Geotechnical Aspects of Underground Construction in Soft Ground, Mair & Taylor (eds)
© 1996 Balkema, Rotterdam. ISBN 90 5410 856 8

Discussion: Comments on the use of non-linear elastic stiffness

K.G.Higgins, D.W.Hight & R.J.Mair
Geotechnical Consulting Group, London, UK

D.M.Potts & R.J.Jardine
Imperial College of Science, Technology and Medicine, London, UK

During the course of the oral discussion attention was drawn to the importance of non-linear elastic stiffness relationships in soil-structure interaction problems. In particular relationships that allow the elastic moduli to vary with strain and mean effective stress were highlighted. Unfortunately no contributor to the discussion presented examples of where such models have been used in practice for prediction or examples of where these predictions have been compared with measurements.

One example of such a constitutive soil model is described by Jardine et al (1986). This particular model has routinely been used for the analysis of soil-structure interaction problems for sometime, both in a research environment and for application to actual construction projects. Jardine et al (1991) provided details of practical applications of this non-linear ground model to a wide variety of schemes including gravity base and piled offshore structures, deep excavations, large raft foundations and various types of tunnels (bored, pipe-jacked and cut & cover).

To illustrate the use of this particular soil model, Hight and Higgins (1994) undertook a simple parametric study of the construction of a deep excavation in a soil profile thought to be typical of conditions in central London. Among other influences, they compared the results obtained when using the anisotropic linear elastic soil model described by Burland and Kalra (1986), in which the soil stiffness increased with depth, with results from analyses using the non-linear elastic model (Jardine et al (1986)). Comparisons were made at the stage of the analyses when the 15m deep excavation had just been completed, before long term conditions had developed and any drainage had occurred. The two models gave similar predictions of surface deformation close to the excavation but importantly the non-linear model gave a greater reduction in movement with increasing distance from the wall. It is important to remember that the stiffness relationship derived by Burland and Kalra (1986) was derived from the back analysis of deformations around deep excavations in London in the short term; sufficient measurements of long term behaviour were not available.

To demonstrate the use of the non-linear relationships for long term predictions, Hight and Higgins (1994) compared predictive heaves with those measured in carefully controlled oedometer tests. Figure 1 shows predictions using the swelling non-linear model for variations in Poisson's ratio together

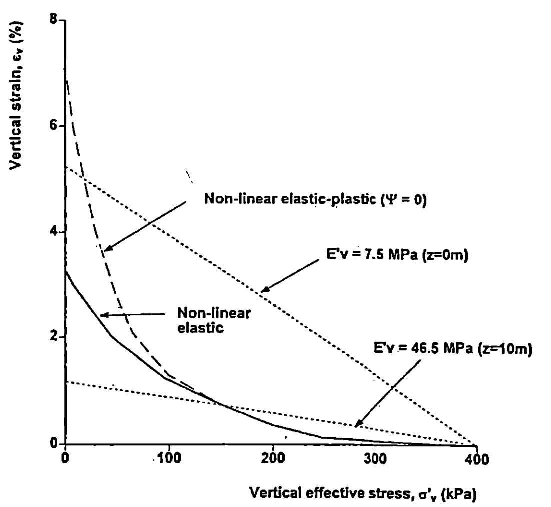

Figure 1: Predictions and measurements of swelling in oedometer tests on London clay

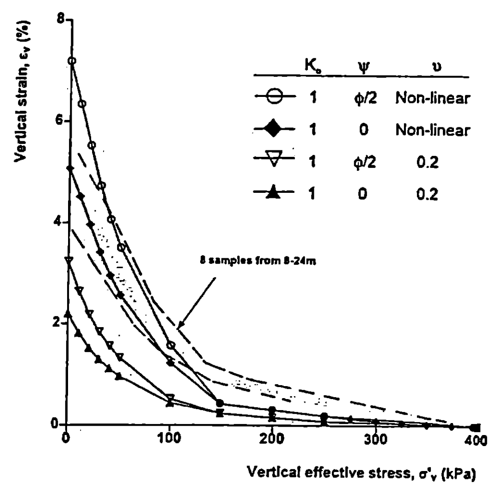

Figure 2: Comparisons of predicted swelling behaviour using linear & non-linear models

with predictions with variations in the angle of dilation. By the very nature of the model, during the course of the analyses using the non-linear model, the soil stiffness was continually updated as the mean effective stress changed and the soil strained. Also shown on Figure 1 are the results of the oedometer tests. The measurements are not well reproduced by predictions using a linear elastic soil model as demonstrated by comparing Figures 1 and 2 whereas the non-linear model does reproduce the laboratory data well. This implies that long term effects cannot be reasonably reproduced by the linear elastic model but that the non-linear model can successfully reproduce both short term and long term behaviour. It gives similar distortions to the empirical model for movements around excavations in the short term and, in the absence of reliable long term field measurements, it is able to reproduce high quality laboratory data for long term effects.

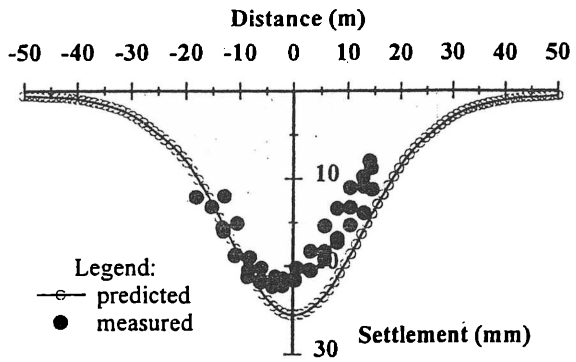

Figure 3: Predicted and measured surface settlements (after Kovacevic et al (1996))

The reliability of this model when used for soil-structure interaction analyses can be further demonstrated by two case histories. Kovacevic et al (1996) report the results of predictions and measurements for a NATM tunnel in London. Predictions of ground movements, tunnel lining distortions and tunnel lining stresses were compared with measurements and good agreement was obtained. Figure 3 summarises the range of observed and predicted surface settlements. An analysis using a linear model to represent the elastic soil response would have given more widespread movement and a flatter settlement trough. In any assessment of potential building damage the shape of the settlement profile is important, not just absolute values at isolated points.

The second case history relates to movements of existing tunnels beneath the excavation for the Waterloo International Terminal, also in London. Hight et al (1993) show measured tunnel deformations for the running tunnels and the station tunnels. Measured tunnel distortions were well predicted but the predicted vertical heave of the tunnels did not match the measurements as well. Even so the predictions were good considering the complexity of the construction sequence which could not be fully reproduced in a two dimensional analysis.

Empirical relationships and relationships for various parameters can be derived from field measurements and have been used successfully. However, they can not be reasonably be used for situations other than those to which they specifically relate. For example, the Gaussian curve (O'Reilly and New (1982)) is commonly used to predict settlement profiles over tunnels, but it relates only to movements associated with single tunnel construction in the short term. Interaction effects associated with construction of two, or more, tunnels in close proximity can be significant. Further complications, such as an excavation in close proximity (eg Higgins et al (1996)), require the use of sophisticated techniques to examine these effects. Such analyses require the use of reliable and proven soil models, such as that described by Jardine et al (1986). However, the user must be aware of the kinematic nature of soil stiffness and apply it to the model in an appropriate way.

REFERENCES

Burland, J.B. & Kalra, J.C. (1986). Queen Elizabeth II Conference Centre: geotechnical aspects. Proc. Instn Civ. Engrs, Part 1, 80: pp1479-1503.

Higgins, K.G., Potts, D.M., & Mair, R.J. (1996). Numerical Modelling of the influence of the Westminster Station excavation on the big Ben clock tower. Proc. Int. Symp. on Geotechnical aspects of Underground Construction in Soft Ground, City University, London. Balkema.

Hight, D.W., Higgins, K.G., Jardine, R.J., Potts, D.M., Pickles, AR., DeMoor, E.K., & Nyrenda, Z.M. (1993). Predicted and measured tunnel distortions associated with the construction of the Waterloo International Terminal. Proc. Wroth Memorial Symposium, Oxford, pp 317-338, Thomas Telford.

Hight, D.W. & Higgins, K.G. (1994). An approach to the prediction of ground movements in engineering practice: Background and application. Proc. of the Int. Symp. on Pre-failure Characteristics of Geomaterials, Sapporo, Japan. Balkema.

Jardine, R.J., Potts, D.M., Fourie, A.B., & Burland, J.B. (1986). Studies of the influence of non-linear stress-strain characteristics in soil-structure interaction. Geotechnique, 36, No.3,pp377-396.

Jardine, R.J., Hight, D.W., St John, H.D. & Potts, D.M. (1991). Some practical applications of a non-linear ground model. Proc. 10th Eur. Conf. SMFE, Vol 1:pp223-228.

Kovacevic, N., Edmonds, H.E., Mair R.J., Higgins, K.G. and Potts, D.M. (1996). Numerical modelling of the NATM and compensation grouting trials at Redcross Way. Proc. Int. Symp. on Geotechnical aspects of Underground Construction in Soft Ground, City University, London. Balkema.

O'Reilly, M.P. and New B.M. (1982). Settlements above tunnels in the United Kingdom - their magnitude and prediction. Tunnelling '82, London, IMM,pp173-181.