Settlement Analysis of a Layered Soil System due to Circular Loading

Preethi Sekar[1], Umashankar B[2], and Madhav M R[3]

[1]Masters Student, Department of Civil Engineering, IIT Hyderabad, Yeddumailram, Medak, Telangana -502 205, India, email: ce13m0002@iith.ac.in

[2]Assistant Professor, Department of Civil Engineering, IIT Hyderabad, Yeddumailram, Medak, Telangana-502 205, India, email: buma@iith.ac.in

[3]Visiting Professor, Department of Civil Engineering, IIT Hyderabad, Yeddumailram, Medak, Telangana -502 205, India, email: madhavmr@gmail.com

Abstract

Many studies are available on the settlement analysis of footings on a homogeneous soil deposit underlain by a rigid base. However, the soil profile is seldom homogenous and typically a layered soil system is encountered in practice. The present study deals with the settlement profiles of soil underneath a circular footing of radius equal to *a*, and resting on a finite two-layered soil system with thicknesses equal to H_1 and H_2. The deformation moduli and Poisson's ratios of the two layers are E_1, υ_1, and E_2, υ_2. The settlement profiles are proposed for varying H_1/a and H_2/a ratios (H_1/a= 0.2, 0.5, 1, 2, 4 and 6, and H_2/a= 1, 2, 4 and 6). The moduli ratio E_1/E_2 is varied as 0.01, 0.05, 0.1, 0.5, 1, 2, 5 and 20. The extent of settlement due to load is also proposed from the surface settlement profile which can help in determining the influence of a footing on the neighboring footing or structure. The analysis is carried out using PLAXIS 2D vAE. In addition, the settlement influence factors are proposed for the above mentioned ratios to estimate the maximum settlement of the footing on a layered system. The results are also compared with the settlement measured in a building on a layered system in Adelaide, Southern Australia, and the results are found to be comparable.

Keywords

settlement, circular loading, layered system, elastic analysis

Introduction

Excessive settlement can impair the serviceability and even the safety of the structure. Settlements are generally classified as immediate settlement (short-term) and consolidation and creep settlements (long-term). Some early methods estimated the settlements based on empirical correlations relating the in-situ test parameters (Terzaghi and Peck[13] (1948) and Meyerhof[10] (1965)). The immediate settlements are mainly estimated based on the theory of elasticity. Stresses and displacements for different loadings within an elastic, homogenous soil medium are well studied and reported in the literature. Schmertmann[7] (1970) proposed settlement influence factors based on elastic strains due to circular loading on an elastic, homogenous soil medium. Poulos and Davis[4] (1991) have provided a comprehensive account of the settlements proposed by various researchers - Boussinesq[5](1885), Newmark[11](1947), Westergaard[14] (1939), Harr[12] (1966), Giroud[8] (1968), Ueshita and Meyerhof[9] (1967), *etc.* Mayne and Poulos[3] (1999) proposed an equation to estimate the settlement of footings resting on semi-infinite and finite layers incorporating foundation geometry, rigidity, and embedment depth. The proposed equation can be applied for homogenous and Gibson soil profiles. Enkhur et al. [1] (2012) proposed settlement influence factors for circular and rectangular footings with corrections for foundation roughness and rigidity. The equivalent circular footing approach was found to overestimate the settlement of rectangular footing with large aspect ratios (L/B>2.0).)

Studies on settlement of footings on a layered system underlain by a firm stratum are limited. Umashankar et al. [2] (2006) proposed charts to estimate the settlements due to uniform circular load acting on a finite two-layer system for a soft layer overlying a stiff layer (E_1/E_2<1.0) and a stiff layer overlying a soft layer (E_1/E_2>1.0). In this study, the surface settlement profiles of circular footing on a two-layer system for a layered system underlain by a firm stratum are provided.

Problem Definition

A uniform circular load, radius equal to *a*, is applied on a two-layer system underlain by a firm stratum. The thicknesses of the top and bottom layers are H_1 and H_2. The deformation modulus and Poisson's ratio of the two layers are E_1, υ_1 and E_2, υ_2, respectively. The maximum settlement and the settlement profiles for this loading situation are to be proposed for E_1/E_2<1 (soft soil over stiff soil), and E_1/E_2>1 (stiff soil over soft soil), and for various H_1/a and H_2/a values.

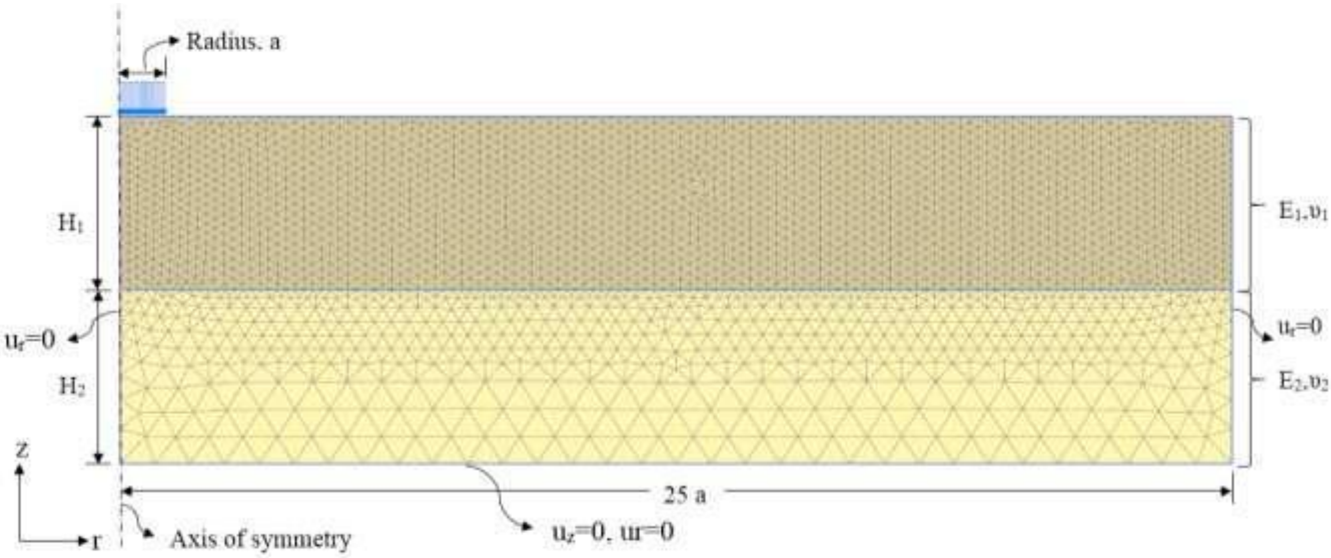


Figure 1 Finite Element Model for H_1/a=4, H_2/a=4

Finite Element Analysis

Finite element software- PLAXIS 2D v AE- was used to analyze the problem. Axisymmetric model was chosen and hence only one half of the model was considered. 15-noded triangular elements were used to discretise the geometry. Mesh and boundary convergence studies were performed, and the boundary was fixed at 25a and mesh was fixed as very fine refinement for the bottom layer

(Figure 1). Finer refinement was adopted to discretize the top layer with element size equal to 0.25 times the element size in the bottom layer. Figure 1 shows the refinement with layered soil system discretized into 5737 elements with an average element size equal to about 186 mm for the case of H_1/a=4 and H_2/a=4. Settlement analysis was performed for an applied stress q = 500 kPa at the surface over a circular loaded area with radius equal to 1.0 m. The default boundary conditions option was chosen, i.e., the bottom boundary is fixed in both r and z directions, while the side boundary is fixed in r direction and the top boundary is free.

Results and Discussion

The settlement influence factor, I_ρ, for the two-layer system is obtained for various combinations of H_1/a=0.1 to 6.0, H_2/a =1.0 to 6.0, E_1/E_2=0.01 to 100 and $\upsilon_1 = \upsilon_2$ =0.2, 0.35 and 0.5. The settlement influence factors can be obtained from the equation

$$\rho = \frac{I_\rho q B}{E_2} \tag{1}$$

where ρ is the settlement due to load of intensity, q, I_ρ is the influence factor corresponding to the maximum settlement, q is the load applied, and B is the diameter of the footing (=2a). The settlement influence factor corresponding to the maximum settlement at the center of the load is designated as $I_{\rho,max}$.

Tables 1 and 2 provide the influence factors that can be used to predict the maximum settlement at the center of loading for a two-layered system with E_1/E_2<1.0 and E_1/E_2>1.0. Figure 2(a) shows the variation of $I_{\rho,max}$ with H_1/a for E_1/E_2<1.0. $I_{\rho,max}$ increases sharply with H_1/a, the thickness of the top, softer layer for H_1/a increasing from 0.2 to 1.6. The rate of increase of $I_{\rho,max}$ with H_1/a is higher for low H_1/a (up to H_1/a = 1.0) compared to that at large H_1/a. This rate of increase is higher for low values of E_1/E_2 (for *e.g.*, E_1/E_2= 0.01, 0.05) than at relatively high E_1/E_2 (for *e.g.*, E_1/E_2 = 0.2, 0.5). Figure 2(b) shows the similar variation for E_1/E_2>1.0 and indicates that the settlement of the two-layer system decreases with increase of the thickness of the top stiff layer. The rate of decrease of $I_{\rho,max}$ with H_1/a is higher for relatively low H_1/a (till H_1/a = 3.0) than for high H_1/a values. This rate of decrease increases with increase in E_1/E_2 values. For instance, $I_{\rho,max}$ corresponding to H_2/a = 1.0 decreases by 81 % as H_1/a increases from 0.5 to 2.0 for E_1/E_2 = 100, whereas it only decreases by 42% for the same increase in H_1/a (0.5-to-2.0) for E_1/E_2 = 5.

Figures 3 and 4 show the surface settlement profiles for H_1/a = 1.0 and 4.0 corresponding to H_2/a = 4.0 for E_1/E_2<1.0 and E_1/E_2>1.0, respectively. For softer top layer, the surface settlements are found to spread to a larger distance away from the loaded area. Table 3 shows the influence factors to obtain the settlement at the edge of the loaded area (*i.e.*, x/a=1.0). It can be found from the Table that the settlement influence factors at the edge of the loaded area for the layered system with E_1/E_2= 0.05 is about 48 times that compared to E_1/E_2=5.0 corresponding to H_1/a=2.0, H_1/a=4.0, and $\nu_1=\nu_2$=0.35.

Case Study and Validation

Kay and Cavagnaro[6](1983) observed the settlement underneath Savings Bank in Adelaide, South Australia. The raft was placed at a depth of 4 m below the ground level and the water table is at a depth of about 20 m. The raft was of dimensions 33.5 m x 39.5 m. The soil profile below the raft consists of two finite layers of thickness equal to 2 m and 8 m with deformation modulus equal to 44 MPa and 60 MPa, respectively. Settlement measured at this site was 16-18 mm for applied load intensity of 134 kPa. The settlement was estimated based on the settlement influence factors proposed in the study. The equivalent circular area of the raft footing was found to be of 20 m radius. Using Equation (1) and Table 1 and taking q=134 kPa, H_1=2m, H_2 = 8m, a = 20m and H_1/a = 0.1, H_2/a = 0.4, E_1 = 44 MPa, E_2 = 60 MPa, the settlement values were obtained. Poisson's ratio equal to 0.2 was assumed according to the onsite conditions as proposed by Kay and Cavagnaro (1983). The corresponding settlement at the center of the raft was obtained as 19 mm which is in good agreement with the measured settlement. The slight difference might be due to (a) approximation of loading on raft with load on an equivalent circular area, and (b) assuming that the raft is at the ground level.

Table 1 $I_{\rho,max}$ values for E_1/E_2<1 using Finite Element Analysis

Parameters		**E_1/E_2=0.01**		**E_1/E_2=0.05**		**E_1/E_2=0.2**		**E_1/E_2=0.5**	
H_2/a	**H_1/a**	**ν=0.2**	**ν=0.5**	**ν=0.2**	**ν=0.5**	**ν=0.2**	**ν=0.5**	**ν=0.2**	**ν=0.5**
1	0.2	8.021	1.712	1.899	0.547	0.752	0.328	0.522	0.284
	0.5	20.402	8.173	4.334	1.838	1.322	0.651	0.719	0.413
	1	38.882	22.162	7.952	4.588	2.153	1.293	0.993	0.634
	2	60.774	41.557	12.239	8.39	3.139	2.171	1.319	0.927
	4	77.053	56.845	15.44	11.397	3.887	2.875	1.577	1.171
	6	83.175	62.687	16.649	12.551	4.176	3.151	1.681	1.271
2	0.2	8.209	1.881	2.088	0.716	0.94	0.498	0.71	0.454
	0.5	20.552	8.31	4.484	1.976	1.471	0.788	0.869	0.551
	1	38.987	22.26	8.058	4.687	2.258	1.392	1.098	0.732
	2	60.832	41.612	12.297	8.445	3.197	2.226	1.377	0.983
	4	77.077	56.868	15.465	11.421	3.912	2.899	1.602	1.195
	6	83.188	62.7	16.663	12.564	4.189	3.164	1.695	1.284
4	0.2	8.353	2.081	2.232	0.853	1.085	0.635	0.855	0.591
	0.5	20.675	8.426	4.607	2.092	1.594	0.904	0.991	0.666
	1	39.082	22.35	8.152	4.777	2.353	1.482	1.193	0.823
	2	60.894	41.671	12.359	8.504	3.258	2.285	1.438	1.041
	4	77.109	56.899	15.496	11.451	3.944	2.929	1.633	1.225
	6	83.207	62.719	16.682	12.583	4.209	3.182	1.714	1.302
6	0.2	8.411	2.072	2.289	0.907	1.142	0.689	0.912	0.645
	0.5	20.726	8.475	4.657	2.14	1.645	0.953	1.042	0.715
	1	39.125	22.391	8.195	4.818	2.396	1.523	1.236	0.864
	2	60.925	41.701	12.39	8.534	3.29	2.315	1.47	1.072
	4	77.128	56.917	15.515	11.469	3.963	2.948	1.653	1.243
	6	83.22	62.731	16.695	12.595	4.221	3.195	1.727	1.314

Table 2 $I_{\rho,max}$ values for E_1/E_2>1 using Finite Element Analysis

Parameters		E_1/E_2=2		E_1/E_2=5		E_1/E_2=20		E_1/E_2=100	
H_2/a	H_1/a	ν=0.2	ν=0.5	ν=0.2	ν=0.5	ν=0.2	ν=0.5	ν=0.2	ν=0.5
1	0.2	0.457	0.266	0.423	0.244	0.39	0.21	0.316	0.149
	0.5	0.45	0.289	0.35	o.215	0.241	0.123	0.138	0.055
	1	0.424	0.283	0.258	0.159	0.133	0.064	0.062	0.022
	2	0.417	0.292	0.202	0.132	0.077	0.039	0.028	0.01
	4	0.431	0.317	0.184	0.131	0.055	0.034	0.015	0.007
	6	0.442	0.332	0.183	0.135	0.05	0.034	0.012	0.007
2	0.2	0.63	0.455	0.585	0.44	0.535	0.4	0.437	0.296
	0.5	0.58	0.432	0.464	0.355	0.331	0.227	0.195	0.108
	1	0.507	0.373	0.326	0.235	0.177	0.108	0.086	0.04
	2	0.459	0.335	0.235	0.162	0.096	0.054	0.022	0.015
	4	0.448	0.331	0.198	0.141	0.063	0.038	0.019	0.009
	6	0.45	0.337	0.19	0.138	0.055	0.036	0.014	0.007
4	0.2	0.715	0.589	0.678	0.581	0.631	0.545	0.522	0.428
	0.5	0.675	0.549	0.551	0.474	0.406	0.332	0.252	0.177
	1	0.579	0.459	0.389	0.316	0.226	0.166	0.115	0.068
	2	0.504	0.384	0.271	0.202	0.12	0.077	0.05	0.024
	4	0.468	0.351	0.214	0.155	0.072	0.045	0.023	0.011
	6	0.463	0.348	0.2	0.146	0.024	0.039	0.016	0.009
6	0.2	0.793	0.64	0.735	0.634	0.675	0.6	0.565	0.483
	0.5	0.714	0.595	0.587	0.522	0.439	0.38	0.281	0.217
	1	0.611	0.498	0.418	0.356	0.251	0.2	0.138	0.089
	2	0.524	0.406	0.29	0.226	0.134	0.093	0.058	0.032
	4	0.482	0.366	0.225	0.166	0.079	0.051	0.026	0.014
	6	0.472	0.357	0.206	0.152	0.064	0.043	0.018	0.01

Table 3 Influence factors to obtain settlement at the edge of the loaded area for various H_1/a ratios for H_2/a=4.0, $\nu_1=\nu_2$=0.35 corresponding to different E_1/E_2 values

H_1/a	E_1/E_2					
	0.01	**0.05**	**0.2**	**2.0**	**5.0**	**20.0**
1.0	16.337	3.476	1.107	0.347	0.264	0.171
2.0	29.740	5.962	1.669	0.127	0.125	0.108
4.0	41.809	8.239	2.171	0.272	0.132	0.049

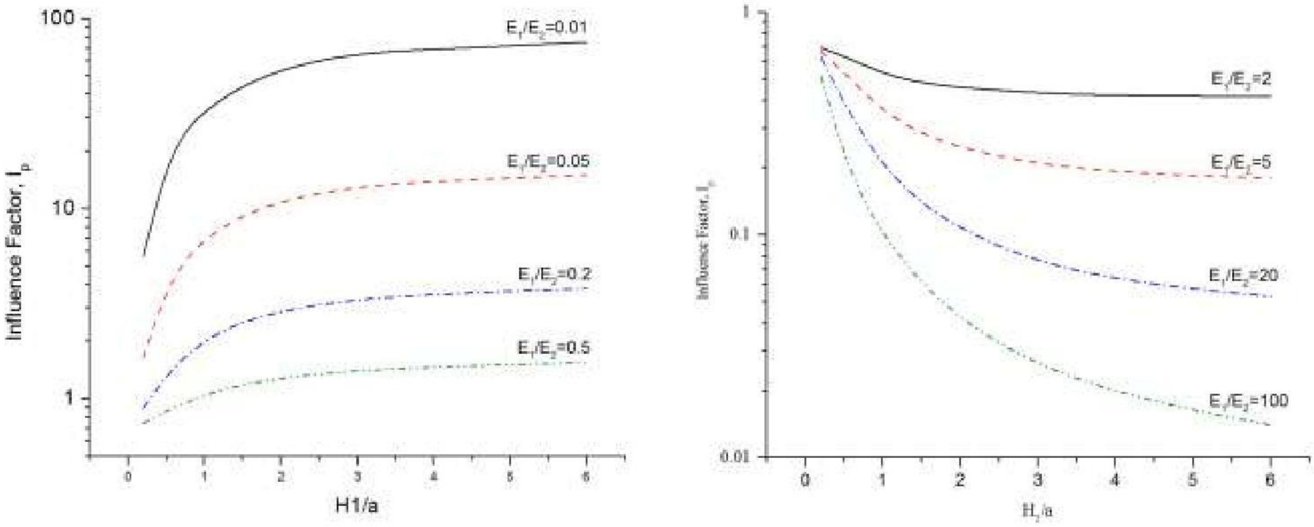
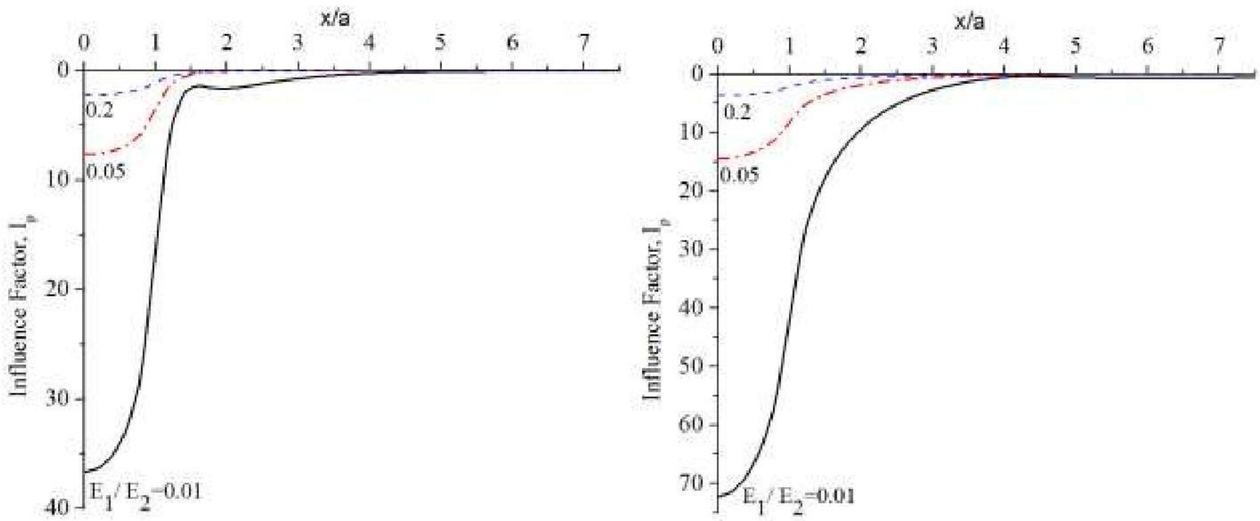


Figure 2 Variation of maximum settlement influence factors, $I_{p,max}$, with H_1/a for (a) $E_1/E_2 < 1$, and (b) $E_1/E_2 > 1$ (H_2/a=4.0 and $\nu_1=\nu_2$=0.35)



H1/a=1 and H1/a=4

Figure 3 Variation of settlement influence factors with x/a for $E_1/E_2 < 1$ corresponding to (a) H_1/a=1 and (b) H_1/a=4 (H_2/a=4.0 and $\nu_1=\nu_2$=0.35)

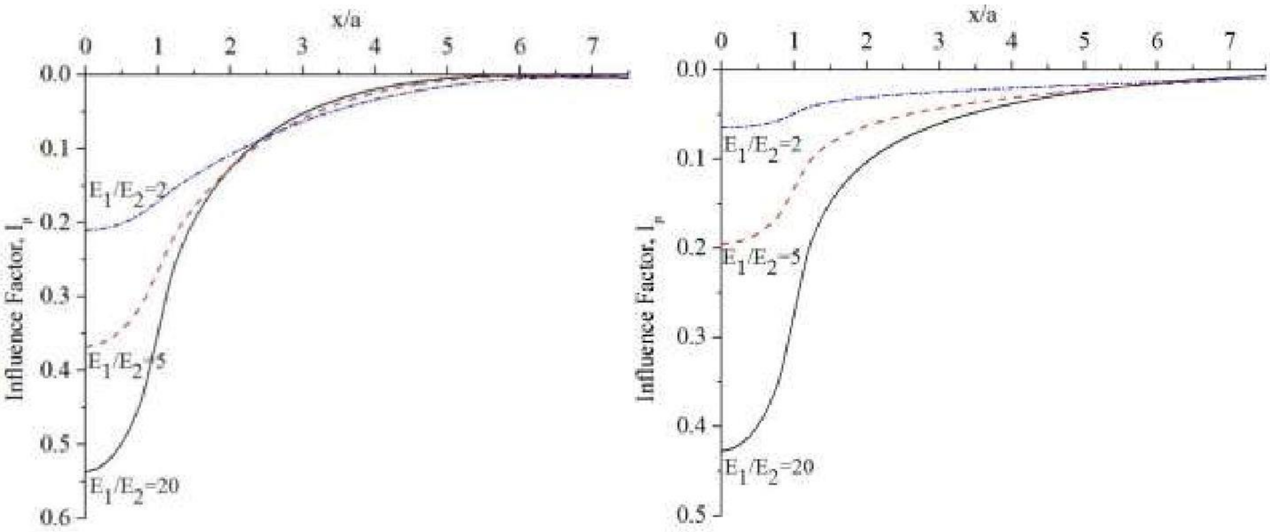


Figure 4 Variation of settlement influence factors with x/a for $E_1/E_2 > 1$ corresponding to (a) $H_1/a=1$ and (b) $H_1/a=4$ ($H_2/a=4.0$ and $\nu_1=\nu_2=0.35$)

Conclusions

Settlement influence factors are proposed to estimate the settlements due to uniform circular load acting on a finite two-layer system for a soft layer overlying a stiff layer ($E_1/E_2<1.0$) and a stiff layer overlying a soft layer ($E_1/E_2>1.0$). The proposed charts help in easy computation of the settlement values for a given geometry and properties of layered soils. The settlements obtained from finite element analysis are found to be comparable with the measured settlements of a structure reported in a case study. The surface settlement profile plots proposed in the study can be used to predict the extent of settlement in the adjacent areas due to uniform circular loading.

References

1. Enkhtur, O., Nguyen,T.D., Kim, J.M and Kinn, S.R. (2013), KSCE Journal OF Civil Engineering(2013) Vol.17, No. 1, pp. 85-95

2. Umashankar, B., Yugandhar, D. and Madhav, M. R. (2013) Settlement Due to Uniform Circular Load: On Finite Two-Layer System, Geotechnical and Geological Engineering, Springer, Volume 31, Issue 1, pp. 255-265

3. Mayne, P. W. and Poulos, H. G. (1999) Approximate displacement influence factors for elastic shallow foundations, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 125, No. 6, pp. 453-460

4. Poulos H. G., Davis E. H. (1991) Elastic solutions for soil and rock mechanics, Center for Geotechnical Research, University of Sydney, Sydney

5. Boussinesq, M. J. (1885) Application des potentiels a l'etude de l'equilibre et du mouvement dessolideselastiques, principalement au calcul des deformations et des pressionsqueproduisent, danscessolides, des efforts quelconquesexercessurune petite partie de leur surface ou de leurinterieur: Memoire suivi de notes etenduessur divers points de physique mathematique et d'analyse, Gauthier Villars, Paris, pp. 722

6. Kay J. N., Cavagnaro R. L. (1983) Settlement of raft foundations. Journal of Geotechnical Engineering, Vol. 109, No. 11, pp.1367-1382

7. Schmertmann, J. H. (1970) Static Cone to Compute Static Settlement over Sand, Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 96, No. 3, pp. 1011-1043

8. Giroud J. P. (1968) Settlement of a Linearly Loaded Rectangular Area, Journal of Soil Mechanics Division, ASCE 94 (SM4), pp. 813–831

9. Ueshita K., Meyerhof G.G. (1967) Deflection of Multilayer Soil Systems, Journal of Soil Mechanics and Foundation Division, ASCE SM5, pp. 257–282

10. Meyerhof, G. G. (1965) Shallow Foundations, Journal of the Soil Mechanics and Foundations Division, ASCE, 91(2), pp. 21-31

11. Newmark N. N. (1947), Influence Charts for Computation of Vertical Displacements in Elastic Foundations, University of Illinois, Eng. Expt. Stn., Bulletin no. 367

12. Harr M. E. (1966) Foundations of Theoretical Soil Mechanics, McGraw Hill, New York

13. Terzaghi, K. and Peck, R. B. (1948) Soil Mechanics in Engineering Practice, 1st Edition, John Wiley and Sons, New York

14. Westergaard H. M. (1939) A Problem of Elasticity Suggested by a Problem of Soil Mechanics: Soft Material Reinforced by Numerous Strong Horizontal Sheets, 60th Anniversary Vol. of S. Timoshenko, Contributions of Mechanics of Solids, MacMillan Pub. Co., New York