Effectiveness study of prefabricated vertical drain using vacuum preloading and surcharge preloading

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Abstract. Prefabricated vertical drain is a method of soil improvement in order to accelerate consolidation settlement. In line with the development of knowledge, vacuum preloading was used to replace embankment preloading to produce stress in soil. This research will compare the effectiveness of vacuum preloading against the embankment preloading through the analysis of the degree and time of consolidation. The prediction of settlement is manually calculated using 1 dimension consolidation Terzaghi’s theory method, while the finite element method by PLAXIS 2D Program and ASAOKA method from settlement on the field. The horizontal coefficient of consolidation used is based on the result of back calculation using ASAOKA’s chart. The ratio of coefficient consolidation \( C_h/C_v \) obtained for vacuum preloading is 5.9 and for embankment preloading is 2.21-4.25. The analysis show that the vacuum preloading method can cut the consolidation time up to 74% comparing the embankment preloading method.

Keywords: Effectiveness, Vacuum Preloading, Embankment Preloading, Prefabricated Vertical Drain (PVD), PLAXIS 2D

1. Introduction
Prefabricated Vertical Drain is an alternative of soil improvement method in soft soil that aims to increase the shear strength of the soil, reduce soil compressibility and prevent a large consolidation reduction in order to avoid structural damage due to large settlement. In the conventional method the preloading is carried out by giving a heap over the soft soil. The preloading material may be sand, rock or water. In 1952 Kjelmann introduced the method of vacuum preloading as a substitute for loading using a heap (surcharge preloading) on conventional Vertical Drain.[1]

Characteristics of vacuum preloading have been tested by comparing vacuum pressure with surcharge load in the laboratory oedometer test. From the test results it was found that by using vacuum pressure resulted in a smaller consolidation settlement compared to the settlement caused by embankment preloading with the same pressure.[3]

2. Research Methodology
In order to determine the effectiveness of both schemes, the comparison of the degree and time of consolidation reached by both scheme will be observed. The observation will be based on the project data located in Banjarmasin – South Kalimantan.
Furthermore, the soil investigation data on the project is used for the calculation of consolidation settlement according to the 1-D consolidation principle of Terzaghi [6] and analysis using soft soil modeling in the finite element program PLAXIS 2D. Then the settlement plate data in the field is used to predict the final settlement by using Asaoka method. For horizontal permeability coefficients used in the analysis of the 1-D Terzaghi consolidation principle and the PLAXIS 2D program are used from back calculation based on the Asaoka method equation [11].

In addition to the analysis using the above three methods, simulations are also used using PLAXIS 2D program with two types of cases. In the first case, for both types of preloading varied the amount of loading (height 2m, 3m, 4m, 4.7m, and 5m for embankment loading and 60, 70, 80, 90 and 108 kPa on vacuum loading) and permeability coefficient ratio \((kh/kv)\) used is set at 2 in both types of preloading. In the second case, 80 kPa modeled loads in both types of loading and permeability coefficient ratios \((kh/kv)\) were varied by 2, 4, 6, 8, and 10. Both types of simulations were then analyzed for variation effects on the consolidation settlement in both types of preloading.

3. Results and Analysis

3.1. Project X Banjarmasin, South Kalimantan

In this project, the embankment is still required to reach the design elevation. The subsoil is dominated by soft soils reaching a depth of ± 22 m. The two main problems faced are a large, long-term settlement of consolidation and low bearing capacity. To solve this problem, soil improvement method was chosen by acceleration of consolidation by using vertical drain with two different types of preloading schemes i.e. embankment preloading and vacuum preloading. The pattern of drain is depended on the preloading scheme, triangular pattern for embankment preloading and rectangular pattern for vacuum preloading scheme. The spacing of drain for both pattern is 1m and the installation depth of drain is 21.5m.

![Vertical Drain Installation Map](image)

Figure 1. Vertical Drain Installation Map: a) Green zone for Embankment Preloading (Triangle Pattern); b) Red zone for Vacuum Preloading (Rectangular Pattern).
(Source: Project X Soil Investigation Data)

3.2. Soil Condition and Soil Investigation Data

Soil properties were obtained from laboratory test and empirical correlation of N-SPT value as shown in Table 1. Based on soil investigation result including N-SPT value, the subsoil can be divided into several layers. In the surface, up to 3m depth, the soil layer consists of fine loose sand. Below this sand layer, the cohesive soil with thickness in range of 3-11 m is found. The consistency of this clay is very soft to soft with an average plasticity. Then at the soil depth of 11-21 m there is a layer of cohesive soil.
with high plasticity. In the depth of 21-24.5 m, the soil layer is dominated by low plasticity of very soft
to stiff silty clay. At a depth of 25 m at the stiff clay is found and no hard soil layer has been encountered.
The groundwater level is found at a depth of 0.6 m.

Table 1. Soil Parameter from Soil Investigation Project X

| Depth (m) | γ (kN/m²) | H (m) | Cc | Cr | Vertical Coef. Consolidation (Cv) | k_v (cm/sec) | e_0 |
|-----------|-----------|-------|----|----|-------------------------------|-------------|-----|
| 0.00 - 3.00 | 20 | 3 | - | - | 0.000305 | 1.68E-05 | 1.981 |
| 3.00 - 4.00 | 14.6 | 1 | 1,171 | 0.187 | 0.000354 | 2.44E-05 | 1.659 |
| 4.00 - 6.50 | 15.4 | 2.5 | 0.689 | 0.133 | 0.000213 | 1.69E-05 | 2.014 |
| 6.50 - 9.00 | 15 | 2.5 | 1.013 | 0.151 | 0.000179 | 1.31E-05 | 1.627 |
| 9.00 - 11.00 | 15.4 | 2 | 0.657 | 0.127 | 0.000184 | 1.79E-05 | 2.02 |
| 11.00 - 12.50 | 14.8 | 1.5 | 0.722 | 0.153 | 0.000198 | 2.00E-05 | 1.863 |
| 12.50 - 14.50 | 14.8 | 2 | 0.616 | 0.138 | 0.00016 | 1.73E-05 | 2.04 |
| 14.50 - 16.50 | 15 | 2 | 0.645 | 0.085 | 0.0001 | 1.73E-05 | 0.969 |
| 16.50 - 19.00 | 14.6 | 2.5 | 0.938 | 0.094 | 0.000213 | 1.73E-05 | 1.957 |
| 19.00 - 21.00 | 15 | 2 | 0.665 | 0.057 | 0.000227 | 1.66E-05 | 0.969 |
| 21.00 - 23.00 | 17.6 | 2 | 0.376 | 0.052 | 0.000863 | 2.57E-05 | 1.818 |
| 23.00 - 24.50 | 17.6 | 1.5 | 0.376 | 0.052 | 0.000863 | 2.57E-05 | 1.818 |

(Source: Project X Soil Investigation Data)

3.3. Back Calculation of Horizontal Coefficient of Consolidation (C_h)

In order to obtain the result of degree of consolidation in accordance with the field then for the purposes
of analysis used the result of back calculation horizontal coefficient of consolidation based on Asaoka
method principle shown in Equation 1.([11])

$$
C_h = \left( -\frac{\ln \beta}{\delta t} - \frac{\pi^2 \cdot C_v}{8 \cdot H^2} \right) \cdot D^2 \cdot F_v
$$

(1)

Through equation 1, we can do the back calculation of coefficient of consolidation in horizontal
direction (C_h).

Table 2. Back Calculation Horizontal Coefficient of Consolidation on Surcharge Preloading

| Settlement Plate | Stage | B | In β | Ch (m²/day) | Ch/Cv |
|------------------|-------|---|------|------------|-------|
| SP01&SP04        | Stage 1 | 0.992 | -0.01 | 0.0022 | 1.07 |
|                  | Stage 2 | 0.969 | -0.03 | 0.0089 | 4.25 |
| SP06             | Stage 1 | 0.995 | -0.01 | 0.0014 | 0.66 |
|                  | Stage 2 | 0.97 | -0.03 | 0.0084 | 3.99 |
| SP09             | Stage 1 | 0.998 | 0 | 0.0005 | 0.25 |
|                  | Stage 2 | 0.991 | -0.01 | 0.0025 | 1.2 |
|                  | Stage 3 | 0.984 | -0.02 | 0.0046 | 2.21 |
|                  | Stage 1 | 0.998 | 0 | 0.0007 | 0.33 |
| SP10&SP11        | Stage 2 | 0.976 | -0.02 | 0.0066 | 3.17 |
|                  | Stage 3 | 0.971 | -0.03 | 0.0083 | 3.96 |
Table 3. Back Calculation Horizontal Coefficient of Consolidation on Vacuum Preloading

| Settlement Plate | $\beta$ | $\ln \beta$ | Ch (m$^2$/day) | Ch/Cv |
|------------------|--------|-------------|----------------|-------|
| 2                | 0.961  | -0.04       | 0.0132         | 6.32  |
| 3                | 0.965  | -0.036      | 0.0119         | 5.69  |
| 5                | 0.964  | -0.036      | 0.0122         | 5.81  |
| Average of SP 2,3,5 | 0.964  | -0.037  | 0.0124         | 5.9   |

3.4. Final Settlement Prediction Analysis

The final settlement prediction analysis uses the 1-D Terzaghi consolidation settlement theory with the type of normal consolidated settlement as described in Equation 2:

$$S_c = \frac{C_v H}{1 + \varepsilon_o} \log \left( \frac{\sigma''_o + \Delta \sigma}{\sigma''_o} \right)$$  \hspace{1cm} (2)

Furthermore, the time consolidation against consolidation settlement curve was made using the consolidation degree analysis proposed by Baron (1948).

$$U_v = \frac{(4T_v \cdot \varpi)^{0.5}}{1 + (4T_v \cdot \varpi)^{3.8} \cdot 0.179}$$  \hspace{1cm} (3)

$$T_v = \frac{t_v \cdot C_v}{H^2}$$  \hspace{1cm} (4)

$$U_h = \left[ 1 - \left\{ \exp \left( -\frac{8 \cdot T_h}{F_h} \right) \right\} \right]$$  \hspace{1cm} (5)

$$T_h = \frac{t_h \cdot D^2}{C_h}$$  \hspace{1cm} (6)

$$F_n = \ln \left( \frac{D}{d_v} \right) - \frac{3}{4}$$  \hspace{1cm} (7)

In addition, the final consolidation settlement analysis using PLAXIS 2D program using soft soil modeling is used. Gouw (2008) explains that vertical drain can be modeled in the PLAXIS 2D program so it needs coefficient permeability equivalent using vertical drain through Equation 8-11.

$$n = \frac{D}{d_v}$$  \hspace{1cm} (8)

$$\mu = \frac{n^2}{n^2 - 1} \left[ \ln(n) - \frac{3}{4} + \frac{1}{n^3} \left( 1 - \frac{1}{4 \cdot n^2} \right) \right]$$  \hspace{1cm} (9)

$$k_v' = k_v + \frac{32}{\pi^2} \cdot \frac{H^2}{\mu \cdot D^2} \cdot k_h$$  \hspace{1cm} (10)

$$k_h' = k_h$$  \hspace{1cm} (11)

Where the $k_v'$ and $k_h'$ values are the permeability coefficients after the vertical drain is attached. The $k_h$ values used is derived from $k_0/k_v$ ratio which is proportional to rasio of $C_h/C_v$ based on back calculation before.
Figure 2. Illustration of PLAXIS 2D Modeling

In the type of vacuum preloading model, the loading is modeled on the left and right as a vacuum effect model when the vacuum preloading is applied.

Based on the above equation then obtained the consolidation settlement against time consolidation curve from consolidation analysis 1-D Terzaghi theory, PLAXIS 2D program and compared to settlement data in the field.

a) Settlement on SP01 and SP04

b) Settlement on SP06
c) Settlement on SP09  
d) Settlement on SP10 and SP11

Figure 3. Analysis Results of Consolidation Settlement in Surcharge Preloading

The consolidation settlement with surcharge preloading (conventional preloading) on the 256th day is about 766 mm to 1300 mm depending on the height of embankment that applied on the field. The height of embankment on the conventional preloading that applied is varied from 2,28 m to 3,80 m with the specific gravity of the embankment soil at 17 kN/m3. Then the pressure that applied on the surface of soil is obtained between 38 kPa to 65 kPa. The average degree of consolidation of each settlement plate varied between 90% to 100% on 256th day. While with vacuum preloading, the consolidation settlement on the 63rd day varied between 1200 mm to 1420 mm. The pressure from vacuum preloading based on the pump reading is 80 kPa. The average degree of consolidation using vacuum preloading is 91.12% which is achieved in 63 days.

The results of analysis based on settlement plate on the field show that the degree of consolidation at 90% with vacuum preloading is achieved in shorter time compared with the surcharge preloading. Based on analysis with Asaoka method, the degree of consolidation at 90% with surcharge preloading could be achieved in 256 days. Meanwhile with vacuum preloading, the degree of consolidation at 90% could be achieved only in 63 days. Therefore, the vacuum preloading could shorten the time consolidation about 74% compared with the surcharge preloading.

Figure 4. Analysis Results of Consolidation Settlement in Vacuum Preloading
The shorter amount of time needed to achieve degree of consolidation at 90% with vacuum preloading is due to influence of type of preloading and soil parameters such as coefficient of consolidation and coefficient of permeability of soil. This is evidenced by previous research [13]. Saowapakpiboon explained that the coefficient of consolidation in horizontal direction using vertical drain with vacuum preloading was larger compared to vertical drain without vacuum preloading that also happened in this research. The Horizontal Coefficient of Consolidation \((C_h)\) obtained from back calculation using Asaoka method show that the horizontal coefficient consolidation using vacuum preloading is larger than the horizontal coefficient consolidation using surcharge preloading.

### Table 4. Summary of Horizontal Coefficient of Consolidation \((C_h)\) Value Obtained from Back Calculation

| SP           | Type of Preloading          | \(Ch\) | \(Ch/Cv\) |
|--------------|----------------------------|--------|-----------|
| SP01&SP04    | Surcharge Preloading (Conventional) | 0.0089 | 4.25      |
| SP06         | Surcharge Preloading (Conventional) | 0.0084 | 3.99      |
| SP09         | Surcharge Preloading (Conventional) | 0.0046 | 2.21      |
| SP10&SP11    | Surcharge Preloading (Conventional) | 0.0083 | 3.96      |
| SP-2, SP-3, SP-5 | Vacuum Preloading     | 0.0124 | 5.9       |

Based on Table 4, the ratio of the \(C_h/C_v\) value produced by the Asaoka method with embankment preloading yields a ratio value ranging from 2.21 to 4.25. While using the type of vacuum preloading obtained ratio of the value of \(C_h/C_v\) produced by Asaoka method about 5.90. Then it can be concluded that the vacuum preloading can produce \(C_h\) value greater than the type of surcharged preloading so it can cause the achievement of the degree of consolidation using vacuum method can be achieved in a relatively shorter time compared to embankment preloading.

#### 3.5. PLAXIS 2D Program Modeling Simulation

To be able to know the influence of the actual type of loading, then done two types of variation parameters using PLAXIS 2D program. The PLAXIS program itself is used as a model to facilitate calculations and produce more accurate modeling (since the Terzaghi method can not model the pressure on the edge of the soil layer with the loading of the vacuum). The two types of parameter variations are:

a. Simulation of both types of loading with the given pressure variations of 60, 70, 80, 90, and 108 kPa at the loading of vacuum type and heap height of 2 m, 3 m, 4 m, 4.7 m (equivalent to 80 kPa vacuum load) and 5 m with the coefficient ratio of \(C_h/C_v\) or \(k_h/k_v\) of 2;
b. Simulation of both types of loading with variations in the ratio of \(C_h/C_v\) or \(k_h/k_v\) coefficients of 2, 4, 6, 8, and 10. With the loading given to both types of loading equal to 80 kPa.

Analysis of the first simulation using a variation of the ratio \(k_h/k_v\), use value \(k_h\)and \(k_v\) in modeling in accordance with Table 5.

### Table 5. Equivalent Permeability After Vertical Drain Installed for PLAXIS Program

| \(k_v\) (m/day) | Variation \(k_h/k_v\) | \(k_h\) (m/day) | \(k_h'\) (m/day) | \(k_v'\) (m/day) |
|----------------|----------------------|----------------|----------------|----------------|
| 2              | 3,70E-05             | 2,48E-02       | 3,70E-05       |
| 4              | 7,40E-05             | 4,95E-02       | 7,40E-05       |
| 6              | 1,11E-04             | 7,43E-02       | 1,11E-04       |
| 8              | 1,48E-04             | 9,90E-02       | 1,48E-04       |
| 10             | 1,85E-04             | 1,24E-01       | 1,85E-04       |

Based on the result of modeling of loading variation in both types of loading, the trendline of the time rate of consolidation degree reached 90% against on the amount of loading variation applied in the model and the settlement trendline \((U = 90\%)\) to the variation of loading load applied as shown in Figure 5 and Figure 6.
In Figure 5 it can be concluded that the greater the load applied, the time required to achieve 90% consolidation degree is also reduced exponentially. When compared between surcharge preloading and vacuum preloading with the same load weight (80 kPa), the time required to achieve 90% consolidation degree on conventional loading is relatively 10% shorter than the time taken by the vacuum loading to achieve a 90% consolidation degree at the same permeability ratio.

Then in Figure 6 it can be seen that the settlement achieved by the surcharge preloading is relatively 32% greater against the settlement caused by the loading of the vacuum with the same load and permeability ratio.

Thus, although the time efficiency achieved by surcharge preloading is relatively short 10% relative to the loading of vacuum. The settlement caused by the surcharge preloading is greater than the settlement caused by the vacuum preloading so that if the settlement of vacuum preloading at a 90% consolidation degree is 1228 mm achieved at 141 days, then on surcharge preloading with equal loading (80 kPa) can be resulting settlement of 1228 mm within 39 days or a relative 72% shorter over the time it takes the vacuum loading to reach a decrease of 1228 mm. It should be remembered also that the above analysis ignores the fact that the values of the permeability ratio will increase with increasing loads working above the ground.

Based on the data of the analysis result in the second simulation, the trendline of the variation of permeability coefficient ratio ($k_h/k_v$) to the time required to achieve consolidation settlement at $U = 90\%$ obtained as below.
Figure 7. Curve of Permeability Ratio Variation ($k_h/k_v$) against Time Consolidation at $U = 90\%$

Based on Figure 7, the result of regression equation is $y = 15.854e^{-0.015x}$ and $y = 17.224e^{-0.018x}$ so it can be concluded that the increasing of permeability coefficient ratio can shorten the time needed to achieve 90% consolidation degree exponentially. It is also known that the greater the permeability coefficient ratio, the difference of time to obtained $U = 90\%$ in both types of loading will be decrease until it matches each other.

4. Conclusion and suggestion

Based on the results of the analysis obtained, the conclusion are as follow:

a. Based on degree of consolidation analysis using final settlement prediction with Asaoka method, the time of consolidation needed with vacuum preloading to achieve degree of consolidation at 90% is 74% more efficient compared to surcharge preloading.

b. Based on Horizontal Coefficient of Consolidation ($C_h$) back calculation using Asaoka method, vacuum preloading produced the coefficient of consolidation ratio ($C_h/C_v$) at 5.90. While with surcharge preloading the coefficient of consolidation ratio ($C_h/C_v$) obtained between 2.21 ~ 4.25;

c. The consolidation settlement increasing linearly with the load applied. In surcharge preloading can produced the settlement of consolidation relatively larger compared to vacuum preloading.

d. The speed of consolidation increases exponentially proportional to the permeability coefficient ratio used in the analysis;

e. Based on simulation using PLAXIS 2D, the time consolidation needed from embankment preloading has more efficient compared to vacuum preloading with the same value of coefficient permeability and same amount of loading;

Suggestions that can be given based on this research for further research is as follows:

a. Further research is needed whether differences in the type of loading also affect the value of the permeability and the consolidation coefficients;

b. Soil parameters used should be based on accurate and complete test results on each layer type, it is intended to minimize the use of correlation. If in the analysis used correlation to find the value of soil parameters then used correlation according to the standard so that the results do not deviate.

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