INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

Modelling embankments with vertical drains – a comparison of numerical methods

Modélisation de remblais avec drains verticaux - comparaison de méthodes numériques

J. Montgomery
Atkins / University of Strathclyde, United Kingdom

M. Karstunen
University of Strathclyde, United Kingdom

ABSTRACT
This paper looks at the various methods available to predict the settlement of embankments constructed on soft soils with vertical drains. It finds that current commercially available finite element modelling (FEM) software is far more sensitive to variations in permeability within the smear zone than variations in the diameter of this zone. The paper uses plane strain analysis to accurately replicate the vertical settlements beneath the Haarajoki test embankment. However, this analysis fails to accurately replicate horizontal deformations. The paper concludes that currently available 3D FEM cannot currently replicate embankment settlements accurately. It suggests improvements required in 3D FEM programmes to allow accurate predictions in the future.

RÉSUMÉ
Cet article évalue les différentes méthodes permettant de prévoir le tassement de remblais avec drains verticaux construits sur sols mous. Il trouve que les logiciels utilisant la méthode élément fini (MEF), disponible sur le marché, sont beaucoup plus sensibles aux variations de perméabilité à l'intérieur de la zone de souillure qu'aux variations du diamètre de cette zone. Cet article emploie l'analyse de déformation plane afin de reproduire avec précision les tassements verticaux en dessous du remblai expérimental Haarajoki. Cette analyse ne parvient toutefois pas à reproduire avec précision les déformations horizontales. Cet article conclut donc que la MEF 3D, actuelle, n'est pas à ce jour en mesure de prévoir les tassements avec précision. Il suggère des éventuelles améliorations aux logiciels MEF 3D qui permettraient des prédictions précises dans l'avenir.

Keywords : geotechnical engineering, finite element, vertical drain, smear, Haarajoki

1 INTRODUCTION

Pre-fabricated vertical drains are commonly used in the construction of embankments over soft soils. These decrease the drainage path within the soil, allowing more rapid dissipation of excess pore pressures, and so increase the rate of settlement. Embankment settlement can have a huge impact on construction programmes and so accurate settlement predictions are vitally important.

During the installation of vertical drains, an area of remoulded soil known as the smear zone is left around the drain. The extent of this zone and the change of properties within it are difficult to measure and there are many different views on how an analysis should take account of these factors.

There are a number of different methods for predicting the settlement of embankments with vertical drains including axisymetric, plane strain and 3D finite element analysis. These methods range from very simplistic to highly complex and time-consuming. As would be expected, the accuracy and appropriateness of the methods vary depending on the situation.

In 1997 a test embankment was constructed in Haarajoki, Finland, by the Finnish national road administration. They organised a competition to calculate horizontal and vertical deformations of the embankment caused by consolidation of the underlying clay, with the aim of improving techniques for settlement predictions. The construction details and results of soil tests (FinnRA 1997) were given to competing teams and the teams submitted their settlement predictions before construction began.

The initial submissions varied greatly and there was very little consensus regarding deformations and pore water pressure dissipation. There have been several attempts since to recalculate the problem, attempting to improve methods and better understand the problem (Aalto et al 1998, Näätänen et al 1998).

This paper uses measured settlements from the Haarajoki test embankment to compare the accuracy and appropriateness of predictions made using simple hand calculations, axisymetric, plane strain and 3D finite element analysis.

It also examines the effect on settlement predictions of varying the parameters of the smear zone. Through greater understanding of the parametric effects, it is hoped that improved testing and modelling procedures can be devised to help improve the accuracy of future modelling.

2 EMBANKMENT AND GROUND CONDITIONS

A longitudinal section of the Haarajoki test embankment is shown in figure 1 below. Half of the embankment was drained using SOLPAC C634TM vertical drains with an average width of 100mm and thickness 3-4mm. The drains were installed in a 1m square pattern to a depth of 15m. This paper considers only the section of the embankment with vertical drains.

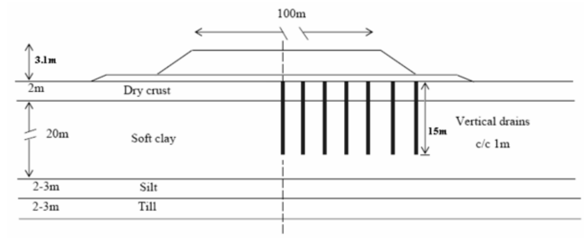

Figure 1. Longitudinal section of Haarajoki test embankment.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)
© 2009 IOS Press.
doi:10.3233/978-1-60750-031-5-1610

The embankment was constructed from a gravel fill with average density 21 kNm^{-3}. The 0.6m working foundation was laid over a week and the vertical drains were installed over the following ten days. The embankment was then left for three days after which the remaining 2.5m was constructed. This was constructed in five 0.5m stages with each stage being constructed over two days and then left for one.

Settlement plates, inclinometers, pieziometer tips, pressure cells, ground screws, extensometers and lateral displacement meters were installed beneath the embankment to measure settlement, lateral displacement and pore water pressures. These instruments were installed immediately after installation of the drains. The measurements from these instruments in the first two years were used to judge the competition and measurements up until 2002 are now available.

3 MATERIAL PARAMETERS

Over 50 oedometer tests and 15 triaxial tests were completed by the Road Administration Consulting Laboratory and the Laboratory of Soil Mechanics and Foundation Engineering of the Helsinki University of Technology. A site investigation was carried out by the Finnish National Road Administration Uusimaa road district. The results of these tests and investigations were published prior to the competition (FinnRA 1997) and these were used to calculate the sub-soil properties to be used in analysis.

Montgomery (2006) covers in detail the methodology and calculations used to find the sub-soil properties for use in analysis. It also includes a summary of all material parameters used and a simple hand calculation of settlement rate.

4 INITIAL ANALYSES

4.1 *Plaxis V8*

The embankment was initially analysed using the finite element programme Plaxis V8 with its soft soil model. Plaxis V8 is a Dutch finite element programme which allows the geometry to be entered with soils split into layers. Soil properties can be assigned to each layer and these properties can be easily varied. The package has an automatic mesh generator which allows the mesh to be refined globally or around points of greatest change to improve accuracy.

In addition to geometry and soil properties other boundary conditions can be stipulated within Plaxis V8. Horizontal and or vertical movement can be restricted at boundaries and the flow of pore water can be closed at boundaries. The programme also allows lines of zero excess pore pressure to be added to a design, thus simulating a perfect drain. The drain can also be turned on and off within different calculation phases, simulating its installation.

Plaxis V8 allows staged construction to simulate the actual construction process taking account of the displacements and associated strength gains of the soil throughout each phase. As consolidation analyses are run, Plaxis V8 simulates the changing pore water pressures in the soil.

Plaxis V8 can solve both axisymetric and plane strain problems. An axisymetric model is used when the problem has radial symmetry around the central y-axis. Deformations and stresses are then taken to be identical in any radial direction. In a plane strain model the cross section is defined in the x and y direction and then assumed to extend uniformly in the z direction. Displacements and strains in the z direction are assumed to be zero. Figure 2 shows examples of axisymetric and plane strain models.

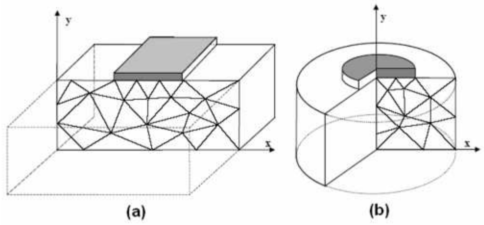

Figure 2. (a) Plane Strain (b) Axisymetric

4.2 *Axisymetric Unit Cell*

An axysimetric unit cell analysis looks at a cylinder of soil around a single drain at the centre of an embankment. The soil cylinder is defined in 2D with the vertical drain as the vertical y-axis around which the cylinder has radial symmetry.

An axisymetric unit cell analysis was used to investigate the effect of varying the parameters of the smear zone. The diameter of the smear zone (d_s) is most commonly given as a function of the effective diameter of the vertical drain (d_w). The horizontal permeability of soil within the smear zone (k_s) is reduced and is generally given as a function of the horizontal permeability of the surrounding soil (k_h).

It is extremely difficult to measure these parameters accurately, and the best method of estimating them has been a source of debate for some time (Bergado et al 1993; Indraratna et al 2001; Hird & Moseley 2000).

To investigate the impact of varying these parameters, a number of unit cell analyses were run. Within these analyses d_s was varied between d_w, $2d_w$, $3d_w$, and $5d_w$ while k_s was varied between $k_h/5$, $k_h/10$, $k_h/20$.

The unit cell analyses showed that varying smear diameter had little effect on the calculated rate of settlement while variations in the horizontal had a major impact on the rate of settlement. This suggests that the finite element analysis is far more sensitive to variations in the permeability within the smear zone than variations in the smear radius.

4.3 *Plane Strain*

A plane strain model takes a 2D cross section of an embankment which is then assumed to extend uniformly in the z direction. This assumed uniformity in the z direction means that the vertical drains are simplified to constant lines along the length of the embankment. It has been shown that this simplified model can be matched to the actual conditions by altering the drain spacing (Geometry Matching) (Hird et al 1995), soil permeability (Permeability Matching) (Indraratna and Redana 2000), or a combination of both (Combined Matching).

Analyses of the Haarajoki test embankment were completed using each of the three matching procedures assuming a smear radius (d_s) of $5d_w$ and smear permeability (k_s) of $k_h/20$. There were no significant differences between the predictions of the three procedures. The combined marching process was selected for use in the further plane strain modelling as it produced the simplest models for input to Plaxis. A graphical excerpt from the Plaxis model is shown in figure 3 below.

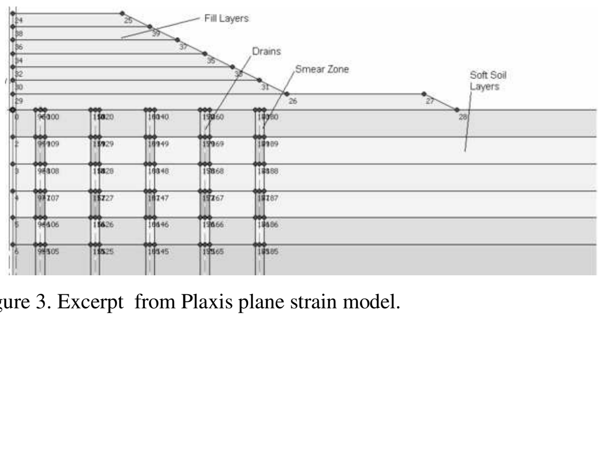

Figure 3. Excerpt from Plaxis plane strain model.

Plane strain models were run using combined matching with a smear radius (d_s) of $5d_w$ and varying the smear permeability (k_s) between $k_h/5$, $k_h/10$, $k_h/15$ and $k_h/20$. As expected, the rate of settlement reduced with lowed smear permeability. A reasonably accurate match to the measured vertical settlements was found when k_s was set to $k_h/20$. Figure 4 below compares the results of this analysis with simple hand calculations, unit cell analysis and the actual measured vertical settlements of the test embankment.

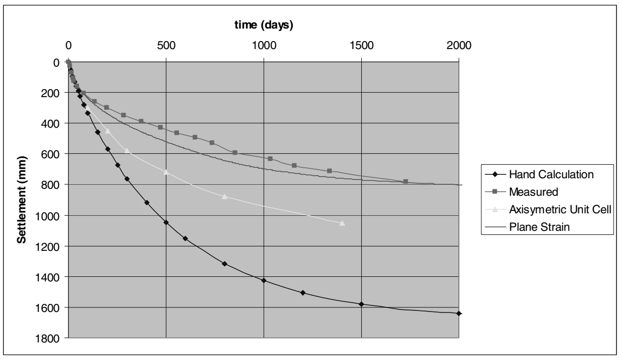

Figure 4. Rate of vertical settlement.

5 3D ANALYSIS

5.1 *Plaxis 3D Tunnel*

Plaxis 3D Tunnel with its soft soil creep model was used to analyse 3D slice models of the Haarajoki test embankment. To create a 3D model in Plaxis 3D Tunnel a cross section must be created in the x-y-plane as with plane strain analysis in Plaxis V8. From this cross section a 2D mesh is generated. A 3D model is then created by defining all relevant z-coordinates to which the cross section and 2D mesh are to be copied. The 3D model is then made up of planes (the copied cross sections) and slices (the volumes between the planes). A 3D mesh is then applied to the planes and slices as shown in figure 5. This does not allow for any geometry variation in the z-direction. However, when calculation stages are defined, loads and geometry objects can be turned on and off in individual planes and slices, giving a 3D model.

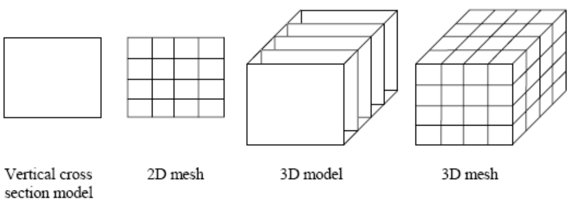

Figure 5. Building the 3D model

Borges (2004) used 3D analysis to compare a theoretical embankment with and without vertical drains. He was able to replicate the increased settlement rate due to vertical drains. However, this was a comparative assessment which did not include smear. This assessment looks to go further by modelling a real embankment and comparing the predictions with the measured settlements to draw conclusions regarding the applicability and accuracy of the method.

5.2 *Comparison of finite element programmes*

There are some differences between Plaxis V8 and Plaxis 3D tunnel which it is necessary to consider in order to allow a comparison of plane strain and 3D model predictions.

When a model is run in Plaxis V8, the programme constantly updates the pore water pressures within the model. Plaxis 3D tunnel does not update the pore pressures in this way. To assess the impact this would have, a simplified plain strain models was analysed in Plaxis V8 firstly updating the pore water pressures and then not. The model without updated pore water pressures predicted significantly larger settlements. This suggested that the 3D model would be likely to overestimate the settlement of the Haarajoki test embankment.

The soft soil model used in Plaxis V8 takes account of the fact that the permeability of a soil will reduce as it consolidates through the change of permeability parameter (c_k). The soft soil creep model used in Plaxis 3D does not take account of this change in permeability. To assess the impact this would have, a simplified plain strain models was analysed in Plaxis V8 firstly setting c_k at its calculated value and then giving it a very high value to simulate no change in permeability. The model with very high c_k predicted a slightly higher rate of settlement. This suggested that the 3D model would be likely to slightly overestimate the settlement rate of the Haarajoki test embankment.

5.3 *3D Slice*

A 3D slice was modelled as a representative section of the Haarajoki test embankment. It represents a 1m slice through the embankment with the drains in the centre. As this model has symmetry in the x direction (through the drain centres) and in the z direction (along the embankment centre line), only half of the embankment and half of the slice is modelled, giving a 0.5m slice.

The first plane was defined with all the soil layers and drains in place. Further planes of interest were then defined to take account of the drains and the smear.

Closed flow boundaries were defined at the bottom and sides of the model. The sides of the model were fixed against horizontal movement while the bottom of the model was fixed against horizontal and vertical movement.

As the model must be defined as a selection of 2D planes, the smear zone was modelled as a square area around each of the drains rather than a cylindrical area. The mesh was automatically calculated for the first plane and then applied and joined to the other planes to create a fully 3D mesh as shown in figure 6 below.

The model was very complicated and took many attempts before it could be run satisfactorily. The complexity of the models meant that each scenario took about a day to fully input into Plaxis and up to a day to run.

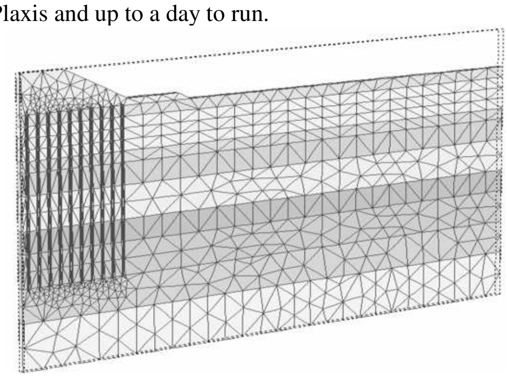

Figure 6. 3D Model

3D slice models were run using a smear radius (d_s) of $5d_w$ and varying the smear permeability (k_s) between $k_h/5$, $k_h/10$, $k_h/15$ and $k_h/20$. As expected, the rate of settlement reduced with lower smear permeability however, the impact of varying the smear permeability was not as great as in the plane strain model. By demonstrating that reducing the smear permeability reduced the rate of settlement, it was shown that the effect of the smear zone can be simulated in a 3D slice model.

The predicted settlements for the scenario when k_s was set to $k_h/20$ were closest to the measure settlements. Figure 7 below compares this analysis with the previous plane strain analysis and the actual measured vertical settlements.

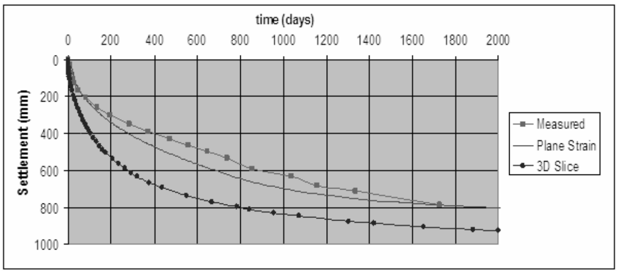

Figure 7. Comparison of Calculation Methods

The 3D slice model with smear permeability $k_s = k_h/20$ overestimates the settlement by approximately 20%. The rate of settlement is also overestimated. These overestimates are consistent with Plaxis 3D Tunnel's inability to account for the change in permeability (c_k) or to update pore pressures as discussed in section 5.2. It is believed that an accurate 3D model could be created if these features were included in a future version of the programme.

While it may be possible to create a 3D model to accurately predict vertical settlements, it should be noted that such a model would take far longer to input and run than an equivalent plane strain model and may give little or no improvement in accuracy.

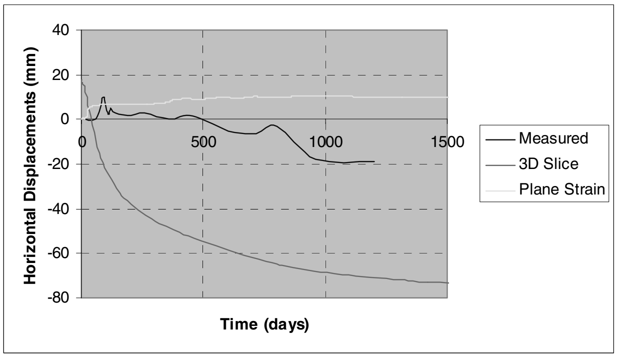

Figure 8. Comparison of Horizontal Deformations

Figure 8 shows the measured horizontal displacements 9m right of the embankment centre line, along with the predicted displacements from the plane strain and 3D slice models. The 3D slice model has predicted deformation in the right direction; however, the magnitude predicted is far higher than that measured.

6 CONCLUSIONS

It is clear that one dimensional unit cell analysis is not sufficient for finding practical values for the settlement rates under embankments with vertical drains. Given the importance of settlement times within construction programmes it would not be reasonable to rely only on one dimensional unit cell analysis.

In modelling vertical drains the permeability within the smear zone has a far greater affect on the rate of settlement than the radius of the smear zone. It would be wise in future to attempt to measure the permeability of the in-situ soil within the smear zone. Having actual in-situ data for this would make modelling more accurate and efficient, giving greater confidence in calculated settlement rates.

Using simple matching procedures it has been shown that a plane strain model can be used to accurately predict the vertical settlement of an embankment with vertical drains. A plane strain model can be input and run in a matter of hours meaning that this method is commercially practical.

It was shown that a 3D model of a representative section of the embankment could effectively replicate drain and smear behaviour. The introduction of smear had less influence on the predicted vertical settlements than in the axisymetric unit cell and plane strain analyses.

The 3D model overestimated vertical settlement; however, it was argued that by making improvements to the FEM programme it may be possible in the future to achieve an accurate model.

The 3D model involved pushing the Plaxis 3D Tunnel programme to its limits and many problems were encountered. Once all these problems were overcome the input and running of each 3D model took up to two days, considerably longer than the equivalent plane strain model. Given the accuracy which can be achieved with plane strain modelling, it is questionable whether a 3D model can give any additional benefit.

Neither the 3D or plane strain model in this report was able to predict accurately the horizontal deformations under the embankment. These could be important in understanding how embankment settlement may affect buildings or construction work adjacent to the embankment.

3D modelling may become simpler and more practical in the future, but at present plane strain analysis remains the most accurate and commercially viable option for predictions of embankment settlement.

AKNOWLEDGEMENTS

The authors are grateful to Harald Krenn for his advice and guidance at the modelling stage, and to Emma Campbell and Ethan Footlik for translation and general support.

REFERENCES

Aalto, A., Rekonen, R., and Lojander, M. 1998. The Calculation on Haarajoki Test Embankment with the Finite Element Programme Plaxis 6.31, Proc. Of 4th European Conf. on Numerical Methods in Geotechnical Engineering, Udine, Italy, 14-16 Oct 1998, 37-46.

Bergado, D. T., Mukherjee, K., Alfaro, M. C., and Balasubramaniam, A.S. 1993. Prediction of Vertical Band Drain Performance by the Finite Element Method, Geotextiles and Geomembranes, **12**, 567-586.

Borges, J.L. 2004. Three-Dimensional Analysis of Embankments on Soft Soils Incorporating Vertical Drains by Finite Element Method, Computers and Geotechnics, 31:665-676.

Finnish National Road Administration. 1997. Competition to calculate settlements at the Haarajoki test embankment, Competition programme, Competition Materials, FinnRA.

Hird, C.C., Pyrah, I.C., Russell, D., and Cinicioglu, F. 1995. Modelling the Effects of Vertical Drains in Two Dimensional Finite Element Analyses of Embankments on Soft Ground, Can. Geotech. J. 32: 795-807.

Hird, C.C., and Moseley, V.J. 2000. Model Study of Seepage in Smear Zone around Vertical Drains in Layered Soil, Geotechnique, Vol 51, 1, 51-54.

Indraratna, B., and Redana, I.W. 2000. Numerical Modeling of Vertical Drains with Smear and Well Resistance Installed in Soft Clay, Can. Geotech. J. 37, 132-145.

Indraratna, B., Bamunawita, C., Redana, I.W., and Balasubramaniam, A.S. 2001. Modeling of Vertical Drains in Soft Clay, Soft Soil Engineering 329-335.

Montgomery, J. 2006. Estimation of Settlement for Embankments with Vertical Drains Including Smear, Uni. of Strathclyde Dissertation.

Näätänen, A., Vesäläinen, P., and Lojander, M. 1998. Finite Element Calculations on the Haarajoki Test Embankment, Proc. Of 4th European Conference on Numerical Methods in Geotechnical Engineering, Udine, Italy, 14-16 Oct 1998, 151-160.