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GEOTECHNICAL ENGINEERING DESIGN FOR SETTLEMENT MITIGATION IN THE DEEP FOUNDATION CONSTRUCTION AREA, NORTH SUMATRA PROVINCE, INDONESIA

Kemal Malik Muhammad[1], Raden Irvan Sophian[2], Faisal Helmi[3], Rahmat Dwi Prasetyo[4], Hilman Damanhuri[5]
[1]Faculty of Geological Engineering Universitas Padjadjaran 45363, Indonesia
[2]PT. Soilens
Corresponding author: kemal20001@mail.unpad.ac.id

ABSTRACT

The construction project in area Y, North Sumatra will be installed with piles as the preliminary foundation for a multi-story building. The installation of these piles resulted in settlement at several boreholes points analyzed using Rocscience Settle3. The settlement ranged from 65 mm -95 mm at over 11 boreholes over the construction area. This settlement has the potential to cause structural damage to the building, therefore geotechnical engineering is needed as a solution to prevent it. Ground improvement as geotechnical engineering can be done to support the design of safer foundations by increasing soil consistency in shallow to deep layers. Vibro compaction geotechnical engineering reduces the total settlement of the research area from 90 mm to 68 mm in BH-01, BH-04, and BH-06. In boreholes with low bearing capacity and medium settlement values such as BH-1, monitoring using a settlement gauge is required to provide efficient prevention in safe foundation planning without neglecting cost effieciency concern.

Keyword: Driven Pile, Settlement, North Sumatera

INTRODUCTION

Settlement is a critical consideration in geotechnical engineering, particularly in the design and construction of deep foundations (Araujo, 2021). It refers to the vertical displacement of the ground caused by the weight of a structure over time, often resulting from the consolidation and compression of the underlying soil layers. While shallow foundations experience settlement predominantly in the upper soil strata, deep foundations such as piles and drilled shafts transfer loads to deeper, more stable layers. However, even deep foundations are not immune to settlement, and careful evaluation is essential to ensure the stability and longevity of the supported structures. (Das, 2018).

The construction area "Y", North Sumatera is the land footprint will be subject to large-scale development. This development will be built as an upper structure on a deep foundation area that will function as main element in supporting the building so that the building can stand safely and stably. In considering the safety and stability, a special review of the land where the building will be built is needed to avoid failure, especially collapse caused by settlement when the building is built. In consideration of this, geotechnical engineering solution is especially needed to mitigate the potential settlement so the construction area can achieve a safe and sustainable development for the duration of its use.

This study aims to determine the amount of settlement that occurs, as well as the foundation engineering that can be done to mitigate the settlement based on the eleven drill holes installed in the research area "Y". The objectives of this study are: 1) Determining the amount of settlement that occurs in the research area when the piles are installed; 2) Determining the most optimal engineering used to mitigate the settlement results that may occur.

RESEARCH METHOD

This stage is carried out using data obtained from the company data of PT. Soilens. The data to be analyzed are as follows: Borehole data including SPT data obtained through field investigations.

Material properties data from the soil in the research area through laboratory tests, to determine the physical and mechanical properties of the soil in the research area. The data will be processed using semi-empirical formulas for deep settlement analysis.

PILE FOUNDATION SETTLEMENT

The maximum settlement for each building varied based on the limiting factor considered. In general, the total allowed settlement for a framed building or a multi-story buildings is 50 – 100 mm (George F. Sowers and F.ASCE, 1964). Click or tap here to enter text.

Table 1. Allowed Settlement (Sowers, 1964)

Limiting Factor	Maximum Settlement
Drainage	15 - 30 cm
Entrance	30 - 60 cm
Brick building	2,5 - 5 cm
Frame building	5 -10 cm
Chimney, silo, raft foundation (mat)	8 - 30 cm

UNIFIED SOIL CLASSIFICATION SYSTEM (USCS)

The Unified Soil Classification System (USCS) is a widely used system for categorizing soils based on their particle size distribution and behavior under different moisture conditions. It was developed by the U.S. Army Corps of Engineers and the Bureau of Reclamation to create a standard for soil classification, particularly for construction and engineering purposes (Masoud, 2019).

Each soil type is given a two-letter symbol to indicate its properties. For example:

GP: Poorly graded gravel.
SC: Clayey sand (sand with clay).
SM: Silty sand (sand with silt)
CL: Low-plasticity clay.

SPT TO UNDRAINED SHEAR STRENGTH CORRELATION

Due to data limitations, there are Undrained Shear Strength values derived from SPT values based on the Terzhaghi and Peck classification (Terzaghi and Peck, 1948) (Table 1).

Table 2. Correlation between SPT

Soil Type and SPT Blow Counts		Undisturbed Soil	
		Cohesion (psf)	Friction Angle (°)
Cohesive soils			
Very soft	(<2)	250	0
Soft	(2–4)	250–500	0
Firm	(4–8)	500–1,000	0
Stiff	(8–15)	1,000–2,000	0
Very stiff	(15–30)	2,000–4,000	0
Hard	(>30)	4,000	0
Cohesionless soils			
Loose	(<10)	0	28
Medium	(10–30)	0	28–30
Dense	(>30)	0	32
Intermediate soils			
Loose	(<10)	100	8
Medium	(10–30)	100–1,000	8–12
Dense	(>30)	1,000	12

ROCK AND SOIL STRENGTH CLASSIFICATION (ISRM, 1981)

The International Society for Rock Mechanics (Labuz et al., 2017; ISRM 1981) classifies soil strength based on UCS values and field tests, the classification is as follows in (Table. 3)

Table 3. Soil strength classification (ISRM, 1981)

Grade	Term	Field Identification	Approx. UCS (psi)
S1	Very soft clay	Easily penetrated several inches by fist.	< 3.62
S2	Soft clay	Easily penetrated several inches by thumb.	3.62 – 7.25
S3	Firm clay	Can be penetrated several inches by thumb with moderate effort.	7.25 – 14.5
S4	Stiff clay	Readily intended by thumb, but penetrated only with great effort.	14.5 – 36.25
S5	Very stiff clay	Readily intended by thumbnail.	36.25 – 72.5
S6	Hard clay	Intended with difficulty by thumbnail.	> 72.5

MOHR-COULOMB FAILURE CRITERION

This model states that if the shear stress on the potential failure plane exceeds the cohesion value, plus the product of the normal stress () with the tangent of the internal friction angle, then failure will occur. The empirical model of Mohr-Coulomb failure according to (Labuz et al., 2018) can be seen in (Equation 1.)

$$\tau = c + \sigma \cdot \tan(\phi)$$

This model also has limitations, namely, constant internal friction angle, constant cohesion, without considering contraction (not considering volume changes during failure), and also these criteria will be modeled linearly between shear stress and normal stress (Figure 1).

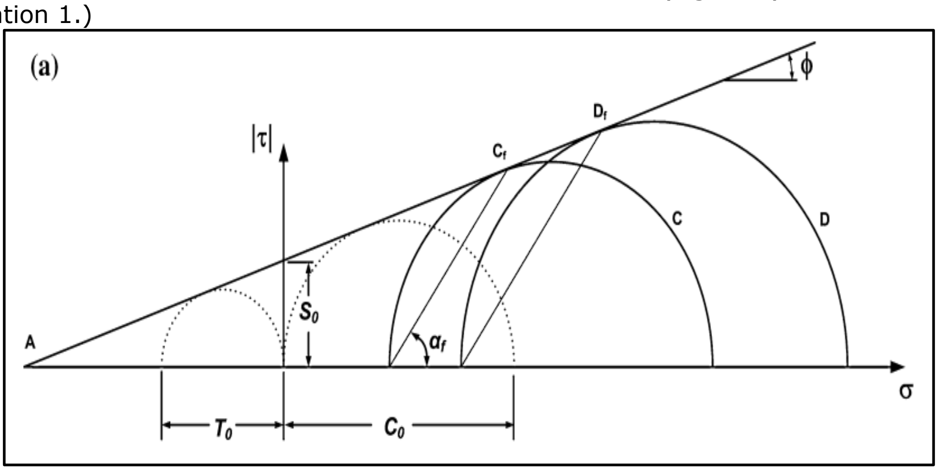

Figure 1. Linear failure envelope (Labuz et al., 2018)

SETTLEMENT ANALYSIS

After the samples are tested in the laboratory, the sample data will be further processed in the RSPile simulation program to obtain axial loads based on soil characteristics, as well as the type and dimensions of the piles to be installed. Data from RSPile will then be imported into Settle3. The data can the be used to measure the amount of settlement that occurs in the research area along with geotechnical engineering that can be done to minimize the adverse impacts that can occur (Ram et al., 2023).

SETTLEMENT MITIGATION – VIBRO-COMPACTION

Ground vibro-compaction is a widely used technique for improving the density and stability of sandy soils. It increases the dry density of sandy soils, which enhances their load-bearing capacity and stability. This is achieved by rearranging soil particles into a denser configuration, reducing voids and increasing soil strength (B. C. Slocombe, 2015).

The soil in the study area is dominated by non-cohesive sandy soil which is very suitable for applying the vibro compaction method. In this process, the method enhances the physical and mechanical characteristics of sandy soils, such as increasing the elastic modulus and internal friction angle, which are critical for the stability of structures like port facilities and foundations (Minaev, 2018). In the specified part for settlement mitigation, it makes them suitable for large-scale projects and deep soil strata, ensuring uniform compaction and improved soil properties at greater depths

RESULTS & DISCUSSION

Geological & Geotechnical Condition

Through the existing wellbore points, subsurface reconstruction was carried out using cross-sections covering BH-10, BH-01, BH-04, and BH-06 (Figure 2). After correlation, it was found that the top soil consisted of silty sand (SM) and clayey sand (SC) (Figure 3). The layer was then followed by a layer of low plasticity sandy silt (ML) covering the hard tuff rocks below (Figure 4).

Based on the Unconfined Compression Test (UCS) in (Figure 4). The soil shows a strength of 20 kPa – 138 kPa which is classified into S1-S4 (Figure 6.)

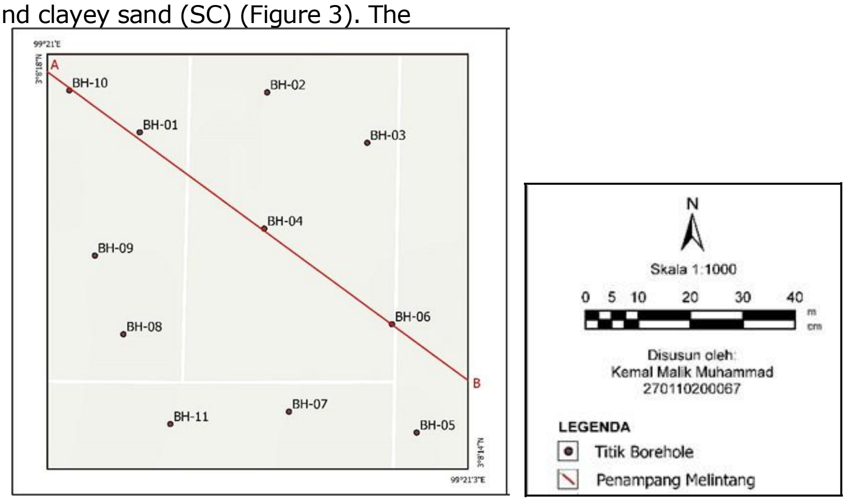

Figure 2. Borehole point distribution map

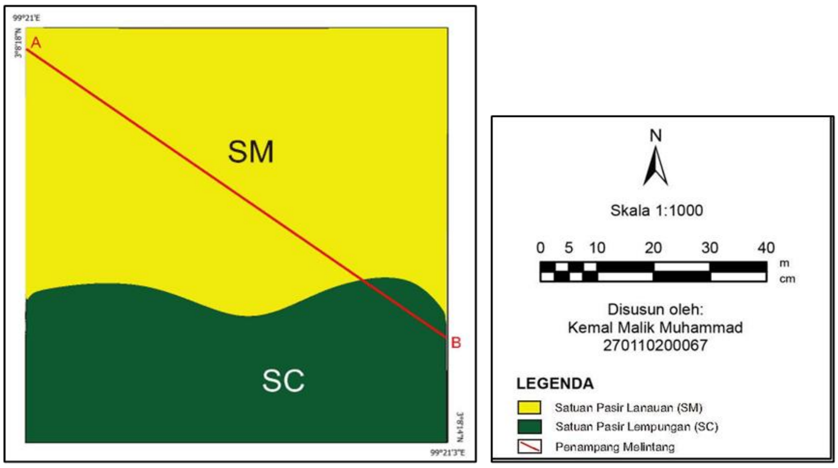

Figure 3. Cross section of the borehole

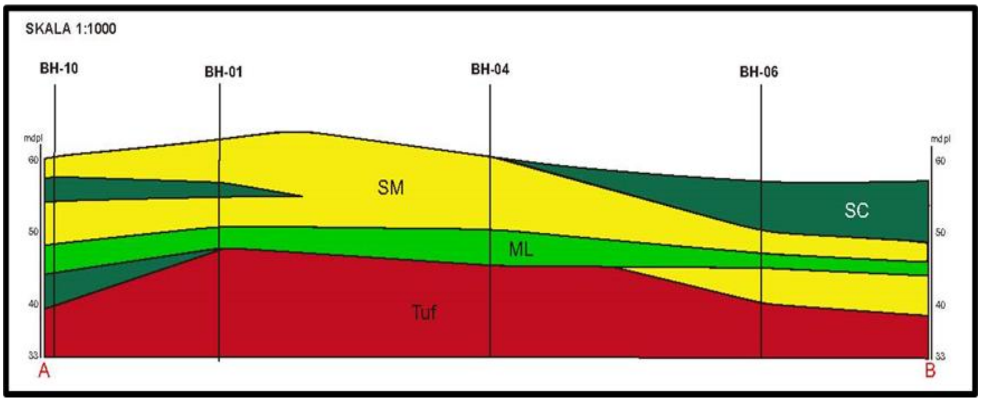

Figure 5. Vertical section of the borehole

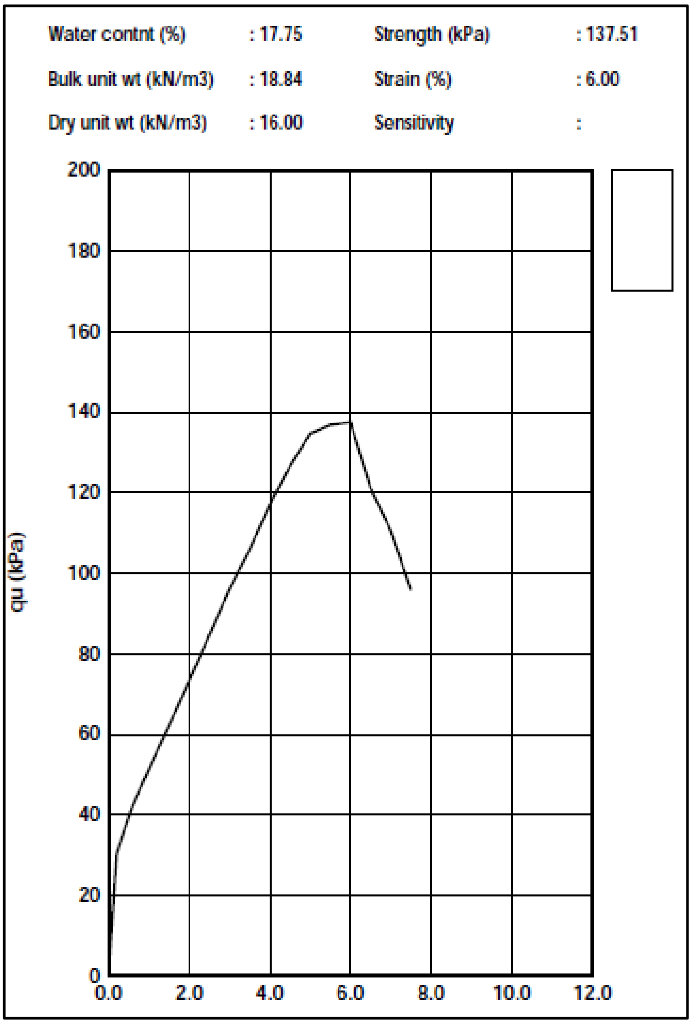

Figure 6. Material UCS value

MATERIAL PROPERTIES LABORATORY TEST RESULTS

From the BH-01 sample test, it was found that the silty sand had a higher original weight and cohesion value in the top layer, the sand was mixed with clay but still had relatively the same parameter values as ordinary silty sand (Table 3). The laboratorium test is based on undisturbed sample from the SPT test.

Tuff

This lithology was observed below the soil layer at a depth of about 15 m (Figure 2). The tuff has a greenish brown color, is fine-grained, and is moderately weathered. This layer is included in the Toba Tuff (Cameron, 1981).

Silty Sand (SM)

This unit consists of soil that has a grayish-brown to greenish-brown color, fine sand grain size, loose to very dense consistency. The hardness of this unit varies from S1-S4

Clayey Sand (SC)

This unit consists of soil that has a grayish-brown to greenish brown color, fine sand grain size, and loose consistency. The hardness of this unit varies from S2-S4.

Sandy Silt (ML)

This unit consists of soil that has a greenish gray color, low plasticity, moist water content, and medium stiff soil consistency. The soil has a hardness of

Table 4. Material properties of BH-01

BH-01					
Kedalaman (m)	**Lithology**	**Unit Weight (kN/m³)**		**Cohesion, c (kPa)**	**Internal Friction Angle, (ϕ°)**
		ϒsat	**ϒdry**		
2.00	Silty sand	18.72	15.94	49.30	17.80
4.00	Silty sand	18.72	15.94	49.30	17.80
6.00	Silty sand	18.72	15.94	49.30	17.80
8.00	Clayey sand	19.38	16.99	45.85	20.30
10.00	Silty sand	18.42	15.66	19.20	26.00
12.00	Silty sand	18.42	15.66	19.20	26.00
14.00	Sandy silt	15.59	9.86	61.20	10.80
15.00	Sandy silt	15.59	9.86	61.20	10.80

From the BH-04 sample test, it was found that the silty sand had a higher cohesive value than sandy silt. This is because silt also contains clay content mixed with sand so that its composition becomes very heterogeneous (Table 4)

Table 5. Material properties of BH-04

BH-04					
Kedalaman (m)	**Lithology**	**Unit Weight (kN/m³)**		**Cohesion, c (kPa)**	**Internal Friction Angle, (ϕ°)**
		ϒsat	**ϒdry**		
2.00	Silty sand	17.24	15.07	42.90	14.80
4.00	Silty sand	18.42	15.78	44.37	16.19
6.00	Silty sand	18.42	15.78	44.37	16.19
8.00	Silty sand	18.58	16.03	41.40	15.30
10.00	Silty sand	18.58	16.03	41.40	15.30
12.00	Sandy silt	17.12	11.92	16.60	18.30
14.00	Sandy silt	17.12	11.92	16.60	18.30
15.00	Sandy silt	17.12	11.92	16.60	18.30

From the BH-06 sample test, it was found that the clay sand had a lower original weight value than the silty sand. However, the internal friction angle was higher than the silty sand (Table 4). The results of cohesion and friction angle in derived from SPT due to limited data by Terzhaghi and Peck Classification (1965).

Table 6. Material properties of BH-06

BH-06				
Kedalaman (m)	**Lithology**	**Unit Weight (kN/m³)**	**Cohesion, c (kPa)**	**Internal Friction Angle, (ϕ°)**
		ϒsat		
2.00	Clayey sand	16.00	27.5	30.00
4.00	Clayey sand	16.00	27.5	30.00
6.00	Clayey sand	16.00	27.5	30.00
8.00	Clayey sand	16.30	18.1	32.40
10.00	Clayey sand	16.30	18.1	32.40
12.00	Sandy silt	18.00	18,8	12.45
15.00	Silty sand	18.58	42.90	14.80

From the BH-10 sample test, it was found that the silty sand had a more cohesive value than the layers below it. The clay content increased the original weight value of the clay sand at a depth of 4-6 m (Table 6).

Table 7. Material properties of BH-10

BH-10					
Kedalaman (m)	**Lithology**	**Unit Weight (kN/m3)**		**Cohesion, c (kPa)**	**Internal Friction Angle, (ϕ°)**
		γsat	**γdry**		
2.00	Silty sand	17.33	15.36	31.20	17.10
4.00	Clayey sand	18.96	16.46	30.46	17.87
6.00	Clayey sand	18.96	16.46	30.46	17.87
8.00	Silty sand	18.96	15.96	31.20	16.95
10.00	Silty sand	18.96	15.96	31.20	16.95
12.00	Silty sand	18.96	15.96	31.20	16.95
14.00	Sandy silt	17.22	12.04	6.90	9.50
15.00	Sandy silt	17.22	12.04	6.90	9.50

SETTLEMENT ANALYSIS

After the laboratory test is conducted, the sample data is further processed in a settlement simulation at each borehole. Axial load is obtained from the simulation results of piles when installed using RSPile software. Settlement is obtained from the results of Settle3 in the (Figure 6.). This settlement is caused by the axial load from the time the pile is installed from the top soil to the hard layer. (Figure 7, left).

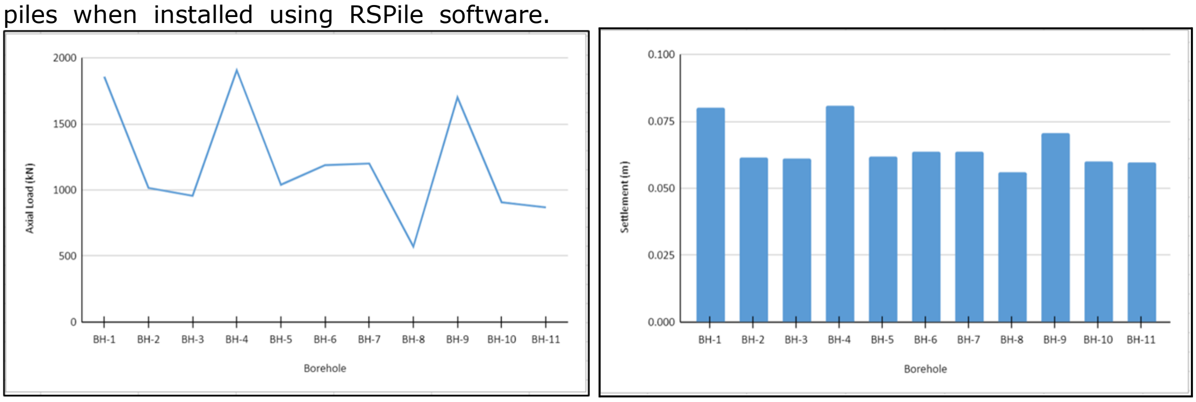

Figure 7. Settlement relationship graph for each borehole

The curves were created by simulating the maximum axial load and settlement experienced by each borehole when the piles were installed. It can be observed that the largest axial load is at BH-4 with a maximum axial load of 1906 kN and a settlement of 0.8091 m. The lowest value was experienced by BH-8 8 with an axial load of 571.7 kN and a settlement of 0.5593 m (Figure 4, right). This difference may be caused by the difference in lithology of BH-8 which is more cohesive than BH-4

GROUND IMPROVEMENT FOR SETTLEMENT MITIGATION

Geotechnical engineering is carried out to reduce settlement at points that are considered to be most likely to experience damage. Vibro compaction, also known as vibroflotation, is a ground improvement technique used to increase the density of granular soils such as sand or gravel. Based on the simulation carried out using the Settle3 program, a settlement value of 70 - 90 mm was obtained for almost 11 installed piles on the 3D image of the study area (Figure 8).

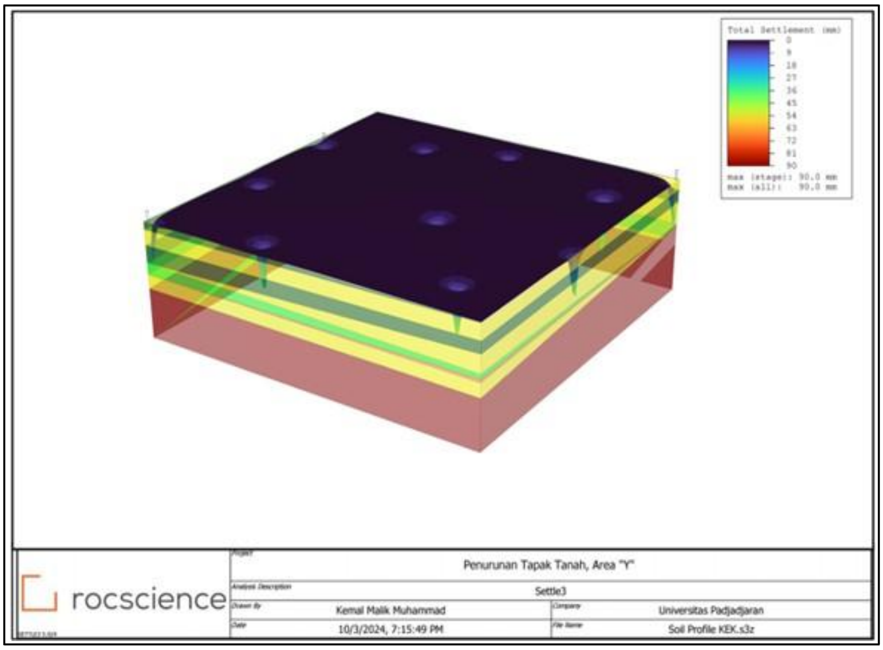

Figure 8. 3D Model of Settlement Area "Y"

Simulations were conducted at 11 bore points, but only 3 wellbore points that were considered to be very effective when applied using vibro-compaction method, the rest of the borepoints only result in a meagre to diminishing decrease in total settlement. By considering the cost-effectiveness of the method when perfomed on the field, the study will only focus only on these 3 wellbore points so that the resulting analysis can be used as a reference for the better planning and maintenance of the construction. As result of the simulation, the vibro-compaction engineering reduced the total overall settlement from 90 mm to 72.1 mm. The operation area can be seen as a three white square cubic spanning a diagonal line (Figure 9), whereas the vibro-compaction will be conducted.

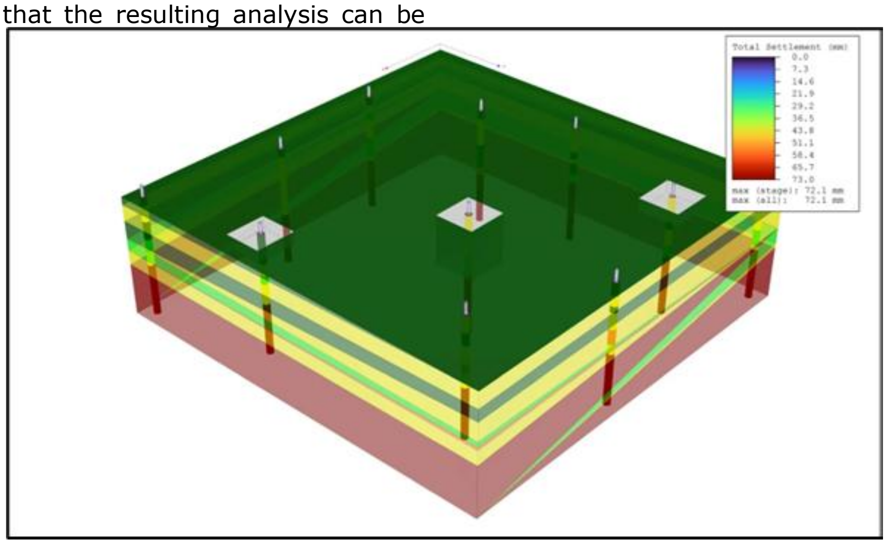

Figure 9. Ground improvement points (white sqares)

Simulation of the vibro-compaction can be used on a greater depth, but only diminishing predetermined depth will the method be focused on. As can be seen on (Figure 10.) the conic shape is the settlement that potentially can happen on the study area, the value of the settlement can be seen from dark blue at the compaction performed on. To address more the cost-effective operation, geotechnical engineering was carried out to a depth of 3 meters at points BH-01 and BH-6, and 11 0 – 20 mm settlement on the top soil to the orange at 50 mm depth or greater, in this case theirs is no red color since the simulation to reduce settlement is carried on; the white result will be achieved, which will will fail to give meaning to the operation so only on the blocks is the depth of the method vibro-meters at point BH-04 (Figure 10.). The geotechnical method resulting in a decreasing value of settlement on the study area from 90 mm to 72,1 mm.

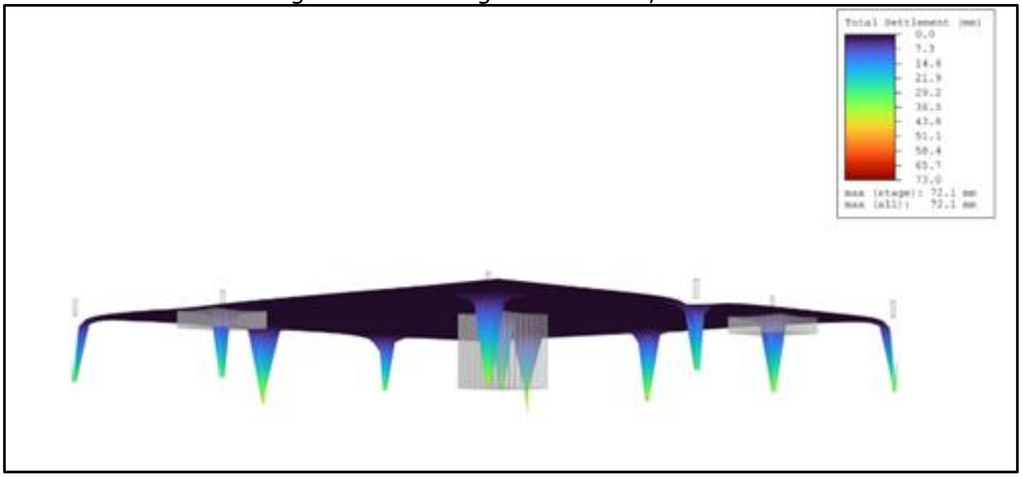

Figure 10. Depth of each ground improvement points (white blocks)

The settlement can be further reduced by increasing the Relative Density target (DR Target %) of the vibro compaction tool. The results of increasing the DR Target from 75% to 90% show a further decrease in the settlement from 72.1 to 68 mm (Figure 11.). Based on this value, it can be assumed that the most effective method in reducing the geological settlement phenomenon in this area is the vibro-compaction method at the three predetermined points (white blocks).

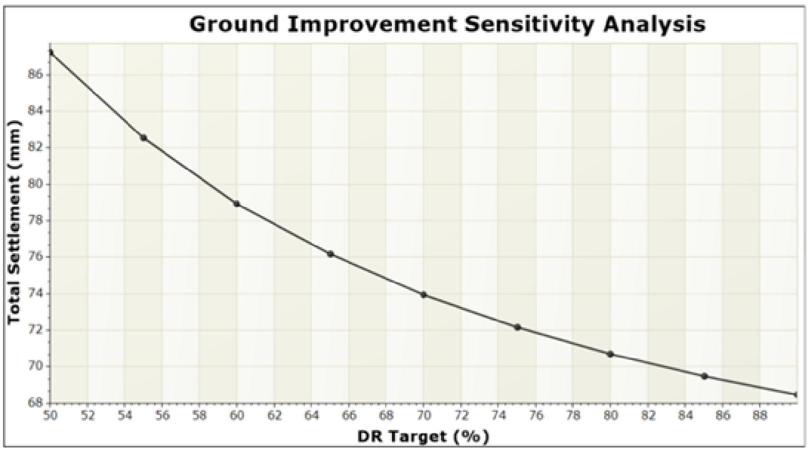

Figure 11. Graph of the relationship between depth and relative density (DR) of vibro-compaction

CONCLUSION

Based on the RSPile and Settle3 settlement simulations, the research area experienced a settlement of 70 – 90 mm over all of the study area. The dominance of sandy soils makes the study area vulnerable to liquefaction when heavy torrent of rain occurs simultaneously.

Ground improvement as geotechnical engineering can be done to support the design of safer foundations by increasing soil consistency in shallow to deep layers. Vibro compaction geotechnical engineering reduces the total settlement of the research area from 90 mm to 68 mm in BH-01, BH-04, and BH-06.

In boreholes with low bearing capacity and medium settlement values such as BH-1, monitoring using geotechnical instruments such as settlementplate, piezometer, a global positioning system (GPS), prism, and other geodetic survey device tomonitor ground settlement in place.

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