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Finite Element Simulation of Vacuum Preloading at Palembang – Indralaya Toll Project

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Highlights:

- Vacuum preloading simulations were performed and produced good correlation with field monitoring data.
- The smear effect, the vacuum model, the fill height, and the rate of loading affected the simulation results.
- The 2D models produced more conservative results than the 3Ds models.

Abstract. Methods for the prediction of soil behavior during the application of vacuum preloading are available but have not been used precisely and have not been proven yet in Indonesia. There are two common approaches to vacuum preloading simulation, based on the application of a uniform external load to the vacuum area, and based on suddenly lowering the groundwater level to create vacuum conditions, respectively. This affects the settlement, lateral deformation, and pore pressure predictions. The objective of this research was to improve the prediction of soil behavior based on high-quality field data by using state of the art vacuum preloading simulations. The results were compared with those of a series of instrumentation equipment, i.e. a settlement plate, an extensometer, and a piezometer. This research used data from the Palembang-Indralaya Toll Road, a section of the Trans Sumatera Toll Road that is approximately 22 km long and has an embankment height of about 4 m to 9 m. It was built over a swampy soft soil area, using vacuum preloading to improve the soil. Axisymmetric analysis of vacuum preloading was conducted for a single-drain system, plane-strain analysis was conducted for single- and multiple-drain systems, and 3D analysis was conducted for single-drain, multiple-drain, and cluster-drain systems. The results show that the proposed method produced a good correlation between the predicted data and the recorded monitoring data.

Keywords: *finite element simulation; instrumentation; numerical analysis; soil improvement; vacuum preloading.*

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1 Introduction

Very soft clays have complex behavior, have a very low bearing capacity and are very compressible [15]. In 2015, the Indonesian government built the approximately 22-km long Palembang-Indralaya (Palindra) Toll Road, as shown in Figure 1, with an approximate embankment height of 4 to 9 m, mostly on soft clays. The soft clay soil had to be improved to meet the rigorous toll road deformation criteria, with a tight construction budget. The vacuum preloading technique was selected because it was considered to be the most suitable option at the time.

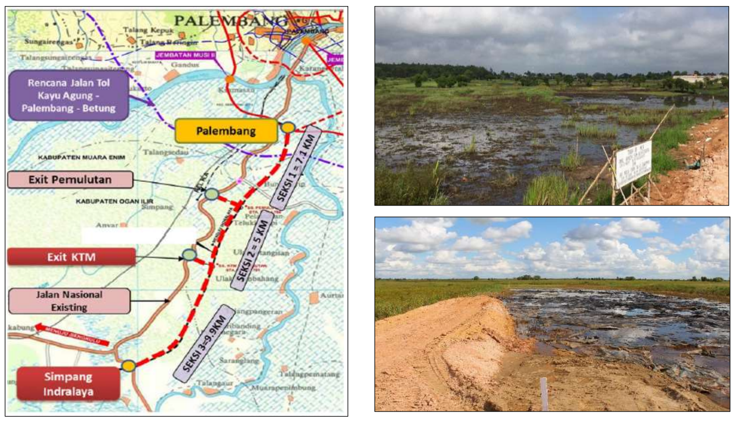


Figure 1 Palindra Toll Road.

The vacuum preloading design for this project was initially developed and analyzed based on the conventional Terzaghi consolidation theory by assuming the vacuum pressure as a uniform external load. The approach was verified using finite-element analysis, where the vacuum pressure was modeled as a sudden drawdown of the water level to create suction. Our preliminary investigation found that both methods produced an overprediction of settlement [2]. Thus, better approaches of analysis and vacuum simulation are required. To investigate the behavior and mechanism of vacuum preloading in this project, field data was collected. A numerical analysis utilizing the finite-element method was performed with the Abaqus software application. The suction pressure was modeled as a boundary condition at the membrane level, while the negative pressure value, including its fluctuation, was set identical to the field pressure monitoring value to get the same behavior between the simulation and the conditions in the field.

2 Palindra Toll Project

The Palindra Toll Road is located in Palembang City, South Sumatra Province, Indonesia. This toll road is part of the approximately 2,818-km long Trans Sumatera Toll Road, which connects areas and cities from Lampung Province in the south to Aceh Province in the north. This 22-km long toll road was built in a swampy area, which is covered with about 1 to 1.5 m of water in flooding conditions. Soil investigation in this area generally found a layer of soft to very soft clays with a thickness of approximately 10 to 15 m, followed by a medium-stiff silty clay layer with an approximate depth of 2 to 6 m. The medium stiff silty clay layer is underlain by a medium to dense sand layer to an approximate depth of 10 to 14 m followed by the bearing layer consisting of very stiff to hard clays. A description of the site conditions and soil stratification are shown in Figure 2.

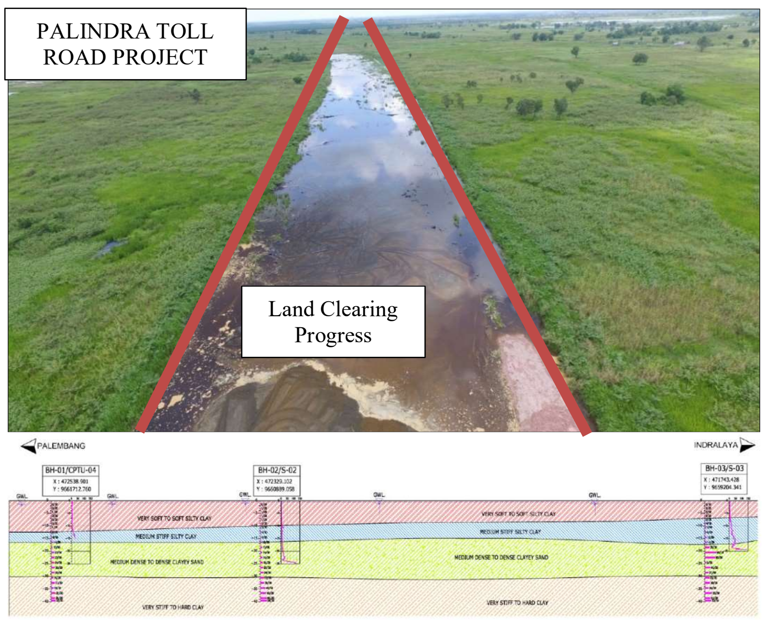


Figure 2 Site condition overview and general soil stratification of the Palindra Toll Road project.

The first layer gives the largest contribution to the total amount of settlement. Unfortunately, without applying soil improvement, the settlement rate could not meet the standard criteria (a maximum residual settlement of 10 cm/10 years, or a maximum of 2 cm per year). In some areas, sand lenses were encountered, which needed to be considered in the vacuum application system due to the potential loss of vacuum pressure.

3 Selected Improvement Method

Initially, several methods were considered as improvement/reinforcement methods for this location, such as conventional prefabricated vertical drain (PVD) preloading, a bamboo pile mattress system (Irsyam, *et al*. [9] and Susila, *et al.* [14]), a modified chicken claw foundation, and even a structural approach with pile slabs and a bridge, as shown in Table 1.

Table 1 Comparison matrix of soil improvement/reinforcement for Palindra Toll Road.

Criteria	Bamboo pile-mattress system	Modified chicken claw (CAM) foundation	Soil improvement	
			Preloading with PVD	Vacuum preloading
Construction cost 1. Low 2. Moderate 3. High	1	2	1	2
Stability criteria				
1. SF > 1.1 Construction Stage	Achieveable	Achieveable	Achieveable	Achieveable
2. SF > 1.3 Service stage	Achieveable	Achieveable	Achieveable	Achieveable
Settlement criteria				
• DOC > 90% Construction stage	No	No	Achieveable	Achieveable
• Rate < 2 mm/year Service stage	No	No	Achieveable	Achieveable
• Settlement < 10 cm/10 years Service stage	No	No	Achieveable	Achieveable
Estimated construction time 1. Shortest 2. Short 3. Long 4. Longest	1	2	3	2
Constructability	Simple, requires supervision	Simple, design from patent holder is required	Simple, common	Special contractors required
Social/environmental issues	No issues	Fire issues, slump area	Flooding	Flooding
Right of way	No issues	No issues	Requires more area for berm/ CW	No issues

The vacuum preloading method was finally selected as soil improvement technique (Irsyam, *et al*. [8]) after comparing the available methods based on constructability, availability of material, construction cost, construction time, and capability to meet the acceptance criteria.

The vacuum preloading technique was first proposed by Kjelmann [10] as a fine-grained soil improvement method. He proposed to use the atmospheric pressure as a temporary surcharge over the area to be improved. The technique utilizes a series of vertical and horizontal drainage channels under a membrane to isolate the soil mass and then reducing the atmospheric pressure by using pumps, resulting in an increase of the effective vertical stress with no change in total stress. If necessary, this method can be combined with a conventional preloading load. The 22 km of the toll road trajectory was divided into 64 vacuum zones. Each vacuum zone was approximately 50 m wide and 320 m long. Due to the soil condition, most areas were improved by applying the vacuum preloading method, except some areas that had better bearing layer conditions and a lower embankment height.

A series of membrane layers and a 1 m x 1 m square pattern of PVDs were selected as part of the vacuum system. The lengths of the PVDs ranged from 14 to 18 m depending on the soil condition. At the edge of the vacuum area, a membrane was buried into a trench at the four boundaries of the area, to an approximate depth of 5 m to contain and preserve the vacuum pressure. A sand layer of about 3 m thickness was used as filler material below the membrane and also as a working platform. A combination of main pipes and secondary perforated pipes was used to apply vacuum pressure by vacuum pumps. Figure 3 shows a typical cross section of the embankment and the vacuum system, while Figure 4 shows the site conditions during set-up and installation of the vacuum system.

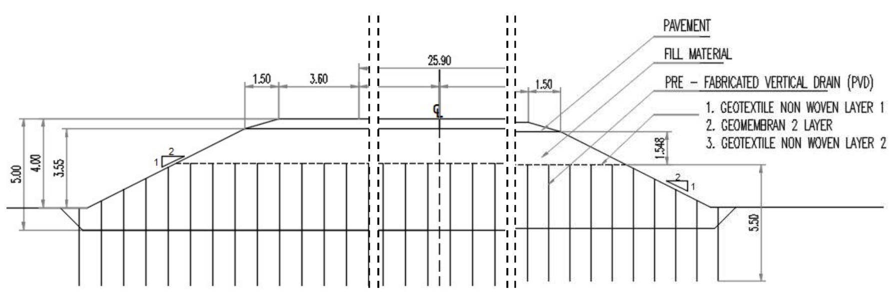


Figure 3 Typical cross-section of the embankment.

A series of instrumentation consisting of a vacuum gauge, a settlement plate, a piezometer, an extensometer, and an inclinometer was installed and monitored daily to control the vacuum preloading process. Generally it took approximately 3 to 4 months to reach minimally 90% degrees of consolidation. The vacuum pressure reached 80 kPa in approximately two weeks, and was maintained until the whole process was finished. During the vacuum process (after 80 kPa was reached and maintained), filling work was carefully conducted to meet the designed minimum load ratio criteria.

Figure 4 Vacuum system and installation.

4 Methodology

Full-scale tests were performed at 2 locations: Location 1 (Zone 1 and 2, STA 0+625) and Location 2 (Zone 29 and 30, STA 17+750), as shown in Figure 5. A series of soil investigations consisting of geotechnical drilling, laboratory tests, and CPTu (and dissipation test) were performed before and after vacuum preloading was applied, so that the original and improved behavior of the soil could be measured. The instrumentation was also applied to the same areas. The instrumented equipment was read every day (morning and afternoon) so that the vacuum preloading behavior was well recorded.

All recorded data from the investigation were interpreted to obtain the soil stratification and parameters for analysis. Numerical simulations were performed utilizing 2D and 3D models built with the Abaqus finite-element software. The results of the finite-element simulations, including settlement time response, were analyzed and compared to the data recorded by the instrumentation.

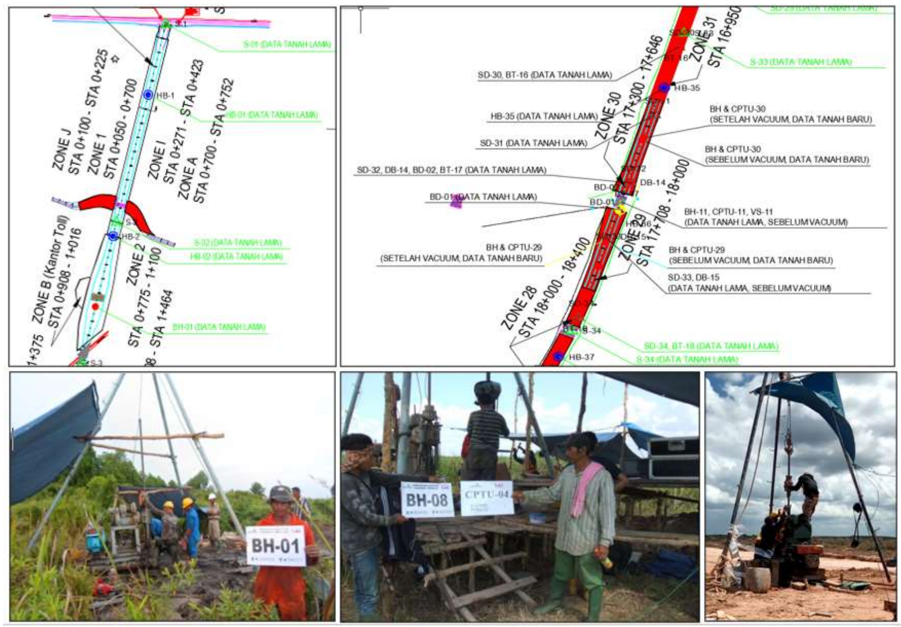


Figure 5 Soil investigation at Location 1 and Location 2.

5 Soil Investigation and Design Parameters

The soil investigation on both locations consisted of 4 deep borings (DB) to a depth of 30 m below the existing ground surface, including a 2-m interval for the SPT test, 4 cone penetration tests with pore pressure measurement (CPTu), CPTu dissipation tests at some depths to get the field soil permeability and consolidation characteristics, and laboratory tests on the UDS samples. The tests were performed before and after the vacuum work at the same points for both locations to find out the changes in soil characteristics, parameters, and elevation. The ground water level was recorded during the DB test from 0.0 to 0.5 meter to the ground surface.

Based on the soil investigation on both locations, the soil stratification can be described as shown in Figure 6.

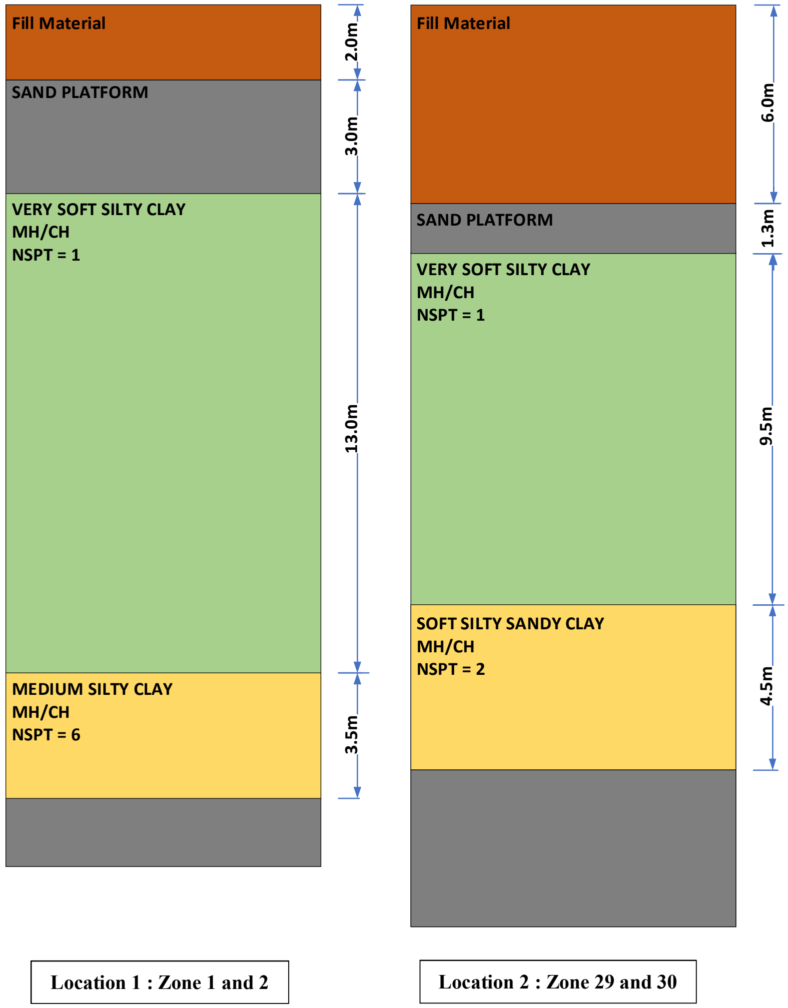


Figure 6 Soil stratification at (a) Location 1 (Zones 1 and 2) and (b) Location 2 (Zones 29 and 30).

Based on the soil layer conditions, the effective length of the installed PVDs was approximately 18 m and 15 m (from the top of the membrane) for Zones 1 and 2, and Zones 29 and 30, respectively. The PVD penetration was stopped at approximately 0.5 to 1.0 m before reaching the sand layer to prevent connection to the permeable layer.

The soil parameters of the modified cam clay soil model are presented in Table 2.

Table 2 Soil parameters for vacuum simulation.

Layer	Soil Type	N	e_0	c_c	c_r	λ	κ	c_v (cm^2/sec)
Location 1								
1	Silty clay, very soft	1	2.80	0.90	0.18	0.391	0.078	2.63E-02
2	Silty clay, medium	6	1.00	0.25	0.05	0.109	0.022	2.71E-02
Location 2								
Layer	**Soil Type**	**N**	e_0	c_c	c_r	λ	κ	c_v (cm^2/sec)
1	Silty clay, very soft	1	2.30	0.60	0.12	0.261	0.052	3.83E-03
2	Silty clay, soft	2	1.40	0.30	0.06	0.130	0.026	6.67E-02

6 Numerical Simulation Set-up

Single- and multiple-drain 2D and 3D simulations of vacuum consolidation at both locations were performed. The modified cam clay (MCC) soil model as continuously used by Indraratna, *et al*. [6] in a vacuum consolidation simulation was selected.

For the 2D single-drain model, Indraratna, *et al*. [6] proposed permeability conversion from axisymmetric to plane strain unit cells. The geometrical boundary conditions were set as follows: fixed laterally and vertically at the bottom (Ux = Uy = 0), only fixed laterally at both sides of the model so the soil can settle freely in the vertical direction (Ux = 0). The PVDs were modeled as soil clusters with larger permeability related to the material specification. The smear layer around the PVDs was also modeled as a cluster, with permeability (ks) values approximately 1/4 times the horizontal soil permeability (kh). The vacuum pressure was modeled as a boundary condition of negative pore pressure at the surface to model the vacuum conditions below the membrane. The value of this negative pore pressure was set identical to the changes in negative pore pressure from the field monitoring readings. For the single-drain analysis, we used the CAX8RP element (8-node axisymmetric quadrilateral, biquadratic displacement, bilinear pore pressure, reduced integration) to analyze the axisymmetric simulation, and CPE8RP element (8-node plane-strain quadrilateral, biquadratic displacement, bilinear pore pressure, reduced integration) for the plane-strain analysis. Figure 7 shows the numerical setup of vacuum preloading for the single-drain model, while the simulation for the multiple-drain model is shown in Figure 8.

For the 2D multiple-drain simulation, the whole multiple-drain system, PVDs, the smear zone and the undisturbed zone were modeled as clusters and layers, also depending on permeability, including the sand platform and the embankment. For this case the CPE8RP element was used.

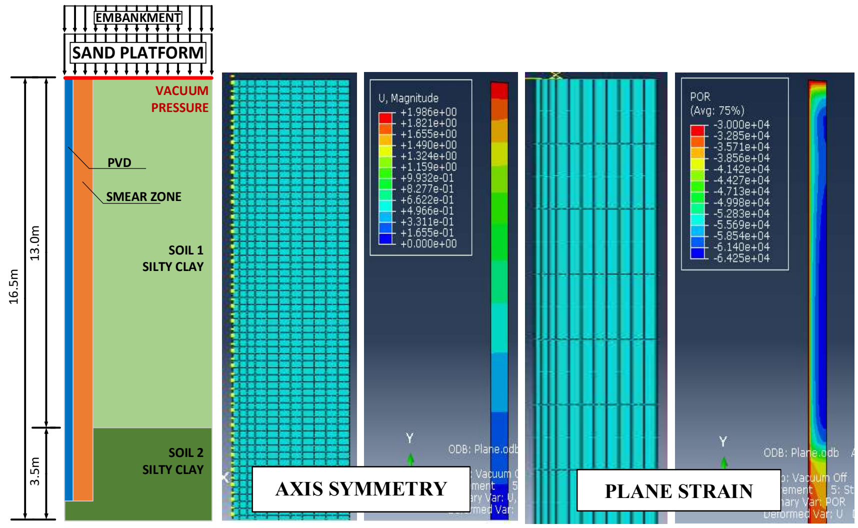


Figure 7 Axisymmetry and plane-strain single-drain simulation.

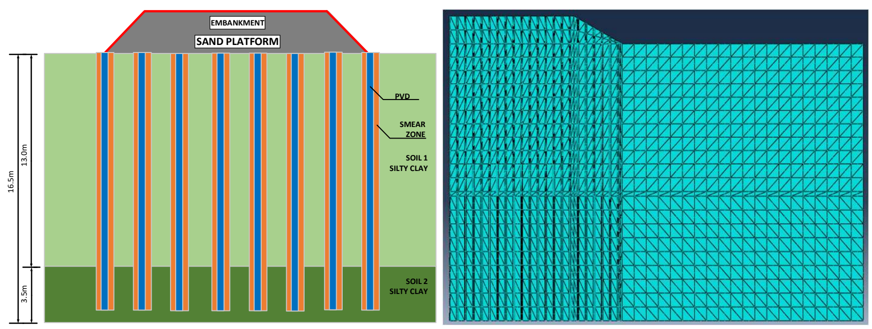


Figure 8 Plane-strain multiple-drain simulation.

To simplify the 3D analysis, the vacuum zone model was divided into four smaller parts as shown in Figure 9 to limit the bandwidth and reduce the computation duration significantly. The utilized software (Abaqus) performed the analyses and combined them (Rujikiatkamjorn, *et al*. [12] has proven that this approach does not affect the results). The C3D8RP element (8-node trilinear displacement, trilinear pore pressure, reduced integration) was utilized.

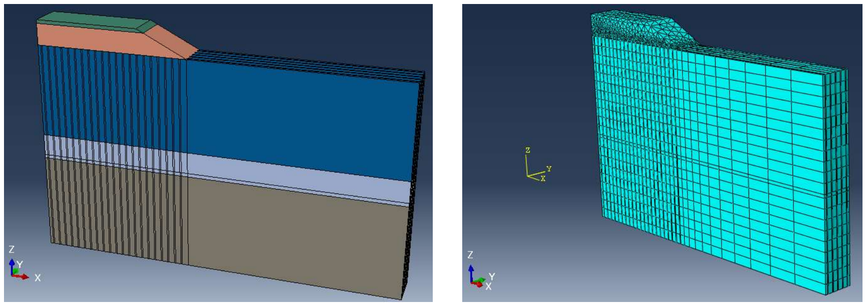


Figure 9 3D multiple-drain simulation.

In the 3D model analysis, the simulation of the PVDs was modeled not only as a multiple-drain system but also as a cluster system (as shown in Figure 10) by using the equivalent permeability proposed by Chai, *et al*. [1]:

$$k_{ev} = \left(1 + \frac{2.5 l^2}{\mu D_e^2}\frac{k_h}{k_v}\right) k_v$$

where l is the PVD length and μ is a factor that corresponds to the equivalent diameter of the drain and the equivalent diameter of the smear zone proposed by Hansbo [3]:

$$\mu = \left(\frac{n^2}{n^2-1}\right)\left[\ln n - \frac{3}{4} + \frac{1}{n^2} - \frac{1}{4.n^2}\right]$$

The approach of dividing the vacuum zone into parts was not required in this case because the model was not as complicated as before; the utilized computer was still able to run the full model simulation well within reasonable time.

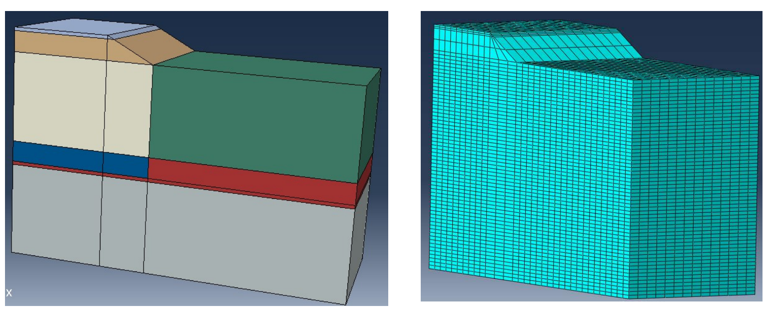


Figure 10 3D cluster-drain simulation.

For all simulations, the well resistance acting on the PVDs, which can reduce the water flow rate through the flexible core, was neglected, as recommended by Indraratna, *et al*. [5], due to the high discharge capacity of the PVDs used. The simulation approach was calibrated by performing re-analysis of selected papers on vacuum preloading with several different models: a single-drain model (Saowapakpiboon, *et al*. [13]), a 2D plane-strain model, assuming the PVD area as a cluster drain (Nghia [11]), and a 2D/3D model (Rujikiatkamjorn, *et al*. [12]). The re-analysis showed that the simulation approach gave relatively the same results.

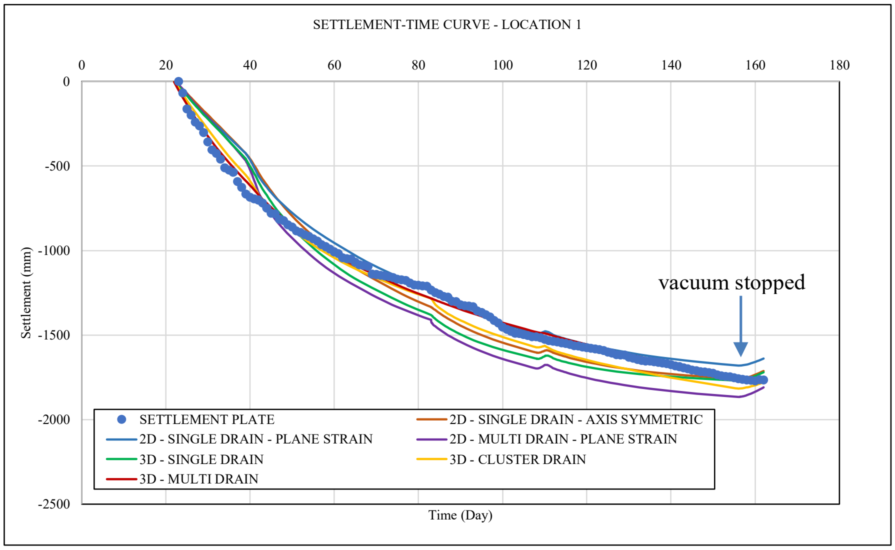
7 Analysis Result

7.1 Settlement

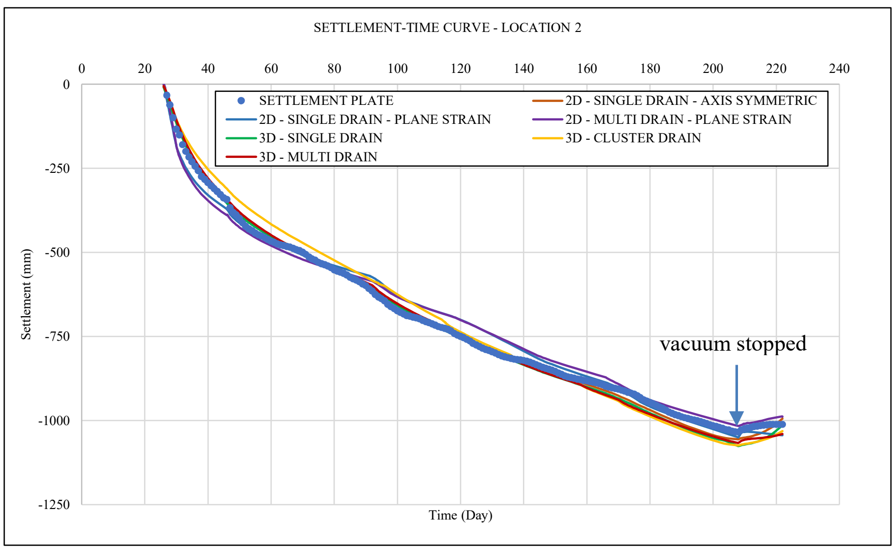
The results of the analyses at both locations are presented in Figure 11. The simulations at both locations were performed using the same soil condition and parameters, constitutive soil model, and stages of construction.

The calculated settlement when the vacuum stopped was about 1.75 m and 1.1 m at Location 1 and Location 2, respectively. These results match the recorded settlement from the settlement plate instrumentation. The results at both sites showed different time-settlement behavior. At Location 1 all simulations as well as the field data showed that settlement tended to asymptotic behavior, which means that the settlement already or at least nearly reached 90% of consolidation, while at the Location 2 the settlement was still in progress to achieve the same condition. Settlement behavior at Location 2 was affected by the fill height, which was three times larger than at Location 1, and the total embankment load applied at the same time when the vacuum pressure started. This condition caused the recorded settlement rate at Location 2 still being at the initial stage of primary consolidation compared to Location 1 at the same time. Moreover, the vacuum progress at this location was stopped before 90% of consolidation was reached for technical reasons.

Unfortunately, there was no field data after the vacuum pressure was stopped. As a result, the calculated settlement behavior during the service stage of the toll road from the numerical analysis could not be compared. The presented figures show that the results of the simulations correlated well with the settlement monitoring data. From all simulations, the 3D analyses (single-drain, multiple-drain, and cluster-drain) produced relatively more accurate results. The 2D simulations in general gave a more conservative settlement, especially at the end of the curves.



(a)

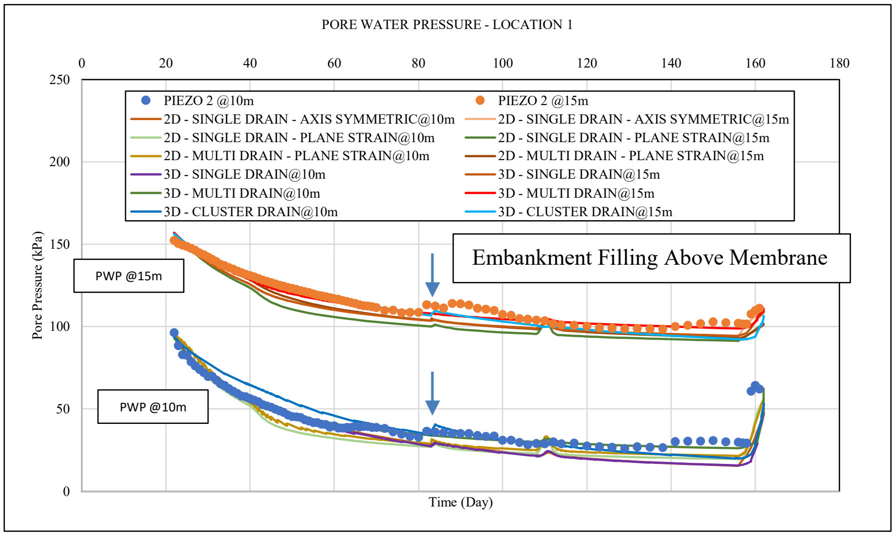


(b)

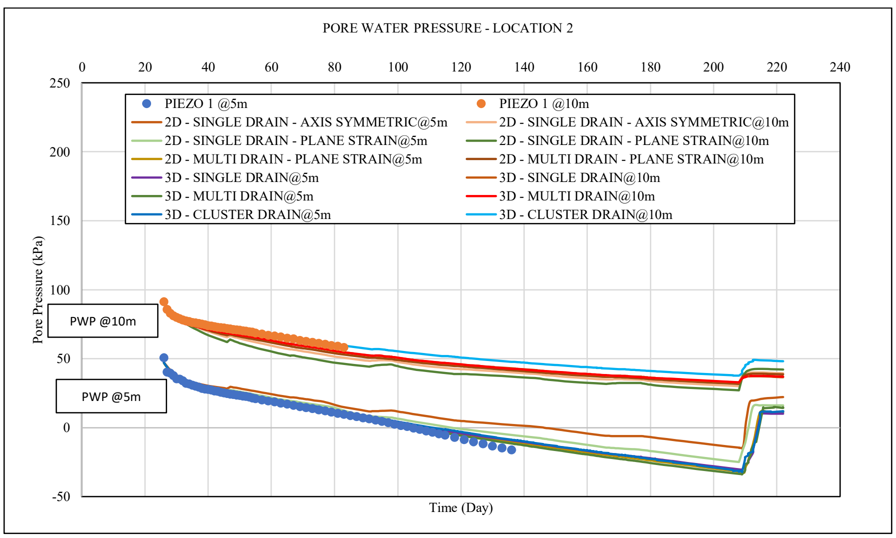
Figure 11 Calculated time-settlement curves: (a) Location 1 (b) Location 2.

7.2 Pore Pressure

The calculated pore pressure was measured at two different depths for both locations. The calculated points were located where vibrating wire piezometers were installed so the results could be compared and analyzed.



(a)



(b)

Figure 12 Calculated and measured pore pressure: (a) Location 1 (b) Location 2.

The results show that the behavior of the calculated water pressure was relatively the same as the measured pore pressure from the field monitoring data, as shown in Figure 12. There were differences in behavior between the calculated and the measured pore pressure curves related to the rate of response to the embankment loading above the membrane. The measured curves indicated a slow rate increase of pore pressure, while the calculated curves showed a higher rate and a lower increase of pore water pressure. Based on this it is inferred that when the vacuum pressure was applied, the simulation was less sensitive to the embankment loading. In the simulation of the vacuum preloading, the vacuum pressure had a more dominant effect than the embankment loading. This could be due to the considered smear effect and the effect of neglecting well resistance.

7.3 Lateral Deformation

Due to limitations of the axisymmetric model that considers boundary fixities at the axis in the lateral direction, the lateral deformation results can only be shown for the 2D multiple-drain, 3D multiple-drain and 3D cluster-drain models. The analyzed points for lateral deformation were taken at approximately 2 m away from the embankment toe, where inclinometers were installed. The calculated lateral deformations were in good correlation with the measured deformation from the inclinometers.

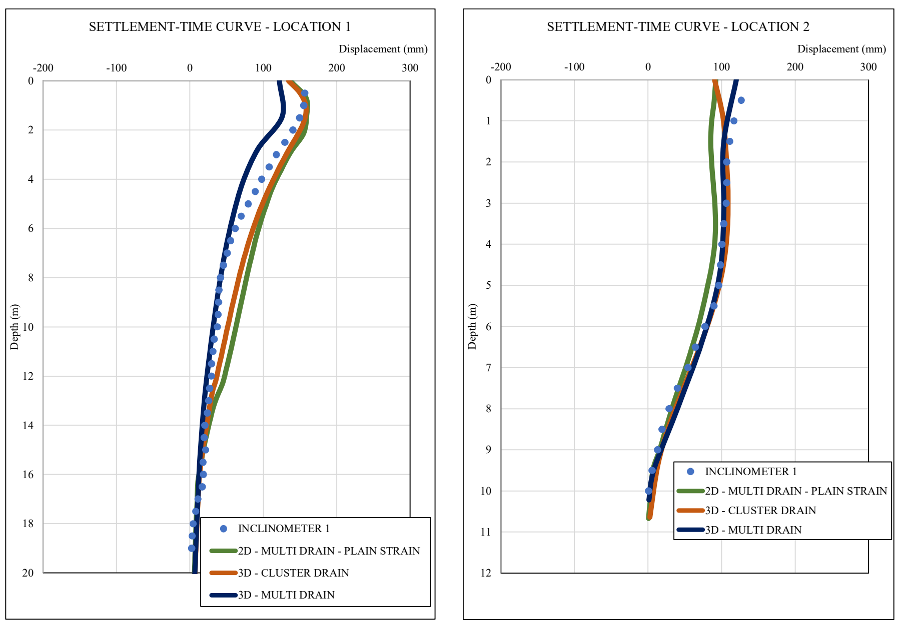


Figure 13 Lateral deformation result.

Figure 13 shows a comparison of the lateral deformation from the finite-element simulation and the inclinometer. The lateral deformations moved approximately 10 to 15 cm during vacuum preloading. In this case, the finite-element simulation and the inclinometer results were in good agreement: lateral deformation occurred up to an approximate depth of 18 m below the existing ground surface. For more general cases, the depth to which vacuum preloading can be effective depends on soil conditions, embankment height, and construction stage.

8 Conclusions

Field tests with an extensive monitoring system and finite-element simulations of vacuum preloading were performed and presented for the Palembang-Indralaya Toll Road. The finite-element simulation data and the field test data showed a good correlation.

There was different time-settlement behavior between Location 1 and 2. Settlement at Location 1 tended to asymptotic behavior, while at Location 2 the settlement was still in progress to achieve the same condition. Fill height and rate of loading were the reasons for this behavior. There were also differences between the calculated and the measured pore pressure curves related to the rate of response to the embankment loading above the membrane. The numerical simulations indicated that when vacuum pressure was applied, the negative pressure had a more dominant effect on the pore pressure behavior than embankment loading. This could be due to the considered smear effect and the effect of neglecting well resistance.

In general, the 2D models produced more conservative results than the 3Ds models but still correlated well with the field test results. This approach can be used for vacuum simulation and design because it requires less computation time and is simpler compared to 3D models. The 3D analysis (single-drain, multiple-drain, and cluster-drain) produced a relatively more accurate result. To simplify the analysis and limit the bandwidth, and to reduce computation duration significantly, partitioning of the vacuum zone is required in 3D models.

This research could not confirm the residual settlement results due to limitations of the monitoring instrumentation at the toll road service stage. For future work it is strongly recommended to ensure that all the installed instrumentation works perfectly and to perform constant monitoring at least up to 10 years of toll road service to confirm the residual settlement prediction. Other challenging research topics are investigation of the smear effect based on field tests, and investigation of well resistance effects based on field instrumented PVDs.

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