Jurnal Teknologi

Performance Prediction of Prefabricated Vertical Drain in Soft Soil using Finite Element Method

Teh Zhi Huan, Rini Asnida Abdullah[*], Mohd For Mohd Amin, Mohd Azril Hezmi, Ahmad Safuan A Rashid, Mohd Nur Asmawisham Alel

Geoengineering and Geohazard Research Group, Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

Graphical abstract
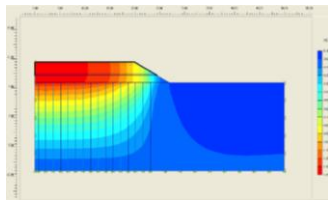
Abstract

Prefabricated vertical drain (PVD) had successfully been applied in many soft ground construction projects. Finite element method (FEM) could assist designers to model very complex subsoil and structural elements. In this study, finite element analysis (FEA) is performed to verify the effectiveness of modelling of PVD in subsoil using computer software, Plaxis V8. The field settlement data were collected at two particular locations and were analysed using Asaoka's method to estimate the ultimate settlement and back-calculated the coefficient of horizontal consolidation for these two particular location. Thereafter, by using back-calculated coefficient of horizontal consolidation, FEA were performed to predict the time rate settlement and compared against field settlement results. From the time rate settlement curves generated by FEM, the ultimate settlements were predicted using Asaoka's method. The ultimate settlement predicted from FEM is slightly lower compared to actual field settlement monitoring result, but the degree of consolidation settlement achieved were higher.

Keywords: Prefabricated vertical drain; Asaoka's method; finite element method

Abstrak

Saliran tegak pra-fabrikasi (PVD) telah banyak digunapakai bagi memperkukuhkan kawasan tanah liat bermasalah. Kaedah unsur terhingga (FEM) dapat membantu memodalkan tanah yang sangat kompleks dan unsur-unsur struktur. Dalam kajian ini, analisis unsur terhingga (FEA) dilakukan untuk mengesahkan keberkesanan pemodelan PVD dalam subtanah dengan menggunakan perisian komputer, Plaxis V8. Rekod enapan di dua lokasi telah dikumpulkan dan dianalisis dengan kaedah Asaoka) untuk meramal enapan muktamad serta analisis-kembali nisbah pekali pengukuhan mendatar. Dengan nisbah pekali pengukuhan dalam arah mengufuk yang diperolehi, FEA digunakan untuk meramal kadar masa enapan dan dibandingkan dengan rekod enapan sebenar di tapak. Daripada lengkungan kadar masa enapan yang terhasil daripada FEM, enapan muktamad diramal menggunakan kaedah Asaoka. Enapan muktamad yag diramal melalui FEM adalah kecil sedikit dibandingkan dengan enapan sebenar di tapak, tetapi darjah enapan pengukuhan yang dicapai adalah lebih tinggi.

Kata kunci: Saliran tegak pra-fabrikasi; kaedah Asaoka; kaedah unsur terhingga

1.0 INTRODUCTION

Soft soils present the unique challenges to geotechnical professionals due to its poor bearing capacity and exhibit large settlement when subjected to loading. In time of urbanization, rapid growth of population and increasing demand of development such as houses, offices and infrastructures has resulted the construction activities on soft ground inevitable. The construction activities which normally build the platform will create external loading to the soft ground. The additional loading imposes to the soft compressible soil would causes significant magnitude of consolidation settlement over a considerable period of time. Thus for the development projects of building, the post construction settlement due to embankment construction would be of primary concern. Easy and fast installation, properties standardisation, and cost effective compared to other ground improvement method make this method gaining popularity.

Vertical drain offers a better way for expediting the consolidation settlement process in soft compressible soil. Hansbo [1] found out that the mechanism of vertical drain is much depend on its configuration either triangular or rectangular form. Beside the analytical approach, designer could also carry out the design of vertical drain using finite element method or empirical method which depends on the preference and proficiency of the designers.

Due to the complexity of today's construction work, finite element method could assist designers to model very complex subsoil and structural elements. However, the accuracy of field data and laboratory test result is of the major parameter inputs to reflect the real condition of the site which is crucial in design that later could match back the field monitoring results.

The comparison between the field monitoring results and finite element analysis would help designers to get better understanding of the real soil behaviour compared to finite element modelling. Hence, suitable tolerance could be allowed in future design work using finite element method. As such, the effectiveness of modelling of prefabricated vertical drain in soft soil using finite element method must be evaluated.

2.0 METHODOLOGY

This study is based on the project involving the construction of an embankment for a mixed development on soft ground area in Kuala Langat District, Selangor. The field monitoring only limited to settlement monitoring which obtained from rod settlement gauges.

Finite element analysis is carried out using commercial software, Plaxis V8. 2D plane strain modelling using Mohr Coulomb (MC) model and Soft Soil (SS) model are used to model the constitutive subsoil properties. The permeability matching derivation by Lin *et al*. [2] is used in this study to obtain the equivalence between axisymmetric behaviour of the vertical drain to plane strain condition in Plaxis modelling. Asaoka's method [3] will be used to predict the final settlement for settlement data obtained from instrumentation and finite element analysis. The time required for 90% consolidation between finite element analysis and field instrumentation monitoring is compared.

2.1 Data Collection

The data obtained for this study is listed as below:
(i) Factual soil investigation report which, contain the data from field test and laboratory test was employed. Important field test data including Standard Penetration Test value (SPT'N), ground water level and field vane shear test. In term of laboratory tests, data such as particle size distribution, moisture content, Atterberg limit, bulk density, unconsolidated undrained triaxial test and one dimensional consolidation test were made used.
(ii) Field settlement monitoring data obtained from rod settlement gauges and monitoring data recorded from commencement of backfilling until removal of surcharge were recorded.
(iii) Construction drawing consisted of site layout plan, construction of fill embankment with PVD, instrumentation layout plan were deployed.

2.2 Subsoil Condition at Proposed Site

Generally, the subsoil at area of this study (subsoil profile around RSG-7 and RGS-8) comprised of a layer of soft clay with 15m thick. Beneath the soft clay layer, medium stiff silty clay and loose to medium dense silty sand was encountered. The hard sandy silty and very dense silty sand was underlain at about 22.0m below existing ground level. The summary of the subsoil properties are tabulated in Table 1.

Table 1 Summary of the soft soil properties

Depth (m)	Cu (kPa)	e_0	Cc	Cr	Cc/ (1+e0)	Cr/(1+e_0)	c_v (m²/yr)	OCR
0 – 15	20	1.44	0.50	0.05	0.205	0.020	1.0	1.0

2.3 Work Programme at Site

The top 1.3 to 1.5m of the filling was done with the sand material. After the sand blanket is laid, PVD were installed at 1.5m c/c spacing in square grids along the road embankment. Generally, the PVD installation length at RSG-7 and RSG-8 are 15m, where the PVD normally will stop at SPT value of 7 – 10N.

The construction sequence at RSG-7 was as below:
  (i)   Filling of 1.2m thick of sand from existing ground as working platform.
  (ii) Install PVD after 14 days.
  (iii) Filling another 0.3m sand and rest for 20 days.
  (iv) 1.5m thick filling of suitable earth material in 20 days and rest for 36 days.
  (v)   Filling of 0.5m thick of suitable earth material and followed by 364 days of rest period.

The construction sequence at RSG-8 was as below:
  (i)   Filling of 1.0m sand from existing ground as working platform.
  (ii) Install PVD after 14 days.
  (iii) Filling of another 0.3m sand and 0.4m suitable earth material. Rest period of 48 days was allowed.
  (iv) 1.1m thick filling in 14 days and followed by rest period of 28 days.
  (v)   Back filling of 0.4m fill and rest for another 322 days.

After the data mentioned above was made available, the data was summarized and interpreted into parameters that needed for settlement assessment in finite element analysis. The subsurface properties was determined and profiled based on the soil investigation report which will be modelled in the finite element software. The field settlement monitoring data was used to predict the ultimate settlement using Asaoka's method [3].

2.4 PLAXIS Modelling

In this study, numerical software by Plaxis V8 is used to carry out the FEM analyses. Plane strain model was selected with 15-node triangular elements for soil layers. Modelling of granular material such as sand and embankment suitable earth fill can be performed using Mohr-Coulomb model. The Mohr-Coulomb model can be considered as first order approximation of real soil behavior which is sufficient for material such as sand and suitable earth fill. The Soft Soil model is a Cam-Clay type model that simulates the situation of primary compression of normally consolidated clays. Soft Soil model exhibits stress dependent stiffness unlike the constant stiffness of Mohr-Coulomb model. The stress dependent stiffness of Soft Soil model is suitable for prediction of consolidation of normally consolidated soft clay.

The vertical drain installed in subsoil can be modelled by the Drains function. The PVDs are modelled as Drains which prescribe lines inside the geometry model where (excess) pore water pressures are set to zero in the consolidation analysis [4]. To account for the delayed of the installation of PVD, Drains are activated in calculation phase instead of initial state.

The subsoil parameters used in the modelling of this study at RSG-7 and RSG-8 are shown in Table 2. The conversion of horizontal plane strain permeability for RSG-7 and RSG-8 are based on back-analysed ch/cv ratio. This ch/cv ratio was found to be 3.2 and 3.8 for RSG-7 and RSG-8 respectively which giving different horizontal plane strain permeability of soft clay. Modelling of stage construction at RSG-7 and RSG-8 were carried out to follow the sequence of works at site as recorded by settlement gauges results.

Table 2 Subsoil parameter used for FEM analysis

Parameter	Unit	Sand Fill	Suitable Fill	Soft Clay	
				RSG-7	RSG-8
Model	-	MC	MC	SSM	SSM
Type	-	Drained	Drained	Undrained	Undrained
γ_{sat}	kN/m^3	20	19	16	16
k_x	m/day	1	1	1.61×10^{-5}	1.65×10^{-5}

3.0 RESULTS AND DISCUSSION

3.1 Analysis Using Asaoka's Method

The ultimate primary settlement is determined by the intersection between the line drawn through the points plotted with 45° line (Figures 1 and 2). The average horizontal coefficient of consolidation, ch can be determined based on the Asaoka's diagram by using Equations and 2:

$$-\frac{ln\beta_1}{\Delta t} = \frac{8c_h}{D^2\alpha} + \frac{\pi^2 c_v}{4H^2} \qquad (1)$$

where H is the drainage path and D is the equivalent diameter of cylinder soil around PVD, also

$$\alpha = n^2 \frac{ln(n)}{n^2 - 1} - \frac{3n^2 - 1}{4n^2} \qquad (2)$$
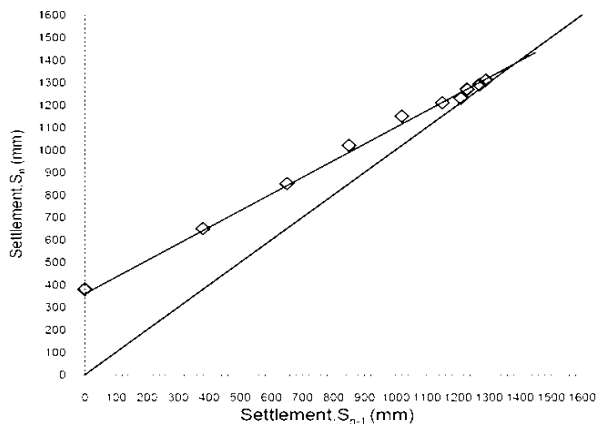
Figure 1 Asaoka's plot of RSG-7

The Asaoka's plot for RSG-7 and RSG-8 based on field settlement monitoring results are shown in Figure 1 and Figure 2. The summary of ultimate settlement and back calculated horizontal coefficient of consolidation is presented in Table 3.
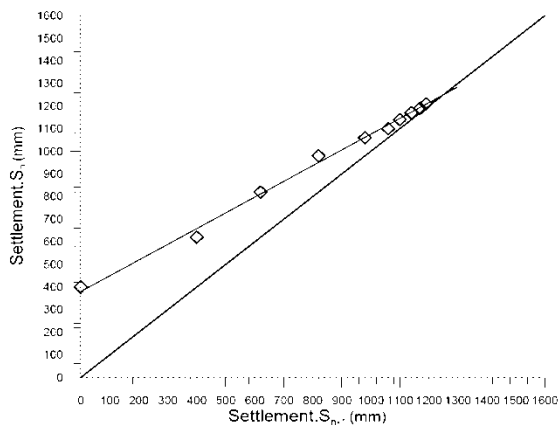
Table 3 Summary of back analysis by Asaoka's Method

Location	St* (mm)	Ch (m²/yr)
RSG-7	1390	3.2
RSG-8	1340	3.8

*St denotes total settlement

3.2 Finite Element Analysis

The consolidation analysis of fill embankment over soft clay was carried out using the back-calculated coefficient of horizontal consolidation at RSG-7 and RSG-8. This was done by using the equivalent horizontal plane strain permeability conversion as proposed by Lin *et al*. [2].

Figure 3 and Figure 4 show the output of the consolidation analysis by FEM at RSG-7 and RSG-8 respectively. Thus, the FEM predicted time rate of consolidation settlement was made comparison with field monitoring settlement results. These comparisons are shown in Figure 5 and Figure 6 for RSG-7 and RSG-8 respectively.
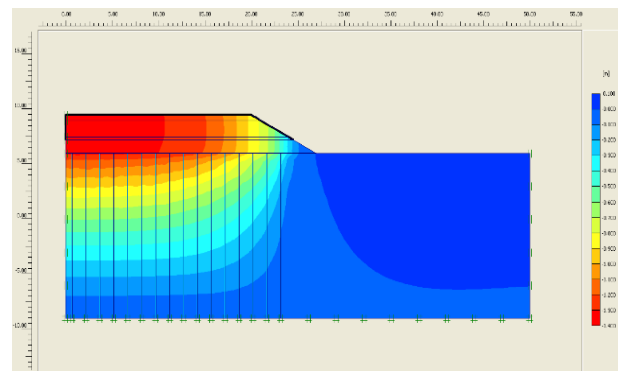

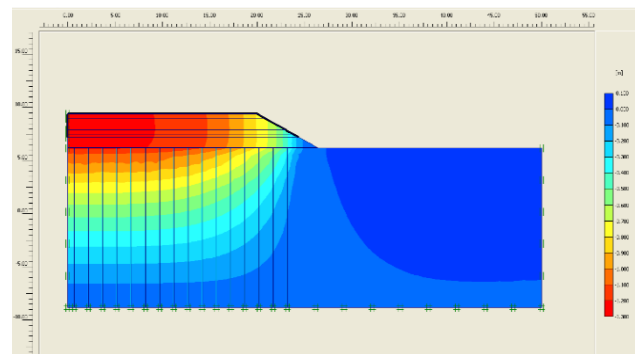**Figure 3** Vertical settlement predicted by FEM consolidation analysis at RSG-7

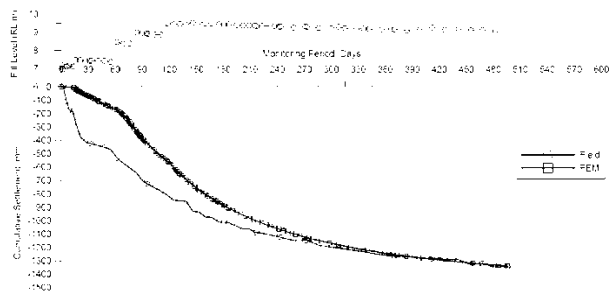**Figure 4** Vertical settlement predicted by FEM consolidation analysis at RSG-8

Figure 2 Asaoka's plot of RSG-8

Figure 5 Comparison of time rate consolidation settlement between FEM and field monitoring result at RSG-7
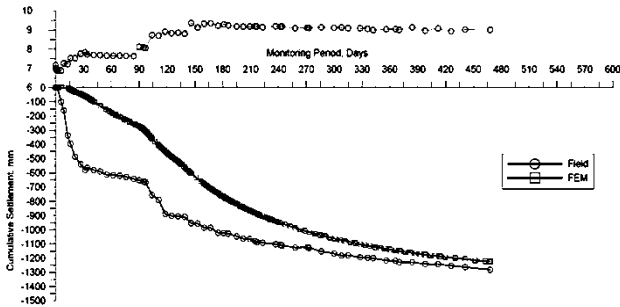

Figure 6 Comparison of time rate consolidation settlement between FEM and field monitoring result at RSG-8

The comparison from Figure 5 and Figure 6 show that consolidation settlement process is faster during initial stage of embankment filling which show a big difference in magnitude of settlement. However, the differences in term of cumulative settlement become lesser and try to converge for a long term resting period. This could be due to the compaction energy that imposed to the upper layer of soft clay during first stage of sand blanket filling that result in higher settlement rate which cannot be modelled. The convergence of consolidation settlement for both RSG at the end of monitoring period also suggested that the equivalent horizontal plane strain permeability adopted in this study were giving encouraging results.

The ultimate settlement predicted by FEM at RSG-7 and RSG-8 were presented in Figure 7 and Figure 8 respectively using Asaoka's method. The magnitudes of ultimate settlement predicted by FEM at both RSG locations are slightly lower than field monitoring results. However, the degrees of consolidation predicted by FEM are slightly higher than field monitoring results. This

phenomenon was observed in a study on Changi East reclamation project in Singapore where ultimate settlement predicted by FEM was slightly lower but higher degree of consolidation [5]. Table 4 indicates the comparison of the actual field monitoring results and FEM method at RSG-7 and RSG-8 locations using Asaoka [3] method.
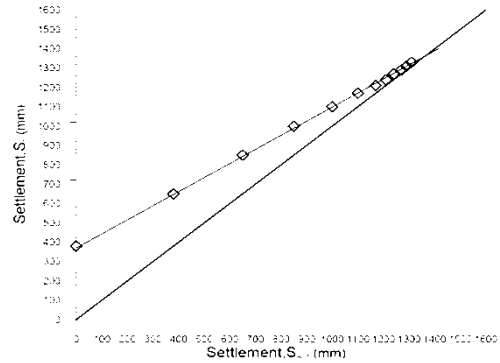

Figure 7 Asaoka plot of RSG-7 by FEM predicted consolidation settlement
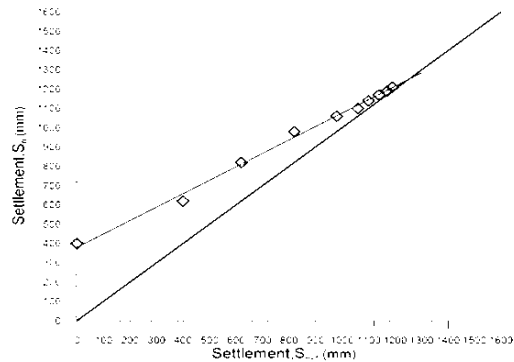

Figure 8 Asaoka plot of RSG-8 by FEM predicted consolidation settlement

From Table 4, the time required to achieve 90% degree of consolidation show some advancement in FEM predicted settlement result. However, the difference was managed in around 5% which show good agreement between FEM and field monitoring results. Thus, it is suggested that when design the resting period of the surcharge which targeted to achieve 90% consolidation settlement, resting period shall allowed additional 5% based on the finding from this study.

Table 4 Comparison of settlement assessed by field monitoring and FEM method

Location	Comparison	Field Monitoring	FEM
RSG-7	Ultimate settlement, mm	1390	1360
	Settlement to date, mm	1345	1337
	Degree of consolidation, %	96.8	98.3
	Time required to achieve 90% consolidation after surcharge, days	236	225
RSG-8	Ultimate settlement, mm	1340	1250
	Settlement to date, mm	1281	1223
	Degree of consolidation, %	95.6	97.8
	Time required to achieve 90% consolidation after surcharge, days	199	199

4.0 CONCLUSION

Based on the study work performed, the following conclusions can be drawn:

(i) From literature review that has been studied, the FEM analysis had successfully predicted the behaviour of soft clay improved with PVD. It is also confirm in this study that the consolidation settlement predicted by FEM analysis shows reasonable agreement with the field monitoring settlement results for PVD treated soft ground by using permeability matching technique proposed by [2].

(ii) Ultimate settlement at site was predicted using Asaoka method. It was found that ultimate settlement predicted from FEM is slightly lower compared to actual field settlement monitoring result.

(iii) The time required to reach 90% consolidation settlement after surcharge level in FEM shows slightly higher compared to actual field settlement monitored. However, the difference is only within 5%, which is in good agreement with the actual field monitored reading. Thus, it is suggested that when design the resting period of the surcharge which targeted to achieve 90% consolidation settlement, resting period shall allowed additional 5% based on the finding from this study.

Acknowledgement

References

[1] Hansbo, S. 1981. *Consolidation of Fine-Grained Soils by Prefabricated Drains*. *Proc. 10th Int. Conf. Soil Mech. and Found. Engg.* International Society of Soil Mechanics and Foundation Engineering, Stockholm. 3(3): 677–682.

[2] Lin, D. G., Kim, H. K. and Balasubramaniam, A. S. 2000. Numerical Modeling of Prefabricated Vertical Drain. *Geotechnical Engineering Journal*. 31(2): 109-125.

[3] Asaoka, A. 1978. *Observational Procedure of Settlement Prediction. Soils and Foundation*. 18(4): 87 – 101. Dec. 1978, Japanese Society of Soil Mechanics and Foundation Engineering.

[4] Plaxis. 2002. *Plaxis Finite Element Code for Soil and Rock Analyses*. 2D-Version 8. Plaxis BV, Delft, The Netherlands.

[5] Arulrajah, A., Nikraz, H. and Bo, M. W. 2005. Finite Element Modelling of Marine Clay Deformation under Reclamation Fills. *Ground Improvement*. 9(3): 105-118.