Technical Sciences 18(4), 2015, 261–270

ANALYSES OF SOIL-STRUCTURE INTERACTION BASED ON VERTICAL LOAD TESTS OF DISPLACEMENT PILES

Vaidas Martinkus, Arnoldas Norkus

Department of Geotechnical engineering
Vilnius Gediminas Technical University

Received 16 September 2015; accepted 23 November 2015; available on line 24 November 2015.

K e y w o r d s: soil structure interaction, displacement pile group, frame, support, cohesionless soil.

A b s t r a c t

The current paper presents a research based on experimental and numerical analysis of three different frame supported by displacement pile groups embedded in sand. The vertical load tests performed under lab conditions have shown different responses of single piles installed at the same pile group, and a densification effect was named as a key player taking the main roll in explaining this phenomenon. A numerical analysis based on experimental data revealed unfavourable changes on deformation and internal forces of three different frame types caused by densification phenomenon. Performed research has emphasised the significance of soil structure interaction analysis, especially when displacement pile groups embedded in sands are used.

Symbols:
E_d – deformation modulus determined using dynamic load plate test, MPa,
ρ – soil density, g/cm^3,
w – soil moisture content, %,
ρ_s – particle density, g/cm^3,
e – void ratio, p.u.,
q_c – cone resistance, MPa,
f_s – sleeve resistance, kPa,
$k_{z,i}$ – vertical stiffness, kN/m’,
$k_{h,i}$ – horizontal stiffness, kN/m’.

Correspondence: Vaidas Martinkus, Department of Geotechnical Engineering, Vilnius Gediminas Technical University, Saulėtekis av. 11, LT-10-223 Vilnius, phone: +37 061 672 542, e-mail: vaidas.martinkus@vgtu.lt

Introduction

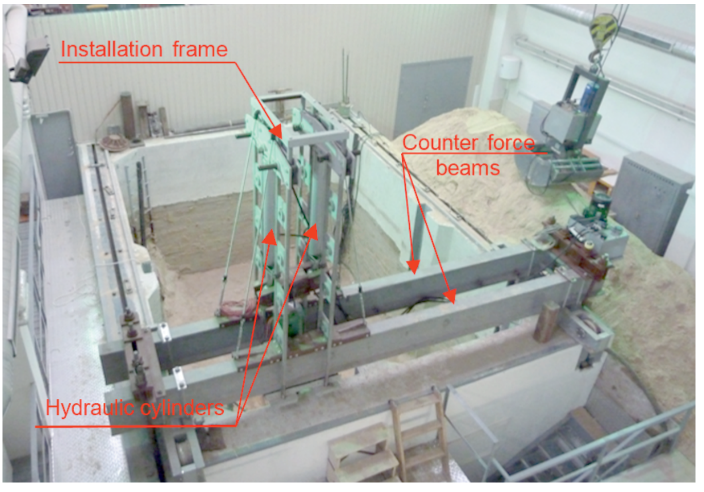
Displacement pile groups are often used in engineering practice as an effective and reliable foundation type, especially in cohesion less soil. Despite an often and long term usage of this foundation type the researchers still perform the experimental and numerical investigations on this field. Some of the most recent works analyse the soil structure interaction (SSI) problems.

A broad numerical analysis of multi-storey 3D frame supported by pile groups embedded in cohesive soil was presented by CHORE et al. (2010). The author concluded that frame's deformation and internal forces have increased significantly when SSI was taken into account. RASAL et al. (2010) performed a similar numerical analysis and reported considerable increase in horizontal displacement of super structure's top floor. KHARE and CHORE (2013) also investigated the same problem and the determined results were in line with the previous author's reports. The results of numerical analyses of single storey multi-span frame, resting on pile groups consisting of different number of piles, was presented by DODE et al. (2014). The researcher highlighted that soil-structure interaction effect was found to be increasing the horizontal displacements and absolute positive and negative moments at the column, and that the effect of the soil-structure interaction is observed to be significant for the configuration of the pile groups. PULIKANTI and RAMANCHARLA (2014) have made an attempt to understand the SSI behaviour of framed buildings supported by the pile groups under transient loading taking into account the pile-soil interface effects. The results have shown that if the contact between piles and soil is modelled, under transient loading the acceleration response of top floor is reduced twice. MOHD et al. (2014) performed a broad parametric analysis of combined piled raft, and finally concluded that the interaction of building foundation-soil field and superstructure has remarkable effect on the structure. Very recent research papers presented by REDDY and RAO (2011, 2012), KRASINSKI and KUSIO (2014), also LANG et al. (2014) are based on experimental investigations of pile groups. Those investigations, in conjunction with the numerical analyses discussed above, have thoroughly exanimated the total response of different parameter displacement pile groups under vertical loading, but none of them has investigated the behaviour of an isolated pile placed in a pile group. Consequently, the first aim of this paper is to show that an isolated displacement pile response differs from that of the same pile in a group embedded in sand and the second one is to emphasize the negative effects on a super structure induced by this phenomenon.

Experimental background

Static vertical load tests of single piles placed in a pile group were carried out in a 5.0 m width, 7.0 m length and 4.5 m height soil box (Fig. 1). First of all, a preparation of the box's soil deposit was carried out, filling it with compacted sand up to the necessary level. The compaction was carried out using 65 kg weight single direction plate compactor (0.61×0.9 m) (Fig. 1b). A watering was used in order to improve compaction properties of the soil deposit. According to the primary prove compaction tests, the average thickness of each soil layer of 0.15 m was chosen. The control of the compaction was carried out using a

a



b

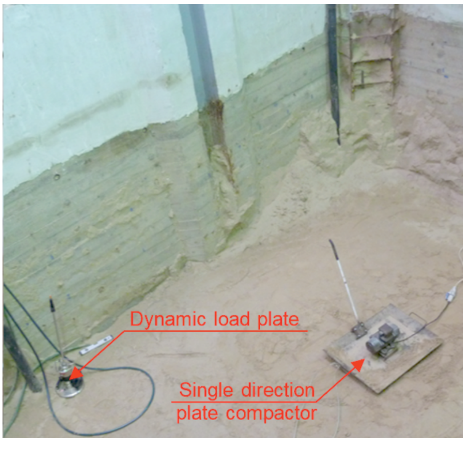


Fig. 1. Soil box: *a* – equipment of installation and loading; *b* – equipment used for soil compaction and compaction's monitoring

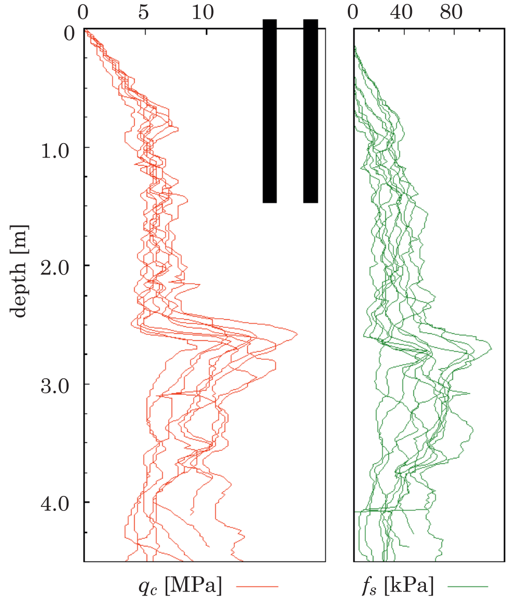


Fig. 2. Cone penetration test data

Dynamic plate load test (DPL). The compaction criterion of each soil layer deformation modulus E_d higher than 19 MPa was adopted. For each layer 12 DPL tests were performed at the same place as for each above soil layers.

From three different levels, 9 soil samples (3 samples for each level) were collected for determination of the soil physical properties (soil density ρ = 1.64 g/cm^3, soil particle density ρ_s= 2.65 g/cm^3, soil moisture content w = 4.38%, void ratio e = 0.69 and mean particle size 0.33 mm). It should be noted that specimen were taken after the watering and compaction of a particular layer, before filling the next one. Sieving test showed that compacted soil is even graded medium coarse sand. According to known geological investigation report of quarry, from which the soil was brought, sand mainly consists of silica particles. All soil's physical properties were determined using standardised procedures.

In total 12 Cone Penetration Tests (CPT) were performed at the same places as DPL tests using the standard probe with 10 cm^2 area and 60^o peak angle cone. All CPT curves are presented at the same graph in order to demonstrate the scatter of cone resistance q_c and sleeve resistance f_s (Fig. 2).

For this research study 0.22 m width and 1.45 m length piles made of regular steel (without any additional surface treatment) were used, which were installed in 0.66 m spacing group, by means of the installation frame consisted of two hydraulic cylinders (Fig. 1a). Maximum pushing velocity of hydraulic

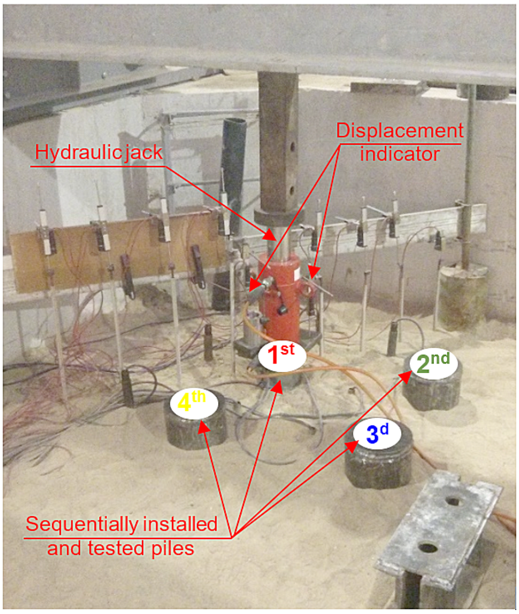


Fig. 3. Vertical load test

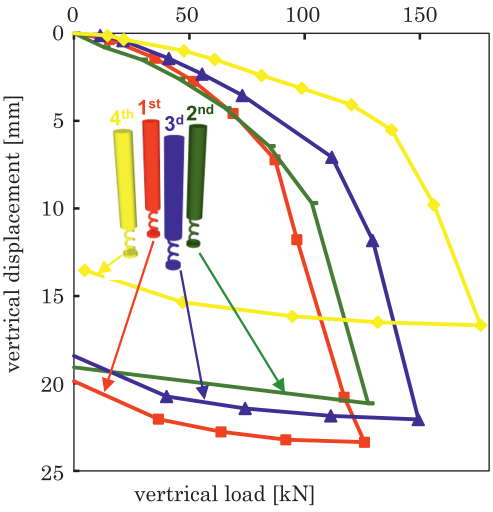


Fig. 4. Load-settlement curves of tested piles

cylinders 5 mm/s was applied. During the installations piles were released for a few times due to lengthening necessity of hydraulic jacks' arms. Piles were installed clockwise starting from 1^{st} to 4^{th} pile as shown in Figure 3. After the installation the piles were tested in the same order as they were installed. The tier loading procedure with 10 loading and 4 unloading steps were used for the static vertical load tests. The duration of loading step was adopted equal to 60 min and for the unloading steps 15 min. The vertical displacement of pile's head was measured by means of two linear pot indicators, and the total load was measured by means of vibrating wire load cell. The ultimate settlement equal to 10 percent of a single pile diameter was adopted as a failure criterion. Experimental load settlement curves are presented in Figure 4.

Numerical analyses

For three different types of frame, which discretization is presented in Figure 5, a static FEM (Finite element method) analysis was performed using SCIA Engineer software. The constitutive model of linear elastic isotropic materials was adopted for the analysis. Considering that relatively small deformation was expected, the solver with linear relation between the deformations and displacements was used for the analysis, it means that none of global or local imperfections, as well as secondary effects were taken in to account. The load combination consisting of self-weight (assigned automatically), dead weight and snow load were applied for all cases. Using the same load combination three different types of support with symmetric and asymmetric orientation were used for each frame (Fig. 6). Using the support type named „Fixed" soil's deformation was eliminated in order to demonstrate the pure deformations of considering frames (Fig. 6). For other two support types named „Springs (pile-cap fixed)" and „Springs (pile-cap hinged)" the linear vertical and horizontal springs were used in order to get the general deformations of frame-support-soil system (Fig. 6).The stiffness of vertical springs were determined from the curves presented in Figure 4, assuming allowable serviceability limit state settlement equal to 5% (5 mm) of pile diameter. The applied ratio of settlement and pile diameter is acceptable in most cases according to codes regulation. The determined secant stiffness are as follows: $k_{z,1}{}^{st}$ = 9.89 MN/m', $k_{z,2}{}^{nd}$ = 10.11 MN/m', $k_{z,3}{}^{d}$ = 12.61 MN/m' and $k_{z,4}{}^{th}$ = 16.48 MN/m'. The stiffness of horizontal springs defined for each pile was calculated according to code CSN 73 1004 increasing by depth and was equal to $k_{h,1}{}^{st} = k_{h,2}{}^{nd} = k_{h,3}{}^{d} = k_{h,4}{}^{th} = 0 \rightarrow 120$ MN/m^3. It must be noted that in order to get a point stiffness with dimensions MN/m', the value shown above should be integrated at particular area of pile side surface.

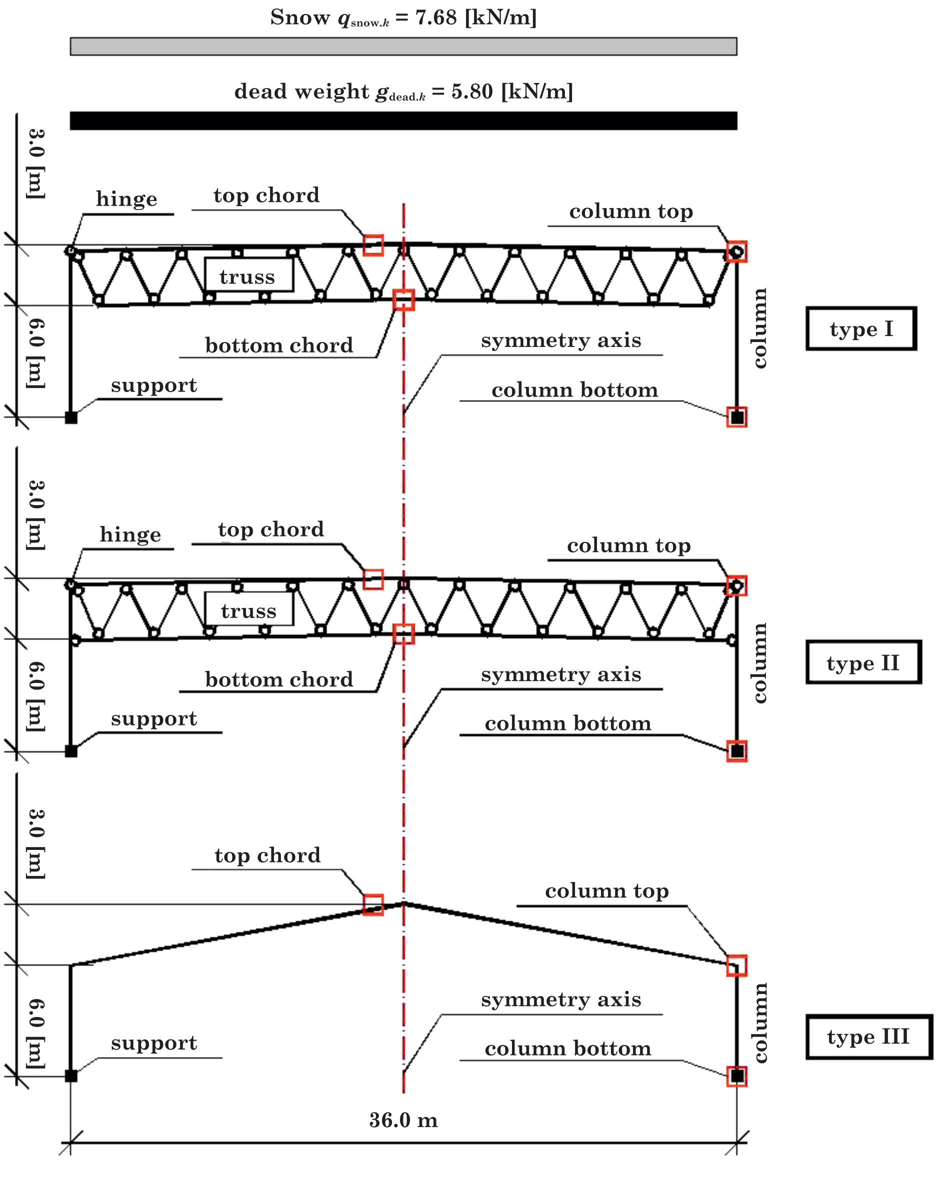


Fig. 5. Computational schemes of analysed frames

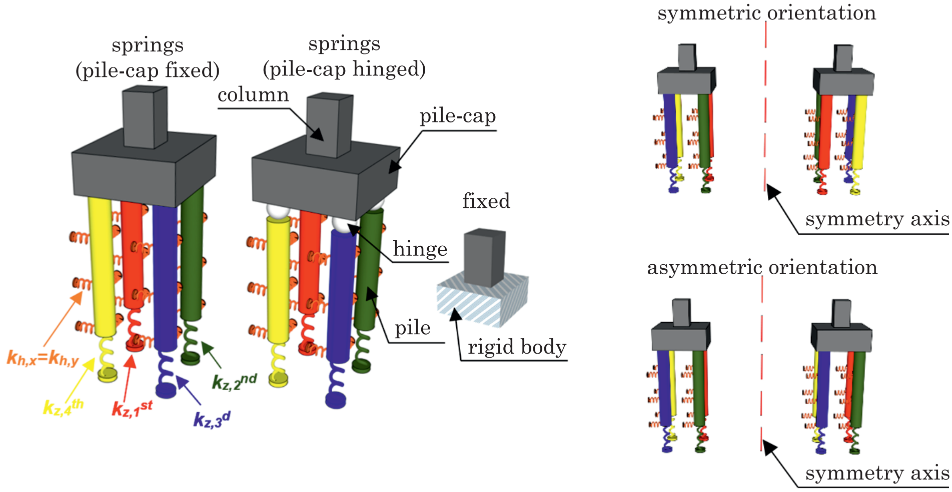


Fig. 6. Types of support defined for each type of frame (springs $k_{z,1}{}^{st}$ to $k_{z,4}{}^{th}$ represent experimental response (stiffness) of each pile; $k_{h,x}$ and $k_{h,y}$ represent horizontal soil stiffness)

Results and Discussion

Closer look to experimental load-settlement curves presented in Figure 4 revealed that displacement pile response (placed in a pile group) under static vertical loading differs according to installation sequence. The performance of the 1st pile has been determined to be the poorest whereas the 4th pile showed the best performance in terms of stiffness. Mean while intervening piles 2nd and 3^{d} have performed respectively ($k_{z,1}{}^{st}<k_{z,2}{}^{nd}<k_{z,3}{}^{d}<k_{z,4}{}^{th}$). It is worth mentioning that the additional settlements induced by adjacent piles' stress fields overlapping was not taken into account, because neighbouring piles were not being loaded, while one of them was tested.

The numerical analysis, which data are presented in Table 1, showed that vertical displacements of column bottom and horizontal translations of column top may be larger respectively up to 830 and 802%, when the soil structure interaction is being considered. It can be concluded that the pile groups' orientation and the type of pile-cap connection depending on frame type had the key influence.

Tension force at truss' bottom chord and compression force at truss' top chord mostly increased (up to 13%) on frame type II. Significant increase (up to 21%) in bending moment appeared at column of frame type III. It should also be mentioned that this amount of internal force increase exceeds the reliability level required in most of the construction design codes.

Table 1

Results of numerical analysis

Frame type	Support		Vertical displacement of column bottom [mm]	Horizontal displacement of column top [mm]	Tension force at truss' bottom chord [kN]	Compression force at truss' (or frame) top chord [kN]	Maximal bending moment at column [kNm]	Vertical reaction of support (vertical spring) [kN]				
	type	orientation						1st	2nd	3d	4th	total
I	fixed	–	0	5.0	1029.5	1025.6	24.5	–	–	–	–	425
I	springs (pile–cap hinged)	symmetric	7.7	5.1 (↑2%)	1028.9 (↓0.1%)	1029.9 (↑0.4%)	19.5 (↓20%)	97	101	116	146	460
I	springs (pile–cap hinged)	asymmetric	7.9	45.1 (↑802%)	1029.2 (↓0.0%)	1027.7 (↑0.2%)	2.8 (↓89%)	115	120	99	126	460
I	springs (pile–cap fixed)	symmetric	7.7	5.1 (↑2%)	1029.0 (↑0.0%)	1029.4 (↑0.4%)	14.6 (↓40%)	96	99	116	149	460
I	springs (pile–cap fixed)	asymmetric	7.8	26.7 (↑434%)	1029.2 (↑0.0%)	1027.6 (↑0.2%)	4.4 (↓82%)	105	108	108	139	460
II	fixed	–	0	4.2	803.9	904.3	346.3	–	–	–	–	425
II	springs (pile–cap hinged)	symmetric	7.5	4.4 (↑5%)	903.5 (↑12%)	943.6 (↑4%)	244.3 (↓29%)	82	85	128	165	460
II	springs (pile–cap hinged)	asymmetric	7.9	9.3 (↑121%)	908.9 (↑13%)	945.5 (↑5%)	221.2 (↓36%)	85	89	126	160	460
II	springs (pile–cap fixed)	symmetric	7.5	4.4 (↑5%)	901.4 (↑12%)	940.8 (↑4%)	253.2 (↓27%)	79	81	131	169	460
II	springs (pile–cap fixed)	asymmetric	7.9	9.0 (↑114%)	907.4 (↑13%)	943.3 (↑4%)	232.1 (↓33%)	82	85	128	165	460
III	fixed	–	0	24.5	–	575.3	1591.8	–	–	–	–	425
III	springs (pile–cap hinged)	symmetric	7.2	62.3 (↑154%)	–	353.1 (↓39%)	1870.8 (↑18%)	60	65	149	186	460
III	springs (pile–cap hinged)	asymmetric	8.0	65.6 (↑168%)	–	349.9 (↓39%)	1853.9 (↑16%)	62	68	147	183	460
III	springs (pile–cap fixed)	symmetric	7.0	54.1 (↑121%)	–	340.3 (↓41%)	1931.0 (↑21%)	40	45	166	209	460
III	springs (pile–cap fixed)	asymmetric	8.3	58.0 (↑137%)	–	337.4 (↓41%)	1916.6 (↑20%)	43	47	164	206	460

Vertical reactions of supports were obtained to be different (up to 45% above the average of frame type III and up to 23% of frame type I) due to different spring stiffness.

Conclusions

When displacement pile groups are used as a support for different type buildings, an analysis of soil-structure interaction must be performed in order to determine more reliable values of structures internal forces and deformation.

While design of pile caps is being performed, the likely increase on internal forces due to uneven pile reaction distribution must be taken into account.

In order to reduce the negative effects (additional deformation and internal forces) on super structures, the correct installation sequence of displacement pile at pile groups in sand must be chosen. Furthermore, the rigid non-rotational connection between piles and cap must be ensured, which decreases the horizontal displacements of super structure.

Concerning the future targets, the results of numerical analysis should be examined experimentally. Furthermore the additional experimental study should be carried out in order to determine the horizontal stiffness of isolated piles, and likely effects caused by installation procedure of neighbouring piles.

References

Chore H.S., Ingle R.K., Sawant V.A. 2010. *Building Frame – Pile Foundation – Soil Interaction Analysis: A Parametric Study*. Interaction and Multi Scale Mechanics, 3(1): 5–79.

Dode P.A., Chore H.S., Agrawal D.K. 2014. *Interaction analysis of a building frame supported on pile groups*. Coupled Systems Mechanics, 3(3): 305–318.

Khare R.J., Chore H.S. 2013. *Interaction of building frame with pile*. International Journal of Electrical, Electronics and Computer Systems (IJEECS), 1(1): 2347–2820.

Krasinski A., Kusio T. 2014. *Comparative model tests of SDP and CFA pile groups in non-cohesive soil*. Studia Geotechnica et Mechanica, 4(36).

Lang R., Liu R., Lian J., Ding H. 2014. *Study on Load-Bearing Characteristics of a New Pile Group Foundation for an Offshore Wind Turbine*. The Scientific World Journal, 2014(2014), article ID 394104. On line: http://dx.doi.org/10.1155/2014/394104.

Mohd A., Mahmoud H.M., Javed M., Mohd A.H. 2014. *3D Analysis of Soil – Foundation – Structure Interaction in Layered Soil. Open Journal of Civil Engineering,* 4: 373–385.

Pulikanti S., Ramancharla P.K. 2014. *SSI Analysis of Framed Structure Supported on Pile Foundations – With and Without Interface Elements*. Frontiers in Geotechnical Engineering (FGE), 1(3).

Rasal S.A., Chore H.S, Dode P.A. 2010. *Interaction of frame with pile foundation*. IOSR Journal of Mechanical and Civil Engineering, 1: 59–62.

Reddy C.R.K, Rao T.D.G. 2011. *Experimental study of a modelled building frame supported by pile groups embedded in cohesion less soil*. Interaction and Multi scale Mechanics, 4(4): 321–336.

Reddy C.R.K, Rao T.D.G. 2012. *Study of soil interaction in a model building frame with plinth beam supported by pile group*. International Journal of Advanced Structural Engineering, 4(11).