Comp. Meth. Civil Eng., Vol. 3, 2 (2012) 15-28

CMCE
Computational Methods in Civil Engineering

Composite piled raft foundation with intermediate cushion in layered soil under seismic forces

V.J.Sharma[a*], S.A.Vasanvala[b], C.H.Solanki[c]

Applied Mechanics Department, Sardar Vallabhai National Institute of Technology, Ichchhanath, Surat-395007, Gujarat, India

Received 5 November 2012; accepted in revised form 20 April 2013

Abstract

In order to mobilize shallow soil to participate in the interaction of piled raft foundation sufficiently, the concept of piled raft has been modified to new type of foundation named composite piled raft. In the system of composite piled raft, the short piles made of flexible materials is used to strengthen the shallow soft soil, while the long piles made of relatively rigid materials is used to reduce the settlements and the cushion beneath the raft is used to redistribute and adjust the stress ratio of piles to subsoil. Finite element method is applied to study the behaviour of this new type of foundation subjected to seismic forces. This paper focuses on behaviour of various components of foundation system such as long pile, short piles and subsoil under seismic force (T2-I-2(1995, HYOUGOKEN_South, EW)) in layered soil related to Surat city geological condition. A comparative study is done to understand the effect of cushion on axial stresses, shear stresses and shear forces along piles and soil beneath the raft.

Keywords: Piles, Raft, Foundation, Analysis.

1. Introduction

In traditional foundation design, it is customary to consider first the use of shallow foundation such as a raft (possibly after some ground-improvement methodology performed). If it is not adequate, deep foundation such as a fully piled foundation is used instead. In the former, it is assumed that load of superstructure is transmitted to the underlying ground directly by the raft. In the latter, the entire design loads are assumed to be carried by the piles. In recent decades, another alternative intermediate between shallow and deep foundation, what is called piled raft foundation or settlement reducing piles foundation, has been recognized by civil engineers. The concept of piled raft foundation was firstly proposed by Davis and Poulos [2], since then it has been described by many authors, including Burland et al. [3], Cooke [4], Chow [5], Randolph [6], Horikoshi and Randolph [7], Ta and Small [8], Kim et al. [9], Poulos [1], and many others . Now the piled raft concept has been used extensively in Europe and Asia. In this concept, piles are provided to control settlement rather than carry the entire load. Piled raft foundation has been proved to be an economical way to

*Corresponding author.
E-mail address: nitk.vijay@gmail.com

improve the serviceability of foundation performance by reducing settlement to acceptable levels. The favorable application of piled raft occurs when the raft has adequate loading capacities, but the settlement or differential settlement exceed allowable values. Conversely, the unfavorable situations for piled raft include soil profiles containing soft clays near the surface, soft compressible layers at relatively shallow depths and some others. In the unfavorable cases, the raft might not be able to provide significant loading capacity, or long-term settlement of the compressible underlying layers might reduce the contribution of raft to the long-term stiffness of foundation. However, most of economically developed cities, especially in Shanghai Economic Circle of China, are located in coastal areas. In these areas, the piled raft concept isunfavorable as mentioned above because building construction often meets with deep deposit soft soil. In order to take advantage of piled raft foundation, civil engineers have developed many methods to practice it in China. Based on the engineering practices, the authors Fa-Yun Liang, Long-Zhu Chen and Xu-Guang Shi [12] developed the concept of piled raft foundation to long-short composite piled raft foundation with intermediate cushion (For short as ‘‘composite piled raft’’) as is shown schematically in Fig. 1 In this new type of foundation, short piles made of relatively flexible materials such as soil–cement columns or sand–gravel columns (also called sand–stone columns in China), etc. are applied to improve the bearing capacity of shallow natural subsoil; the long piles made of relatively rigid materials such as reinforced concrete are embedded in deep stiff clay or other bearing stratum to reduce the settlement; and the cushion made of sand–gravel between the raft and piles plays an important role in mobilizing the bearing capacity of subsoil and modifying load transfer mechanism of piles. The advantages of different ground-improvement methodologies may be used fully.

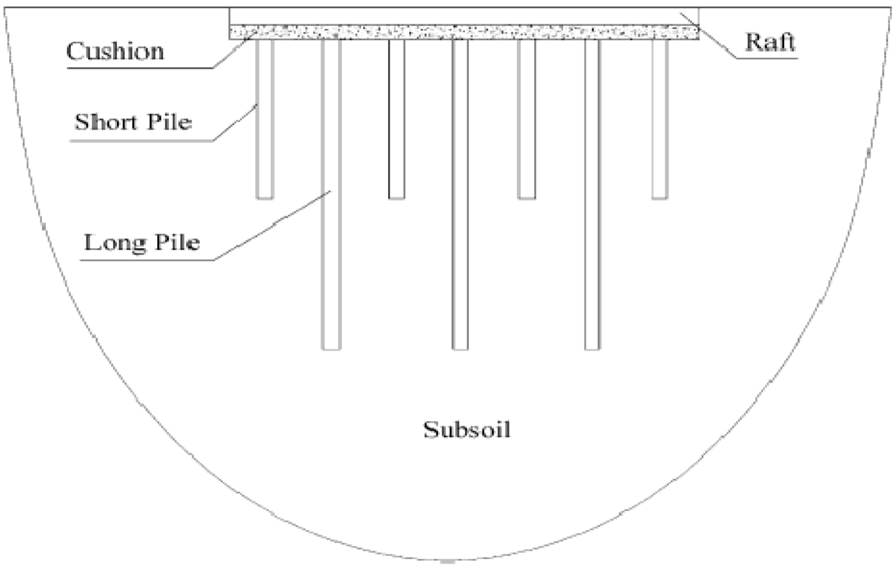


Figure 1. Sketch of composite piled raft foundation

This paper emphasizes on effect of horizontal force on piled raft foundation in seismically active zone . A comparison is done between composite pile raft foundation with cushion and without cushion under seismic force. The dynamic analysis was carried out for earthquake T2-I-2(1995) considering Surat city (India) geological conditions .The parameters of study includes effect of horizontal shear forces , vertical stresses at head of piles and throughout the depth of subsoil.

2. Method

In this part of the paper, a - model of composite piled raft foundation system ,which has been successfully validated and from which results for general effect of cushion on behaviour of composite piled raft foundation under axial load has been obtained, is checked under seismic forces. Fig. 2, shown below,gives clear idea of the model used for dynamic analysis. The model consists of 2.7m x 2.7m X 0.5m square raft resting on 15mX0.45mX0.45m long R.C.C pile at the centre surrounded by four 5.4m X0.45mX0.45m short piles (soil-cement columns).A cushion of sand gravel 0.3m thick is introduced between raft and piles. The analysis was carried out by FEM code using Midas GTS 2012 (v2.2).

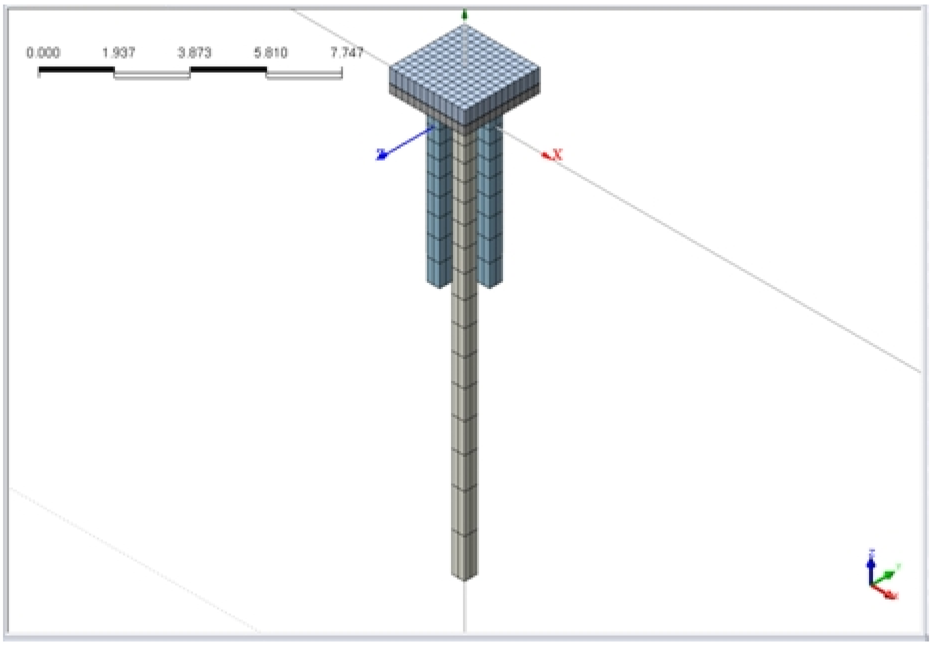


Figure 2. Three dimensional models used for study under seismic forces

The parameters used for analysis are enlisted below in Table 1 Subsoil parameters are not presented in the table, as subsoil consists of four layers of different soil properties, and is represented in detail in Table 2.

Table 1. Parameters of materials for seismic + gravity loading in layered soil

Material	Long piles	Short piles	Cushion	Raft
Elastic modulus(Mpa)	$E_{p1} = 2.8x10^4$	$E_{p2} = 200$	E_m=25	E_c= $3x10^4$
Poisson's ratio	μ_{p1}=0.2	μ_{p2}=0.3	μ_m=0.3	μ_c=0.2
Unit weight (kN/m^3)	25	18	17	25

Table 2 given below, represents geological stratification of Surat city. The table presents generalized data based on soil investigation report on Urea Plant Kribhco unit-III Surat (1995) and forging shop at L & T limited. West Hazira complex, district Surat(2009).

The water table is encountered at 8-10m depth below ground level.

Table 2. Properties of stratified soil (Surat City)

Soil type	Depth (m)	Elastic modulus(MPa)	Poisson's ratio	Unit weight (kN/m^3)
Clayey Soil(CH or CL)	0-5	5	0.40	14.0
Silty Sand (SM)	5-10	40	0.35	15.5
Medium to fine well graded sand (SW)	10-17	50	0.35	17.0
Highly plastic clay(CH)	17-45	45	0.35	16.5

Before carrying out Time history analysis, eigen value analysis was done using Midas GTS tutorial. Sub grade reactions coefficients were calculated both in horizontal and vertical directions. Only horizontal sub grade reactions coefficients are calculated for upper three layers and applied along lateral boundary in both X and Y –direction. Both vertical reaction coefficients and horizontal reaction coefficients are obtained for bottommost layer and are applied along lateral and bottom boundary. The formulae used for the calculations of the horizontal and vertical reaction coefficients were as follow:

Vertical reaction coefficients: $K_v = K_{vo} * (B_v/30)^{-3/4}$ (kgf/cm^3) (1)

Horizontal reaction coefficients: $K_h = K_{ho} * (B_h/30)^{-3/4}$ (kgf/cm^3) (2)

Here, $K_{vo} = \alpha E_o/30 = K_{ho}$, $B_v = \sqrt{A_v}$, $B_h = \sqrt{A_h}$ (3)

where α is scalar parameter depends on types of test conducted to find E_o.

A_v is area for which vertical reaction coefficient was calculated.

A_h is area for which horizontal reaction coefficient was calculated.

The values of K_h and k_v calculated from equations (1), (2) and (3) for different layers for no cushion case are tabulated below:

Table 3. K_v and K_h values for no cushion case.

Soil layers	Horizontal reaction coeff.(K_h) (kN/m^3)	Vertical reaction coeff.(K_v) (kN/m^3)
Layer 1	1612.0	----------
Layer 2	12645.0	----------
Layer 3	14850.5	---------
Layer 4	7607.3	5885.3

The horizontal reaction coefficient was applied along the vertical boundary of the model whereas the vertical reaction coefficient was applied at the base of the model as surface springs and Eigen value analysis was carried out. There are no major changes in case of cushion except for K_h value in upper layer as cushion is introduced between piles and raft in upper subsoil layer. The value of K_h becomes 1578.1 KN/m^3 whereas rest remains the same.After Eigen value analysis dampers were applied to the model for which following damper calculation was done.

About P-wave, $C_p = \sqrt{(\lambda + 2G)\rho}$ (4)

S-wave, $C_s = \sqrt{G * \rho}$ (5)

Here, $\lambda = \nu * E / (1+\nu)(1-2\nu)$ (6)

$G = E/(1+2\nu)$ (7)

where λ =Volumetric elastic Modulus ($tonf/m^2$)

G= Shear Modulus ($tonf/m^2$)

E= Elastic Modulus

ν= Poisson's ratio

A= Cross -section area.

Using equations (4), (5), (6) and (7) dampers are calculated for different soil layers and applied along lateral boundaries for upper three layers. For bottommost layer the dampers are applied along lateral and bottom boundary as well. The values for damper calculation at different soil layers are tabulated below.

Table 4. C_p and C_s values from damper calculation

Soil layers	C_p (kNs/m)	C_s (kNs/m)
Layer 1	123.65	50.48
Layer 2	318.5	153.0
Layer 3	372.8	179.1
Layer 4	348.4	167.3

The values in above Table 4 are applied to both cushion and no cushion case. Time history of T2-I-2 (1995, HYOUGOKEN_South, EW) earthquakes was applied on the model with scale factor of 1 along X-axis and 0 along both Y and Z-axis respectively. The history plot for T2-I-2 is shown below in Figure 3. The comparison was done with cushion and without cushion considering horizontal shear forces and axial stresses.

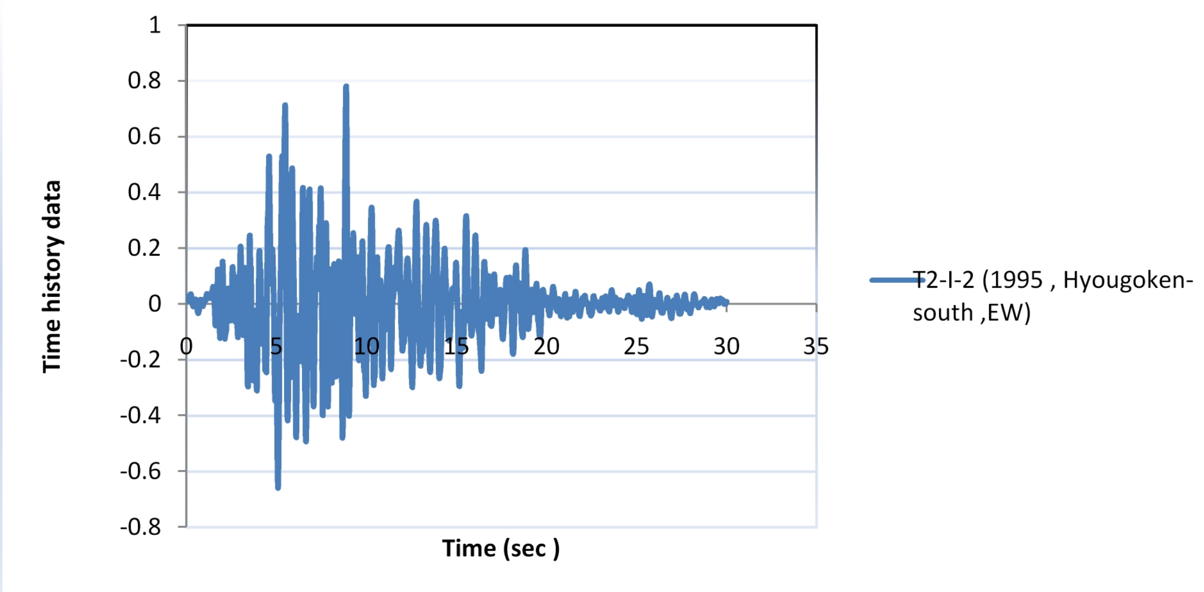


Figure 3. Input earthquake loading of T2-I-2 (1995, HYOUGOKEN_South, EW) earthquakes

3. Results and discussion

The results for T2-I-2(1995, HYOUGOKEN_South, EW) , 1995 has been discussed below.

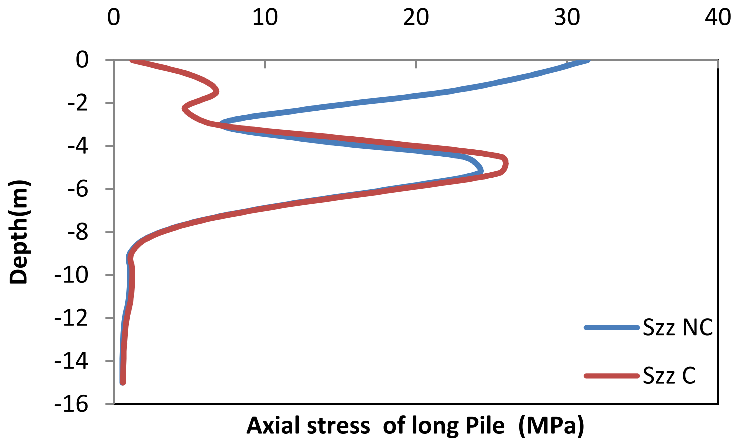


Figure 4. Effects of cushion on load transfer mechanism for long pile under T2-I-2(1995, HYOUGOKEN_South, EW) time history (layered soil)

The graph above in Figure 4 is extracted from contour diagrams of S_{zz} deformed and undeformed behaviour of long pile under seismic excitation in Midas GTS. The contour diagram shows that for no cushion case the tension is developed at the head and at the depth of 4.5m, however this tension is reduced to great extend at the head by entering cushion between raft and piles. Also its visible from the graph above that long pile is under tension due to lateral earthquake forces which reduces as depth of the pile increases for both cushion and no cushion case. The displacement of long pile is prominent along positive X-direction as scale factor of time forcing function for ground acceleration is kept 1 along X-direction and 0 along both Y-direction and Z-direction. The contour diagrams for deformed + undeformed behaviour of S_{xy} along the length of long pile under seismic excitation of T2-I-2 are obtained. The contour diagram shows that for no cushion case the S_{xy} is maximum at the depth of 4.5m; however this shear stress reduces as the depth of long pile increases. The shear stress increases at the head for cushion case with maximum at 4.5m depth of long pile. The graph plotted from these contours showing Sxy distribution is shown below in Figure 4**.**

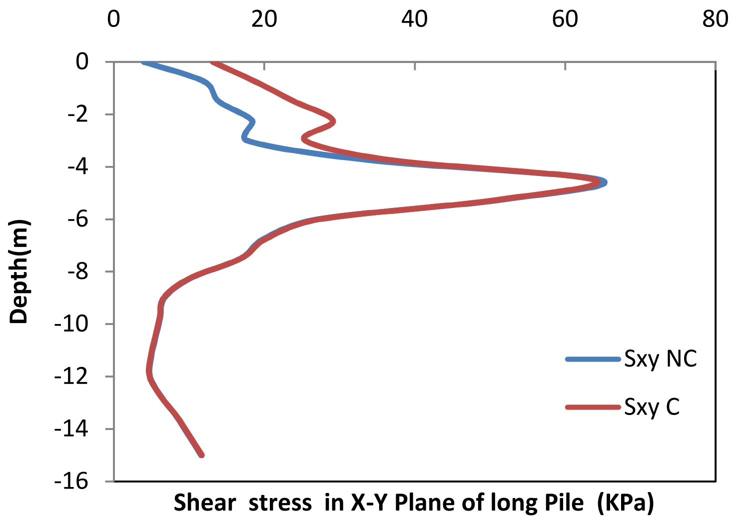


Figure 5. Effects of cushion on S_{xy} distribution along long pile under T2-I-2(1995, HYOUGOKEN_South, EW) time history (layered soil)

It is clear from the graph in Figure 5 that S_{xy} beyond 4.5 m reduces along the depth of pile with slight increase at the bottom.

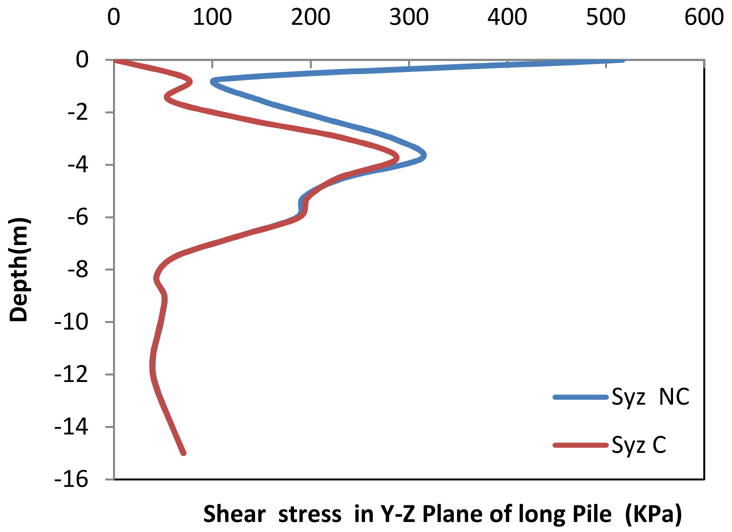


Figure 6. Effects of cushion on S_{yz} distribution along long pile under T2-I-2(1995, HYOUGOKEN_South, EW) time history (layered soil)

The graphs obtained from contour diagrams of S_{yz} behavior throughout the length of long pile under seismic excitation is shown in Figure 6 For no cushion case the shear stress S_{yz} is addressed maximum at the head and at the depth of 3.75m , however this shear stress is totally diminished at the head by entering cushion between raft and piles. Also its visible

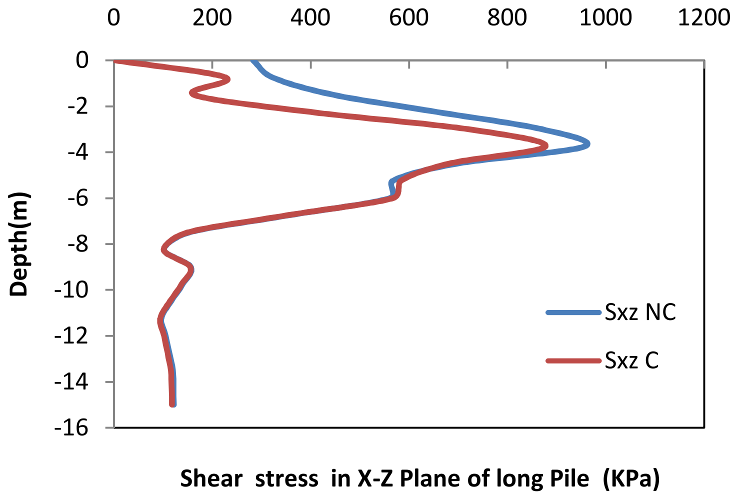
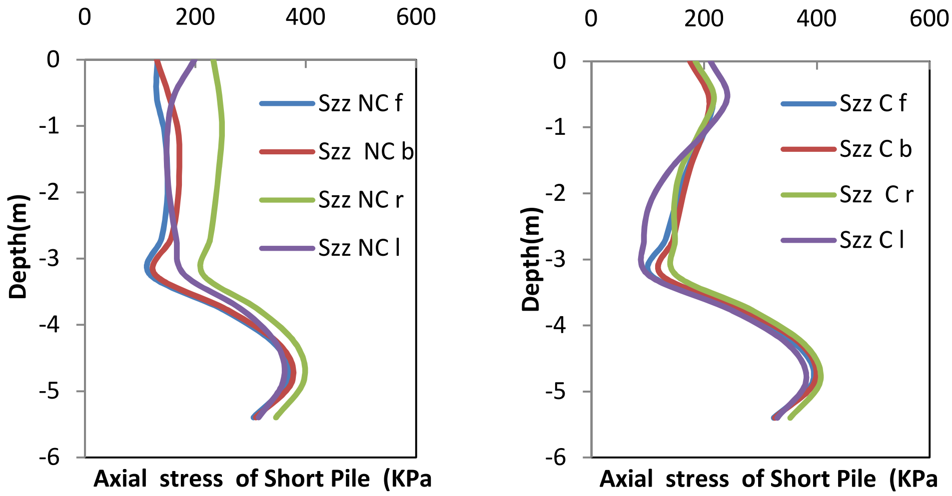


Figure 7. Effects of cushion on S_{xz} distribution along long pile under T2-I-2(1995, HYOUGOKEN_South, EW) time history (layered soil)

From the graph that S_{yz} has same behavior beyond 3.75m depth along the long pile which becomes constant for both cushion and no cushion case.

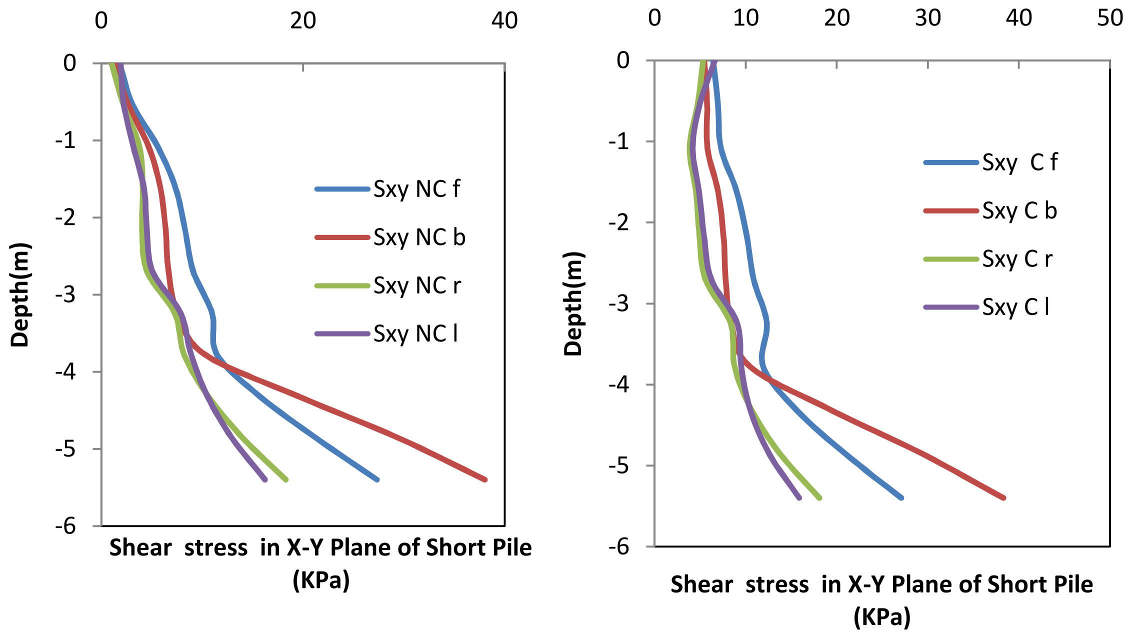
The graph in Figure 7 is obtained from contours of S_{xz} distribution throughout the length of long pile under seismic excitation. The graph shows that for no cushion case the shear force S_{xz} is addressed maximum at the head and at the depth of 3.75m , however this shear stress is totally diminished at the head by entering cushion between raft and piles. Also its visible from the graph that S_{xz} has same behaviour beyond 3.75m depth along the long pile which becomes constant for both cushion and no cushion case.



(a) No cushion case (b) Cushion case

Figure 8. Effects of cushion on load transfer mechanism for short piles under T2-I-2(1995, HYOUGOKEN_South, EW) time history (layered soil)

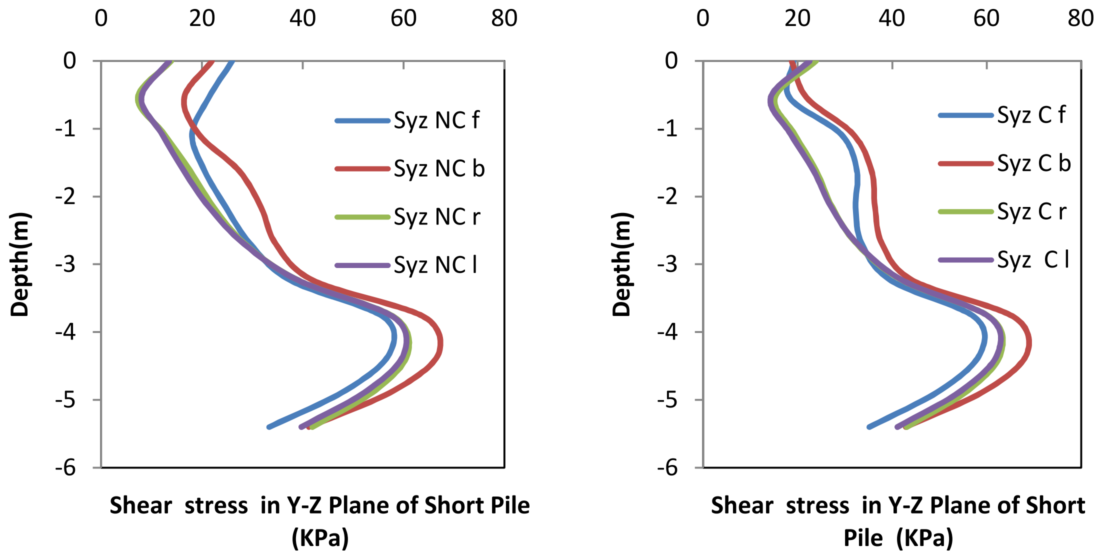
The graphs shown in Figure 8 that the differences occur at the head where the values for Szz are on higher side for no cushion case and vary with each other (all short piles) , however the stress has been reduced only for right short pile by introduction of gravel cushion between raft and piles and all the axial stresses merge to approximately same value.



(a) No cushion case (b) Cushion case

Figure 9. Effects of cushion on S_{xy} distribution for short piles under T2 -I-2(1995, HYOUGOKEN_South, EW) time history (layered soil)

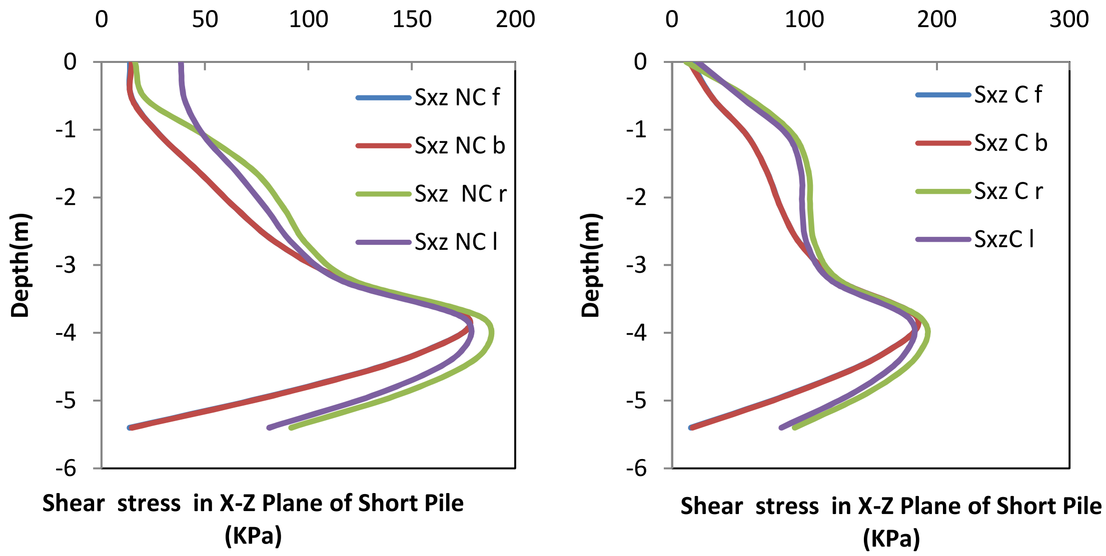
The contours for deformed and undeformed shape of short piles under seismic force in Midas GTS give exact idea of short piles behavior under T2-I-2 (1995) earthquake. The stress concentration is same at the bottom of short piles for both cushion and no cushion case. The graphs in Figure 9 obtained from contour diagram show that the shear force S_{xy} has increased at the head of short piles for cushion case and further follow same trend as that for no cushion case for all short piles. The values of S_{xy} for right and left short piles are almost same throughout the length of short piles in both cushion and no cushion case.



(a) No cushion case (b) Cushion case

Figure 10. Effects of cushion on S_{yz} distribution for short piles under T2-I-2(1995, HYOUGOKEN_South, EW)time history (layered soil)

The graphs shown in Figure 10 extracted from the contours of S_{yz} distribution shows that S_{yz} is maximum for front and back pile compared to right and left pile in no cushion case. Also there is difference in S_{yz} values at head which are almost negligible below 3meter depth. From the graph of cushion, it can be drawn that the S_{yz} for front and back pile has been reduced and converged to a common value along with left and right pile at the head.



(a) No cushion case (b) Cushion case

Figure 11. Effects of cushion on S_{xz} distribution for short piles under T2-I-2(1995, HYOUGOKEN_South, EW) time history (layered soil)

The graphs above shown in Figure 11 that shear stress S_{xz} are higher at the head of right and left short pile for no cushion case whereas the values of S_{xz} are almost same for front and left short pile. These values of shear stress for right and left pile are reduced and merged to a common value with front and left pile for cushion case. For the lower portion the behavior is almost same for both the cushion and no cushion case.

The results for behavior of subsoil below the raft under the influence of T2-I-2 (1995) earth quake are discussed below.

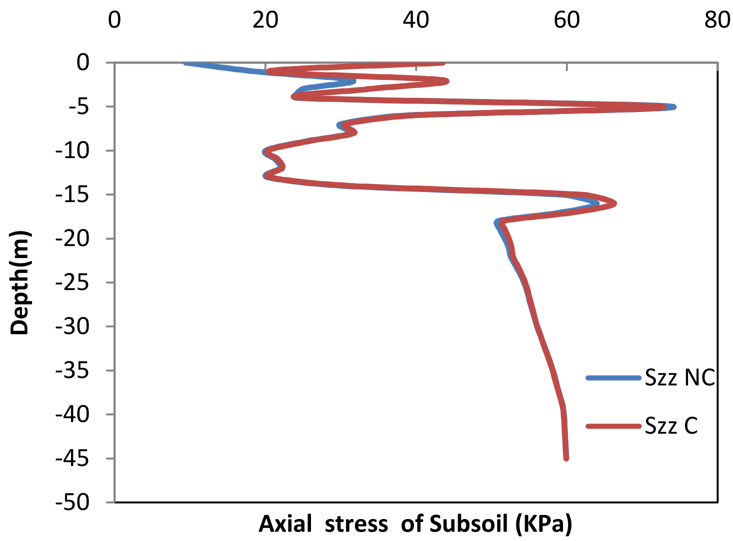


Figure 12. Effects of cushion on load transfer mechanism for subsoil under T2-I-2(1995, HYOUGOKEN_South, EW) time history (layered soil)

The axial stresses (superimposed stresses) subsoil shown in Figure 12 indicates that the soil mass below the raft for both cushion and no cushion case is under tension. For both cases the tension has been accumulated at the bottom of long piles which exponentially reduces and then gradually increases down to bottom of the soil mass. With inclusion of cushion the tension in upper portion of soil mass increases significantly. Also the S_{zz} values for both cushion and no cushion cases have increased at the depth of around 5m. The layer 1 of the whole subsoil mass have the lowest modulus of elasticity and also it terminates around depth of 5m and layer 2 of relatively higher modulus starts, thus the graph indicates stress concentration at this transition zone.

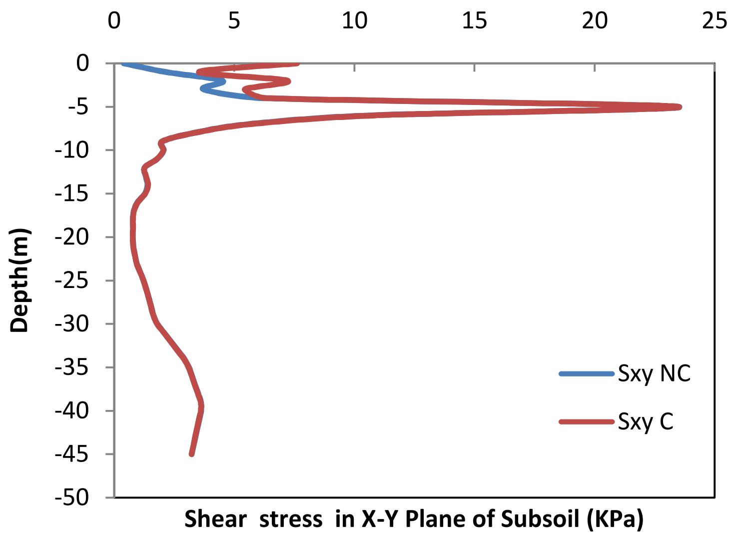


Figure 13. Effects of cushion on S_{xy} distribution along subsoil under T2-I-2(1995, HYOUGOKEN_South, EW)time history (layered soil)

The graph shown in Figure 13 it clear that shear stress Sxy has increased at top portion of soil mass after inclusion of cushion. Also the shear stress has been accumulated at depth of 5m in both cases where the stratification of soil mass changes. Further the shear stress exponentially decreases with gradual increase of depth.

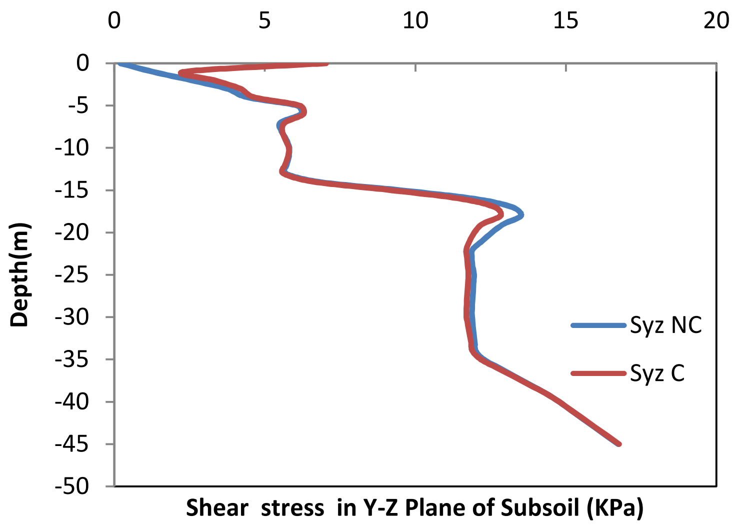


Figure 14. Effects of cushion on S_{yz} distribution along subsoil under T2-I-2(1995, HYOUGOKEN_South, EW)time history (layered soil)

The above graph in Figure 14 shows result for Syz for cushion and no cushion case below the raft in soil mass till bottom. For both cases shear stress increases throughout the depth of soil mass. Thus, when comparing both curves follow same trend. However for cushion case the Syz has increased compare to no cushion case.This increase is from top of subsoil mass down to shallow depth of 2.5 meters.

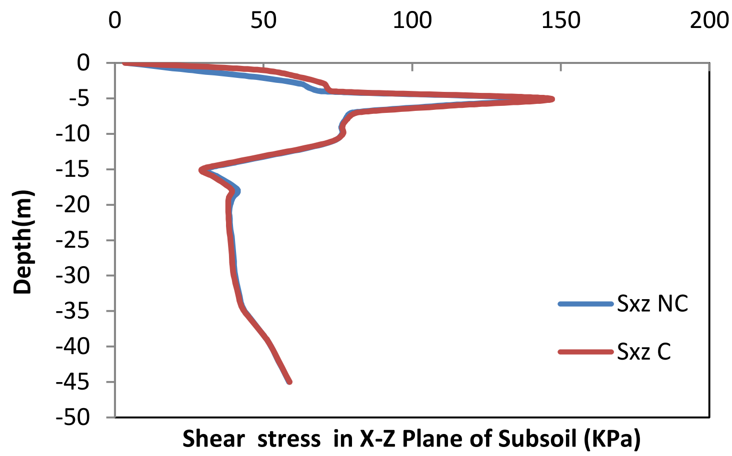


Figure 15. Effects of cushion on S_{xz} distribution along subsoil under T2-I-2(1995, HYOUGOKEN_South, EW) time history (layered soil)

The graph for Sxz cushion shown in Figure 15 indicates that there is no drastic change after application of cushion , however the values of S_{xz} for cushion are slightly on higher side when compared with no cushion case for overall depth of soil mass below the raft and between the piles same trend i.e. there gradual increase upto depth of 3m and then sudden exponential increase at depth of 5m due to the transition zone and then sudden fall followed with gradual decrease in S_{xz} and then finally gradual increase till the bottom portion of soil mass

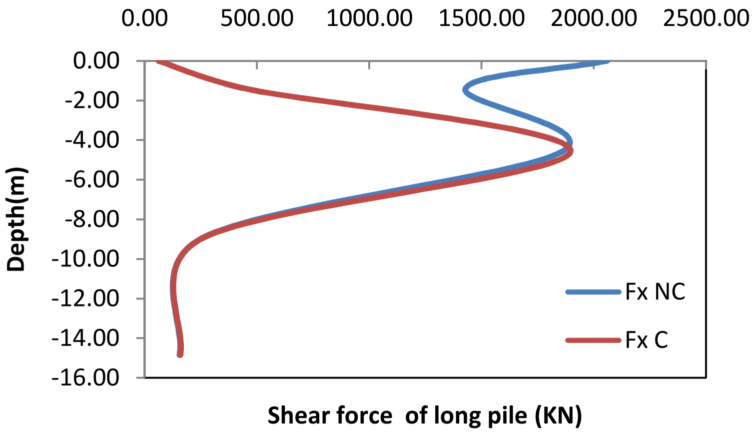
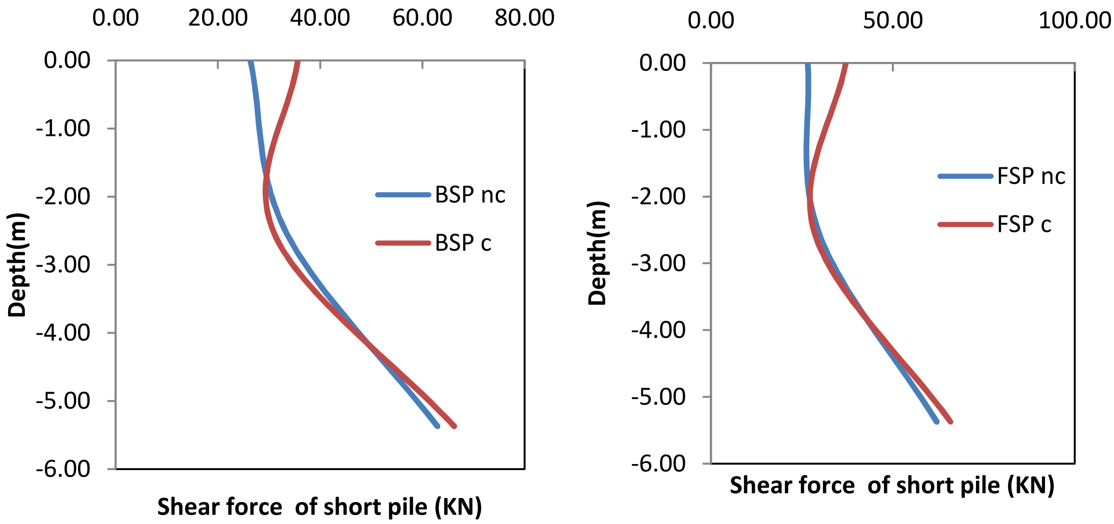
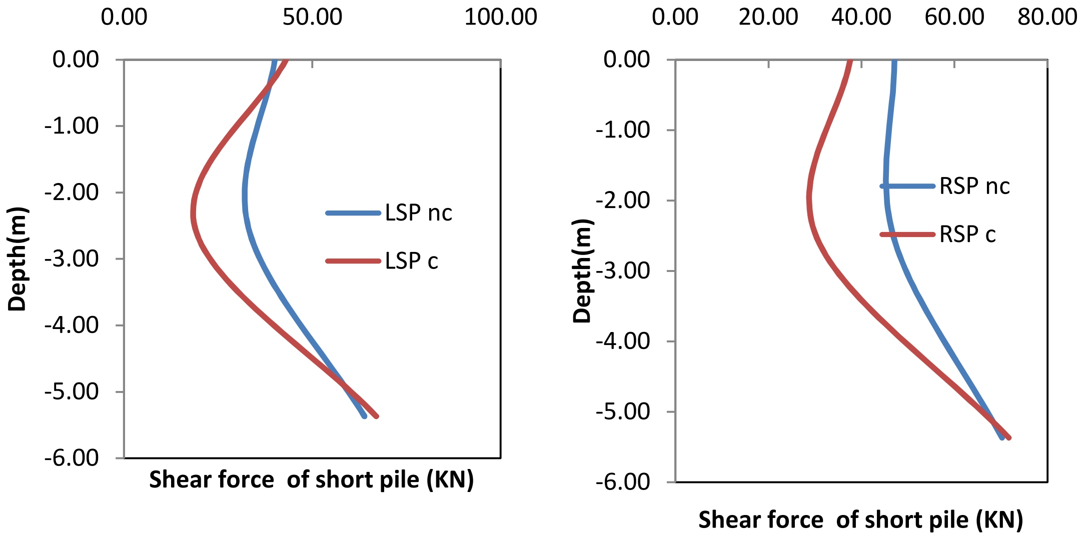


Figure 16. Comparison of F_x for both cushion and no cushion case throughout long pile for T2-I-2(1995, HYOUGOKEN_South, EW) time history (layered soil)

The above graph in Figure 16 represents shear force along the length of long pile. The shear force at the head of pile for connected condition is on higher side compared to detach condition. Thus by applying cushion technique the shear force accumulated at the head of long pile is released.



(a) Back Short pile (b) Front short pile



(c) Left Short pile (d) Right short pile

Figure 17. Comparison of F_x for both cushion and no cushion case throughout long pile for T2-I-2(1995, HYOUGOKEN_South, EW) time history (layered soil)

The above graphs shown in Figure 17 that shear force has slighty increased at the head of back and front short pile for cushion case whereas for rest of the length of short pile its almost same. For right and left short pile the shear force has decreased at the mid-height and almost same at the bottom tip for both cushion and no cushion case., however at the head of left pile the shear force is same in both the cases whereas as decreased at the head of right pile for cushion case.The bending moment developed at the head of long pile is very small almost negligible for case of no cushion which is further reduced after inclusion of cushion.For short piles (soil cement pile) as they are made of soil cement they are naturally not connected to raft for both cushion and no cushion case.

4. Conclusions

The effect of seismic forces along with axial load on composite piled raft foundation system in layered soil was studied considering horizontal shear force, axial stresses and shear stresses on long pile, short piles and subsoil. Earthquake T2-I-2 (1995) was applied and following conclusions were drawn.

- The tension at the head of long pile developed due to lateral earthquake forces has been reduced by 96.14 % with inclusion of cushion, which further reduces as depth of the pile increases for both cushion and no cushion case.
- With inclusion of cushion the tension at the top of short piles had increased by 6 % and 78.2 % at the top of subsoil mass respectively , thus it can be deduced that tension developed on overall foundation system is managed evenly among the piles and surrounding subsoil masses by using cushion technique.
- The shear force developed at the head of long pile due to seismic forces has been reduced by 97 %, thus indicating that cushion reduces constraint reactions between connected long pile head and raft.
- The shear forces in case of short soil cement piles has increased slightly by 5 to 6% with inclusion of cushion thus indicating that the cushion brings bearing capacity of short piles in use to tackle the lateral seismic forces.

- The shear stresses S_{xy} has increased with considerable amount at the head of long pile, short piles and top portion of subsoil with introduction of cushion, where as S_{yz} has reduced at the head of piles ,while S_{xz} has slighty increased in upper portion of subsoil mass.

References

[1] HG. Poulos, Pile raft foundations: design and applications. Geotechnique 2001;51(2):95–113.
[2] EH. Davis, HG. Poulos, The analysis of piled raft systems. Australia Geotechnique Journal 1972;2:21–7.
[3] JB. Burland, BB. Broms, et al, Behavior of foundations and structures. Proceeding 13th International Conference on Soil Mechanics and Foundation Engineering, Tokyo 977;2:495–546.
[4] RW. Cooke, Piled raft foundation on stiff clays—a contribution to design philosophy. Geotechnique 1986;36(2):169–203.
[5] YK. Chow, V. Thevendran ,Optimisation of pile groups. Computers and Geotechnics 1987;4:43–58.
[6] MF. Randolph, Design methods of pile group and piled rafts:state-of-the-art report. Proceeding 13th International Conference on Soil Mechanics and Foundation Engineering, New Delhi 1994;2:61–82.
[7] K. Horikoshi, MF. Randolph, Centrifuge modeling of piled raft foundation on clay. Geotechnique 1996;46(4):741–52. [8] Ta LD, Small JC. Analysis of piled raft systems in layered soils. International Journal for Numerical and Analytical Method in Geomechanics 1996;20(1):57–72.
[8] KN. Kim, SH. Lee et al. Optimal pile arrangement for minimizing differential settlements in piled raft foundation. Computers and Geotechnics 2001;28(2):235–53.
[9] A. Eslami, S. Salehi Malekshah, "Analysis of non-connected piled raft foundations (NCPRF) with cushion by finite element method", Comp. Meth. Civil Eng., Vol. 2, 2 (2011) 153-168.
[10] A. Eslami, M. Veiskarami, M.M. Eslami, Piled-Raft Foundation (PRF) optimization design with connected and disconnected piles, Proceedings of the 33rd Annual and 11th Int'l Conference on Deep Foundations, Deep Foundations Institute (DFI), New York, NY, U.S.A., (October 15-17, 2008), 201-211.
[11] F.Y. Liang, L.Z. Chen, Shi X.G. "Numerical analysis of composite piled raft with cushion subjected to vertical load". Computers and Geotechnics 30 (2003) 443–453.
[12] Midas (2012), Midas GTS 2012, analysis user manual Version 2.2.
[13] Midas (2012), Midas GTS 2012, Theory manual Version 2.2.