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3D analytical method for mat foundations considering coupled soil springs

Jaehwan Lee, Sangseom Jeong* and Joon Kyu Lee

Department of Civil and Environmental Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 120-749, Republic of Korea

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Abstract. The 3D numerical analysis is carried out to investigate the settlement behavior of flexible mat foundations subjected to vertical loads. Special attention is given to the improved analytical method (YS-MAT) that reflects the mat flexibility and soil spring coupling effect. The soil model captures the stiffness of the soil springs as well as the shear interaction between the soil springs. The proposed method has been validated by comparing the results with other numerical approaches and field measurements on mat foundation. Through comparative studies, the proposed analytical method was in relatively good agreement with them and capable of predicting the behavior of the mat foundations.

Keywords: soil-structure interaction; mat foundation; soil spring; coupling effect; settlement

1. Introduction

Mat foundations are usually used as a load distributing element supported by piles or directly placed on soils or rocks having sufficient load-carrying capacity. The mat foundations are cost-effective, with savings up to 20% of the total cost, compared to deep foundations (Briaud 1993).

The structure part of mat foundation can be modelled as a flexible or a rigid plate. The conventional rigid method has been used for practical design of mat foundation. This method assumes a mat to be a rigid body, which does not consider the mat flexibility and the thickness would have to be greater. Also, even very thick ones deflect when loaded by the superstructure loads (Bowles 1997). Alternatively, mat foundation can be designed as the flexible plate. The flexible theory of plates can be categorized as the thin and thick plate theory. In practice, there are two main approaches to model the soil beneath the shallow foundation. These models are known as the Winkler model and the continuum model which makes use of the FE analysis (Dutta and Rana 2002, Colasanti and Horvath 2010).

The continuum model is computationally difficult to exercise and requires extensive training because of the three-dimensional and nonlinear nature of the problem. Also the time consuming, both in modelling and computation, can be exhausting. However, the Winkler model is relatively easy and simple to exercise. For the design and analysis of the flexible mat foundation, the

*Corresponding author, Professor, E-mail: soj9081@yonsei.ac.kr

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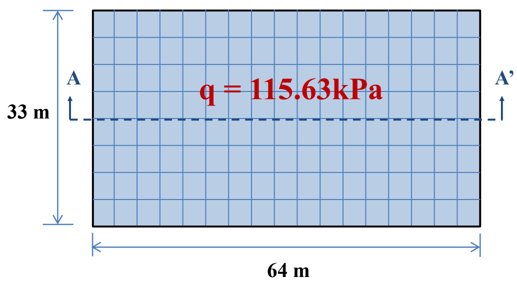
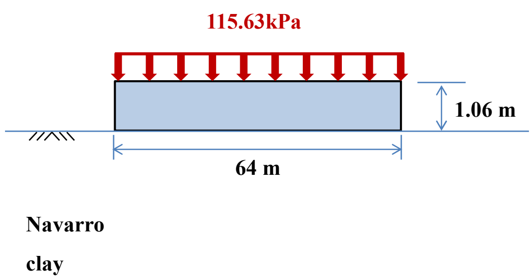
Second numerical example is the uniformly distributed load (Fig. 6(b)). The settlement and bending moment are plotted in Fig. 8. The existing spring analysis method based on the Winkler foundation model gives a uniform displacement and moments equal to zero. This is because the foundation does not have any curvature due to the fact that the soil springs are not coupled to each other. On the other hand, the settlement results by the proposed method differ from that by the Winkler model which has a uniform displacement. The proposed method gives a dish-shaped settlement of the mat foundation which would be expected in a real situation, and is in good agreement with literature reviews (Straughan 1990, Vallabhan and Das 1991, Dutta and Rana 2002), because the soil springs do interact with each other. It is found that the proposed analytical method closely approaches the settlement and bending moment of FEM than Winkler analysis. Therefore, it is thought that YS-MAT can be used with some confidence in the preliminary design of mat foundations.

4. Comparison with field measurement data

Validation was also undertaken against field data form the literatures. The mat and soil properties used the same as their research reports. The measured settlement of the mat foundation reported by Johnson (1989) is compared with the predicted values from YS-MAT and FEM. The test site was located in the northwest sector of Lackland Air Force Base near San Antonio, Texas. The large mat is 33×64 m with a thickness of 1.06 m and supports the 11 story Wilford Hall Hospital. The applied uniform pressure of 115.63 kPa was applied over the whole mat area, and the mat was installed in clay soils. Fig. 9 shows the schematic figures of mat foundation and



(a) Plan view



(b) Section view

Fig. 9 Wilford Hall Hospital

Table 2 Material parameters used for a field case

Case	Material Properties										
	Type		Depth (m)	E (MPa)	v	γ (kN/m^3)	ϕ (deg.)	c (kPa)	H_s (m)	Model **
Johnson (1989)	Mat	Concrete	0 ~ 1.06	30,000	0.2	24	-	-		L.E.
	Soil	Clay	0 ~ -16.2	140.9	0.3	17.3	27	287	66	M.C
				k_s (kPa/m) *			k_g (kN/m) *			YS-MAT
				3,770			1,192,324			

* k_s: The value obtained from Johnson (1989), k_g: Estimated by Eq. (6b)
** M.C. is Mohr Coulomb elasto-plastic model, L.E. is linear elastic model

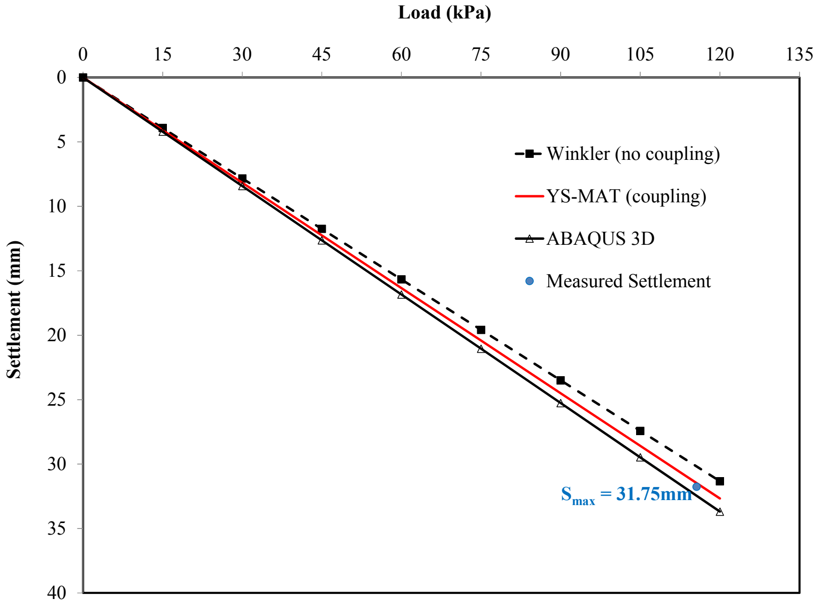


Fig. 10 Settlement behavior of large mat foundation

subsurface profile. The input parameters are summarized in Table 2.

Fig. 10 shows a series of settlement curve of the large mat foundation. The measured maximum settlement is about 31.75 mm, Winkler foundation is 30.11 mm, YS-MAT is 31.48 mm, and ABAQUS 3D is 32.46 mm. These numerical methods provide an acceptable design prediction. The proposed methodology YS-MAT approximately predicts the settlement of mat foundation when compared with the results from Winkler foundation.

5. Conclusions

The main objective of this study is to propose an improved analytical method for analyzing a mat foundation that can consider mat flexibility and soil coupling effect. Through comparisons with other numerical methods and field measurement, it is found that the proposed analytical method is in good agreement with measured data. On the basis of the findings of this study, the following conclusions are drawn:

- The analytical method is intermediate in complexity and theoretical accuracy between general three-dimensional FE analysis (ABAQUS 3D) and the conventional analysis method (Winkler spring model).
- By taking into account the mat flexibility and soil coupling, the proposed analytical method is an appropriate and realistic representation of the settlement behavior of flexible mat foundation. It provides results that are in good agreement with the field measurement and numerical analyses.
- Proposed analytical method produces a relatively larger settlement of mat foundation than the results obtained by the existing method. Also, the settlement and bending moment of mat foundation obtained by the proposed method is similar to that of ABAQUS 3D when compared with the results of the existing method.
- Compared to the results of the field measurement, the proposed method is shown to be capable of predicting the settlement of a large mat foundation. The membrane action of flat shell element and soil coupling effect can overcome the limitations of conventional method. Therefore, the proposed method could be used in the preliminary design of large mat foundation.

Acknowledgments

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References

ABAQUS (2012), Theory Manual, Version 6.12; Published by Hibbitt, Karlsson and Sorensen Inc., USA.

Ayvaz, Y. and Oguzhan, C.B. (2008), "Free vibration analysis of plates resting on elastic foundations using modified Vlasov model", *Struct. Eng. Mech., Int. J.*, **28**(6), 635-658.

Bowles, J.E. (1997), *Foundation Analysis and Design*, McGraw-Hill, New York, NY, USA.

Briaud, J.L. (1993), "Spread footing design and performance", (Contribution to a short course at the occasion of the 10th annual International Bridge Conference, Department of Civil Engineering, Texas A&M University, College Station, TX, USA.

Calim, F.F. and Akkurt, F.G. (2011), "Static and free vibration analysis of straight and circular beams on elastic foundation", *Mech. Res. Commun.*, **38**(2), 89-94.

Choi, C.K. and Lee, W.H. (1996), "Versatile variable-node flat-shell element", *J. Eng. Mech., ASCE*, **122**(5), 432-441.

Civalek, O. (2007), "Nonlinear analysis of thin rectangular plates on Winkler-Pasternak elastic foundations by DSC-HDQ methods", *Appl. Math. Model.*, **31**(3), 606-624.

Clancy, P. and Randolph, M.F. (1993), "An approximate analysis procedure for piled raft foundations", *Int. J. Numer. Anal. Method. Geomech.*, **17**(12), 849-869.

Colasanti, R.J. and Horvath, J.S. (2010), "A practical subgrade model for improved soil-structure interaction analysis: Software implementation", *Pract. Period. Struct. Des. Constr.*, **15**(4), 278-286.

Darilmaz, K. (2009), "An assumed-stress hybrid element for modeling of plates with shear deformations on elastic foundation", *Struct. Eng. Mech., Int. J.*, **33**(5), 573-588.

Dutta, S.C. and Rana, R. (2002), “A critical review on idealization and modeling for interaction among soil-foundation-structure system”, *Comput. Struct.*, **80**(20-21), 1579-1594.

Filonenko-Borodich, M.M. (1940), “Some approximate theories of elastic foundation”, Uchenyie Zapiski Moskovskogo Gosudarstvennogo Universiteta, *Mekhanica*, **46**, 3-18. [In Russian]

GEO 5 manual (2012), User’s guide; Version 16. Fine Ltd.

Guler, K. (2004), “Circular elastic plate resting on tensionless Pasternak foundation”, *J. Eng. Mech.*, **130**(10), 1251-1254.

Houy, L., Breysse, D. and Denis, A. (2005), “Influence of soil heterogeneity on load redistribution and settlement of a hyperstatic three-support frame”, *Geotechnique*, **55**(2), 163-170.

Horvath, J.S. (2002), *Soil-Structure Interaction Research Project*; *Basic SSI Concepts and Applications Overview*; Report No. CGT-2002-2, Manhattan College, School of Engineering, New York, NY, USA.

Jeong, S.S. and Cho, J.Y. (2014), “Proposed nonlinear 3-D analytical method for piled raft foundations”, *Comput. Geotech.*, **59**, 112-126.

Jeong, S.S. and Seo, D.H. (2004), “Analysis of tieback walls using proposed *P–y* curves for coupled soil springs”, *Comput. Geotech.*, **31**(6), 443-456.

Johnson, L.D. (1989), “Design and construction of mat foundations”, Miscellaneous Paper GL-89-27, US Army Corps of Engineers, Washington, D.C., USA.

Kerr, A.D. (1964), “Elastic and viscoelastic foundation models”, *J. Appl. Mech.*, **31**(3), 491-498.

Lal, A., Singh, B.N. and Kumar, R. (2007), “Natural frequency of laminated composite plate resting on an elastic foundation with uncertain system properties”, *Struct. Eng. Mech., Int. J.*, **27**(2), 199-222.

Lee, J.K., Jeong, S.S. and Lee, J.H. (2014), “Natural frequencies for flexural and torsional vibrations of beams on Pasternak foundation”, *Soil. Found.*, **54**(6), 1202-1211.

Maheshwari, P. and Khatri, S. (2012), “Nonlinear analysis of infinite beams on granular bed-stone column-reinforced earth beds under moving loads”, *Soil. Found.*, **52**(1), 114-125.

Pasternak, P.L. (1954), “On a new method of analysis of an elastic foundation by means of two constants”, Gosudarstvennoe Izdatelstvo Literaturi po Stroitelstvui Arkhitekture, Moscow. [In Russian]

Poulos, H.G. (1994), “An approximate numerical analysis of pile-raft interaction”, *Int. J. Numer. Anal. Method. Geomech.*, **18**(2), 73-92.

Selvadurai, A.P.S. (1979), *Elastic Analysis of Soil-Foundation Interaction*, Elsevier Scientific Publishing Company, Amsterdam, Netherlands.

Straughan, W.T. (1990), “Analysis of plates on elastic foundations”, Dissertation; Texas Tech University, Lubbock, TX, USA.

Vallabhan, C.V.G. and Das, Y.C. (1991), “Modified Vlassov model for beams on elastic foundation”, *J. Geotech. Eng.*, **117**(6), 956-966.

Vlasov, V.Z. and Leontiev, N.N. (1960), *Beams, Plates and Shells on an Elastic Foundation*, USSR: Fizmatgiz, Moscow, Russia. [In Russian]

Winkler, E. (1867), *Theory of Elasticity and Strength*, (H. Dominicus), Prague, Czech Republic.

Won, J.O., Jeong, S.S., Lee, J.H. and Jang, S.Y. (2006), “Nonlinear three- dimensional analysis of pile group supported columns considering pile cap flexibility”, *Comput. Geotech.*, **33**(6-7), 355-370.

Zhang, H.H. and Small, J.C. (2000), “Analysis of axially and laterally loaded pile groups embedded in layered soils”, *Proceedings of the 8th Australia-New Zealand Conference on Geomechanics*, Hobart, **1**, 475-483.

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