

LAND RECLAMATION USING PREFABRICATED VERTICAL DRAINS (PVD) IN PORT OF MOMBASA

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Abstract

Land reclamation is used to describe two different activities. In the first sense, it involves modifying wetlands or waterways to convert them into usable land, usually for the purpose of development. It can also be a process in which damaged land is restored to its natural state. In both cases, the term is used to refer to some sort of process that is designed to fundamentally alter the characteristics of a piece of land to achieve a desired end goal. The need for additional port capacity in Kenya has rapidly risen over the last few years due to globalization. Due to high cost of land procurement, land reclamation has become a very promising alternative for expanding and constructing new ports. The presence of soft marine clay poses a major challenge for port development as it requires ground improvement. The Mombasa Port Development Project in the Republic of Kenya involved the filling of approximately 6 million cubic metres of sand for the land reclamation of a total area of about 49 hectares. Land reclamation was carried out using fill materials obtained from dredging granular material from the seabed at the borrow source situated near Tiwi in Kwale County. The ground improvement technique that involved combination of prefabricated vertical drain (PVD) with preloading was successfully applied in this project to improve the underlying compressible soils. The project comprises the installation of prefabricated vertical drains and the subsequent placement of surcharge to accelerate the consolidation of the underlying marine clay. The objective of the research is to assess the disparity of performance of ground improvement and to validate the performance of the prefabricated vertical drain system. Several geotechnical instruments were installed to monitor the degree of consolidation at both areas with PVD and areas without PVD as control area. This paper provides a case study of the ground improvement works carried out with prefabricated vertical drains at the Mombasa Port Development Project will attain a higher degree of consolidation than the control area by about 60%.

Key words: Land reclamation, prefabricated vertical drains, field instrumentation, ground improvement and preloading

1.0 Introduction

From June 2012 till May 2013, the Mombasa Port Development Project (MPDP) in the Republic of Kenya involved the filling of approximately 6 million cubic metres of sand for the reclamation of a total land area of about 49 hectares. The land reclamation works were carried out in one phase. Land reclamation was carried out using fill materials obtained from dredging granular material from the seabed at the borrow source. The combination of prefabricated vertical drain (PVD) with preloading ground improvement technique was successfully applied in this project to improve the underlying compressible soils. The project comprises the installation of prefabricated vertical drains and the subsequent placement of surcharge to accelerate the consolidation of the underlying marine clay.

In the entire project, a total of 5.367 million linear meters of vertical drains were installed making it the largest project in Kenya in which pre-fabricated vertical drains were used. In order to monitor the performance of ground improvement and to validate the efficiency of the prefabricated vertical drain system several geotechnical instruments were installed to monitor the degree of consolidation at both area with PVD and area without PVD as control area. Settlement gauges including deep settlement gauges were installed at the top of each sub layers whereas piezometers were installed at the centre of each compressible sub layer in order to monitor the settlement and pore pressure dissipation. Settlement and pore pressure were monitored with close interval in the first three months and wider interval at the later part of monitoring. Ultimate settlements were predicted using the field settlement results applying the Asaoka and hyperbolic methods.

1.2 Objectives of the Study

The main objective of this research was to compare the effect of using PVD and without use of PVD on ground improvement works carried out at Mombasa Port Development Project (MPDP).

1.2.1 The Specific Objectives

Specific objectives of the study was to establish the difference in degree of consolidation when using PVD and when not using PVD.

2.0 Materials and Methods

2.1 Prefabricated Vertical Drains

Historically the design of structures on soft compressible soils (clays) has created problems for civil engineers. Construction without some sort of soil treatment is usually impractical due to unpredictable long-term settlement. Although surcharging increases water pore pressure, settlement can take considerable time, often years, as the water lacks an easy path to leave the soil. Consolidation of soft cohesive soils using prefabricated vertical drains (also called wick drains or band drains) can reduce settlement times from years to months. Most settlement can occur during construction, thus keeping post-construction settlement to a minimum. Consolidation of a compressible soil occurs as pore water is squeezed from the soil matrix. The time for consolidation depends upon the square of the distance the water must travel to exit the soil. The installation of prefabricated vertical drains provides shortened drainage paths for the water to exit the soil. Larger prefabricated drains called strip drains are used for horizontal water removal at the surface replacing the previously used sand blanket. The strip drains are less expensive, install more easily and quickly, and provide better drainage.

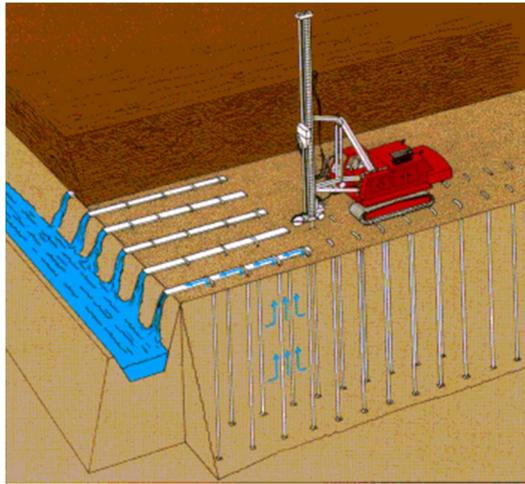


Figure 1: Vertical drain (PVD) installation with horizontal strip drain

2.2 Geotechnical Field Instrumentation

Geotechnical instrumentation is the only means available of providing continuous records of the ground behavior from the point of instruments installation. Without a proper geotechnical instrumentation method or program, it would be difficult to monitor at any point of time the current degree of improvement of the soil. By analyzing the instrument monitoring results, it is possible to determine the degree of consolidation of the foundation soil before allowing the removal of the surcharge load and it is possible to ascertain the achievement of required effective stress and to indicate the necessity for remedial action.

In order to study the performance of compressible soils under reclaimed fill, geotechnical instruments have to be installed. Various geotechnical field instruments were installed in instrumentation clusters to enable the instruments functions to complement each other. All instruments found in the instrument clusters were also extended and protected throughout the surcharge placement operations. In coastal land reclamation projects, instruments were installed either offshore prior to reclamation or on- land after reclamation to the vertical drain installation platform level.

Field instruments suitable for the study of consolidation behavior of underlying soils and monitoring of land reclamation works included surface settlement plates, deep settlement gauges, multi-level settlement gauges, liquid settlement gauges, pneumatic piezometers, electric piezometers, open-type piezometers, water standpipes, inclinometers, deep reference points and total earth pressure cells. A total of 75 geotechnical instruments (which includes 52 settlement plates, 9 inclinometers, 10 standpipes and 4 piezometers) were installed at the Mombasa Port Development Project (MPDP). Instrument monitoring was carried out at regular

intervals so that the degree of improvement could be monitored and assessed throughout the period of the soil improvement works for the project. Instruments were monitored at close intervals of up to 2 times a week during sand filling and surcharge placement operations.

2.3 Instrumentation Assessment

Assessment of degree of consolidation could be carried out by means of field instrument monitoring at regular time intervals. Degree of improvement can be monitored and assessed throughout the period. Two simple instruments that can assess the degree of consolidation are settlement plates and piezometers. Details on assessment of degree of consolidation have been discussed by Bo et al. (1997) and Arulrajah *et al.* (2005, 2004a, 2004b).

Degree of consolidation for settlement gauges can be computed based on the field settlement. Degree of consolidation is defined as percentage of magnitude of settlement that occurred at time t upon ultimate primary consolidation settlement as indicated in Equation 1. From measured field settlement and predicted ultimate settlement, degree of consolidation can be estimated. Ultimate settlement can be predicted for marine clays treated with vertical drains and preload by the Asaoka (Asaoka, 1978) or Hyperbolic (Tan, 1995) methods.

$$U_s (\%) = S_t / S_\alpha \dots\dots\dots(1)$$

Where S_t = field settlement at any time t ; S_α = ultimate settlement; and $U_s (\%)$ = average degree of consolidation.

Piezometers are utilized to measure the pore pressure in the soil. If regular monitoring is carried out to measure the piezometric head together with static water level, dissipation of excess pore pressure can be detected and thus degree of consolidation can be assessed. Average residual excess pore pressure is defined as ratio of excess pore pressure at time t upon initial excess pore pressure. Therefore degree of consolidation for a soil element, U_u can be defined as shown in Eq. 2.

$$U_u (\%) = 1 - (U_t / U_i) \dots\dots\dots(2)$$

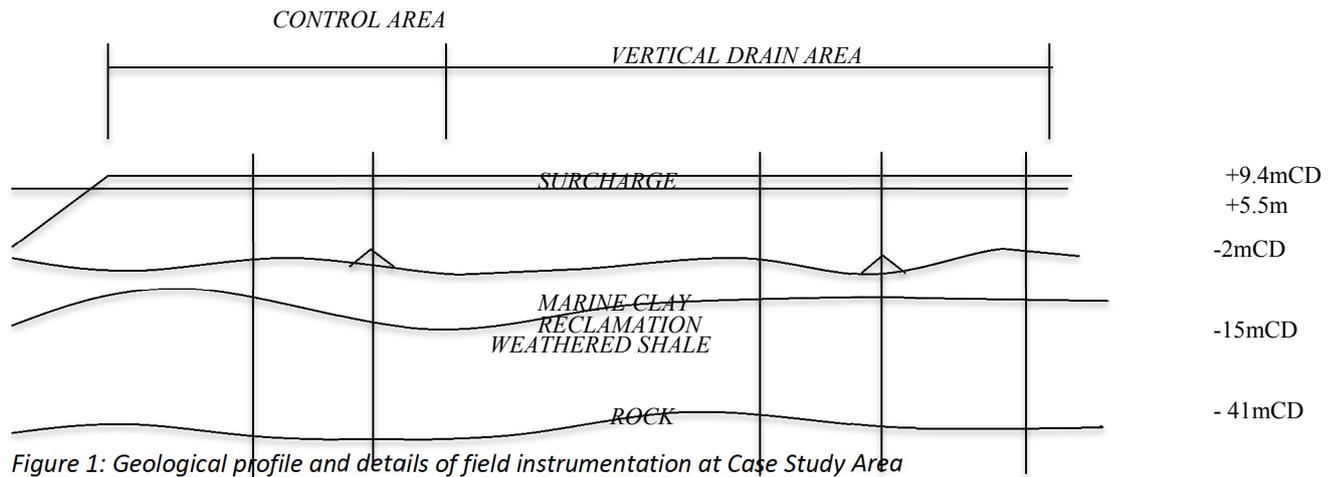
Where $U_u (\%)$ = degree of consolidation for a soil element; U_t = the excess pore pressure at time t ; and U_i = initial excess pore pressure which is equal to the additional load.

3.0 Results

Mombasa's coastline is sheltered by a coral reef running parallel to the shore about one mile out from the high-water mark. Beaches of fine sand and gentle slope provide ideal sites for a rapidly developing hotel and cottage resort industry. Most of Mombasa sits on loose, sandy soil, but the eastern part stands on a porous coral base. The project site had three main soil formations as follows.

- (i) Cohesive soils (very soft marine clay) deposits formed from the surrounding shale erosion. Classified as CH (clay with high plasticity and the silt content is <10%). The N value was found to be 0 to 1. The shear strength was averaged to be 20-25 kN/m².
- (ii) Weathered Shale (stiff clay and silt) also referred to as decomposed shale. Classified as CL-ML (clay with silt, silty clay) mostly 10-20% silt content. The N value was found to be above 30. The shear strength was averaged to be 26-30 kN/m².
- (iii) Rock, which is highly, weathered shale with N value more than 50. The shear strength was averaged to be above 30 kN/m².

The Case Study Area consists of a PVD area at which vertical drains were installed at 1.2 meters spacing to an average depth of 25 meters, as well as an adjacent Control area where no vertical drains were installed. This enabled comparisons to be made between an area treated with vertical drains with an untreated area. Both the areas were treated with the same height of surcharge preload. Instruments were installed and monitored at both the Vertical Drain Area and the Control Area. The instruments in the Control Area were installed prior to reclamation in off-shore instrument platforms. These instruments were protected as the reclamation filling works commenced in the area. Figure 1 shows the geological profile of the Case Study Area and the typical details of on-land and adjacent off-shore field instrumentation clusters.



Instruments in the PVD area were installed on-land at the vertical drain platform level of +4.5 m CD just before or soon after vertical drain installation at 1.2 meter square spacing. Surcharge was subsequently placed to +9.4 m CD. The analysis of the instrumentation results was carried out for both the PVD area and Control area after a monitoring period of about 10 months. Fig. 2 shows the construction sequence of works at the Case Study Area. The profile of the field instrumentation elevations at the Case Study Area has been recently described by Arulrajah *et al.* (2005, 2004a, 2004b).

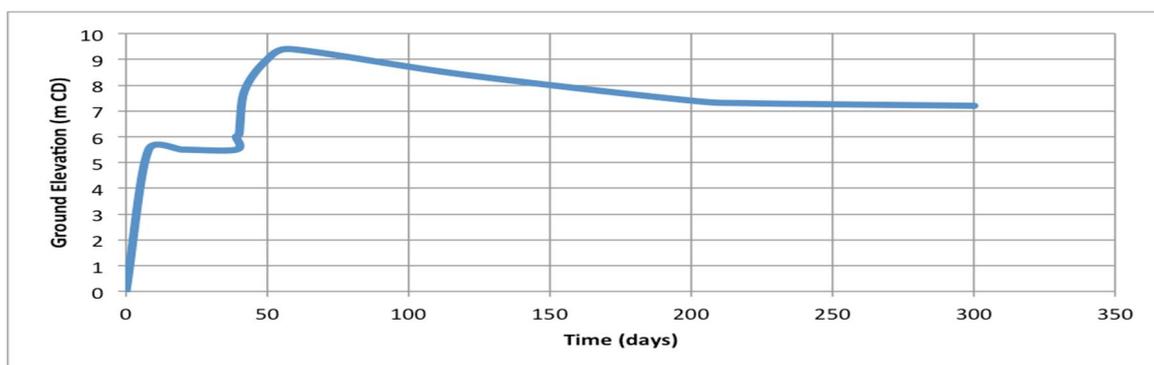


Figure 2: Construction sequence of the works at Case Study Area

3.1 Settlement Measurements

Figure 3 indicates the scales of settlements in the Prefabricated Vertical Drain (PVD) area. The deep settlement gauges that were installed in the different sub-layers indicate decreasing settlement with depth as would be expected. The PVD area indicated much greater settlement magnitudes as compared to the Control area. This indicates that the vertical drains are functioning. The settlement plates and the piezometer that were installed at the original seabed level gave similar reading for the magnitude and rate of settlement.

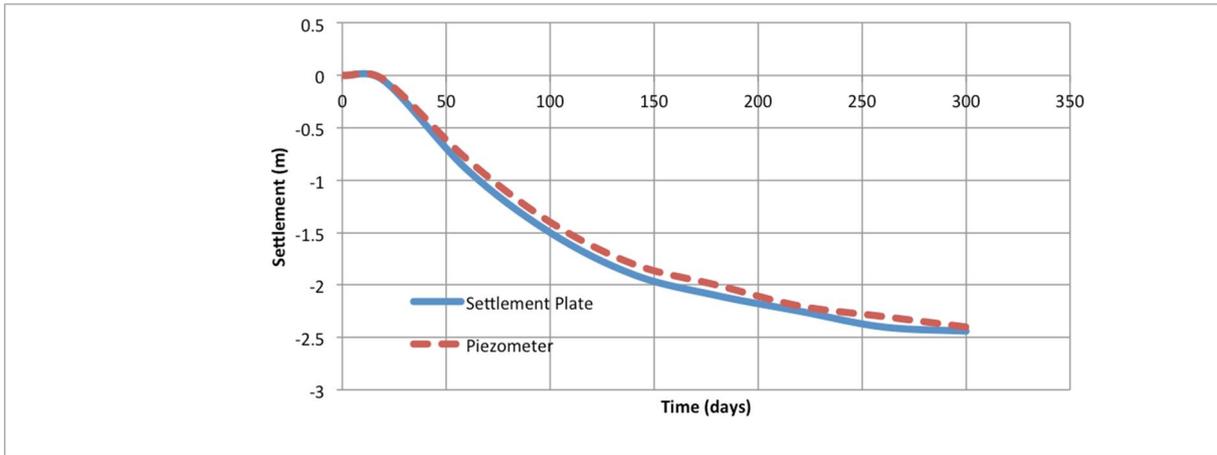


Figure 3: Field settlement results at Prefabricated Vertical Drain Area

Figure 4 compares the settlement plate results between the PVD area and Control area. The vast improvement of the PVD as compared to the Control Area is clearly evident in the figure 4 below. As expected the magnitude and rate of settlement of the PVD area is much higher than that of the Control area.

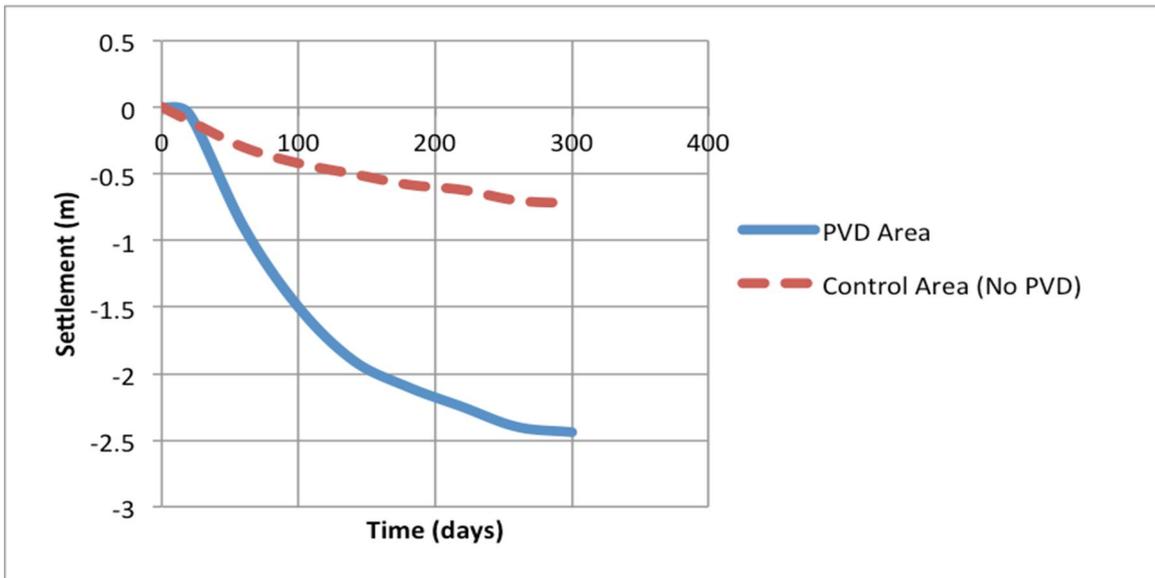


Figure 4: Comparison of field settlement at Case Study Area

3.2 Pore Pressure Measurements

The piezometer monitoring data in the PVD area after correction of the piezometer tip settlement is shown in Figure 5.

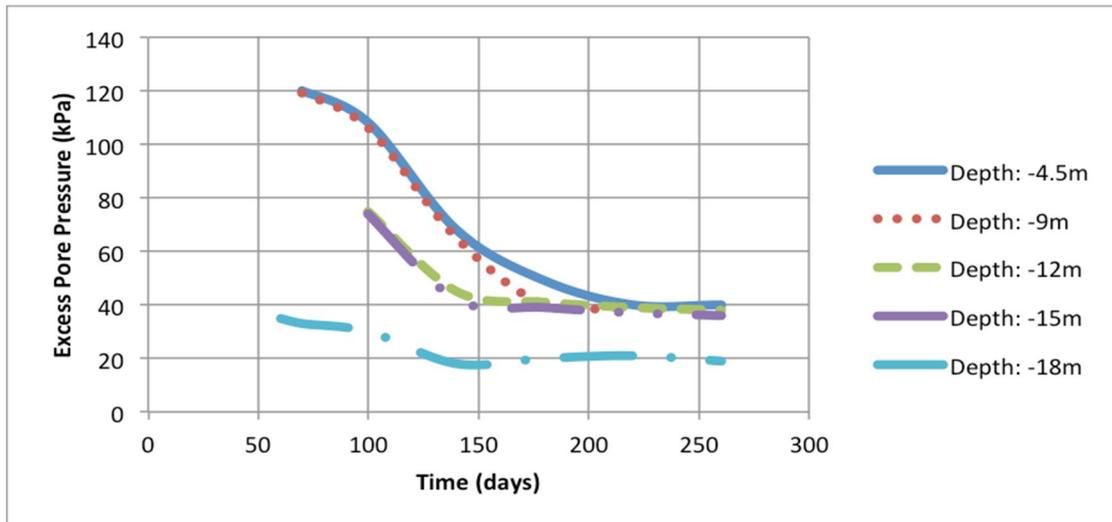


Figure 5: Excess pore pressure at Prefabricated Vertical Drain Area

Figure 6 indicates the comparison of excess pore pressure isochrones between the PVD area and Control Area at various periods after surcharge placement. The rapid disappearance of excess pore water pressure with time is clearly evident in the PVD area. The slow rate of dissipation of excess pore water pressure with time is also noted at the Control area. It is evident that the degree of consolidation of the PVD area is far greater than that of the Control area.

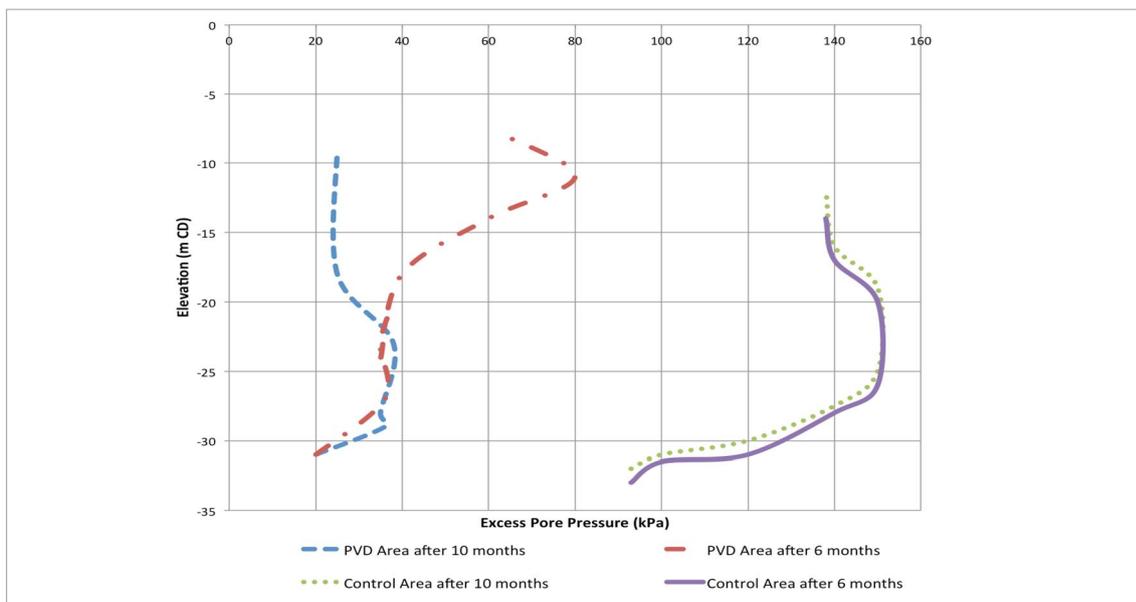


Figure 6: Comparison of piezometer excess pore pressure isochrones

Figure 6 shows a considerable change in pore pressure for the PVD area between 6 months and 10 months after commencement of the study. While the pore pressure for the Control area is averagely constant during the same period.

3.3 Degree of Consolidation

The degree of consolidation was assessed from the settlement plates by the Asaoka (Asaoka 1978) and Hyperbolic (Sridharan and Sreepada 1981; Tan 1995) methods. The approaches of application of these methods for land reclamation projects on marine clay have been discussed by Arulrajah *et al.* (2004b) and Bo *et al.* (1997).

Figure 7 compares the degree of consolidation as obtained from the settlement plates and piezometer results. Table 1 compares the degree of consolidation as obtained by the observational methods at the PVD area. It is seen that the methods give consistent results. The degree of consolidation of the piezometers was obtained from the isochrones of the piezometers. The degree of consolidation estimated from the pore pressure measurements is found to tie in well with that of the settlement plates at the PVD area, which is about 80%. The degree of consolidation estimated from the pore pressure measurements in the Control area is less than 20%.

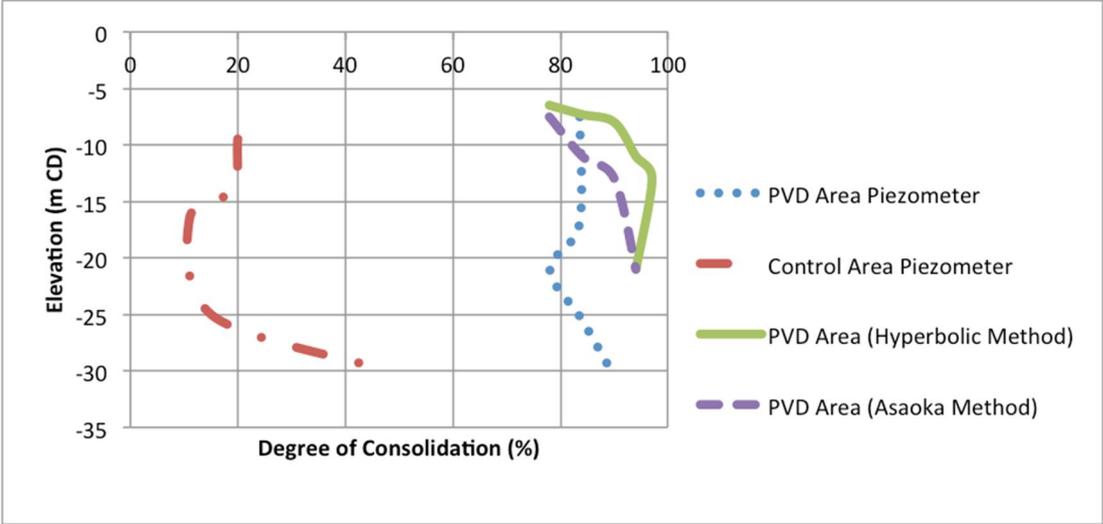


Figure 7: Comparison of degree of consolidation between PVD Area and Control Area

Table 1: Degree of consolidated comparisons at Vertical Drain Area

| Description | Asaoka | Hyperbolic | Piezometer |
|--------------------------------|--------|------------|------------|
| Ultimate Settlement (m) | 2.500 | 2.505 | - |
| Settlement to Date (m) | 2.004 | 2.005 | - |
| Degree of Consolidation, U (%) | 80.15 | 80.05 | 80.0 |

4.0 Discussions and Conclusion

The ultimate settlement predicted from the settlement plates by application of the Hyperbolic and Asaoka prediction methods was found to be about 2.5 meters. The assessment of degree of consolidation is found to be in good agreement for the Asaoka, Hyperbolic and piezometer methods. The settlement plates and piezometers indicate that the degree of consolidation of the PVD area had attained a degree of consolidation of about 80%. The piezometers indicate that the Control Area had only attained a degree of consolidation of about 20%. The instrumentation results in the Prefabricated Vertical Drain Area (PVD) indicates much higher degree of improvements as compared to the Control Area which indicates that the vertical drains are performing to improve the soil drainage system.

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