

УДК 624.131

## **PILE-RAFT FOUNDATIONS IN SOFT SOIL**

**Martin Vozár**

*Словацкий технический университет, строительный факультет,  
кафедра геотехники, г. Братислава, Словакия*

На площадках, где на значительную глубину от поверхности простираются слабые грунты с низкой несущей способностью и высокой деформативностью, фундаменты глубокого заложения, такие как сваи, обычно принимаются проектировщиками при строительстве высотных зданий, что приводит к высокой стоимости строительства. Тем не менее, в некоторых случаях, относительно дешевый тип фундамента, такой как сплошная плита, при применении может препятствовать возможности разрушения при сдвиге благодаря огромным нагрузкам на нижележащие грунты, но результирующая осадка будет намного больше допустимой. Таким образом, для того чтобы иметь экономически выгодный тип фундамента, сплошной фундамент устанавливается над основанием предполагаемого здания, а сваи устанавливаются в определенном месте под плитой с целью увеличения несущей способности комбинированной системы с уменьшенной результирующей осадкой. Однако в уплотняемых слабых грунтах, взаимодействие между грунтом, плитой и сваями становится зависимым от времени. В данной статье предлагается простая методика для проектирования свайно-плитных систем и ее сравнение с такой же моделью МКЭ.

In areas where soft soil of low strength and high deformability extends over considerable depth from ground surface, deep foundation like

piles are adopted by the designers for construction of high rise buildings, resulting high cost of construction. However, in such cases, a relatively cheaper foundation system like raft if adopted can counteract the possibility of shear failure due to huge super structural loads on the sub soil but the resulting settlement would be too large to be permitted. Thus, to have an economic foundation system, a raft is provided over the base of the proposed building and some piles are installed at specified location below the raft to increase the load carrying capacity of the combined system with reduced resulting settlement. But in a consolidating soft soil, the interaction between soil, raft and pile becomes time dependent. In this paper, a simple design methodology for pile raft system is proposed and with the same MKP model is compared.

---

<sup>1</sup>Ing. Martin Vozár, Katedra geotechniky, Stavebná fakulta STU v Bratislave, Radlinského 11, 813 68 Bratislava, tel.: 02/59274281, e-mail: martin.vozar@stuba.sk

## **1. Introduction**

In soft clayey subsoil, performance of a foundation is very much affected by time dependent soil deformation. Time dependent behaviour of soil results from properties of consolidation which has certain non linear characteristics. In soft ground, piled raft foundation are widely used and employed in construction of high rise buildings for their low overall and differential settlement with higher bearing capacity. The design of piled raft is based on the soil – structure interaction between the constituting elements and this is achieved through different method proposed by Poulos (2001), Katzenbach et al. (2000), Randolph (1994), Franke (1991). However, the piled raft subsoil interaction problem is highly complicated as it depends on large number of parameters like pile-raft geometry, pile spacing, sub soil characteristics etc. Especially, load deformation of soft soil may become non linear under high stress level. In case of submerged condition soft ground displays low strength, sensitive thixotrophy and high compressibility. Hence, in realistic design of piled raft foundation system time dependent behaviour of soil deformation and consolidation characteristic of the founding ground should be given due importance.

In this paper, an attempt has been made to formulate a design method for calculation of load carrying capacity of piled raft system in a soft consolidating underlying soil stratum. Pile elements are used to control

or restrict the average settlement to a permitted value and at any point of time, the raft shares a portion of load so that the piles carry the remaining super structural load. The effect of ongoing consolidation settlement is considered in design. The time effects of interaction of piled raft and soil is numerically modelled.

As a result, the time dependent behaviour of interaction of the piled raft and the soil is investigated in this paper by incorporating the effect of consolidation of the sub soil. Proposed method includes the field performance of pile from routine pile load test conducted at the construction site in Eastern part of Kolkata city in a very unique soft clay deposit extending from 2 m to 16 m (more or less) below ground level. But it is necessary compare this results with MKP models.

## **2. Literature Survey of Analytical studies on Piled-Raft**

In the analytical field, pioneering work was started by Butterfield & Banerjee (1971) and thereafter important developed models are Strip-Spring model by Poulos (1991), Plate-Spring model of Clancy and Randolph (1992), Boundary element method by Sinha (1997), FEM application in raft and Boundary element for pile by Hain and Lee (1978), Franke et al. (1994), FEM analysis involving plain strain & axisymmetric problem by Hooper (1974); Prokoso & Kulhawy (2001), 3D FEA by Zhang et al. (1991). All these methods do have specific objectives in studying the overall & differential settlements, raft bending and parametric effects. Time effects in soil structure analysis was first considered by Wood et al. (1975) on the basis of 1D Terzaghi's model of consolidation by virtue of finite difference method. Then the time dependent response of the piled-raft-soil interaction system under vertical loading was analysed by Cheng et al. (2004) using 2D FEM based on Biot's theory of consolidation. The linear creep Page 3 of 11

In the analytical field, pioneering work was started by Butterfield & Banerjee (1971) and thereafter important developed models are Strip-Spring model by Poulos (1991), Plate-Spring model of Clancy and Randolph (1992), Boundary element method by Sinha (1997), FEM application in raft and Boundary element for pile by Hain and Lee (1978), Franke et al. (1994), FEM analysis involving plain strain & axisymmetric problem by Hooper (1974); Prokoso & Kulhawy (2001), 3D FEA by Zhang et al. (1991). All these methods do have specific objectives in studying the overall & differential settlements, raft bending and parametric effects. Time effects in soil structure analysis was first considered by

Wood et al. (1975) on the basis of 1D Terzaghi's model of consolidation by virtue of finite difference method. Then the time dependent response of the piled-raft-soil interaction system under vertical loading was analysed by Cheng et al. (2004) using 2D FEM based on Biot's theory of consolidation. The linear creep model was incorporated by Viladkar et al. (1993) into FEM in interaction analysis and it is found that bending moment, contact pressure and differential settlement vary with time. A simplified rheologic element model was used by Xia (1994) to evaluate the distribution of raft contact pressure on visco-elasto plastic soil. A three dimensional FEM is proposed by An et al. (2001) to predict the creep settlement of foundation on elasto visco plastic soil. The interaction analysis considering time effects induced by both viscosity and consolidation was conducted by Wang et al. (2001) in which a closed form fundamental solution of stresses of saturated visco elastic soil underlying raft under vertical loading is derived. However, a critical study of Poulos (2001) showed that results from such models shows large scatter from each other.

For the present work, to understand the raft soil, raft pile and pile soil interaction of composite pile raft foundations some practical assumptions have been made for the stress strain behaviour of the pile, the subsoil and raft. The interaction of the pile and soil responses is restricted in linearly elastic region. Such assumptions have resulted in satisfactory outcome in the piled raft researches based numerical model of Roy and Chattopadhyay (2011) and on finite element models of Mossallamy et al.(2009), Jeong et al. (2003).

The proposed method is formulated basically to determine the time required, iteratively, by the piled raft composite foundation where load sharing and consequent load transfer between the pile and raft reaches an optimum balanced state for a super structural load on it in a soft consolidating sub soil. Study was also done to evaluate the separate individual load carrying capacities of raft and pile. As piles take huge load on a very small amount of settlement, corresponding load sharing and settlement of the raft is also studied. The time settlement relationship for the raft is also obtained taking into consideration consolidation properties of the existing soil profile. This is done to recognize time effects in interaction of piled raft and sub soil as it has got a practical significance as Chun-yi Cui et al. (2005) through his EVP soil model has shown that reactions and deformation of pile raft foundation varies with time in consolidating soft ground condition. Capacity of pile is determined through load test. The total settlement and load settlement char-

acteristic of pile is determined through load settlement curves obtained from the routine load test.

### 3. Capacity of piled raft foundation

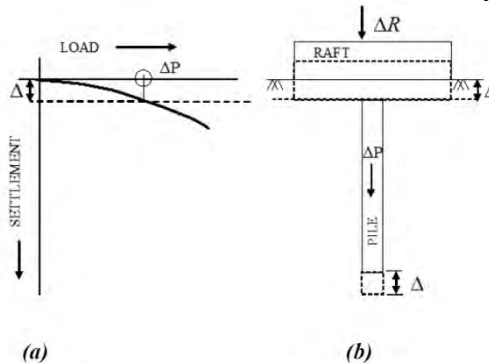
For a raft, proposed design approach starts with evaluation determination of its bearing capacity from both the shear failure criteria and permissible settlement limits for existing subsoil profile. The safe load for the raft is finalized following the most critical condition of the above two criteria. Now from the routine pile load tests the load that could be safely taken by the pile is evaluated through load settlement curves. Thus for a chosen settlement of „ $\Delta$ “, if raft carries a load,  $\Delta R$  and pile carries a load,  $\Delta P$ , then the capacity of piled raft foundation,  $\Delta P_R$  can be expressed as

$$\Delta P_R = \Delta R + \Delta P \quad (1)$$

Here settlement „ $\Delta$ “ takes care of both immediate and consolidation settlement of the subsoil profile. Figure 1 illustrates the schematic presentation of pile load test result and piled raft load sharing.

### 4. Calculation of $\Delta P$

The value of settlement „ $\Delta$ “ of the combined pile-raft system, can be taken and adopted as per project requirement or subsoil condition and corresponding load on pile i.e.  $\Delta P$  can be obtained directly from the load settlement curves of the conducted routine load test on pile. The value of „ $\Delta$ “ can be varied to obtain required load sharing mechanism between the piles and the raft within linear zone of the load settlement curve of the pile.



Example Figure 1: Schematic diagram (a) Load settlement curve of routine pile load test; (b) Load taken by raft and pile at chosen settlement,  $\Delta$ , from pile load test curve.

## 5. Calculation of ‘DR’

As mentioned previously, „D R“ in the proposed approach is the total settlement i.e. sum of both initial and consolidation settlement for the raft. The value of „D R“ for raft is calculated considering both consolidation settlement and immediate settlement of the existing subsoil profile. At a consolidation settlement of  $\Delta c$ , let the load taken by the raft be  $\Delta R_c$ . At that load of  $\Delta R_c$ , corresponding immediate settlement,  $\Delta I$  is calculated.  $\Delta R_c$  can be derived from the consolidation equation. From the above equation, DR can be written as

$$\Delta c = \frac{C_c}{1 + e_o} H \log_{10} \frac{p_o + \Delta R_c}{p_o} \quad (2)$$

$$\Delta R_c = [10^{\frac{\Delta c}{C_c H}}] p_o - p_o \quad (3)$$

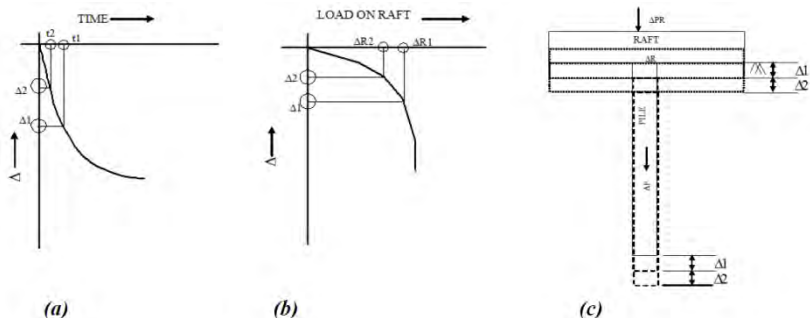
$p_o$  – is the initial overburden pressure ;  $H$  – height of compressible strata;  $C_c$  – compression index;  $e_o$  – initial void ratio of the consolidating layer.

So that the total settlement of the raft and pile becomes almost identical and hence „D R“ can be written as

$$\Delta R_c = \Delta R$$

Figure 2 illustrates the schematic representation of time settlement curve of raft, load settlement of the raft and gradual consolidation settlement process of the piled raft foundation respectively. In addition, the time settlement of raft is incorporated to obtain the optimum time required to reach the balanced state of the piled raft foundation where load transfer and total settlement of piled raft becomes almost negligible and full load carrying capacity of the piled raft foundation is mobilised.

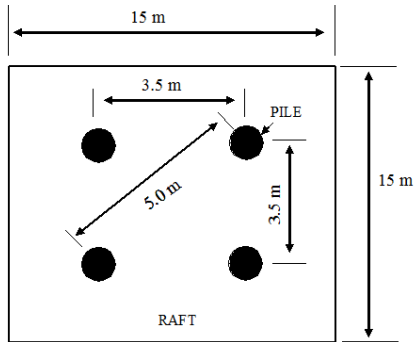
Water table was found to be at 0.8 m below existing ground level. From geological exploration we have return results before equalization subgrade surface. It was equalization for 8.0 m below existing ground level.



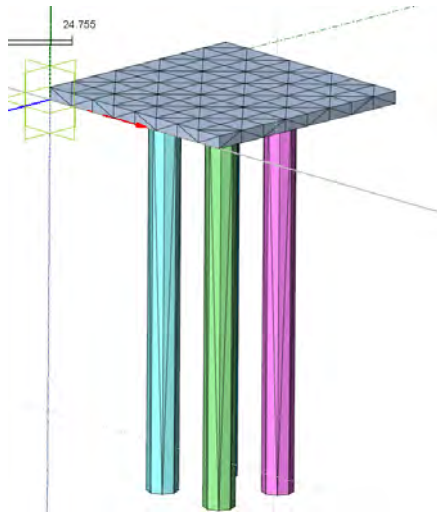
Example Figure 2: Schematic diagram (a) Time settlement curve of raft; (b) Load settlement of raft at chosen settlements; (c) gradual consolidation settlement of pile raft composite.

Example Table 1: Soil profile with design soil parameters

Stratum thickness (m)	Description of soil	N	NMC (%)	$\gamma$ (kN/m <sup>3</sup> )	Shear parameters		$\frac{C_c}{1 + e_o}$	$m_v$ in m <sup>2</sup> /kN x 10 <sup>-4</sup> Range (kPa)		
					C (kPa)	$\phi$ (°)		25-50	50-100	100-200
III (8 to 16)	Silty clay with decomposed vegetation	3	42	16	20	1	0.13	5.3	5.5	4.4
IV (16 to 22)	Bluish medium silty clay	18	28	17	45	1	0.08	3.5	3.3	3.00
V (22 to 30)	Medium dense silty sand with mica	38	33	19	57	28	-	-	-	-
VI (30 to 33) Bore stopped	Yellowish dense sand	58	35	18	-	35	-	-	-	-

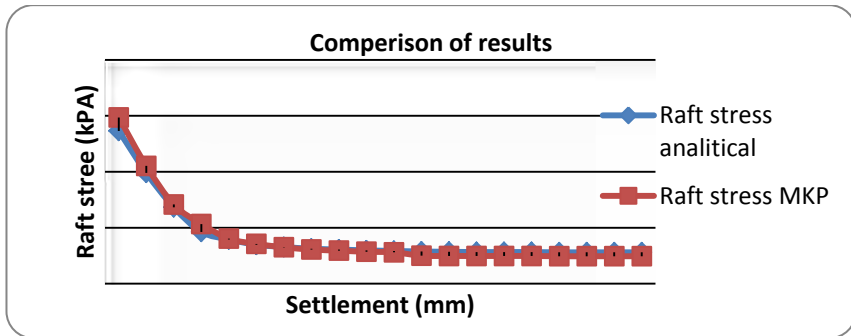


Example Figure 3: Adopted piled-raft geometry 15x15 m raft; 1000 mm diameter pile having length 30 m



Example Figure 4: MKP model of pile-raft foundation





Example graf 1: Comperison of results

## 6. Conclusions

The present method is in good agreement with the established model (1 -8%). In this proposed method the pile dimensions, raft dimensions, different suitable methods of pile group arrangement could be incorporated in tentative designs to make a most cost effective and efficient foundation system for a prototype foundation system. The present method by virtue of its procedures, includes the all the soil-structure interaction effects of pile, raft and composite piled raft foundation system as the method is solely based on the determination of all the engineering characteristic of a site physically and capacity of pile is directly calculated from the routine load tests.

## References

1. An G.F. and Gao D.Z. (2001) "3D FEM Application to the Prediction of Creep Settlement of Soft Clay Consideration Elastic-Visco Plastic Consolidation", *Journal of Tongji University*, 29(2): 195-199.
2. Butterfield, R. and Banerjee, P. K. (1971) "The Problem of Pile Group- Pile Cap Interaction, Geotechnique", 46(2), 135-142.
3. Cheng, Z.H., Ling, D.S. and Chen, Y.M. (2004) "Time Effects on Pile Raft Foundation on Vertical Loading", *China Civil Engineering Journal*, 37(2): 73-77.
4. Chun-yi Cui, Mao-tian Luan and Ying-hua Zhao (2005) "Time-dependent Behaviour of Piled Raft on Soil Foundation with Reference to Creep and Consolidation", *EJGE*, Vol.14, Bund. A, 1-14.

5. Clancy, P. and Randolph, M. F. (1992) "Analysis and Design of Piled Raft Foundations", *Research Report No. G 1062*, Department of Civil Engineering, University of Western Australia, Perth, Australia.

6. Franke, E. (1991) "Measurement Beneath Piled Rafts", Keynote Lecture, *ENPC Conf.*, Paris, 1-21.

7. Franke, E., Lutz, B. and El-Mossallamy, Y. (1994) "Measurements and Numerical Modeling of High Rise Building Foundations on Frankfurt Clay", *Geotechnical Special Publication*, ASCE, 40, 1325-1336.

8. Hain, S. J. and Lee, I. K. (1978) "The Analysis of Flexible Pile Raft System", *Geotechnique*, 28(1), 65-83.

9. Hooper, J. A. (1974) "Observations on the Behavior of Piled Raft Foundation on London Clay", *Proc. Institution of Civil Engineers, Part 2*, 55, 855-877.

10. Jeong, Gyo-Sung and Choi sik-Kyung, (2003) "Design Charts of Piled Raft Foundation on Soft Clay", *Proc. 13th Int. Offshore and Polar Engg. Conf., Honolulu, Hawaii, USA, May, 2003*, 753-755 Page 11 of 11

11. Poulos, G. Harry. (1991) "Analysis of Piled Strip Foundations", *Computer Methods and Advances in Geomechanics*, (Eds.) Beer, G., Booker, J.R. and Carter, J. P., Balkema, Rotterdam, 153-191.

12. Poulos, G. Harry. (2001) "Piled Raft Foundation: Design and Application", *Geotechnique*, 51(2), 95-113.

13. Prokoso, W. A. and Kulhawy, F. H. (2001) "Contribution to Piled Raft Foundation Design", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 127(1), 17-24.

14. Randolph, M.F. (1994) "Design Methods for Pile and Piled Rafts", *Proc. 13th Int. Conf. on Soil Mech. Found. Engg.*, New Delhi, 61-81.

15. Roy, S. and Chattopadhyay, C. B. (2011) "A Simple Procedure for Design of Piled Raft System", *Proc. 3rd Indian Young Geotechnical Engineers Conference*, 25-26, March, 2011, 121-126.

16. Roy, S. and Chattopadhyay, C. B. (2010) "Piled-Raft Foundation Behaviour on Consolidating Soft Soil", *ICSECM\_2011/SEC-11-49*, 1-10.

17. Sinha, J. (1997) *Piled Raft Foundations subjected to Swelling and Shrinking Soils*, Ph. D. Thesis, University of Sydney, Australia.

18. Viladkar, M.N., Ranjan, G. and Sharma R.P. (1993) "Soil-Structure Interaction in the Time Domain", *Computer and Structure*, 27(2): 429-442.

19. Wang, J.H., Chen, J.J. and Pei, Jie. (2001) “Interaction between Super structure and Layered Visco- Elastic Foundation Considering Consolidation and Rheology of Soil”, *Journal of Building Structures*, 35(4): 489-492.

20. Wood, L.A. and Larnach, W.J. (1975) “The Interactive Behaviour of Soil-Structure System and its Effect on Settlements”, *Symposium on Recent development in Analysis of Soil Behaviour and their Applications to Geotechnical Structures*, University of New South Wales, Australia, 75-87.

21. Xia, Z.Z. (1994) “Calculation of Contact Pressure Distribution on Elasto-Visco Plastic Soil Medium”, *China Civil Engineering Journal*, 27(2): 56-64.

22. Zhang, G. M., Lee, I. K. and Zhao, X. H. (1991) “Interactive Analysis Behavior of Raft-Pile Foundations”, *Proc. Of Geo coast*, 91, Yokohama, 719-764.