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Numerical Simulation of Embankment Settlement in Vacuum Preloading Systems

I. B. Mulyawati*[a], M. Riza[a], H. Dermawan[a], V. Pratiwi[b]

[a] *Department of Civil Engineering Education, Universitas Pendidikan Indonesia, Bandung, Indonesia*
[b] *Department of Civil Engineering, Universitas Komputer Indonesia, Bandung, Indonesia*

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ABSTRACT

In Indonesia, the construction of the road has challenges because the road was built on soft clay soil. The vacuum preloading method was used to improve the shear strength and compressibility properties of soft soil in this project. Moreover, what needs to be a concern for practitioners is the issue of increasing simulation accuracy in predicting soil settlement in a vacuum preloading system. The research objective of this study was to determine changes in soil settlement behavior that occurred from the vacuum preloading system using a numerical simulations Geostudio with the 2D Multi Drain-Plane Strain approach and the settlement result of the simulation will be compare with instrumentation data. In this study the vacuum pressure distribution is modeled using water total head negative pore water pressure and the pressure value used following vacuum gauge data in the field with distribution approach is 100% at the surface of the sand platform, 85% to a depth of 5 m, then 60% to the end of the PVD. Based on the simulations, the conlusion is the vacuum pressure applied along the vertical drainage is not modeled constant, but changes with depth, the value of 60% at the bottom of the vertical drainage is quite representative of the conditions in the field and the settlement from the simulation is quite good at approaching the field observation with a prediction of the settlement due to vacuum preloading of ±0.93 m, when compared to the field observation data there is a difference of about 1.6%.

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1. INTRODUCTION

Indonesia has accelerated the building of roads to enhance connections between regional corridors and support the nation's economic growth. Soil conditions need to be considered because in Indonesia soft clay and peat are evenly distributed around 20 million hectares or about 10 percent of the total land area [1]. It will be going to be challenging to build roads on soft soil. The fact that one of Indonesia's roads is built on soft clay soil that has a low shear strength value and a relatively high compressibility. For civil engineering engineers, resolving problems in settlement and stability during construction would be a significant challenge [2].

Vacuum Preloading which was first discovered by Kjellman [3] is a method of improving soft soil that can accelerate the consolidation process so that the shear strength of the soil will increase and can reduce excessive settlement after the construction period. The basic concept of vacuum preloading pressure vacuum of about 40 – 90 kPa to the soil so as to create a pressure difference between the drainage channel usually used Prefabricated Vertical Drain (PVD) and the surrounding soil. Utilization of PVD has become an economical and feasible option because of its fast installation with simple equipment [4]. Then, the applied negative pressure will continue to pull the pore water out of the soil, thus accelerating the consolidation process [5, 6]. so that the soil will decrease in a relatively fast time.

Analysis of soil settlement behavior due to vacuum preloading has become important and in recent years the popularity of numerical modeling has increased to predict soil settlement behavior. In general, vacuum preloading still uses 1D numerical modeling [7, 8] where the results show that the decreased value is lower than the actual conditions in the field. Following the development of the previous simulation, the analysis was further expanded using 2D numerical modeling of plane strain

*Corresponding Author Institutional Email: isahbelamulyawati@upi.edu (I. B. Mulyawati)

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with multi-drain to include the smear zone as in the study [9-11]. Increasing accuracy in numerical modeling is a challenge for geotechnical engineers in predicting soil settlement behavior using vacuum preloading so that the results are close to actual conditions in the field.

The research objective of this study was to determine the changes in soil settlement behavior that occurred from the vacuum preloading system using a numerical simulation, namely Geostudio. Numerical simulations were carried out using a 2D Multi Drain -Plane Strain approach, where the clay soil zone was modeled using Modified Cam Clay material and the vacuum pressure distribution was modeled using negative pore water pressure. The smear zone due to PVD penetration is modeled using soil clusters with lower permeability compared to the surrounding undisturbed soil.

2. METHODS

2. 1. Procedure for Plane Strain Condition in Numerical Simulation

Based on the theory of Indraratna and Redana [12], Indraratna et al. [13] pressure simulation approach vacuum for vertical drains is shown in Figure 1. In this theory, the three-dimensional model can be converted to equivalent plane strain in the following three ways.

a. Geometric approach, where the vertical drain changes but the permeability of the soft clay soil is constant.
b. Permeability approach, where the soil permeability is changed to an equivalent value, but the drain remains unchanged.
c. The combined permeability and geometric approach, where the equivalent permeability value is determined by the spacing drain.

Indraratna et al. [14] proposed a solution for vacuum preloading with vertical drains equation strain [15] and assumed a trapezoidal along the vertical drain to describe the possible loss of vacuum pressure, as illustrated in Figure 2. Permeability parameters of undisturbed and smeared conditions plane strain can be calculate by the following equation [16]:

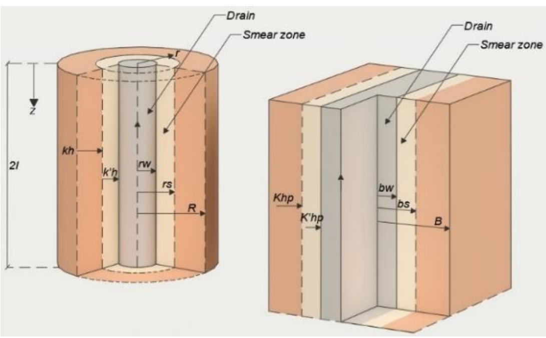

Figure 1. Conversion of axisymmetric unit cell to plane strain condition

$$\frac{k_{h.ps}}{k_{h.ax}} = \frac{0.67}{[\ln(n) - 0.75]} \quad (1)$$

where, n = B/bw, $k_{h.ps}$ is the coefficient horizontal permeability for plane strain condition, and $k_{h.ax}$ is the coefficient horizontal permeability for axisymmetric condition.

For the smear is determined by the following Equations (2) to (5) [16].

$$\frac{k_{s.ps}}{k_{h.ps}} = \frac{\beta}{\frac{k_{h.ps}}{k_{h.ax}}\left[\ln\left(\frac{n}{s}\right) + \left(\frac{k_{h.ax}}{k_{s.ax}}\right)\ln(s) - 0.75\right] - \alpha} \quad (2)$$

where:

$$s = b_s/b_w \quad (3)$$

$$\alpha = \frac{2}{3} - \frac{2b_s}{B}\left(1 - \frac{b_s}{B} + \frac{b_s^2}{3B^2}\right) \quad (4)$$

$$\beta = \frac{1}{B^2}(b_s - b_w)^2 + \frac{b_s}{3B^3}(3b_w^2 - b_s^2) \quad (5)$$

$k_{s.ps}$ = the coefficient horizontal permeability in the smear zone for plane strain condition

$k_{s.ax}$ = the coefficient horizontal permeability in the smear zone for axisymmetric condition

2. 2. Numerical Simulation Set-up

One of the road constructions in Indonesia is planned to use a vacuum preloading. In general, the soil condition in the project is soft clay soil. Where the soil stratification based

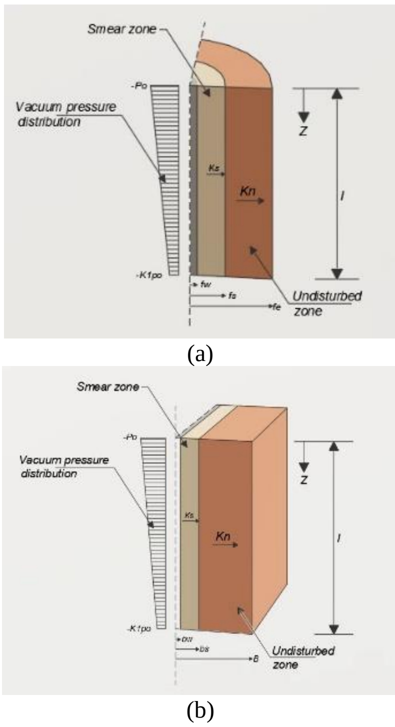

Figure 2. Distribution of vacuum pressure in the unit cell (a) Axisymmetric conditions, (b) Plane strain conditions

on soil investigation at a depth of 0 - 13 m is very soft clay to soft clay consistency, then at a depth of 13 - 15.5 m is a medium clay. The vacuum preloading uses a membrane type with a sand platform layer thickness of 1.6 m, and a 2.7 m embankment and 13.5 m long PVD. Table 1 is the PVD parameters installed with 1 m spacing and a typical cross section can be observed in Figure 3.

In this case, a numerical simulation was carried out using SIGMA/W Geostudio to describe the consolidation behavior of the soft clay soil due to vacuum preloading. Simulation 2D multi-drain-plane strain based on Equations (1) to (5) and the constitutive model of Modified Cam-Clay [17] were used in this analysis. Based on several studies that have been collected by Iskandar [18], the value of the ratio of *kh/ks* ranges from 2 - 14. In this analysis, the value of *kh/ks* of 12 is used. The design soil parameters used in the analysis are determined based on the test results field, laboratory data, and empirical correlations are summarized in Table 2. Then, constitutive model of sand platform and embankment material using Elastic Plastic, parameters can be seen in Table 3.

Numerical simulation done by modeling PVD, smear, and undisturbed soil as a whole. The boundary conditions in this simulation use joint placement at the bottom (displacement on the horizontal and vertical axes = 0, Ux = Uy = 0) and on both right and left sides are used roller placement (displacement on the horizontal axis = 0, Ux = 0). For the mesh use a Global Element Size of 0.75 m consisting of 3800 and 3730 Nodes elements (Figure 4).

The vacuum preloading simulated using SIGMA/W is divided into two stages as follows:

a. Before the vacuum pressure was activated, the sand platform was spread with a thickness of 1.6 m, PVD installation and horizontal drainage were carried out for 200 days.

a. When the vacuum pressure is activated, on the 50th day the embankment load started. The vacuum pressure was stopped after 240 days.

The vacuum pressure was modeled with the negative total head water boundary condition on the PVD according to the vacuum gauge pressure distribution vacuum changing with depth as is reported by Indraratna and Chu [16], Tuan Vu and You Yang [17]. The vacuum

TABLE 1. Vertical Drain Parameter

Vertikal Drain Parameter	Value
Spacing, s	1 m
PVD Width, a	0.003 m
PVD Thickness, b	0.1 m
Discharge Capacity, q_w	0.00008 m^3/s
PVD Length	13.5 m

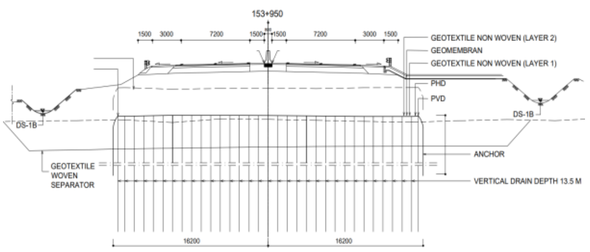

Figure 3. Typical cross section of road construction

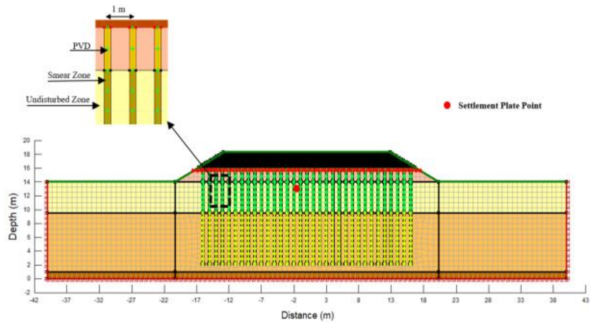

Figure 4. Plane Strain multi drain simulation

TABLE 2. Vertical Drain Parameter

Parameter	Symbol	Clay, Very Soft	Clay, Soft	Clay, Medium
Depth, (m)	-	0 - 4.5	4.5 - 13	13 - 15.5
Wet weight, (kN/m^3)	γ_{sat}	15	15	16
Poisson's ratio	ν	0.35	0.35	0.43
Effective Friction Angle, (°)	ϕ’	24	25	26
Void ratio	e	1.2	1.1	1
Slope of critical state line	M	0.941	0.984	1.027
Slope of The Isotropic NC Line	λ	0.096	0.208	0.167
Slope of The Isotropic OC (swelling) line	κ	0.019	0.042	0.033
Vertical Permeability, (m/s)	k_v	2.50E-07	2.00E-07	1.80E-07
Horizontal Permeability, (m/s)	k_h	5.00E-07	4.00E-07	3.60E-07
Undisturbed Plan Strain Permeability, (m/s)	k_{hp}	5.00E-07	4.00E-07	3.60E-07
Smeared Plan Strain Permeability, (m/s)	k'_{hp}	2.08E-10	1.66E-10	1.49E-10

TABLE 3. Sand Platform and Embankment Parameters

Parameter	Symbol	Unit	Sand Platform	Backfill
Wet weight	γsat	kN/m³	16	16
Young modulus	E	kN/m²	30000	10000
Poisson's ratio	ν	-	0.35	0.35
Friction Angle	ϕ	°	30	-
Cohesion	c	kN/m²	10	30

pressure distribution approach in this study is 100% at the surface of the sand platform, 85% to a depth of 5 m, then 60% to the end of the PVD.

3. RESULTS AND DISCUSSION

The stages of vacuum implementation are divided into 5 stages as follows:

- Preparation stage

Preparation starts from determining the location for research, determining the area to be vacuum preloading, the type of instrumentation to be used, and the number of instrumentation installation points, as well as determining the point of installation test for in-situ testing/laboratory test.

- Instrumentation installation stage

At this stage the installation of instrumentation tools corresponds to the initial planning. The instrumentation tools used included:

a. Inclinometer, this instrument is used to monitor the lateral movement of the soil due to vacuum.
b. Settlement plate, this instrument is used to monitor the total decrease soil due to vacuum and applied loads.
c. Extensometer, this tool is used to determine the decrease at a certain depth (layered settlement).
d. Piezometer, this tool is used to monitor changes pore water pressure value at a certain depth.
e. Vacuum gauge, this tool is used to monitor the vacuum pressure applied to the repair area.

The instrumentation that will be used as a reference in this study is a settlement plate and a vacuum gauge as shown in the schematic drawn in Figure 5.

- Stage of implementation of vacuum preloading and instrumentation monitoring

At this stage vacuum preloading work in the study area is carried out. During the vacuum preloading work, instrumentation monitoring is carried out daily on the value of the drop, lateral deformation, vacuum pressure, and pressure spread, unless there is data showing settlement rate or pore water pressure that is drastically reduced, there is an indication that this vacuum activity will be completed so that the instrumentation readings will be enlarged.

- Stage of interpretation of the results of monitoring and evaluation of work in the field

At this stage the results of the instrumentation monitoring data are interpreted whether the vacuum preloading work worked has shown good results or needs additional data, so that this work can provide sufficient data for later analysis. Furthermore, field and laboratory testing is carried out for soil conditions after the vacuum work is completed.

After the last stage is carried out, then in this study will be compared how the settlement behavior of the results of finite element analysis with monitoring data in the field.

The analysis finite element results of the changes in soil settlement behaviour, total stress, and shear stress due to vacuum preloading are shown in Figures 6 to 8. It can be seen from the contour of the settlement that the

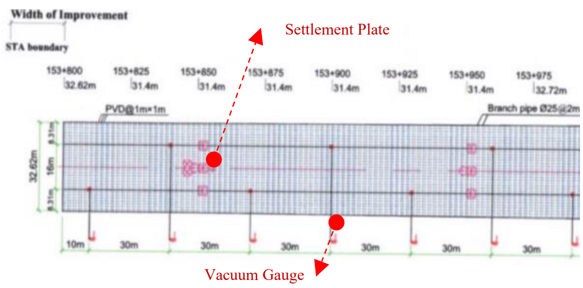

Figure 5. Settlement plate and vacuum gauge location

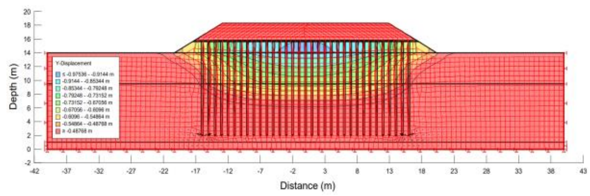

Figure 6. Contour of Settlement after construction 240 days

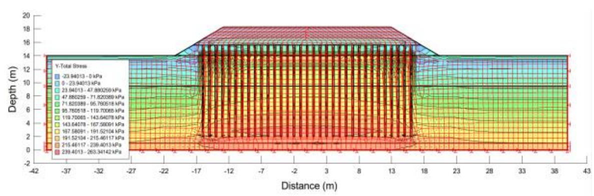

Figure 7. Contour of Y-Total Stress

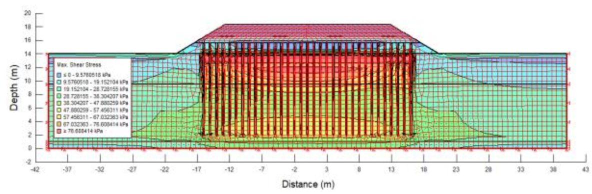

Figure 8. Contour of Shear Stress

embankment area experienced greater deformation and tended to move inwards the repair area. The results of the analysis will be verified based on observations of the settlement plate installed in the repair area as shown in Figure 9.

Figure 9 is a comparison curve for settlement from numerical simulations and field monitoring plotted against construction time. The soil settlement recorded at the end of construction in the field was ±0.945 m while the numerical simulation results of ±0.93 m contained a difference of about 1.6%. In general, the settlement trendline on the 130th to 240th days gives results that are very close to field monitoring. However, there is a different settlement trendline on day 50 between the results of numerical analysis and field monitoring (the difference is about 23%). The monitoring data vacuum gauge (Figure 9) that in the first 50 days the vacuum pressure tends to be unstable due to improvements to the geomembrane and the vacuum area, but after 50 days the vacuum pressure tends to be constant around 80 – 82 kPa even though there are several times the generator stops.

As stated by Feng et al. [18] the Finite Element model using Plaxis 2D gave a different settlement result compared to field monitoring (a difference of about 62%) in the first 10 days (Figure 10). This is because the FE

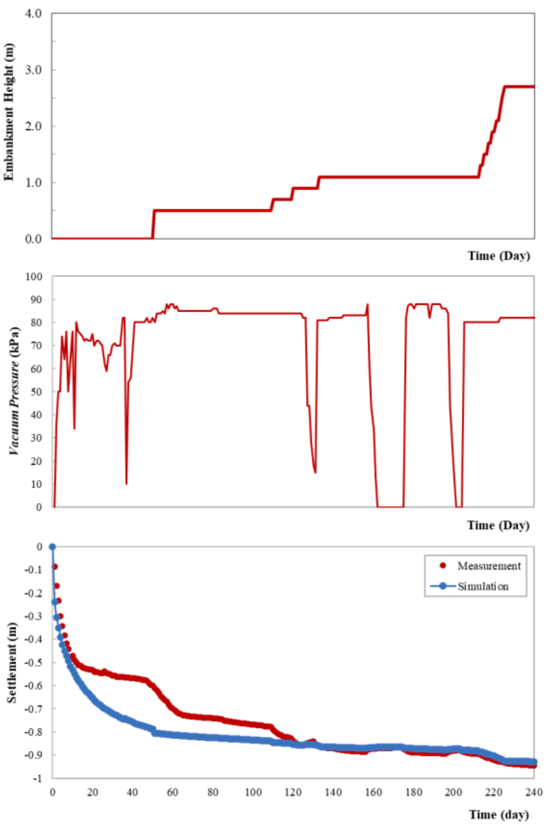

Figure 9. Typical monitoring data and calculated time-settlement curve used SIGMA/W

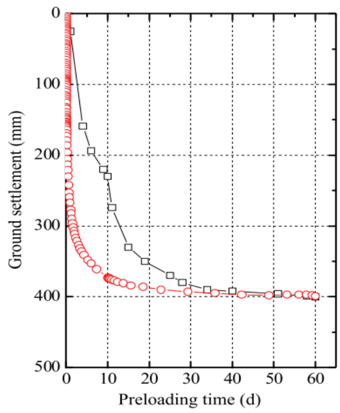

Figure 10. Settlement of conventional vacuum preloading [18]

model uses a constant value of hydraulic conductivity in the field, this value can decrease when there is an increase in pressure. Then, in the first 10 days is the vacuum pressure test phase, so that the monitoring data was incomplete because there was a process of checking the tightness of the membrane. But beyond that stage, the vacuum pressure tends to be stable.

In addition, the vacuum preloading 2D multi-drain plane simulation was conducted by Pardsouie et al. [19] the model used Geostudio with constant value of vacuum pressure and also without smear zone showed that there was a good correlation between the prediction of settlement and the measurements in the field except that in the first 50 days. That simulation results gave overestimate the settlement value (Figure 11).

The constitutive model of the material that was used, the determination of the permeability value of the plane-strain condition, and the distribution of vacuum pressure to depth are the parameters that significantly affect the settlement results. The discussion above shows that the numerical simulations carried out give a settlement pattern that matches quite well with the observed points of the settlement plate after carrying out various approaches such that the simulation stages approach the conditions in the field.

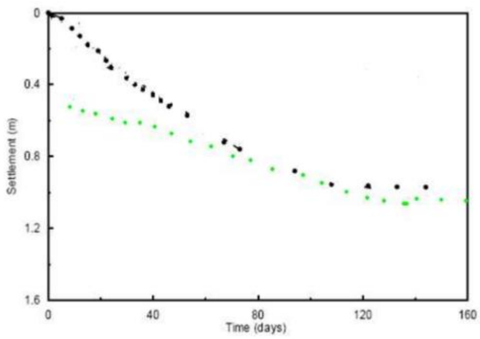

Figure 11. Comparison of Model Simulation Results with Monitored Field Data's [19]

4. CONCLUSION

Based on the results of the vacuum preloading with SIGMA/W that has been carried out, it can be concluded several things that is the simulation of vertical drainage and smear in 2D multi-drain-plane strain, the permeability value of the axisymmetric must be converted into plane strain, and then the vacuum pressure applied along the vertical drainage is not modeled constant, but changes with depth, the value of 60% at the bottom of the vertical drainage is quite representative of the conditions in the field. Afterward, the settlement pattern generated from the simulation is quite good at approaching the field observation points with a prediction of the magnitude of the settlement due to vacuum preloading of ±0.93 m, when compared to the field observation data there is a difference of about 1.6%.

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Persian Abstract

چکیده

در اندونزی، ساخت جاده با چالش هایی همراه است، زیرا جاده بر روی خاک رسی نرم ساخته شده است .برای بهبود مقاومت برشی و خواص تراکم پذیری خاک نرم در این پروژه از روش پیش بارگذاری خلاء استفاده شد .علاوه بر این، آنچه باید برای پزشکان نگران باشد، مسئله افزایش دقت شبیه‌سازی در پیش‌بینی نشست خاک در یک سیستم پیش بارگذاری خلاء است .هدف تحقیق این مطالعه تعیین تغییرات رفتار نشست خاک ناشی از سیستم پیش بارگذاری خلاء با استفاده از شبیه‌سازی عددی Geostudio با رویکرد 2 بعدی Multi Drain – Plane Strain بود و نتیجه نشست شبیه‌سازی با داده‌های ابزار دقیق مقایسه می‌شود .در این مطالعه توزیع فشار خلاء با استفاده از فشار آب منفذ منفی کل سر آب مدل‌سازی شده است و مقدار فشار استفاده شده به دنبال داده‌های گیج خلاء در میدان با رویکرد توزیع 100 درصد در سطح سکوی ماسه، 85درصد تا عمق 5است .متر، سپس 60٪ تا پایان .PVD بر اساس شبیه‌سازی‌ها، نتیجه این است که فشار خلاء اعمال شده در طول زهکشی عمودی ثابت مدل‌سازی نمی‌شود، اما با عمق تغییر می‌کند، مقدار 60درصد در پایین زهکشی عمودی کاملاً معرف شرایط مزرعه و نشست است .از شبیه سازی در نزدیک شدن به مشاهدات میدانی با پیش بینی نشست به دلیل پیش بارگذاری خلاء 0.93 ±متر بسیار خوب است، در حالی که در مقایسه با داده های مشاهدات میدانی تفاوت حدود 1.6٪ وجود دارد.