PERFORMANCE OF PRE-FABRICATED VERTICAL DRAINS & PRE-LOADING FOR A MAJOR CONSTRUCTION PROJECT

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ABSTRACT: Trial embankments were constructed to test the performance of pre-fabricated vertical drains (PVD) for accelerating consolidation of soft clay strata for the construction of a major construction project. At three different trial locations PVD were installed at different spacing and test embankments were constructed to evaluate the performance of the PVD and to arrive at the optimum spacing to be adopted for the project. Soil instrumentation including piezometers and settlement gauges were installed to monitor progress of soil consolidation. Boreholes were carried out both before and after ground improvement to determine the increase in bearing capacity of the underlying weak clay stratum as a result of consolidation. On the basis of the trial, it was decided to replace deep pile foundations for certain structures with shallow foundations resulting in considerable savings in cost of foundations for the project. The paper describes the details of the trial and reviews the results comparing them with the theoretical time-consolidation relationship. Based on the results of the trial, the ground improvement design for the project was finalized.

INTRODUCTION
The subsoil conditions at the project site consisted of thick deposits of soft clay underlying medium dense silty sand stratum. To reduce the cost of foundations for the project, the possibility of constructing shallow foundations for at least some structures where foundation loading did not exceed 7T/sq.m was considered. The safe bearing capacity of the underlying soft clay stratum was low and excessive foundation settlement could be expected under such foundation loading. The feasibility for improving the bearing capacity as well as to reduce the post construction settlement in soft clay, several methods to improve the soft clay were considered. It was finally decided that the most cost-effective method for achieving this would be by accelerating the clay consolidation with prefabricated vertical drains (PVD) and pre-loading. In order to confirm this proposal, a trial was carried out at three locations at site adopting three different PVD spacing and pre-loading.

SUBSOIL CONDITION
Soil investigation at the site confirmed the average subsoil profile for the site as follows. Medium dense silty sand existed from ground level to a depth of 6-7 m which is underlain by soft compressible silty clay up to approx 20m below GL. Below the soft clay layer existed stiff clay to considerable depth. The soft silty clay was normally consolidated with low shear strength and was moderately to highly compressible, CH soil. The average properties of the strata are included in Table 1.

As the soft clay extended to large depths, it was clear that pile foundation to support the loading will be deep and expensive. The need to explore possibility of shallow foundation for moderately loaded structures arose as a result of this. However the proposal of PVD and pre-loading had to be tested at site in a trial before adopting this method for the project.

TRIAL GROUND IMPROVEMENT
Three locations were chosen for the trial, details of which are given in Table 2.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Summary of Soil Profile and Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property</td>
<td>M. Dense Sand</td>
</tr>
<tr>
<td>Strata Thickness</td>
<td>6-7m</td>
</tr>
<tr>
<td>Bulk Density, kN/m³</td>
<td>17</td>
</tr>
<tr>
<td>Cohesion, cu, kN/m³</td>
<td>-</td>
</tr>
<tr>
<td>LL,%</td>
<td>-</td>
</tr>
<tr>
<td>PL,%</td>
<td>-</td>
</tr>
<tr>
<td>Compression Index, Cc</td>
<td>-</td>
</tr>
<tr>
<td>Coeff. Consolidation, Cv,m²/yr</td>
<td>-</td>
</tr>
<tr>
<td>Initial Voids Ratio</td>
<td>-</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Details of Trial Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial Area</td>
<td>Size of Test Area</td>
</tr>
<tr>
<td>Area-01</td>
<td>50 m length x 50 m width</td>
</tr>
<tr>
<td>Area-02</td>
<td>50 m length x 50 m width</td>
</tr>
<tr>
<td>Area-03</td>
<td>50 m length x 10 m width</td>
</tr>
</tbody>
</table>

The size of test areas denote the top of the pre-loaded areas excluding side slopes. Geotechnical instruments were installed in the above test areas as follows.
Settlement gauges – 5 nos, one at the centre of the pre-load area and others at locations between the centre and the periphery.

Piezometers - 2 nos at centre of pre-load area, one at 10m below GL and another at 15m below GL.

Instrument observations were made for a period of about 10 months.

The PVD was installed using a hydraulic drain stitcher using a steel mandrel and a disposable drain shoe. The maximum depth of band drain installation was 20m below GL. The upper silt layer overlying the soft clay stratum was medium dense and the drain stitcher had difficulty penetrating this layer. The machinery had to be suitably modified prior to band drain installation.

A sand drainage blanket 300mm thick was spread above the installed band drains to allow easy flow of the discharged pore water from the drains during consolidation.

All three test areas were pre-loaded with earth up to height 4m above GL with side slope 1V:2H. The earth pre-load was placed in layers 300mm thick and was compacted to requirement. Area-02 & 03 were preloaded within a period of one month. However, Area-01 preloading took a much longer period of more than three months.

**SETTLEMENT OBSERVATIONS**

Settlement observations at the centre of the three pre-loaded areas after full preload placement only have been reported. The observed settlement for the three trial areas are included in Fig- 1.

The peak excess pore pressures registered and expressed as percentage of applied pre-load for the piezometers are given in Table.3.

<table>
<thead>
<tr>
<th>TEST AREA</th>
<th>P1,15m Depth, m</th>
<th>P1,15m Preload, %</th>
<th>P2,10m Depth, m</th>
<th>P2,10m Preload, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA-01</td>
<td>0.635m 9%</td>
<td>1.115m 16%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AREA-02</td>
<td>3.5m 51%</td>
<td>2.09m 31%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AREA-03</td>
<td>1.02m 15%</td>
<td>1.796m 26%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Pre-load pressure considered as 68 kN/sq.m

It may be noted that maximum excess pore pressure registered was about 50% of applied pre-load at the centre of the clay layer when large area is pre-loaded. The stress distribution in clay may have been influenced to some extent by the thick medium dense sand layer overlying the clay layer.

**PIEZOMETER OBSERVATIONS**

Though piezometer observations were made since their installation, only observations after full preload placement have been reported here. However a number of piezometers were damaged and observations could not continue for long periods.

Piezometers were installed at depth 15m (P-1, approx. mid depth of clay) and 10m (P-2, about 2m below clay surface) below GL for all three trial areas and they showed peak excess pore pressures soon after full pre-load was placed and dissipation took place gradually during the period of observation. The observations are included in Fig- 2. As may be seen some negative pore pressure was observed at some locations towards the end of the observation period. However this may be due to some difference in reference levels considered rather than actual negative pore pressures.

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**Fig.1 Settlement Observations**

It may be noted that initially consolidation settlement took place rapidly but the progress of consolidation after a period was found to be rather gradual for larger PVD spacing as may be expected. It is clear from the above, that much longer periods are necessary to achieve the required degree of consolidation as the PVD spacing increases.

Settlement at Area-01 was slower initially compared with that for Area-02 even though the preload area and height were similar. The reason for this could be the much longer preloading period for Area-01.
DEGREE OF CONSOLIDATION
In order to determine the degree of consolidation achieved within each trial area, it is necessary to determine the total expected primary consolidation settlement under the applied pre-load ($U = 100\%$). The procedure proposed by Asaoka [1] was adopted for determining the total primary consolidation settlement from observed settlement. This procedure had been adopted successfully for several ground improvement projects earlier [2,3]. Using this procedure, the maximum primary consolidation settlement for the three trial areas under the 4m high preload was predicted to be about 510mm. Based on this final consolidation settlement, the degree of consolidation achieved at the centre of the pre-load area for the three trial locations were computed and results are shown in Fig- 3. Please note that the period to achieve the degree of consolidation shown is the period after the full pre-load placement.

![Fig.3 Degree of Consolidation](image)

For Area-01 with PVD spacing 1.5m, the period of observation was not sufficient to achieve $U=90\%$. However from the trend of settlement observed, this should take longer than 12 months after preloading. For Area-02 with PVD spacing 2.5m also $U=90\%$ was not achieved within the observation period. By extrapolation it may also be expected to take more than 12 months after preloading. For Area-03 with PVD spacing 1.25m and $U=90\%$ has taken place 240 days or about 8 months after pre-loading. It is therefore clear that given the low soil permeability at site, if the consolidation period is to be shortened, it is necessary to reduce the PVD spacing or increase the pre-load or both.

SOIL INVESTIGATION & TESTS
Confirmatory soil investigation including boreholes, soil sampling and in-situ tests were carried out at the end of the observation period at the centre of the three trial areas up to a depth of 20m below GL. Laboratory tests for shear strength and consolidation parameters were conducted on undisturbed clay samples collected from the boreholes.

UN-DRAINED COHESION
In-situ vane shear tests were conducted after ground improvement to determine un-drained shear strength of the soft clay. Laboratory unconfined compression tests on undisturbed samples of clay were also carried out to confirm the results. The results have been presented in Fig. 4. For comparison the initial average profile of the un-drained cohesion with depth has also been included.

![Fig.4 Un-drained Cohesion](image)

The un-drained clay cohesion after consolidation varies from 35 to 60 kPa for the soft clay layer up to depth 18m as may be seen from Fig. 4. The average cohesion may be considered as about 40kPa. The average soft clay cohesion before ground improvement had been established as not more than $c = 20$ kPa. Considering this base cohesion, it may be concluded that the increase in un-drained cohesion after ground improvement expressed as a percentage of the applied preload, $\Delta c/\Delta p$ varied from 25% - 30%. Similar range of improvement has been observed for soft clay by other researchers [4].

CONSOLIDATION PARAMETERS
Post consolidation soil investigation also established the consolidation parameters of the clay. Coeff. of consolidation, $C_v$ varied from 0.8m$^2$/yr to 1.1m$^2$/yr. Average $C_v$ may be considered as 0.9m$^2$/yr for the clay layer. Similarly Compression Index, $C_c$ varied from 0.37 to 0.7 and Initial Voids Ratio, $e_0$ from 0.898 to 1.248 with average values of 0.5 and 1.1 respectively.

BEARING CAPACITY
The safe bearing capacity for shallow foundation may be considered based on the following.

- The shear strength of the soft clay layer should be adequate to support the imposed foundation load without failure.
- The long term and uneven settlement should not exceed recommended values for the proposed structures.

Considering the minimum post consolidation un-drained cohesion $c=35$kPa, the maximum allowable safe bearing capacity for shallow foundations on clay may be as follows.

For $\phi=0$, allowable bearing capacity

$$q_{allow} = 5.7 \times 35kPa/2.5 = 80 \text{ kPa or 8 T/sq.m}$$
This is commensurate with the applied pre-load for the ground improvement as may be expected. However, the maximum foundation load intensity may be limited to 7T/sq.m to reduce post construction settlement, if any to a minimum.

The long term settlement that can be expected after ground improvement may depend on the following.

- The degree of consolidation achieved prior to removal of pre-load
- The imposed foundation load after construction of the facility
- Possibility of long term secondary consolidation of the soft clay.

If degree of consolidation 90% is achieved under the imposed foundation load, then expected further foundation settlement should not exceed 10% of the total primary consolidation settlement expected. This is of course considering that the max foundation load will not exceed the pre-load and secondary consolidation settlement will be small. In this case, the post consolidation settlement may not exceed 50-60mm under the foundation load considering a total expected settlement of 510mm under the applied pre-load. One good aspect of the ground improvement using band drains and pre-loading is that post construction settlement in such cases, if any, will be more or less uniform as reported in an earlier study [5].

Soil investigation has shown that the soft clay is not organic in nature. Organic clays exhibit relatively large secondary consolidation phenomenon and since the clay is not organic, secondary effects of this clay may be considered to be small.

CONCLUSIONS

The trial ground improvement carried out using PVD and preloading has achieved the requirements set out for the project in terms of post construction settlement and safe bearing capacity. The trial ground improvement established the basis for selecting optimum PVD spacing and preloading to be adopted to achieve the required degree of consolidation as well as the period required to achieve it.

The increase in un-drained cohesion of soft clay after ground improvement expressed as percentage of pre-load intensity (Δc/ Δp) was found to vary from 25% - 30% for this site.

The trial ground improvement established that it is possible and safe to construct shallow foundations for structures with maximum foundation load intensity 7T/sq.m on soft clay after ground improvement with PVD and preloading.

Careful design of the requirements, proper soil investigation before and after ground improvement as well as instrumentation and monitoring the progress of consolidation are vital for successful ground improvement projects.

REFERENCES


ACKNOWLEDGEMENT

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