported on batter and vertical pile groups with uniform and triangular variation of soil modulus have been tabulated in Table 1.1 and Table 1.2. Table 1.1 shows response of superstructure considering flexible base of superstructure without accounting for kinematic interaction factor. Table 1.2 presents the response considering the kinematic interaction factor.

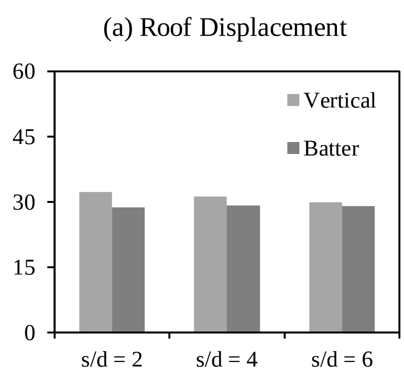
Table 1.1. Summary of super structure roof displacement and base shear without KIF

Soli Modulus Variation	Pile Groups	Roof Displacement (mm)			Base Shear (kN)		
		s/d = 2	s/d = 4	s/d = 6	s/d = 2	s/d = 4	s/d = 6
Uniform	Vertical	32.21	31.26	29.96	2008	1991	2025
	Batter	28.67	29.16	29.05	1835	1880	1879
Triangular	Vertical	70.14	65.60	54.95	2551	2501	2294
	Batter	31.09	32.42	34.01	1946	1954	1940

Table 1.2. Summary of super structure roof displacement and base shear with KIF

Soli Modulus Variation	Pile Groups	Roof Displacement (mm)			Base Shear (kN)		
		s/d = 2	s/d = 4	s/d = 6	s/d = 2	s/d = 4	s/d = 6
Uniform	Vertical	19.24	19.35	19.13	1199	1232	1293
	Batter	17.18	16.16	17.14	1100	1042	1108
Triangular	Vertical	59.05	56.86	44.76	2147	2168	1868
	Batter	14.22	17.43	19.57	890	1051	1116

The roof displacement and base shear obtained in case of uniform soil modulus condition without considering KIF are compared in Fig. 1.8 for structure supported on various configurations of pile groups. Fig. 1.9 shows the same but with triangular variation of soil modulus.



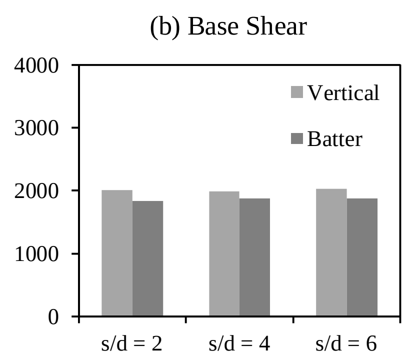
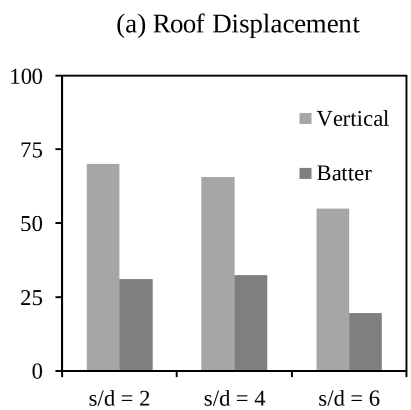


Fig. 1.8. Comparison of structural response for uniform soil modulus condition without KIF (a) Roof displacement (b) Base shear



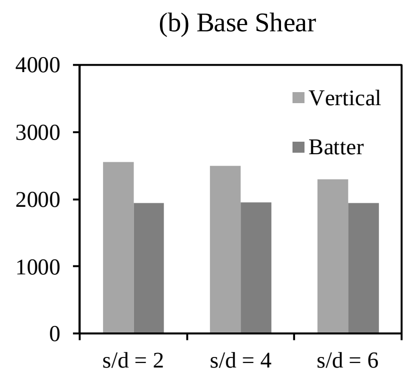


Fig. 1.9. Comparison of structural response for triangular variation of soil modulus without KIF (a) Roof displacement (b) Base shear

The roof displacement and base shear obtained in case of uniform soil modulus condition with consideration of KIF are compared in Fig. 1.10 for structure supported on various configurations of pile groups. Fig. 1.11 shows the same but with triangular variation of soil modulus.

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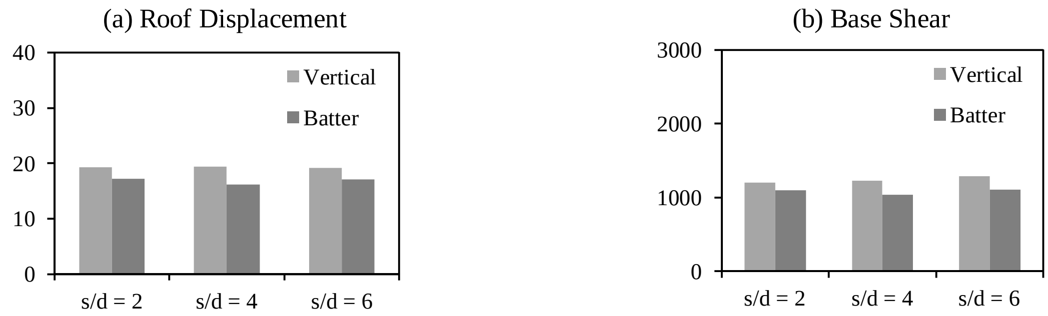

Fig. 1.10. Comparison of structural response for uniform soil condition with KIF (a) Roof displacement (b) Base shear

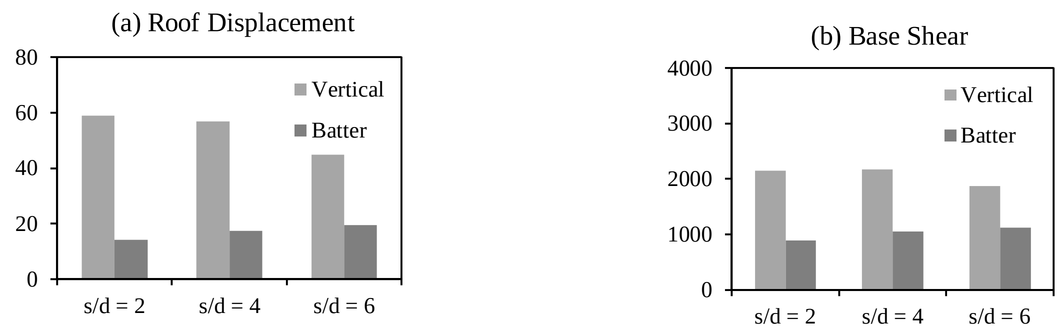

Fig. 1.11. Comparison of structural response for triangular variation of soil modulus with KIF (a) Roof displacement (b) Base shear

A comparison of response of structure supported on vertical and batter pile groups considering uniform soil condition clearly indicates better performance of batter pile groups. The approximate reduction of roof displacement is 13% and that for base shear is 12%. Moreover, for triangular variation of soil modulus, a substantial reduction of roof displacement and base shear is observed in case of batter pile groups. The percentage reduction is more than 50% for both the response quantities. This highlights substantially better performance of batter pile groups even in case of idealized nonlinear soil conditions.

Q. Comparative Reinforcement Design of Piles

The percentage of reinforcement for a single pile of both the pile groups have been worked out using IS: 2911 (Part 1/Sec 4) - 1984 and SP: 16 (1980) considering both uniform and idealized non-linear soil profiles. Both fixed base and flexible base (with and without KIF consideration) conditions have been considered and a comparative assessment has been made. Clear cover to main reinforcement was assumed to be 40mm.

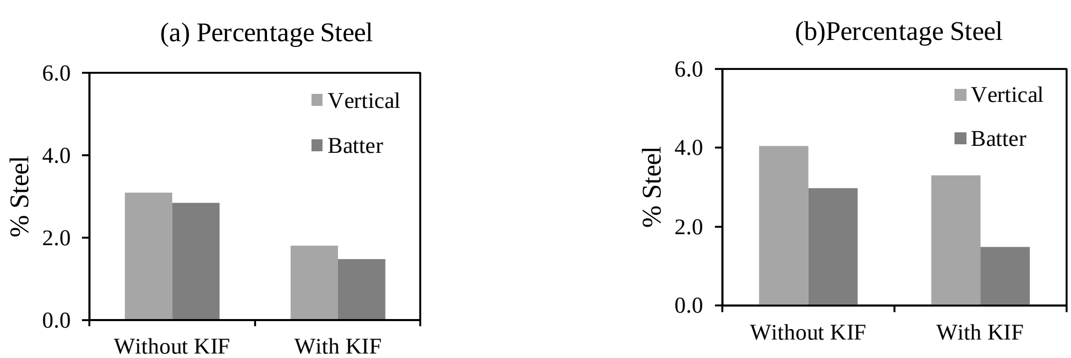

Fig. 1.12. Comparison of percentage steel (a) Uniform soil modulus (b) Triangular variation of soil modulus

For fixed base condition, the reinforcement required is 2.82%. In comparison, for flexible base with uniform soil modulus condition, required steel increases if KIF is not considered in the analysis. However, consideration of KIF results in a decrease in the required reinforcements. These results are shown in Fig. 1.12(a).

A similar trend is observed for the pile groups with idealized non-uniform soil modulus condition as shown in Fig. 1.12(b). However, the required percentage steel increases in case of triangular variation of soil modulus. Under all the conditions, the requirement of steel is lesser for batter pile groups as compared to vertical pile groups.

R. Summary of the Study

In this study, three-dimensional dynamic analysis had been carried out to evaluate the relative seismic performance of vertical and batter pile groups. Seismic performance of 2 x 2 pile groups with s/d ratio of 2, 4 and 6 were evaluated in terms of dynamic stiffness and kinematic interaction factors. Preliminary analyses were conducted considering uniform soil modulus throughout the depth of the pile. Subsequently nonlinearity of soil was incorporated in idealized manner by considering triangular variation of soil modulus along the depth. Results of the analyses have been compared and presented in dimensionless terms. To demonstrate the significance of the findings a five storied portal frame structure was considered. The response of the structure supported separately on vertical and batter pile groups have been compared considering the modified time history of El Centro (1940) earthquake.

II. CONCLUSION

The following major conclusions can be drawn from the results presented in this report.

A. The dynamic stiffness of batter pile groups are higher in comparison to that of vertical pile groups for the range of exciting frequencies and various soil moduli considered in the present study.

B. For the same s/d ratio, batter pile groups perform better as compared to vertical pile groups for all the soil modulus values. This is attributed to less overlap of pressure bulb of the individual piles of the batter pile groups.

C. A general trend of decrease in KIF with frequency is observed for both the pile groups. However, for softer soil conditions batter pile groups show a significant reduction in KIF at higher excitation frequencies.

D. The investigation on seismic performance of superstructure highlights substantially better performance of the structure supported on batter piles in comparison to the structure supported on vertical piles.

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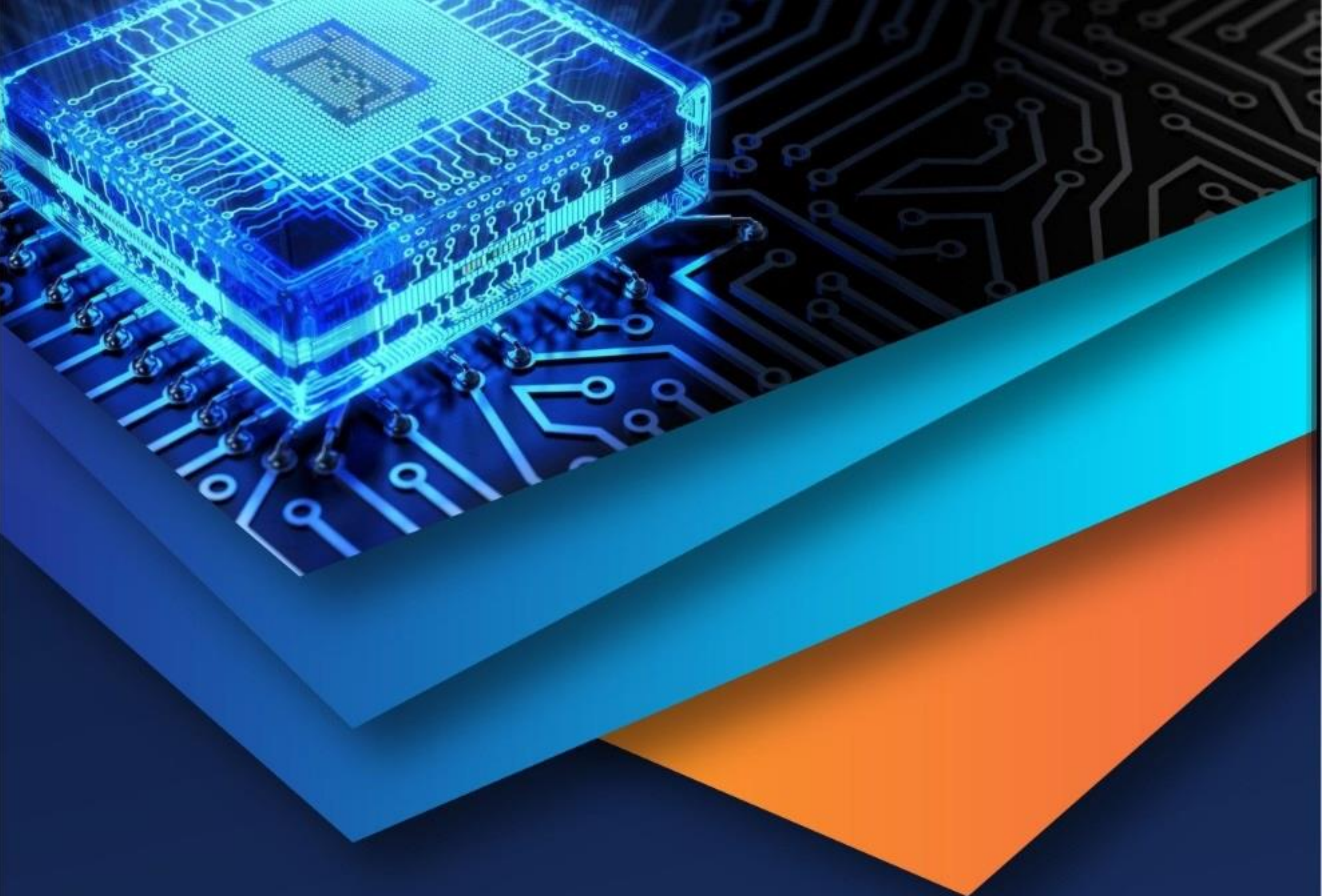

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