Soil settlement analysis in soft soil by using preloading system and prefabricated vertical draining runway of Kualanamu Airport

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Abstract. The method of soil improvement, using the combination of prefabricated vertical drain (PVD) and preloading, was used to accelerate the process of consolidation and the consolidation settlement in the runway of Kualanamu International Airport, which was constructed on the soft soil sediment like silty clay. In this research, the investigated area was the runway of Kualanamu International Airport zone I which had 11 meter-thickness of soft soil. Geotechnic instruments surveyed was settlement plate. Monitoring was done toward the behavior of landfill such as basic soil settlement. The result were compared with the analysis of finite element method of full scale in Mohr-Coulomb model by verifying the vertical drain of asymmetric unit cell and equivalent plane strain unit cell condition. The results of the research showed that there were an interesting behavior between the data in field observation and finite element of Mohr-Coulomb model. It was also found that the result of soil settlement of finite element method of Mohr-Coulomb model was closed to the result of settlement plate monitoring.

1. Introduction
Due to the rapid development of urbanization and the population increase along coastal lines, exploitation of undeveloped low-lying areas has become a necessary strategy for many countries [1]. Development of urban transportation and expansion also occurred in North Sumatra, this occurred at the turn of Polonia Airport with the new Airport, known as Kualanamu Airport, located in Kualanamu area, North Sumatra. The airport construction will include runway, taxiway, exit taxiway, apron and other supporting facilities. Given the problem of soft clay soil that is influential in the success of infrastructure development, so must be done soil repairs so that infrastructure is not damaged before the planned age.

Based on above, it is necessary to improve the soft soil conditions. Preloading of soft clay with vertical drains is one of the most popular methods used to increase the shear strength of soft soil and control its post-construction settlement. Since the permeability of soils is very low, consolidation time to the achieved desired settlement or shear strength may take too long [2]. Using prefabricated vertical drains (PVDs), means that the drainage path is shortened from the thickness of the soil layer to the radius of the drain influence zone, which accelerates consolidation [3]. Introduced prefabricated band shaped drains and cardboard wick drains for ground improvement. Typically, prefabricated band drains consist of a plastic core with a longitudinal channel surrounded by a filter jacket to prevent clogging. Most vertical drains are approximately 100 mm wide and 4 mm thick [4]. The soft soil...
improvement by prefabricated vertical drains (PVDs) combined with preloading is one of the most successful applications to this site [5].

2. Methodology

2.1. Prefabricated Vertical Drain (PVD)
Barron [6] describes the area of influence (De) mounting PVD with a function of vertical drains as shown in Fig.1.
For triangle pattern values [6]:

\[ D_e = 1.05S \]  

While for rectangular values:

\[ D_e = 1.128S \]  

Where:

\( S \) = Distance spacing drainase vertical

![Configuring vertical drain; (a) triangle, (b) rectangle](image1)

Figure 1. Configuring vertical drain; (a) triangle, (b) rectangle

2.2. Equivalent drain diameter of band-shaped vertical drain
The size of the band-drain or PVD is mostly rectangular cross-section. For the purpose of calculating PVD, the cross section of the PVD will be modeled into a circle with the calculation of the equivalent diameter assumed as the circumference of the rectangle as shown in Figure 2.

![Conceptual drawing of a band-shaped PVD and equivalent diameter well.](image2)

Figure 2. Conceptual drawing of a band-shaped PVD and equivalent diameter well.

Assumption is based on Hansbo's formulation as below [7]:

\[ d_w = \frac{2(a + b)}{\pi} \]  

Where \( d_w \) = equivalent diameter vertical drains, \( a \) = wide vertical drains, \( b \) = thick vertical drains.

2.3. Discharge capacity PVD
Based on the results of laboratory testing Holtz et al [2] suggested for large discharge capacities of PVD ranging from 100 to 150 m³/year.
2.4. Smear Zone
PVD is inserted into the ground by using mandrel and at the end of the shoe is given. As a result of this installation, the soil layer stabbed with mandrill will be disrupted. The disturbance that occurs is called smear zone while the result will be a reduction in the coefficient of permeability of soil radial ($k_r$). Smear zone effect is decrease permeability coefficient value for clay soil near PVD or PVD diameter used is minimized, this is due to process of remolding during installation of PVD.

Assumption is based on Chai and Miura [3] formulation as below:

$$d_s = 3d_m$$  \hspace{1cm} (4)

Where $d_s$ = equivalent diametersmear zone, $d_m$ = equivalent diameter mandrel.

2.5. Modeling Verification of PVD

The planeting pattern of PVD installed in the local field, at a certain distance, while in the FEM program the facility of implementing PVD is plane strain as shown in Fig. 3. To be able to implement PVD installed in the field into the program, it must first be verified in the form of plane strain that will produce a new soil permeability coefficient ($k$), then with the new soil permeability coefficient ($k$) the new simulation process in the FEM program can do.

![Figure 3. Conversion of an axisymmetric unit cell into plane strain condition.][8, 9]

According to Hird, et al [8, 10]. The equivalent process can be done in several ways:

1. The distance between PVD at plane strain condition can be changed (geometric change), with permeability made fixed at axisymmetric and plane strain conditions ($k_{ax} = k_{pl}$).
2. The permeability of plane strain conditions can be altered (permeability change), with the same geometry being created.
3. Combines geometry and permeability changes.

3. Results and Discussion

3.1 Field of measurements
Settlements that occured during construction are observed with the help of settlement plate tools. In this study the decrease was reviewed at three points of observation as shown in Figure 4.

The points reviewed in the data monitoring of settlement plate by 3 points, namely point S-19, point S-20, and point S-21. Each point had different settlement at the same consolidation times. Point had S-19 settled 0.578 m, point S-20 settled 0.355 m, and point S-21 settled 0.212 m.
3.2. Finite Element Modeling
Predictions were made using plane strain finite element analyses (FEA). The embankment and soil condition were in model two dimensional.

3.2.1. Unit Cell Analysis
In the field the pattern of PVD planeting is done locally with a certain distance, whereas in the FEM program the implementation of PVD is continuous (plane strain). Using Table 1 and 2, the first stage was verification of the axisymmetric cell unit with the coefficient of permeability of axisymmetric conditions and then equate the same water discharge with the condition of the plane strain in the form of unit cell plane strain (Figure 5).

![Figure 4. Settlement Comparison of three-point settlement plates](image)

Table 1. Geometry for Unit Cell Analysis

| Depth (m) | w (m) | t (m) | re (m) | rw (m) | dm (m) | rs (m) |
|-----------|-------|-------|--------|--------|--------|--------|
| 11        | 0.1   | 0.05  | 0.6563 | 0.0334 | 0.2873 | 0.1437 |

Table 2. Coefficient of Permeability for Cell Unit Analysis

| Material     | Kondisi Axysimetric | Kondisi Plane Strain |
|--------------|----------------------|----------------------|
|              | kh (m/day)           | kv (m/day)           | output  | kh (m/day) | kv (m/day) | output  |
| Silty Sand   | 2,7376x10^-4        | 1,3688x10^-4        | non smear zone | 1,0950x10^-4 | 5,4752x10^-5 | non smear zone |
|              | 1,0950x10^-4        | 5,4752x10^-5        | smear zone (kr<kr/2,5) | 4,38x10^-5 | 2,19x10^-5 | smear zone (kr>kr/2,8) |
Figure 5. Degree of consolidation versus time of the axisymmetric and plane strain conditions

3.2.2. Full Scale Analysis

Limits modeled on the full-scale element calculations have a length of 150 m in the horizontal direction and 20.26 m in the vertical direction of the lower layer with a heap of 6.02 m. Only half of the heap is modeled because the heap is symmetrical. Horizontal fixities are applied to the finite element mesh on the left and right sides and on vertical movement (Vertical fixities) at the top and bottom of the mesh. In the full-scale analysis of the disturbed area effects considered is $k_h / k_s = 2.8$ this value is taken from the value of the near-field matching.

Geometry and mesh model of the Sta 0 + 750 runway of landfill is shown in Fig. 6 and Fig. 7. The soil parameters used in the analysis using the finite element method is shown in Table 3.

Table 3. Properties of Land Parameters Mohr-Coulomb Model

| Properties | Unit | Preloading | Embankment Struktur | Sand Blanket | Silty Sand | Sand |
|------------|------|------------|---------------------|-------------|-----------|------|
| $c$        | kN/m$^2$ | 5,000      | 5,000               | 10,000      | 9,600     | 5,000 |
| $\varphi$  | derajad | 30,00      | 30,00               | 30,00       | 7,750     | 30,00 |
| $\psi$     | angle   | -          | -                   | -           | -         | -    |
| $k_x$      | n/day   | 8,640      | 8,640               | 8,640       | 9.78E-05  | 0.061 |
| $k_y$      | n/day   | 8,640      | 8,640               | 8,640       | 4.99E-05  | 0.012 |
| $J_{av}$   | kN/m$^3$ | 16.00      | 16.00               | 16.00       | 7.7       | 16   |
| $J_{sat}$  | kN/m$^3$ | 19.00      | 19.00               | 19.00       | 14.6      | 19   |
| $E$        | kN/m$^2$ | 5000       | 10000               | 5000        | 3300      | 34500 |
| $\nu$      | -       | 0.300      | 0.300               | 0.300       | 0.300     | 0.350 |

Figure 6. Runway geometry modeling at Sta 0 + 750
3.3. Deformation pattern

Points reviewed in the calculation of the finite element method are two points, namely point A (0,0) and point B (30,0) indicating the position of the settlement plate location points shown in Fig. 8. Each point has a varying magnitude of decline but the required consolidation time is the same for all points.

![Figure 7. Mesh runway at Sta 0+750](image)

![Figure 8. Displacement deformation pattern Mohr-Coloumb Model](image)

![Figure 9. Settlement graph of nodal point A (0;0)](image)
In Figs. 9 and 10 show the decrease graph that occurs in the silty sand layer with the Mohr-Coloumb model with two points of view i.e. the point node A with a maximum decrease of 0.3162 m, while at the point node B of 0.2427 m with the length of time The same consolidation at both points of review amounted to 758 days.

3.4. Discussion
The settlement comparisons between the field observations and Mohr-Coloumb soil model are shown in Table 4.

| Method | Field Observation (m) | Mohr-Coloumb soil model |
|--------|-----------------------|--------------------------|
|        | S-19                  | S-20                     | S-21                  |
|        | 0.578                 | 0.355                    | 0.212                 |
|        |                       | Point A                  | Point B               |
|        |                       | 0.316                    | 0.243                 |

4. Conclusion
From the results of the research, it could be concluded that:
1. From the embankment analysis using FEM 2D program using Mohr-Coloumb soil model, it was obtained the settlement at both points, point A equal to 0.316 m and point B equal to 0.243 m.
2. From field monitoring results using settlement plate from three points of view, point S-19 settled 0.578 m, point S-20 point settled 0.355 m, and point S-21 settled 0.212 m.
3. The major differences in the settlement at each point could be due to the difference of the soft soil across the runway that was not monitored on bore hole sampling that was performed only on the middle allong the runway.

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