

THE EFFECT OF SOIL IMPROVEMENT PATTERNS USING DEEP CEMENT MIXING (DCM) ON SOFT SOIL SETTLEMENT

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ABSTRACT: Soft soil is a type of soil that has high compressibility, very low shear strength, low permeability coefficient, and high compression. Deep cement mixing (DCM) is a method for improving soft soil. In this modeling, the DCM column patterns with the same total volume of work are varied with the aim of knowing which pattern is effective in reducing settlement. The DCM column pattern is modeled into 8 pattern variations in accordance with the provisions of BS EN 14679:2005 by the British Standard Institution. These patterns are rectangular patterns, triangular patterns, line patterns, wall patterns, block patterns, area patterns, lattice patterns, and overlaid column patterns. In this model, 550 cubic meters of volume DCM is modeled as deep as 28 meters. The number of columns and diameter varies with 25 columns with 1 m diameter for rectangular patterns, 22 columns with 1.06 m diameter for triangular patterns, 47 columns with 0.73 m diameter for line patterns, 67 columns with 0.61 m diameter for wall patterns, 61 columns with 0.64 m diameter for block pattern, 149 columns with 0.41 m diameter for area pattern, 265 columns with 0.30 m diameter for lattice pattern and 123 columns with 0.45 m diameter for overlaid pattern. Based on the results of modeling using PLAXIS 3D, it can be concluded that the greatest reduction in settlement and consolidation time occurs in models with lattice patterned DCM, which can reduce settlement up to 97.45% and reduce consolidation time up to 89.60%.

Keywords: Deep Cement Mixing, Soil Improvement, PLAXIS 3D, Soft Soil.

1. INTRODUCTION

In modern times, there is an increasing number of construction project developments, in this case especially in Indonesia. The development that has taken place has not only grown in big cities but also in small towns on the outskirts of Indonesia. One of the causes of the increasing number of construction developments in big cities and small cities is population growth. The population of Indonesia in 2022 is 275,501,339, and it has grown by 10.1% in the last 10 years [1]. With increasingly high population growth, facilities and infrastructure buildings are also skyrocketing according to the demand for facilities that can be used to support daily activities, such as residences, hospitals, offices, shopping centers, and other facilities.

With the skyrocketing growth in construction development and population, the available land to build construction is also decreasing [2]. Currently, there are more and more constructions that are forced to be carried out on soil with problematic behavior or low bearing capacity. Soils with low bearing capacity generally tend to have large settlement values that have the potential to damage the construction built on its surface in the future. Some types of problematic soil are soft clay soil, peat soil, expansive soil, collapsible soil, and soil prone to liquefaction. One type of problematic soil that is often found in Indonesia is soft clay soil. Soft soil is a type of fine-grained soil that has high

compressibility and small shear strength. Soft clay soil can be identified based on results from the Cone Penetration Test (CPT) and Standard Penetration Test (SPT). For example, thick soft clay soil is also found in Central Java. In these areas, soft soil has high plasticity and is susceptible to changes in its shear strength parameters due to changes in soil water content [3]. This condition can certainly have fatal consequences in the long term. Therefore, soil improvement is highly recommended before construction is carried out on soft soil.

There are various soil improvement methods that are commonly used as a soil improvement. Such as making columns in the ground. The column material can be stone (Stone Column), which can increase the load capacity of the soil [4], or a mixture of existing soil and other additives (Deep Mixing Column). DMC is one of the soil improvement types. The DMC method can be interpreted as a soil improvement method that mixes other materials with the soil. The aim of using DMC is to improve soil quality by stabilizing the soil in the field and increasing the bearing capacity of the soil [5].

There are two methods for applying DMC in the field, namely, the wet method and the dry method. The wet method is carried out by mixing the binding material with water before mixing it with the soil, while in the dry method, the binding material is mixed with the soil while it is dry [6]. DMC is commonly used on slope areas, bridge pillars,

building foundations, and breakwaters. DMC helps control the amount of settlement that occurs so that soil settlement can be minimized.

Several additive materials can be used in DMC applications. Generally, the selection of additives is based on the type of soil in the field that needs to be improved (Table 1):

Table 1. Additive material based on clay soil type [6]

Soil Type	Additive material
Clay	Lime
	Mixture of lime and cement
Very sensitive clay	Lime
	Mixture of lime and cement
Organic clay	Mixture of lime and cement
	Mixture of slag and cement
	Mixture of cement and gypsum

In the past, lime was the only binding material used to stabilize and repair soft soil, but since the mid-1980s, cement has become another alternative for soft soil improvement because it has higher strength [7]. DMC, which uses cement as a binding material, is then known as Deep Cement Mixing (DCM). The way DCM is applied in the field is by injecting cement using pumps and then mixing it with soft soil using a special tool [8]. The main objective and function of the application of DCM is to increase the bearing capacity of the soil [9] and to reduce the settlement of soft soil. Adding cement material to the soil can reduce the expansive properties of the soil, reduce plasticity, and increase the soil's bearing capacity [6].

DCM has an important role in soil improvement efforts in various parts of the world. In Japan, DCM with a diameter of 1 meter is used to reduce settlements that occur in buildings. DCM is applied in a square or rectangular pattern with a DCM mixture UCS value of 2 - 4 MPa and a cement content of 200 - 300 kg/m³[10]. In China, DCM with a diameter of 0.5 m and an area ratio of 22% are used to strengthen high-rise buildings. Supporting data for the DCM mixture in this case is 530 - 650 kPa with a cement content of 20% [11].

In Indonesia, DCM is also often applied as reinforcement in soft soil. One of them is at the new double-track location that connects Purwokerto and Kroya. DCM, with 12.6% of cement mixing, is used as ground improvement work. Other than that, one layer of geogrid was also installed on top of DCM in order to increase embankment stability. 2803 columns with a diameter of 1 m and a distance between columns of 2.5 are effectively used in embankment construction to increase the bearing capacity of soft soil and reduce settlement that occurs in the area [12].

The diameter of DCM columns ranges from 0.5 m - 1 m with a center-to-column distance of 1 m - 1.5 m or generally based on the available DCM machine auger diameter. Generally, the closer the distance between columns, the greater the stability achieved [13]. Table 2 contains examples of DCM mixing machine specifications used in DCM applications in the field. Column length varies between 10 m and 30 m or according to the area and thickness of the soft soil to be improved [14].

Table 2. Machine ability to perform DCM based on depth, type of soil, and additive material [6]

Type	DJM 1070	DJM 2070	DJM 2090	DJM 2110
Max Depth	20 m	26 m	33 m	33 m
Blade Diameter	1 m	1 m	1 m	1-1.3 m
Soft Soil Classification	N < 6	N < 6	N < 7	N < 9
Additive Material Distribution	25-120	25-120	25-120	25-120

Note: additive material distribution displayed in kg/min

In its application in the field, there are several patterns/configurations that can be applied, namely rectangular patterns, triangular patterns, line patterns, wall patterns, block patterns, area patterns, lattice patterns, and overlaid column patterns (Fig. 1) [15].

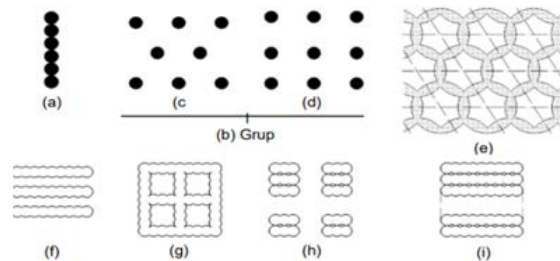


Fig.1 Deep cement column installation patterns

In the application of DCM as soft soil improvement, there are several things that need to be planned to obtain maximum results, including the diameter of the DCM column, the distance between each DCM column, the depth of the DCM column, and the pattern of DCM application [6]. In general, the installation diameter of the DCM depends on the size of the mixing machine available, which is also adjusted to the needs of soft soil improvement in the project. The depth of the DCM column is generally applied based on how thick the soft soil is at that location. The distance between the DCM columns and the pattern of the DCM application can be different in each case. In previous studies, an analysis of the foundation

capacity on soil improved with square pattern DCM was carried out [16]. To find out how much influence the DCM column pattern has on reducing the settlement that occurs, further analysis is needed. The aim of the modeling carried out in this study is to determine the DCM pattern that is most effective in reducing consolidation settlement and the length of time consolidation occurs on soft clay soil. In this research, the model was created using PLAXIS 3D.

2. RESEARCH SIGNIFICANCE

Soft clay soil is a type of soil commonly found in Indonesia. DCM is a soil improvement that can be carried out on soft clay soil. One factor that can be varied in using DCM in soft clay is the installation pattern. The effect of installation patterns on improving the quality of soft soil needs to be analyzed to provide an overview of the effectiveness of each DCM installation pattern. DCM installation pattern analysis can be carried out using a 3-dimensional numerical method using PLAXIS 3D so that the installed DCM pattern can be depicted in its entirety.

3. METHODOLOGY

3.1 Soil Parameter

In this analysis, the soil is modeled using a hardening soil model. The hardening soil model on PLAXIS is a soil model that accommodates more advanced stiffness values. The stiffness values accommodated in this soil model are the values of E_{50} (soil elastic stiffness at primary deviatoric loading condition), E_{ur} (soil stiffness at primary consolidation), and E_{oed} (soil stiffness at unloading/reloading condition). Generally, this soil model is used for cases that are closely related to soil settlement or cases that involve an excavation stage. Because in this case, soil settlement is the variable to be analyzed, the soil hardening soil model is suitable for use in describing the behavior of the soil under consideration.

In this modeling, the deep mixing column is applied to a very soft clay layer 26 m thick. Clay is soil composed of fine-sized grains of soil 0.002 mm – 0.005 mm. Apart from being based on the grain size, which is between 0.002 mm – and 0.005 mm, clay can also be classified based on the presence of particles that give plastic properties to the soil when it meets water [17]. The specific gravity of clay ranges from 2.68 to 2.72. The porosity value of soft clay ranges from 66% –75% with a plasticity index value >7 . The soft clay void number is between 1.90 – 3.00. The permeability value of clay soil ranges between 10^{-8} – 10^{-5} mm/s. The water content of soft clay is approx. 70% - 110% [18].

In the UCS test results, soft clay is identified as

having a q_u value of less than 50 kN/m^2 and in CPT test results, the cone resistance value of soft clay is less than 5 kg/cm^2 . NSPT for soft clay soil has a value of less than 5. Based on these values, soft clay soil has low shear strength, high compressibility, and a small permeability coefficient. The soil data used in PLAXIS 3D modeling is based on assumptions (Table 3).

Table 3. Soil parameter that used in the model

Layer	1	2	3	4	5
Depth	0-26	26-27	27-30	30-32	32-40
Soil Type	Very Soft Clay	Loose Sand	Medium Clay	Medium Dense Sand	Medium Dense Sand
Drainage Type	Undrained A			Drained	
γ_{sat}	12.5	21	19.5	23	19
γ_{unsat}	11	19.5	17.5	21	15
c'	5	1	5	1	1
ϕ'	20	25	25	37	30
E_{50}^{ref}	1000	5000	5000	36000	18000
E_{oed}^{ref}	1000	5000	5000	36000	18000
E_{ur}^{ref}	3000	15000	15000	108000	54000

Note: γ_{sat} and γ_{unsat} displayed in kN/m^3 units, c' and E in kN/m units.

3.2 Cement Column Parameter

In this modeling, the DCM column is modeled as soil cluster (soil volume) with a linear elastic soil model. The DCM column is modeled as non-porous or does not have the ability to pass water. The DCM column parameters (Table 4) used in this modeling are taken based on laboratory test results [19].

Table 4. Deep cement column parameter

Parameters	Deep mixing column	Unit
Soil Model	Linear elastic	-
Drainage Type	Non porous	-
γ_{unsat}	16.76	kN/m^3
E	5.26×10^5	kN/m^2
v	0.15	-

4. MODEL SIMULATION

In this research, the model was created using PLAXIS 3D. PLAXIS 3D is a 3-dimensional-based software used in geotechnical engineering. Plaxis 3D is software that adopts the finite element method.

To determine the effect of DCM on soft clay soil, the modeling carried out includes modeling without DCM improvements and with the presence of DCM with varied patterns. DCM is modeled as soil

volume with varied patterns and varied diameters with the same volume, which is 550 cubic meters with 28 meters depth, so the diameter and number of DCM are different for each pattern. The number of columns and diameter varies which 25 columns with 1 m diameter for rectangular patterns, 22 columns with 1.06 m diameter for triangular patterns, 47 columns with 0.73 m diameter for line patterns, 67 columns with 0.61 m diameter for wall patterns, 61 columns with 0.64 m diameter for block pattern, 149 columns with 0.41 m diameter for area pattern, 265 columns with 0.30 m diameter for lattice pattern and 123 columns with 0.45 m diameter for overlaid pattern.

The area that needs improvement is assumed to be 10 m x 10 m. In this area, it is assumed that there is a structural load, which is modeled as a uniform load of 48 kN/m². To avoid soft soil collapsing during construction, steel plates as working platforms are also modeled on the ground surface of the area to be improved by 14 m x 14 m in the area (Fig.2). Geotextile was also installed to prevent soil collapse. The use of geotextiles together with DCM is commonly used in the field to increase soil stability or increase embankment stability [3].

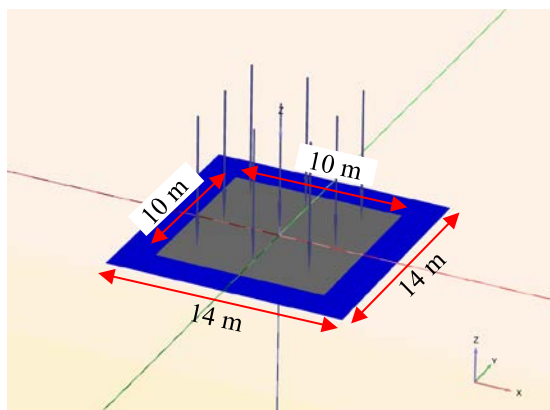
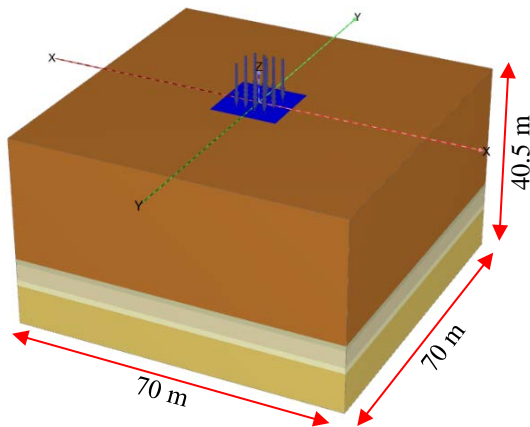


Fig.2 Model

There are 8 DCM improvement models with different column configuration patterns, namely rectangular patterns, triangular patterns, line

patterns, wall patterns, block patterns, area patterns, lattice patterns and overlaid column patterns (Figs.3-10). The column is modeled to have a length of 28 meters and the DCM volume used is 550 cubic meters so the diameter and number of columns may be different for each pattern.



Fig.3 Line pattern column model

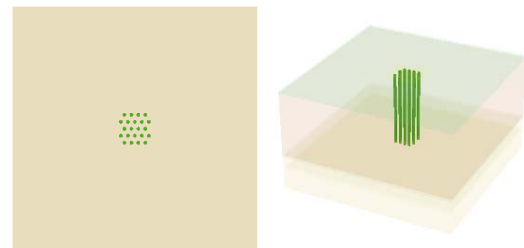


Fig.4 Triangular pattern column model

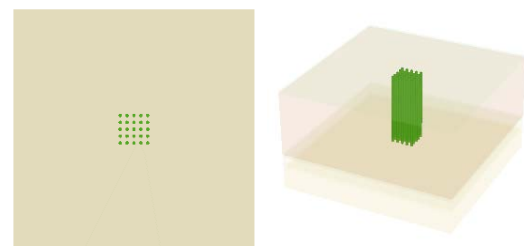


Fig.5 Square pattern column model

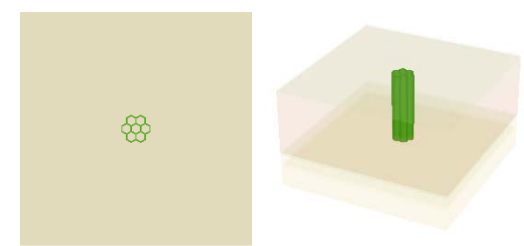


Fig.6 Overlaid pattern column model

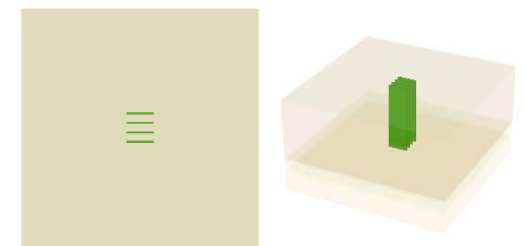


Fig.7 Wall pattern column model

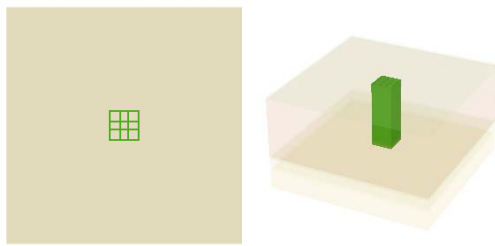


Fig.8 Lattice pattern column model

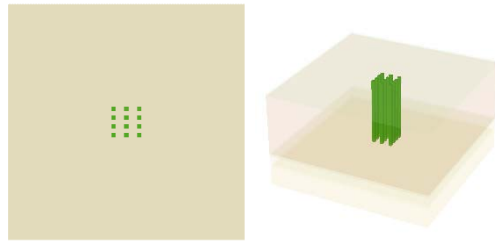


Fig.9 Block pattern column model



Fig.10 Area pattern column model

5. OUTPUT AND ANALYSIS

In this research, all models have the same soil parameters, DCM parameters, DCM volume, load and structure. The difference between each model is the DCM installation pattern. Based on the simulation results of the finite element method model using PLAXIS 3D, it is possible to determine the settlement and collapse patterns that occur in areas that need to be improved. The settlement and collapsed area that occurs in the model without DCM and in each model with variations in the DCM installation configuration pattern can be known by analyzing the modelling output (Figs.11-19).

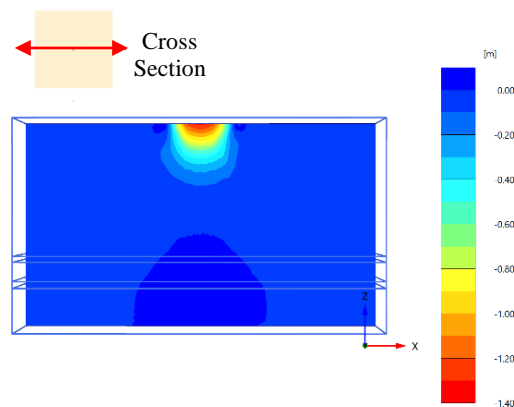


Fig.11 Settlement without DCM

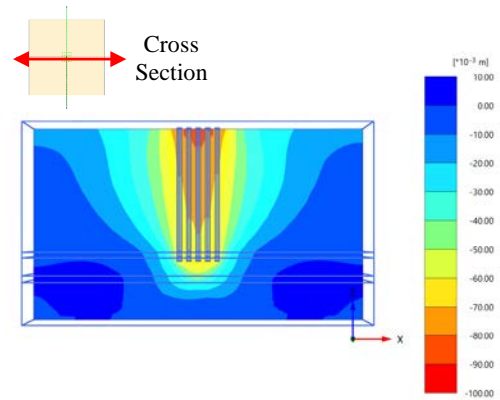


Fig.12 Settlement with rectangular pattern model DCM

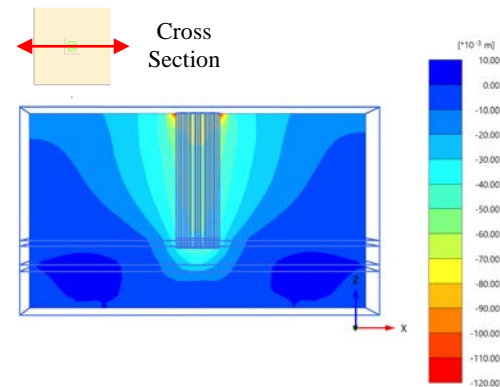


Fig.13 Settlement with triangular pattern model DCM

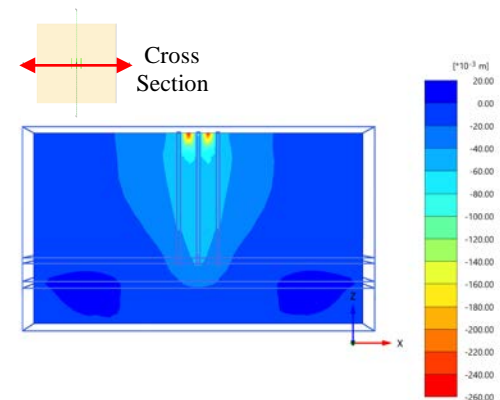


Fig.14 Settlement with line pattern model DCM

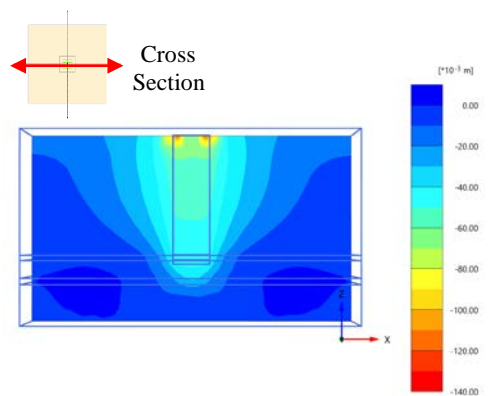


Fig.15 Settlement with wall pattern model DCM

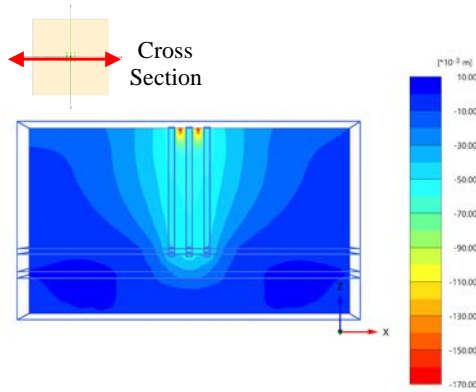


Fig.16 Settlement with block pattern model DCM

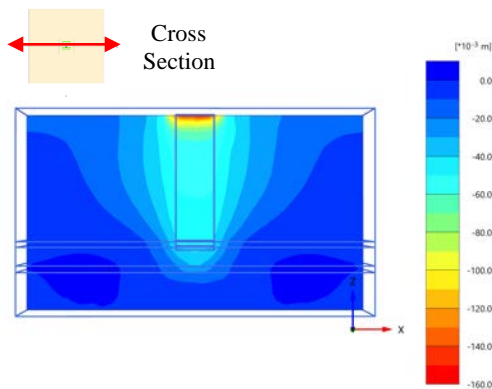


Fig.17 Settlement with area pattern model DCM

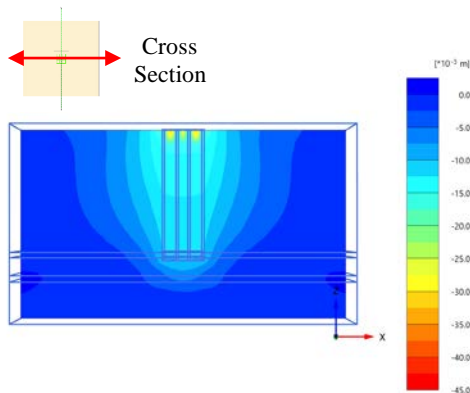


Fig.18 Settlement with lattice pattern model DCM

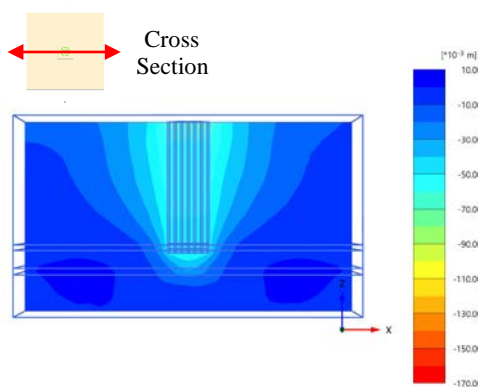


Fig.19 Settlement with overlaid pattern model DCM

Table 5. Consolidation Settlement

Pattern	Consolidation Settlement (m)	Reduction Percentage (%)
Without DCM	1.331	-
Rectangular	0.085	93.61
Triangular	0.112	91.59
Line	0.249	81.29
Wall	0.118	91.13
Block	0.167	87.45
Area	0.153	88.50
Lattice	0.034	97.45
Overlaid	0.083	93.76

Table 6. Consolidation Time

Pattern	Consolidation Time (day)	Reduction Percentage (%)
Without DCM	12630	-
Rectangular	1614	87.22
Triangular	4967	60.67
Line	4639	63.27
Wall	4828	61.77
Block	4746	62.42
Area	4320	65.80
Lattice	1313	89.60
Overlaid	4794	62.04

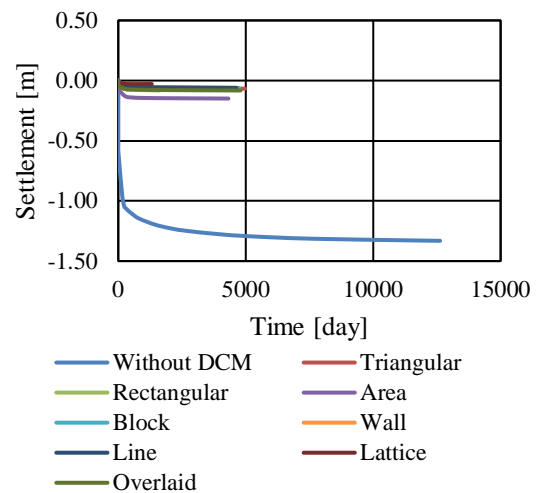


Fig.20 Consolidation settlement and time graph

Table 5-6 and Fig. 20 above shows that modeling with DCM reduces consolidation settlement and the time that consolidation settlement occurs. The largest percentage reduction in consolidation settlement and reduction in consolidation time was found in the lattice pattern which can reduce settlement up to 97.45% and reduce consolidation time up to 89.60%. The lattice

DCM model consists of 265 columns with a diameter of 0.3 m with a depth of 28 m which has the same work volume as the other patterns, which is 550 cubic meters. This lattice DCM model has the largest number of columns compared to other patterns.

Based on this result, it can be seen that the volume of work that is more widely distributed in a pattern has a tendency to have a greater influence on reducing the consolidation settlement and the consolidation time. The consolidation time required is also shorter because the consolidation decline that occurs is reduced. Pattern symmetry, the diameter of the column, the number of columns, and the distance between columns are factors that influence the settlement that occurs in these varied pattern models.

6. CONCLUSIONS

Based on the results of the modeling analysis of soft clay soil improvement using the finite element approach method using PLAXIS 3D, which was carried out above, it can be concluded that the DCM installation pattern influences reduced settlement that occurs in the improved soft soil. The most effective DCM pattern in this case to reduce the settlement and consolidation time is a lattice pattern that reduces settlement by up to 97.45% and reduces consolidation time by up to 89.60%.

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