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Optimum geometric design in spacing and depth for prefabricated vertical drains (PVDs) to accelerate the consolidation rate with validation by finite element modelling (PLAXIS 3D)

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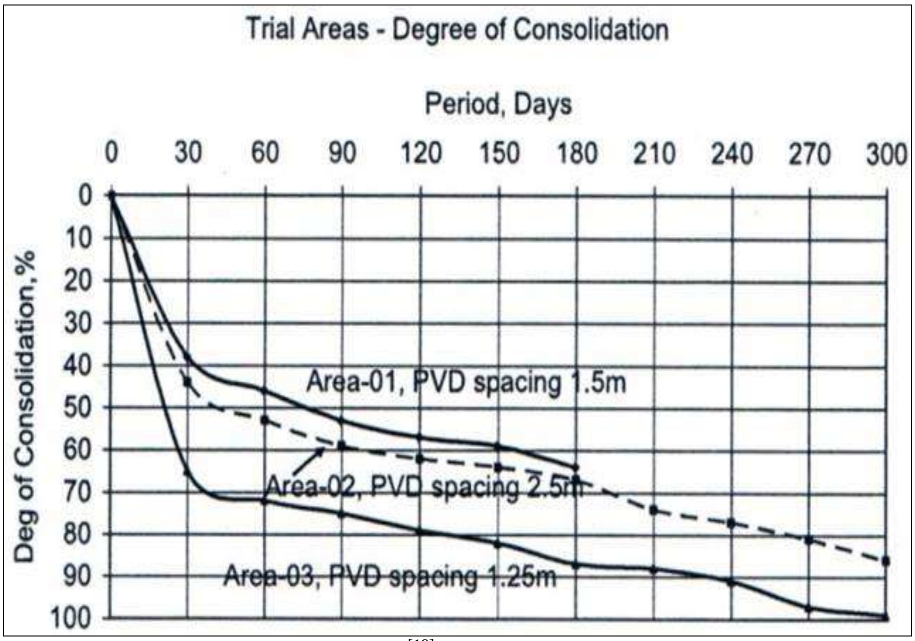
Abstract
One of the common practices in the field of geotechnical engineering is the use of prefabricated vertical drains (PVDs) for ground improvement work. PVDs provides shorter drainage paths to hasten the consolidation process. The performance of the PVDs depend on the spacing, length and characteristics of the PVDs, and the condition of the surrounding subsoil. Three case studies were carried out for the validation process by comparing the actual results from PLAXIS 3D with manual spreadsheet predictions. For this research, PVDs with four 4 different spacings and lengths were constructed at the sites to obtain an optimum geometric design. Based on the analytical calculations, simulation predictions and actual results from the sites, the PVDs installed with a triangular pattern and a spacing of 1.2 m and depth of 36 m achieved the highest settlement reading and consolidation rate in 6 months, with an accuracy of 86.5% for the validation process.

Keywords: Consolidation, PVD, ground improvement

1. Introduction

One of the effective methods for ground improvement work, which has shown extremely good results in accelerating the consolidation rate, is the use of prefabricated vertical drains (PVDs). Vertical drains have undergone a lot innovation, starting out as sand drains and currently being produced as PVD with a plastic core and geotextile filter jacket, depending on the site conditions (Scorza, 2014) [1]. The most important factor that influences the performance of PVDs is the capability of the drains to discharge the pore water from the soil. The installation of PVDs enables the pore water to travel faster, where the water will flow horizontally to the drain and vertically, by pressure, through the drain until it is discharged at the drainage layer (Scorza, 2014) [1]. For a given subsoil condition, the effect of the vertical drains depends on few factors such as - (i) the drain spacing and equivalent drain diameter; (ii) the well resistance (discharge capacity); (iii) the smear effect, and (iv) the drainage boundary condition (Miura, 1999) [8]. The consolidation time depends on the square of the distance that the water must travel to exit the soil (Machine, 2014) [10]. Time and cost in a project involving the ground improvement work are a critical issue to be monitored (Rahim Afikah Abdullah, 2020) [6]. The critical issues that must be monitored in a project involving ground improvement work are time and cost. Some of the sites that are using PVDs as a ground improvement method are facing problems in predicting the settlement time, where the settlement reading is more or less the same as the predicted reading, but the rate of consolidation differs. This will have an impact on the duration and cost of the project. Moreover, several projects that used prefabricated vertical drains as a major soft ground improvement technique to improve soft deposits had an excess settlement a short time after the projects had been in service (Hoang Hung Tran Nguyen, 2013) [7]. In most of the PVD designs, it is assumed that the surrounding soft soils are homogeneous and that the subsoil profiles are similar, based on several borehole tests and samples. Not much attention is given to the geometry of the prefabricated vertical drains, especially during their installation at the site. This is because the compilation of the settlement and consolidation computations in the multi-layered ground, and the choice of the layout, including the spacing and depth of the PVDs, are still by way of trial and error (Vu, 2014) [20]. Most designers will provide the spacing and the installation pattern, be it triangular or square, for the PVD.

The arrangement of the PVDs at the site is based on the contractor's experience and the instructions of some site personnel. The most important consideration when designing a PVD is that it must be able to reduce the length of the drainage path and the spacing of the drains (Craig, 2012) [3]. The closer the spacing between the PVDs, the shorter will be the time required for the consolidation process (A.R. Kambekar, 2013) [4]. According to a case study on a design and build project in Salt Lake Valley, the field tests indicated that prefabricated vertical drains (PVDs) with a spacing of less than 1.75 m do not give significant changes to the settlement rate (Rollins, 2009) [27]. While the spacing between the drains should be more than the equivalent drain diameter (Jabir, 2013) [2]. The drain spacing may be varied to optimize the design, and when the drains are installed closer to each other, the consolidation time will be reduced, but the installation costs will increase (Kishore, 2004) [13]. Figure 1 illustrates, the results of the consolidation process for the three research areas with different PVD spacings. It shows that the consolidation process was faster when the PVDs were spaced closer to each other, where for Area 03 with a PVD spacing of 1.25 m, a degree of consolidation of 70% was achieved in 30 days, while for Areas 01 and 02, the degree of consolidation achieved was in the range of 40% to 50% for the same period.



(Modified from R. Radhakrishnan, 2011) [19]

Fig 1: Degree of consolidation versus period with spacing

It was clearly shown that when the clay permeability is low, it will be necessary to reduce the PVD spacing in order to shorten the consolidation period (R. Radhakrishnan, 2011) [19]. However, it is the view of this researcher, that reducing the PVD spacing will actually decrease the flow path of the pore water, thereby enabling the pore water to be discharged at a faster rate. Based on the research above, it can be concluded that the degree of consolidation increases with a closer spacing, but the limitation on how close it can be is questionable, and the optimum spacing required for the PVD to perform effectively without the smear effect must be explored. Based on the previous researches by Vu Truong Vu, R. F. Craig, Aniket S. Shukla, A. R. Kambekar, Saye, Haider S. Al Jubair, Murtada M. Jabir and Nand Kishore, it can be summarised that a detailed research still needs to be carried out on the consolidation process by taking into consideration the effect of the spacing and length of the PVDs.

1.1 Consolidation of Soil

Consolidation is the process of discharging water from the soil by applying surcharge. This process is governed by the rate of excess pore pressure dissipation, the coefficient of consolidation (C_v) of the soil, and the thickness of the consolidating layer (Hansbo, 1979) [1]. Consolidation is the gradual reduction in volume of a fully-saturated soil of low permeability due to drainage of the pore water, with the process continuing until the excess pore water pressure set up by an increase in total stress has completely dissipated (Craig, 2012) [3]. Consolidation is divided into three phases, namely, the initial compression phase, primary consolidation phase, and secondary compression phase. For clayey soil in a fully-saturated condition, the initial compression happens immediately after a load is imposed, and this will change the shape of the clay layer. This is because the low permeability of the soil will lead to an undrained condition, and this will be followed by a vertical compression together with a lateral expansion. The primary consolidation phase develops when the stress induced by the external load is immediately taken up by water and is assumed to be incompressible. The excess pore water pressure will then gradually dissipate as the water seeps out from the soil through drainage boundaries, and the pressure is transferred to the soil skeleton (Ali Parsa Pajouh 1, 2014) [11]. The length of the vertical drain is designed based on the borehole test result, which shows the compressible layer and the N value below 8. The typical length can be up to 15 m or 20 m. The length of the PVD must not be more than the thickness of the clayey layer (Jabir, 2013) [1]. If the PVDs are too long, their performance will be affected as the lateral pressure can lead to a reduction in the discharge capacity. It has been suggested that a vertical drain should not be used at a lateral pressure of 150 kPa or above (Hoang Hung Tran Nguyen, 2013) [7]. The discharge capacity of the drain depends on the condition of the soil, the rate of water flow, and the long discharge behaviour (Park *et al*., 2000) [28]. In a case study of ground improvement work at Saga Airport, PVDs were installed at different depths on the test embankment to observe the effect of the PVD length on the consolidation. From the result, it could be seen that reducing the PVD length from 25 m to 21 m did not have much of an effect on the consolidation rate, but when the PVD length was reduced to 15.5 m, the consolidation rate decreased. This means that the depth of the PVD determines its capability to discharge the pore water (J.C.Chai, 2009) [23]. By providing the depth information in the subsoil profile, the possibility of constructing shallow foundations can be determined, where the length of the PVD can be installed at the optimum depth (R. Radhakrishnan, 2011) [19]. The majority of PVDs are of a standard size, with a width of 100 mm and thickness of 4 mm, while some with larger dimensions are used for special purposes. These dimensions will also influence the consolidation process. An apparent opening size (AOS) of O95 (opening size for 95% retained weight), which is less than or equal to 75 um, has been specified to avoid clogging and to provide sufficient permeability (Myint Win Bo, 2015) [19]. The tensile strength of a PVD is very important because it is the main factor that enables the PVD to withstand the stress during the installation process. Therefore, a PVD is required to have a specified tensile strength to enable it to achieve a certain permissible elongation without affecting the main dimensions of the drain (Myint Win Bo, 2015) [19]. The required permeability for PVDs, especially geotextile PVDs, should be 10 times more than that of the surrounding soil (Holtz R D, 1991) [26]. Permeability is one of the important criteria to be analysed because the higher the permeability, the greater and faster will be the volume of water that can penetrate into the PVD. The discharge capacity is the ability of the PVD to remove a specific volume of pore water at a given time. The degree of consolidation cannot be achieved in the estimated timeframe if the PVD is unable to discharge as per the requirement. The discharge capacity is influenced by a few factors, namely, the lateral stress, buckling and siltation (Myint Win Bo, 2015) [19]. It can be concluded that the ground conditions must also be such to provide minimum obstruction, such as not many boulders, no gravel in the soil layer, the soil must be accessible and will not require a special installation system, which can disturb the permeability of the surrounding soil.

1.2 Problem Statement

The predicted settlement reading and consolidation time do not match the actual outcome from the field, and this big difference has an impact on projects, whereby the total cost and timeframe will be increased. The most common PVD design is used in terms of the spacing, pattern and length, while there is no specific geometric design for the treatment area. Therefore, no guidance is available with regard to the installation of the PVDs at the site, such that as many PVDs as possible are installed based on the given space and length. The performance of the PVDs is measured when they achieve the estimated settlement according to the schedule or earlier than that, depending on the instrument used. The cost of soil improvement work can increase if the length and number of PVDs installed are not controlled. This happens when the differential subsoil profile layer and the need for short drains are neglected. The length of the PVD is important because it can influence the deformation pattern of the subsoil (Buddhima Indraratna, 2010) [5].

2. Research Methodology

This research was divided into five stages. The first stage defined the objectives of this research based on the problem statement. In the second stage, the locations of the available projects for conducting this research were identified. To be more precise, three projects were identified in three different locations for this research. The first two projects were for the validation process, while the third project was the main focus of this research. The third stage was the modelling phase, where the predicted values were generated from a spreadsheet and simulation process. The fourth stage defined the implementation of the site and the monitoring process, and gathered all the results from the actual site for the purpose of analysis. The last stage involved a discussion to obtain an overview as to whether the results met the objectives of this research. As this research was conducted at three different locations, the outcome was more reliable as various influences that would have impacted the results were studied and analysed, including the modelling process, to measure the accuracy between the predicted and actual results. The three cases studies that were carried out for this study were:

a) Proposed mixed development at Mukim Tanjong 12, Kuala Langat District, Selangor (Case 1).
b) Alternative road connecting Parit Jalil (J126) to the Bakau Chondong (FT005) road in Batu Pahat, Johor (Case 2).
c) Construction of a new radar building with an administration office and 2 units of quarters in Kuala Gula, Perak (Case 3).

The first two locations in the research area, namely, Tanjung 12 and Parit Jalil, were used for the validation process, whereby the spreadsheet settlement predictions were compared with the actual results together with a PLAXIS 3D analysis. Meanwhile, for the Kuala Gula project, the earlier design was compared with the newly-proposed geometric design PVD with the support of a PLAXIS 3D analysis to evaluate the actual results at the site. Figure 2 illustrates the research method that was used, based on the identification of the problem and the establishment of the research objectives following the location of the research area. The next step involved the data collection for the subsoil parameters and the modelling analysis. After that, the PVDs were constructed at the site and the actual results were obtained for the discussion and conclusion of this research.

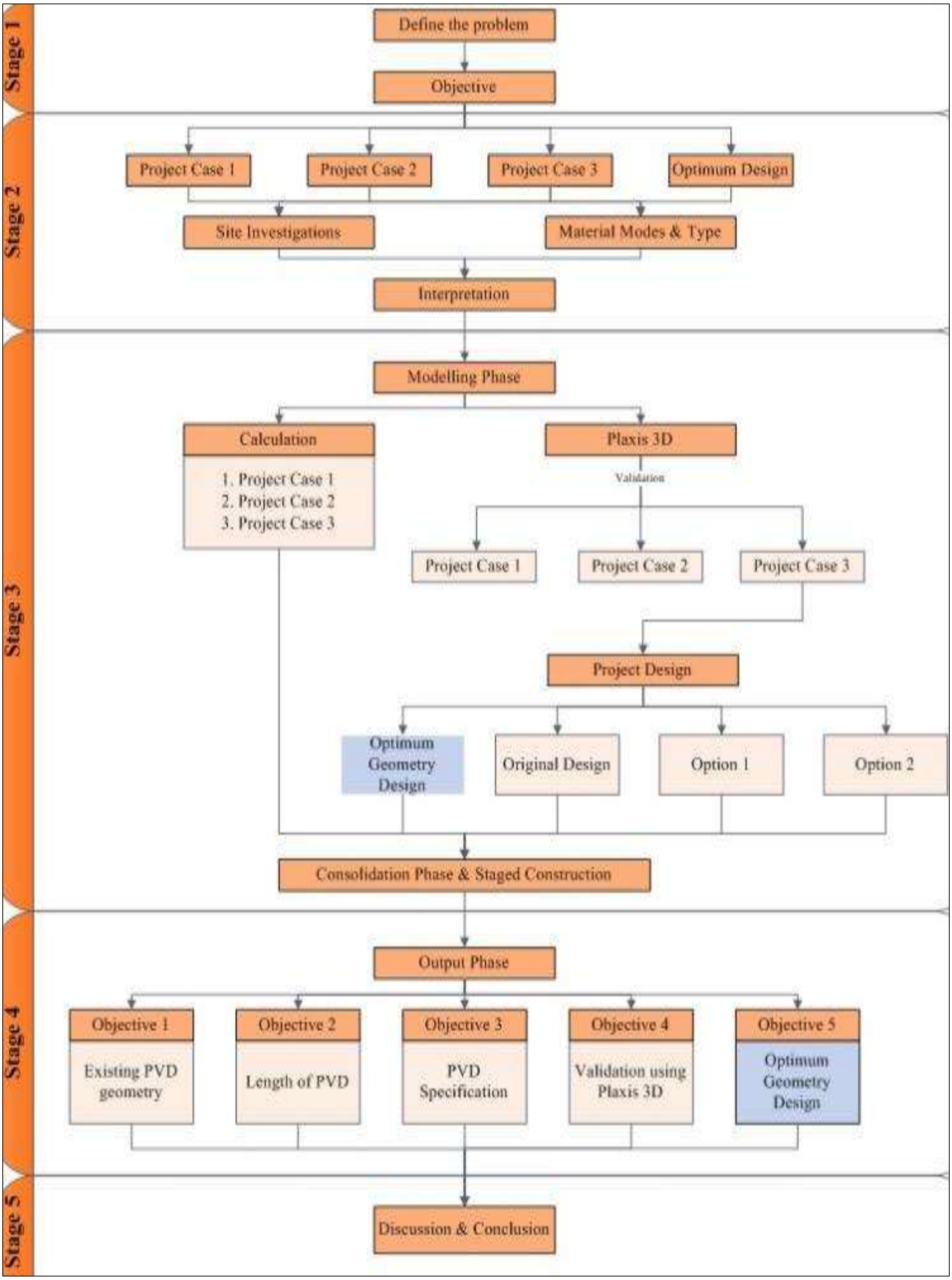


Fig 2: Flowchart of research methodology

3. Modelling Phase

Figure 3 shows the subsoil profile for the borehole test number 3. The soil profile was up to a depth of 45 m, and it consisted of five different layers of clay with unique characteristics based on the nature of the soil, with a sandy gravel layer at the bottom of the clay after the soft soil layer. Each layer was projected in a different colour according to the characteristics and soil parameters, including the SPT-N value. The original design for the ground improvement work, in this case, was to construct a 3-metre-high embankment with (PVDs) with a spacing of 1.4 m in a triangular pattern and for a depth of 33 m.

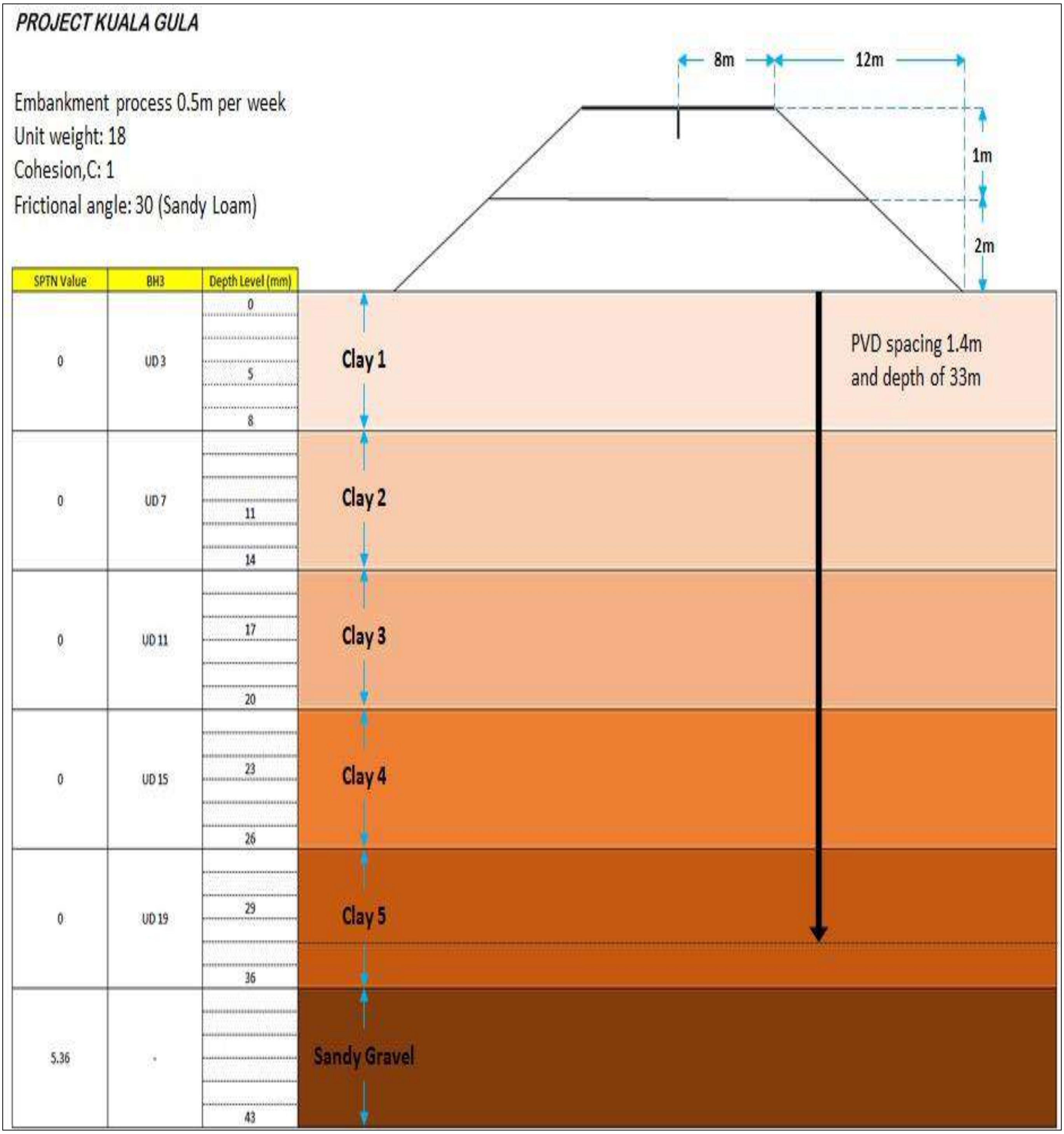


Fig 3: Subsoil profile and ground improvement work model (Case 3)

equation was used to analyse the total settlement. Equation 1 is given as follows:

$$\rho = m_v \Delta\sigma H \quad (1)$$

Where
m_v is the coefficient of volume compressibility,
H is the thickness of the layer, and
σ is the stress.

Figure 4 below shows the process for obtaining an effective pressure from a certain depth of the subsoil profile. In Case 3, this was based on borehole number 3. An undisturbed sample 1 was obtained at a depth of 5 m. The SPT-N value at this depth was 0, which indicated that this soil was classified as soft soil. The type of soil at this level was clay, with a bulk density of 15.22 kN/m2. For borehole number 3, the groundwater level was considered as being fully saturated. The effective stress at a depth of 5 m was 53.07 kN/m2. For design purposes, the consolidation parameters of the cohesive subsoil (compressible strata) were determined and interpreted from the results of a one-dimensional (1-D) consolidation test.

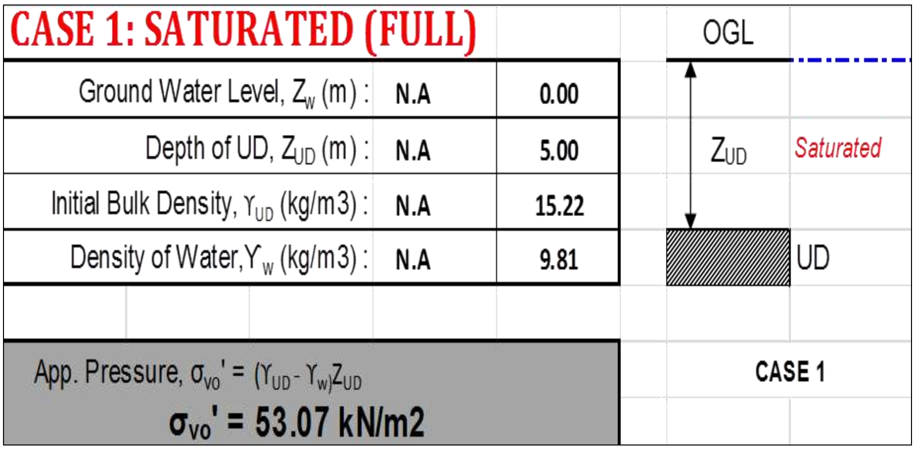


Fig 4: Effective stress for undisturbed sample 1

Table 1 below shows the readings that were obtained from the one-dimensional test to generate the values of the coefficient of consolidation (Cv), and the coefficient of volume compressibility (Mv). These two values were determined for the specific effective pressure at a depth of 5 m.

Table 1: Summary of coefficient of consolidation Cv and coefficient of volume compressibility, Mv

Press	Cv	Mv
(kN/m2)	(M2/yr.)	(m2/MN)
6.25	3.36	2,27
12.5	2.38	1.86
25	3.08	1.93
50	2.18	2.00
100	1.02	1.93
200	1.26	1.11
400	1.76	0.50

The coefficient of consolidation in the vertical direction (C_v) for each idealized stratum at every subdivided location is determined based on the pressure of the proposed embankment. Meanwhile, for the coefficient of consolidation in the horizontal direction (C_h), the values can be correlations that might be referred to in determining C_h, such as the time factor method (Houlsby, 1991) [24] and the simplified relationship method (P.K. Robertson, 1992) [25]. Alternatively, rough estimations can be made for other interpreted strata which are not represented by the strata involved in the dissipation test.

Thus, an average ratio value of 1.5 is taken into the estimation, where the ratio of C_h: C_v is normally between 1 and 2. Figure 5 and Figure 6 present the particular Cv and Mv, respectively for a certain depth and pressure, and these values were generated from the graph as the main input in the spreadsheet calculations for the total settlement and the primary settlement analysis. In Case 3, five undisturbed samples were collected and tested to produce and generate the necessary input for the settlement analysis.

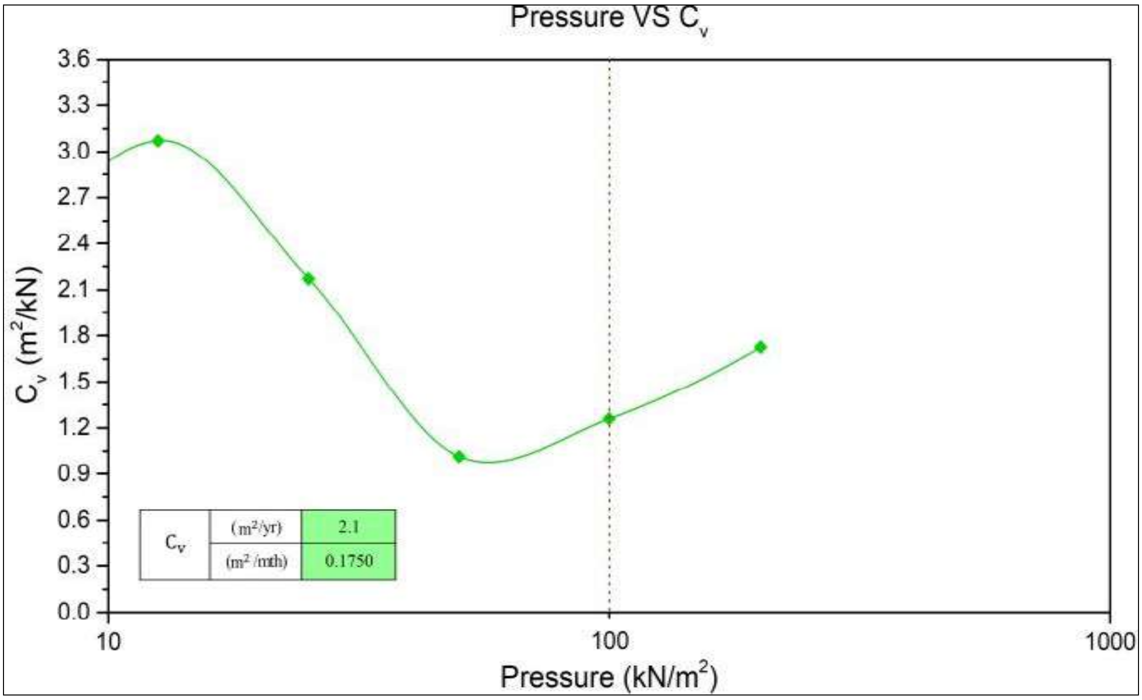


Fig 5: Applied pressure versus coefficient of consolidation, Cv

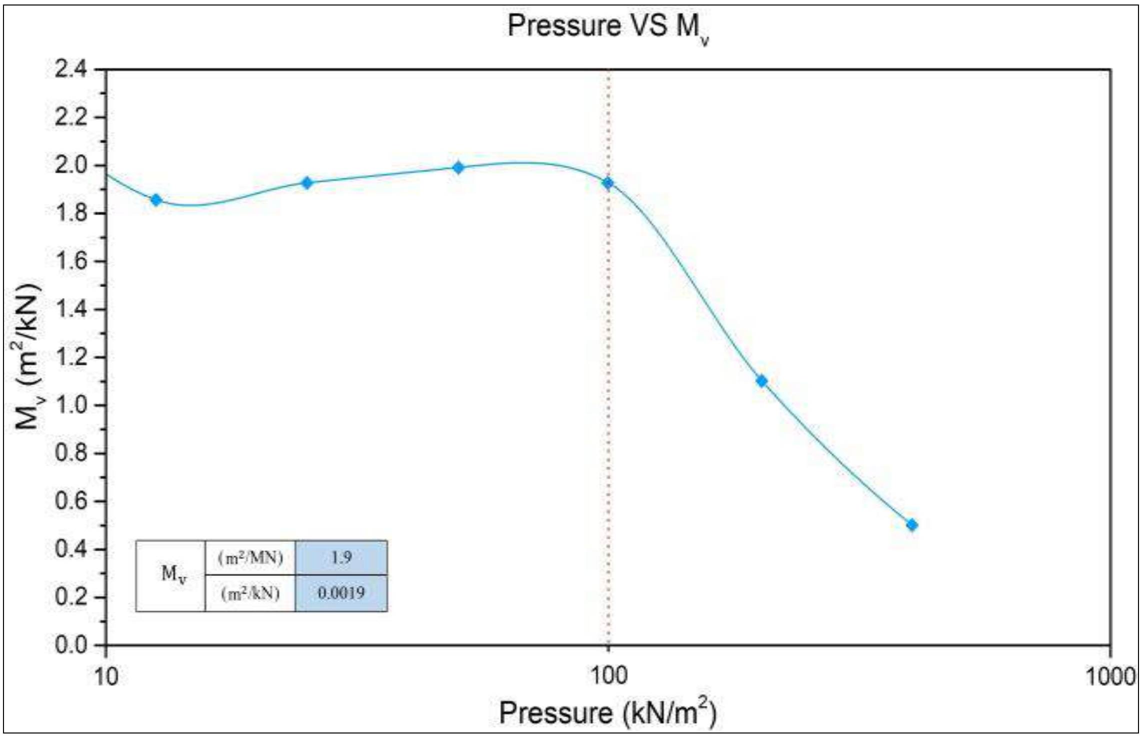


Fig 6: Applied pressure versus coefficient of volume compressibility, Mv

3.1 Spreadsheet Calculations

Figure 7 below shows the settlement analysis from the spreadsheet calculations. By using the values of the coefficient of consolidation (Cv) and the coefficient of volume compressibility (Mv), which were generated from the graphs for the five undisturbed samples, the analysis showed that the optimum geometric design with a spacing of 1.2 m, rather than the original design with a spacing of 1.4 m, would increase the rate of the consolidation process. The settlement reading in 6 months for a spacing of 1.2 m was 2426 mm, and after the embankment process, which took 90 months, the settlement reading was 2745 mm, with a post-construction settlement of 174 mm compared with settlement readings of 2266 mm for the original design with a spacing of 1.4 m in 6 months and 2568 mm in 90 months, with a post-construction settlement of 159 mm. Even though the two readings for the post-construction settlement were below the recommended value of 250 mm, the settlement readings for the optimum geometric design were higher than the original design. For the construction period of 30 months, which included the ground improvement work, the settlement reading was 2601 mm, and the consolidation of 90% (T_{90}) was 2583 mm. This showed that a consolidation of 90% was achieved during the construction stage.

It was proposed that the soft layer be treated using a PVD with an optimum design for a depth of 36 m, which was much deeper than the original design of 33 m because the SPT N-value was more than 8 at a depth of 36 m. Figure 8 below shows the graph of the settlement versus time for the optimum geometric design. It can be seen that the rate of consolidation was faster than with the original design. The predicted settlement value was more with the optimum design. The primary settlement happened very fast with this geometric design because of the spacing, which allowed the pore water to flow (hydraulic conductivity) to the PVD without causing much disturbance to the surrounding soil. In addition, the PVD, which terminated at the exact depth, was able to influence the pore water to flow vertically without friction and to efficiently maximize the function of the PVD at the topmost level. Also, the permeability of the surrounding soil and the characteristics of the PVD probably influenced the settlement process and consolidation rate. This assumption was made as the soils surrounding the PVD were homogeneous.

Settlement Analysis
KUALA GULA

DATA AND PROPERTIES :

Drain centres, Dc (m)	1.2	Effective D	1.26	**REF. BH:**	**REF. CH:**	**DATE:**
Drain width, d' (m)	0.066	Ratio n=D/d'	19.09			Today 15-Jun-20
Drain pattern, TRI/SQR	TRI	Mu	2.21			
Month drains installed	1	Sett. des. life (mths)	240			Time 1-Apr-19

SOIL PROPERTIES	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Soil type	CLAY	CLAY	CLAY	CLAY	CLAY
Top of clay (m MCD)	0.0	-8.0	-14.0	-20	-26
Base of clay (m MCD)	-8.0	14.0	-20.0	-26	-36
Thickness, H (m)	8.0	6.0	6.0	6	10
1 or 2 way drainage	1	1	1	1	1
mv (m2/kN)	0.00190	0.00120	0.00112	0.00090	0.00063
Cv (m2/month)	0.1750	0.3500	0.5167	0.3975	0.25
Ch (m2/month)	0.3500	0.7000	1.0334	0.795	0.5
C'-alpha	0.008	0.008	0.008	0.008	0.008
Drains	d	d	d	d	d
Factor	1	1	1	1	1

COMMENTS:

Settlement Analysis No.4:

1. Embakment Ht : 2.0 m
2. Say **3 mths** to build
3. Traffic Load : 0 kPa
4. **Duration of construction** : 30 months
5. Say START WORKS : April 2019
6. TREATMENT : 1.4m c/c tri PVD + 1.0m ht Surch for 6 mths

SETTLEMENT WITH TIME :

Time (months)	Load (kPa)	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Second. compr.	Totals for section	Residual settlement	Date 1-Apr-19
1	18	0.016	0.014	0.016	0.012	0.006	0.000	0.065	2.805	1-May-19
2	36	0.317	0.213	0.222	0.167	0.159	0.000	1.079	1.791	31-May-19
3	54	0.601	0.355	0.351	0.273	0.284	0.000	1.864	1.005	1-Jul-19
4	54	0.724	0.382	0.362	0.289	0.323	0.067	2.147	0.722	31-Jul-19
5	54	0.778	0.388	0.363	0.291	0.335	0.118	2.272	0.597	31-Aug-19
6	54	0.802	0.389	0.363	0.292	0.338	0.154	2.337	0.532	30-Sep-19
7	54	0.812	0.389	0.363	0.292	0.340	0.182	2.377	0.492	30-Oct-19
8	54	0.817	0.389	0.363	0.292	0.340	0.205	2.405	0.465	30-Nov-19
9	54	0.819	0.389	0.363	0.292	0.340	0.224	2.426	0.443	30-Dec-19
10	54	0.820	0.389	0.363	0.292	0.340	0.241	2.444	0.426	30-Jan-20
11	54	0.820	0.389	0.363	0.292	0.340	0.256	2.459	0.410	29-Feb-20
12	54	0.820	0.389	0.363	0.292	0.340	0.269	2.472	0.397	31-Mar-20
18	54	0.820	0.389	0.363	0.292	0.340	0.328	2.531	0.338	29-Sep-20
24	54	0.821	0.389	0.363	0.292	0.340	0.367	2.571	0.299	31-Mar-21
30	54	0.821	0.389	0.363	0.292	0.340	0.398	2.601	0.268	29-Sep-21
36	54	0.821	0.389	0.363	0.292	0.340	0.422	2.625	0.244	31-Mar-22
60	54	0.821	0.389	0.363	0.292	0.340	0.489	2.692	0.177	30-Mar-24
84	54	0.821	0.389	0.363	0.292	0.340	0.532	2.736	0.134	30-Mar-26
150	54	0.821	0.389	0.363	0.292	0.340	0.606	2.810	0.060	28-Sep-31
240	54	0.821	0.389	0.363	0.292	0.340	0.665	2.869	0.000	27-Mar-39
Final settlement		**0.821**	**0.389**	**0.363**	**0.292**	**0.340**	**0.665**	**2.869**	-	-

Total Settlement : **2869 mm**
5 years post construction settlement : **165 mm**
T_{90} : **2583 mm**

Fig 7: Settlement analysis for Case 3 with optimum geometric design

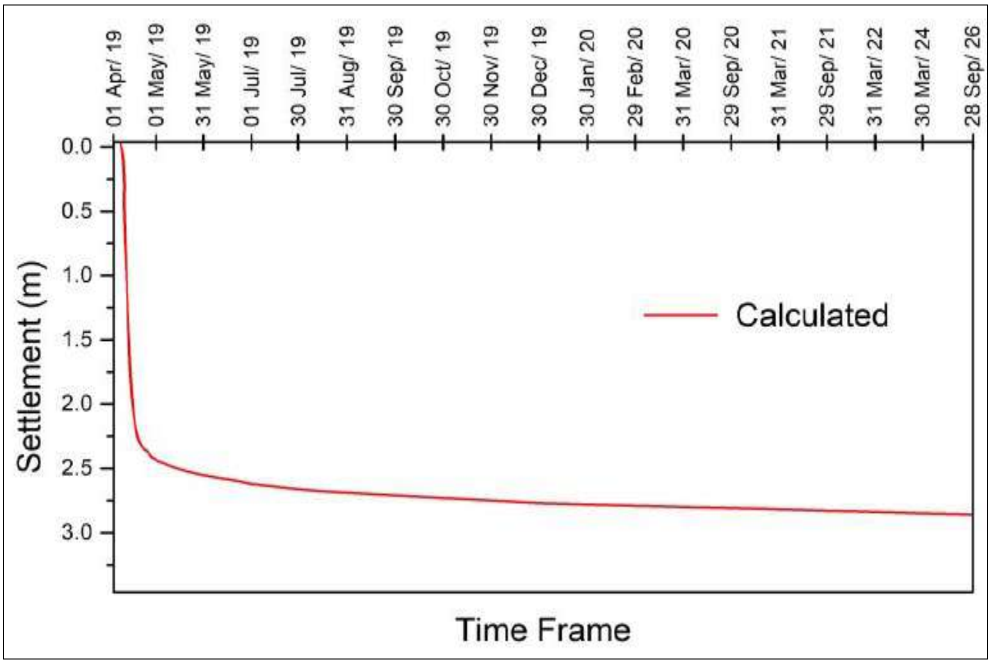


Fig 8: Settlement versus time with PVD spacing of 1.2m and depth of 36m

3.2 Analysis using PLAXIS 3D

A finite element analysis was carried out using PLAXIS 3D in plane strain modelling. Many types of constitutive soil models have been developed based on stress-strain mechanics and other theories such as plasticity and elasticity, which contain very complex mathematical equations. PLAXIS also allows for the simulation of staged constructions with regard to drained or undrained conditions for different loads and ground conditions. According to (R.B.J. Brinkgreve and W. Broere, 2004) [22], geotechnical applications require advance constitutive models for the simulation of the non-linear, time-dependent and isotropic behaviour of soils. PLAXIS is equipped with features to deal with various aspects of complex geotechnical structures. Since soil is a multi-phased material, special procedures are required to deal with hydrostatic and non-hydrostatic pore pressures in soil. PLAXIS is capable of performing realistic simulations of construction and excavation processes by activating and deactivating clusters of elements, the application of loads, and changing of water tables. This procedure allows for a realistic assessment of the stresses and displacements that are caused. Soft soils are considered as being similar to normally-consolidated clay and clayey silts. Considering the tangent stiffness module at an oedometer pressure of 100 kPa, the E (oed) of normally-consolidated soil is equal to between 1 to 4 MPa, depending on the type of clay. The soft soil model is suitable for very soft soils, with a high compressibility of E (oed)/E50 < 0.5. A lot of comparisons have been made between the actual site results and the predictions, but by using different approaches and methods. Some of these results were unique because each site represented a different type of ground condition, and might not be used as comparison data but can be used as a reference. In a case study on ground improvement work in Southern Vietnam, a settlement analysis was carried out using the PLAXIS 2D v8.5 software. The first study was conducted at the Saigon East-West Highway, Ho Chi Minh City. Based on the evaluation, it could be seen that the computed settlement significantly diverged from the monitored settlement at a large consolidation settlement, where the researcher surmised that the assumption of the ideal performance for the PVD was not relevant for a large consolidation settlement (Hoang Hung Tran Nguyen, 2013) [7]. The second study was conducted at the approach embankment of the Can Tho Bridge, similar to case study number one. The simulated results were also analysed using the software, and it was found that the computed settlement agreed well with the monitored settlement up to a certain height, and when the surcharge was increased, the simulated settlement was marked as having diverged from the monitored settlement at the fill (Hoang Hung Tran Nguyen, 2013) [7]. In this research, the simulations were carried out on the assumption that all the factors affecting the PVD were neglected. Referring to Figure 9, the total settlement reading was 2642 mm in 6 months and 2742 mm in 90 months, with the post-settlement reading for 5 years being 99.9 mm. The optimum geometric design for the prefabricated vertical drain used a spacing of 1.2 m and a depth of 36 m. Figure 10 shows the settlement versus time graph generated by PLAXIS 3D, where the settlement of 2642 mm was starting to become stagnant after 5 months during the rest period.

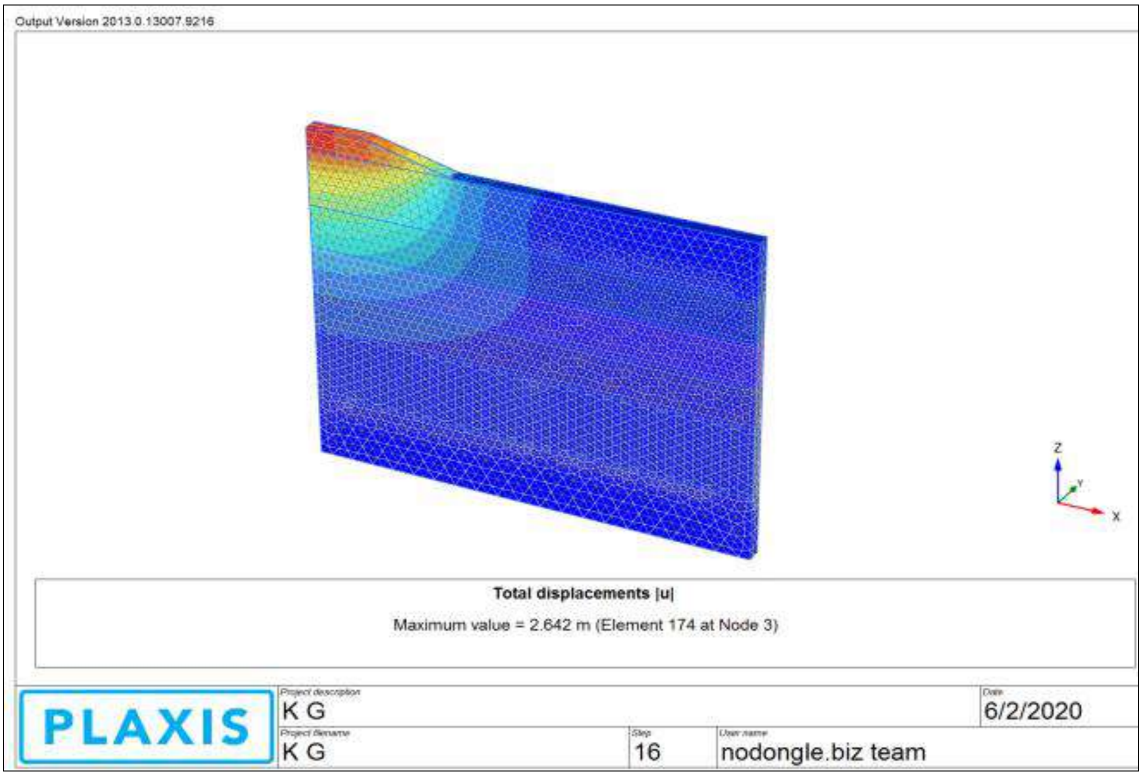


Fig 9: Deformed mesh: 2642mm (6 months)

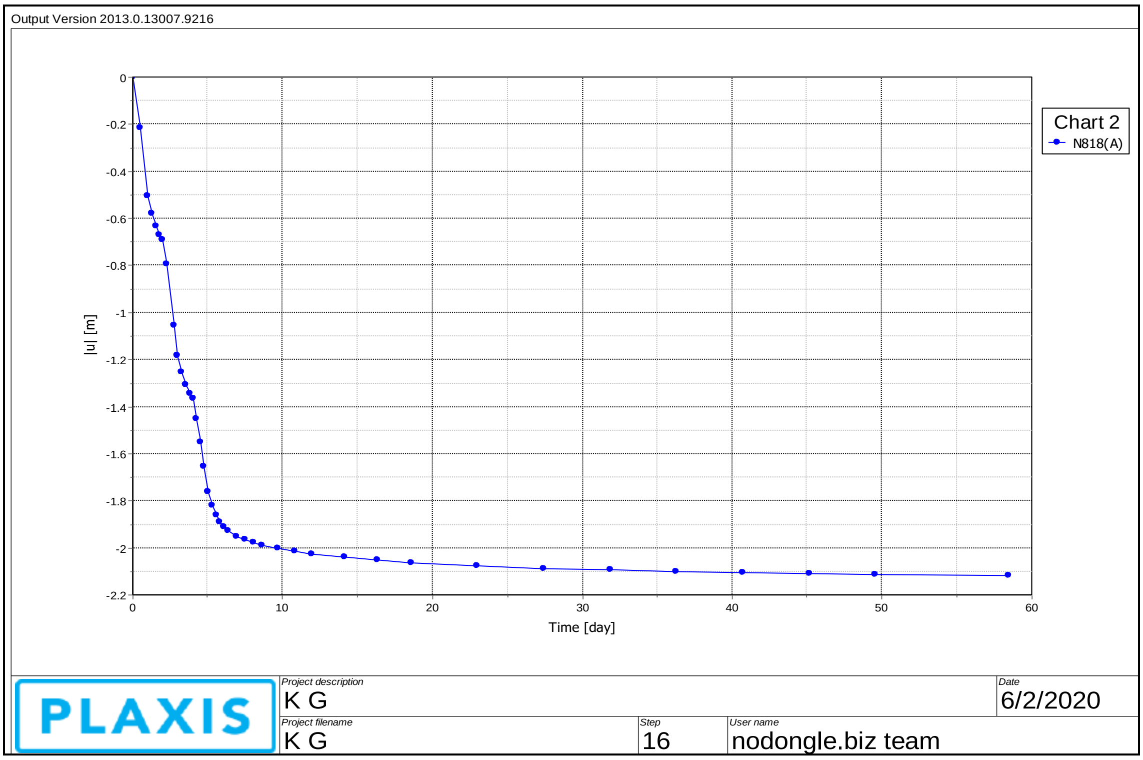


Fig 10: Settlement versus time

4. Actual Site Results

The monitoring instrumentations provided for the areas involved in the proposed embankment and retaining structures were a surface settlement marker for monitoring the vertical movement of the ground due to the embankment fill, and a rod settlement gauge for monitoring subsoil settlements in order to establish the settlement profile for the construction planning and control. The instrumentation monitoring scheme was scheduled to be implemented during the construction of the embankment and was to be continued for a certain period, even after the completion of the construction. Frequent monitoring was conducted during the construction stage compared to after the completion of the embankment. For the purpose of this research, four settlement gauges were selected and installed according to Figure 11, which illustrates the layout of the settlement monitoring instruments for SG3 (original design), SG4 (optimum geometric design), SG5 (option 1) and SG6 (option 2).

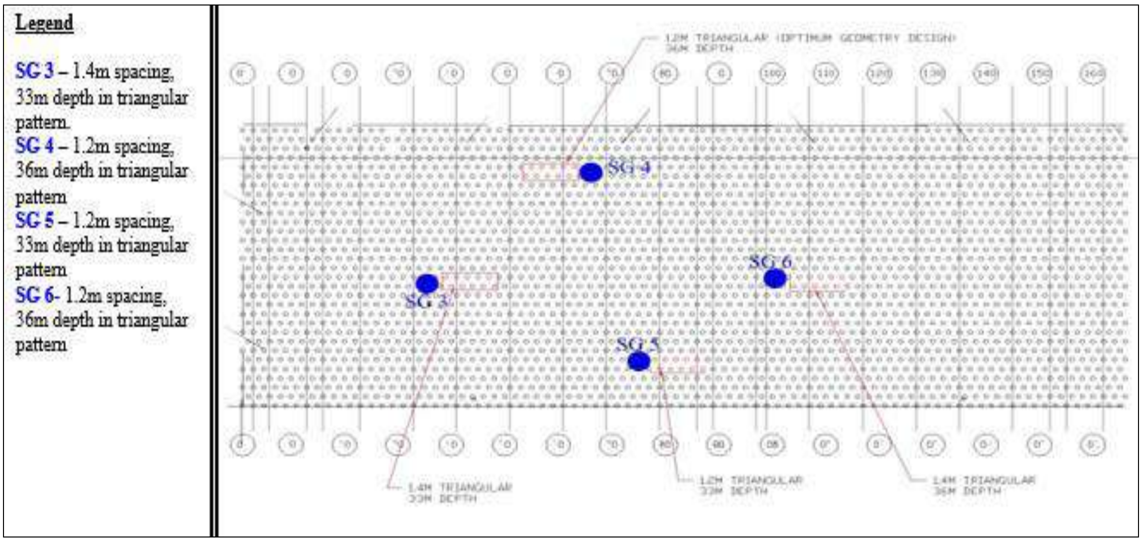


Fig 11: Layout of the settlement monitoring instruments

Figure 12 below describes the actual field settlement data from the dedicated settlement gauge numbers 3 to 6. The projection shows the settlement reading taken for 8 months from the completed surcharge process. From the figure, settlement gauge number 4 (SG4), which was the optimum geometric design, showed the highest settlement reading during the 4th month of the settlement period among the other three settlement gauges. The outcomes of these actual field data showed the achievement of this research paper.

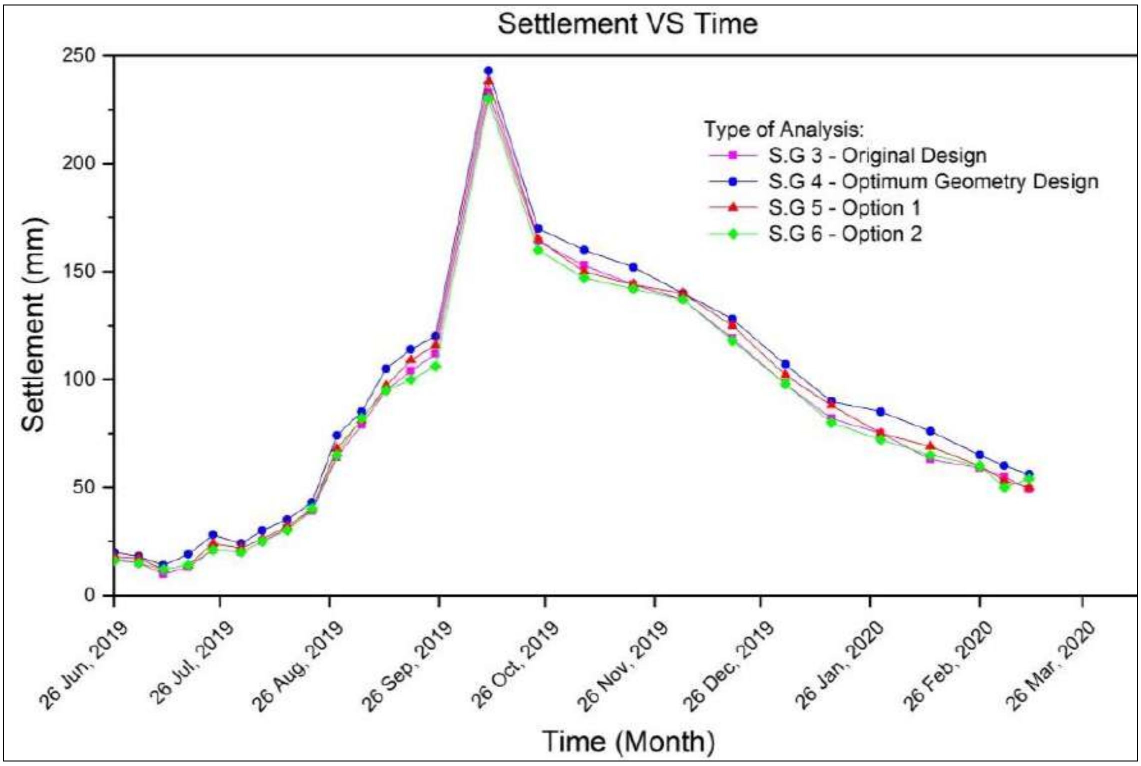


Fig 12: Settlement reading based on the settlement gauge

According to Table 2, the highest settlement reading was generated from the actual field data for all the four cases from SG3 to SG6, and it was concluded here that the SG4, which was the optimum geometric design, produced the highest settlement reading of 2286 mm in a settlement period of 6 months. This showed that more primary settlement happened with the optimum geometric design. The lowest settlement reading was at SG 6 for option 2, with a settlement reading of 2074 mm in 6 months. The difference between the highest and lowest case was 212mm.

Table 2: Summary of the actual settlement results

Type of Analysis	PVD Spacing (m)	PVD Depth (m)	Total Settlement (mm)	Time (Months)
Original design (SG3)	1.4	33	2096	6
Optimum Geometry Design (SG4)	1.2	36	2286	6
Option 1 (SG5)	1.4	36	2158	6
Option 2 (SG6)	1.2	33	2074	6

5. Discussion

Table 3 gives a comparison of the original geometric design with the optimum geometric design together with options 1 and 2. The settlement in each case is shown when the PVDs were installed with the same spacing (1.4 m) as the original design, where option 2 produced settlement readings that were very much closer, but when compared with the different spacings (1.2 m) for the optimum design and option 1, the consolidation was much better. The optimum geometric design generated a better consolidation and settlement reading when the PVD was installed at a depth with an N value of more than 8. For the case with the same spacing but different depth, the settlement process was not affected for the PVDs with the original design and option 2. However, for those cases with different spacings and depths, which involved the optimum geometric design and option 1, a more effective settlement reading was generated.

Table 3: Settlement summary for Case 3

	Manual (mm)	PLAXIS 3D (mm)	Actual (mm)
Original design (1.4m S & 33m D)	2266	2553	2096
Optimum (1.2m S & 36m D)	2426	2642	2286
Option 1 (1.2m S & 33m D)	2304	2548	2158
Option 2 (1.4m S & 36m D)	2381	2553	2074

Figure 13 shows the comparison of the results for all the cases to achieve the 4th objective of this research, where the predicted settlement results generated from the PLAXIS 3D were compared with the actual site results. In Case 1 for Tanjong 12, due to insufficient soil data as an input for the simulation process, the results showed a very high settlement compared with the actual site results. This was because most of the data that were used were empirical data and the analysis was done while assuming that the subsoils were homogeneous. Hence, it showed that the consolidation process occurred without any defaults or damage from the PVD and the surrounding soil. Meanwhile, for Case 2, the data input parameters were enough for the analysis, and the predicted values were close to the actual settlement results. The soil data is very important in the prediction process because it can represent the soil condition as being similar to the real condition. When all the necessary data have been established from the 1-dimensional consolidation test and are enough for the simulation process, then the analysis can be done perfectly so that the predicted value will be reliable and sufficiently accurate with the actual site results. In Case 3, based on the four options for the validation process, the optimum geometric design gave the most accurate results with a low difference between the predicted values and the actual site results.

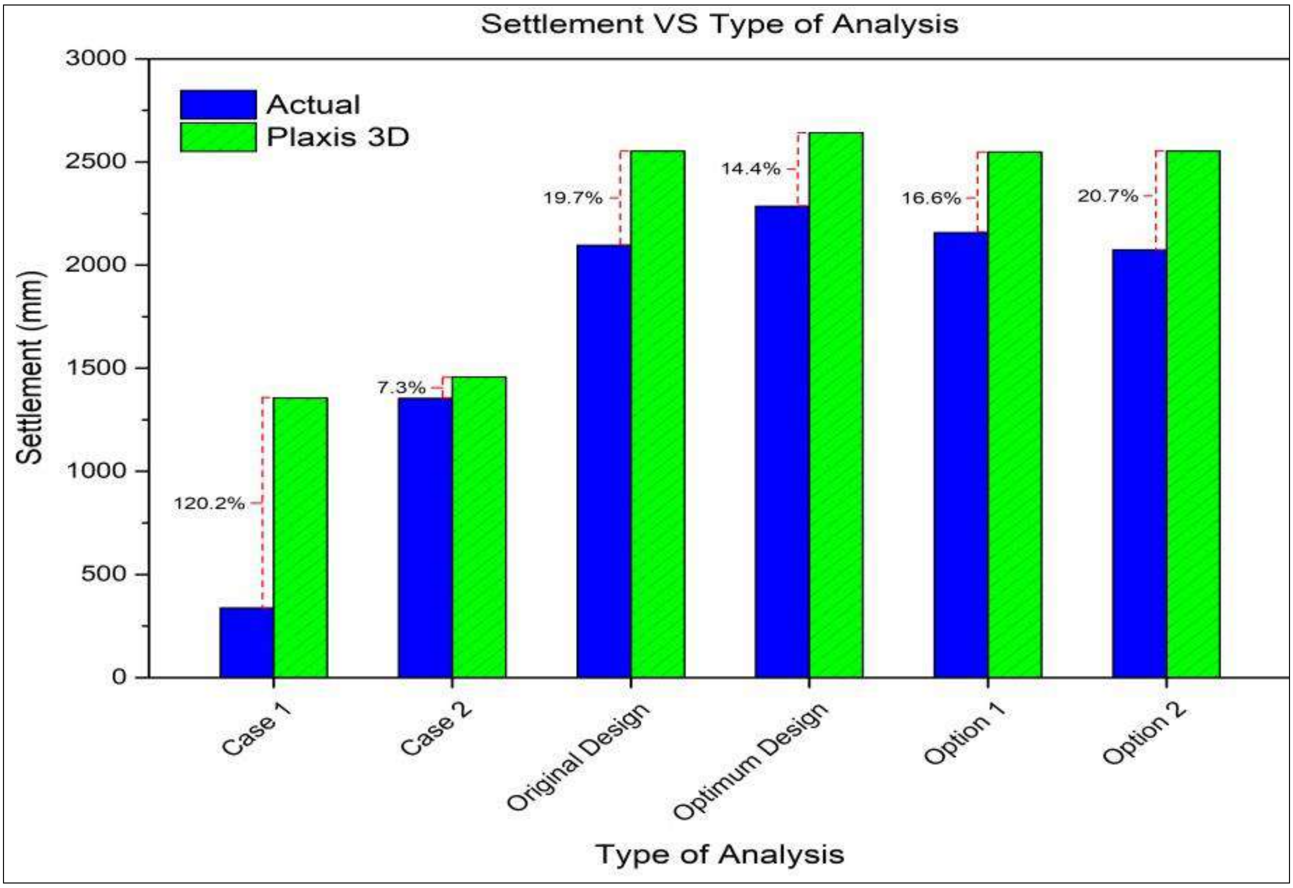


Fig 13: Validation for each case between PLAXIS 3D and actual site results

The validation process was successfully done using the PLAXIS 3D, and the predicted data were reliable because, in the case of the optimum geometric design, the results were only more than 14.4% close to the actual results, whereas the other three cases showed results that were more than those of the optimum geometric design case. Table 4 below gives the outcome of the comparison between PLAXIS 3D and the actual site results with the difference and the accuracy shown to prove that the PVD design with a spacing of 1.2 m and depth of 36 m was the most optimum and suitable design for the Kuala Gula project (Case 3). For the optimum geometric design, a result of 2426 mm was obtained, based on the manual spreadsheet calculation, while for the PLAXIS 3D, the result was 2642 mm. Both conditions were predicted values, while the actual site result was 2286 mm. The three outcomes were generated within a period of 6 months. The manual calculations produced more accurate data than what was predicted by the PLAXIS 3D because in the manual spreadsheet calculations, the values used for the analysis were the coefficient of consolidation (Cv) and the coefficient of volume compressibility (Mv), whereas in the PLAXIS 3D, soft soil models and the Van Genuchten equation (USDA) were used for the analysis. Even though the analytical methods were different, the soil data that were used as the parameters were basically generated from the same undisturbed soil sample that had been gathered and produced from the lab test. From all the analyses, the optimum geometric design with a PVD spacing of 1.2 m and depth 36 m was effective for the consolidation process and proved that the settlement result, especially with this optimum geometric design, produced a high consolidation compared with the other options and within the estimated timeframe.

Table 4: PLAXIS 3D and the actual site results comparison

	PLAXIS 3D (mm)	Actual (mm)	Difference (mm)	Accuracy (%)
Case 1 (validation)	1356	338	1018	24.9
Case 2 (validation)	1457	1354	103	92.9
Original design (1.4m S & 33m D)	2553	2096	457	82.1
Optimum (1.2m S & 36m D)	2642	2286	356	86.5
Option 1 (1.2m S & 33m D)	2548	2158	390	84.7
Option 2 (1.4m S & 36m D)	2553	2074	479	81.2

6. Conclusion

The consolidation process can happen most effectively when the ground improvement work is combined with embankments and prefabricated vertical drains. Moreover, it was proven that prefabricated vertical drains installed in a triangular pattern with a spacing of 1.2 m and at a depth of 36 m were able to consolidate more than the other options or designs. In the analysis with the original design and option 2, there was not much difference in the settlement. The same could be said of the optimum design and option 1, where there was less settlement even though the depths were different but with the same spacing. As an objective of this study, when the analysis was combined with a closer spacing and a longer depth, according to an SPT-N value of more than 8, the efficiency of the design could be proven from the actual outcome of the settlement at the site. It was clearly shown that with the low clay permeability at the site, if the consolidation period were to be shortened, it would be necessary to reduce the PVD spacing (R.Radhakrishnan, 2011). Figure 14 below shows the actual results that were obtained in Case 3. A comparison was done using the predicted values generated from the PLAXIS 3D with the actual site results. With reference to the first and second objectives of this research, the spacing and depth of the prefabricated vertical drains played an important role in the consolidation process. This research proved the influence of these two elements. In practice, when it comes to construction that needs to be carried out at the site, it is definitely impossible to use a mandrel and measure accurately during the installation of the prefabricated vertical drains, and when they are installed too close to each other, a smear effect will happen to the PVDs, including some damage from the machinery. In the simulation process, the predicted value was much higher because of the soil parameters, even though the samples were taken from the same source with the original ground conditions. The parameter values used for the analysis were close enough to the ground soil conditions. For Case 3, it was recommended that a prefabricated vertical drain spacing of 1.2 m in a triangular pattern with a depth of 36 m performed well. As the third objective of this research, the characteristics of the prefabricated vertical drains were very much related to the permeability of the ground conditions, and the tensile strength of the geotextile and the plastic core to solidly sustain the embankment loading. The friction between the filter sleeve of the PVDs and the soil mass surrounding the PVDs may cause synchronous deformation of both the subsoil and the PVDs (Hoang Hung Tran Nguyen, 2013). The characteristics of the PVD can actually influence the efficiency of the consolidation process. The external factors that can actually impact the settlement process, which is directly influenced by the prefabricated vertical drains, are the damage that can happen during the installation process, improper handling or over-exposure to sunlight, insufficient installation depth and an uneven subsoil profile with kink problems. The fourth objective of this study was achieved by conducting the validation process using simulations, and in this research, the PLAXIS 3D was chosen for the simulation analysis. The prediction settlement value in this case had to be reduced by 15% of the generated value to meet the actual results. This was because the actual results may have been influenced by external factors such as the vicinity of the settlement gauge due to lorry movements, soil parameter interpretations of the lab test, the compaction process to and from the embankment may have been regular, and most important of all, errors during the recording of the data (Assoc.Prof.Ir.Dr.Ramli Nazir, 2013). For the fifth objective, which was the most important task of this research, the new optimum geometric design for prefabricated vertical drains was generated and implemented at the site with a validation process, and these successfully performed efficiently and well by producing the highest settlement value within 6 months and the fastest consolidation process with a spacing of 1.2 m in a triangular pattern with a depth of 36 m. In conclusion, a lot of research has been done with regard to prefabricated vertical drains, but this research was unique in the sense that the analysis alone was done using simulations and a spreadsheet, but the practical testing and research were carried out at the site in real site conditions, whereas other previous researches were carried out more on samples, which did not fully represent the actual ground conditions. This optimum geometric design for PVDs can be used in all ground conditions and for all sites using a spacing of 1.2 m and a length with an N value of more than 8 as a reference for geotechnical engineers.

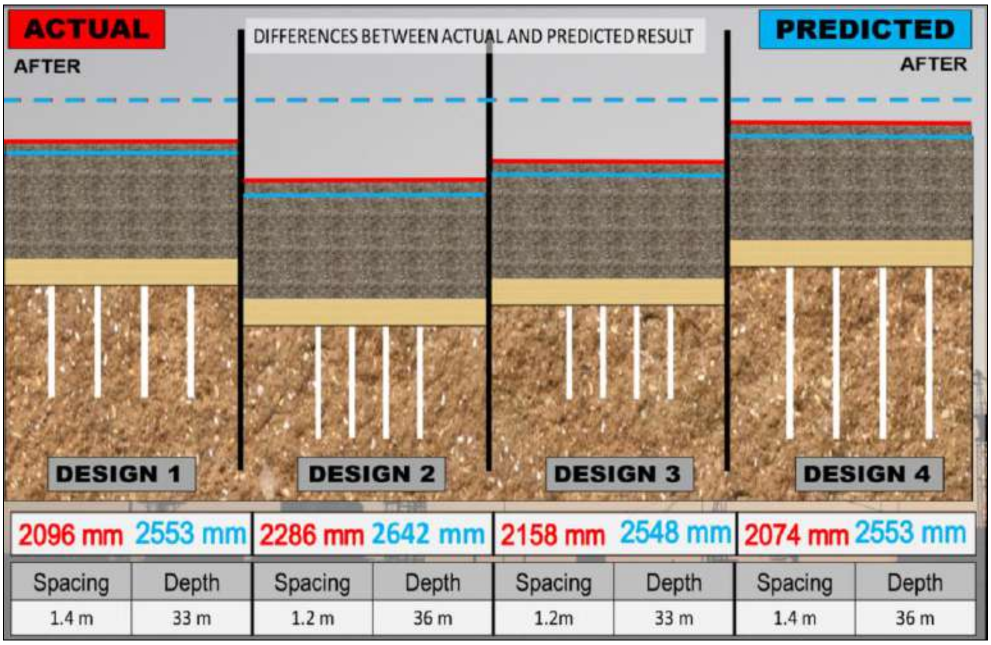


Fig 14: Settlement projection

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