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INDIVIDUAL AND GROUP COLUMNS FAILURE OF DEEP CEMENT MIXING (DCM) IN GRATI SOFT SOIL

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ABSTRACT: The structural failures were due to the soft soil identified in Indonesia and other countries. Most of them occurred due to negligence, lack of knowledge, and a lack of data sites. The alternative improvement method should meet stability requirements and avoid high costs for structural maintenance. There are some steps to mitigate the failure. First, recognize the potential of soft ground in an area. Second, use the base knowledge to choose a suitable structure for field conditions or make efforts to reduce the risk of collapse. It has soft ground as clayed silt and the potential for slope stability problems in an embankment in Grati soft soil in which the natural moisture content is close to the liquid limit. The Deep soil mixing method will be applied to reduce the risk of collapse on the pavement structure. Portland cement has been a stabilizing material as a binder. The objectives of this study were to identify the potential risk of Grati soft soil and propose steps to mitigate internal and external failure. The result of the laboratory experiment determines that the failure mode of a single column could occur due to the strength of improved soil requiring a high percentage of cement. Adjusting the cement content according to the soil moisture content or the arrangement of columns that are very close to or overlap each other will increase internal and external stability. FEM application for DCM constructions delivers a high safety factor for soil-structure interaction.

Keywords: Deep cement mixing, Soft soil, Failure mode, Coulumn, Embankment

1. INTRODUCTION

The term soft soil is associated with a low shear strength of less than 25 kN/m^2, and it becomes very soft soil when the shear strength is less than 10 kN/m^2. The low bearing capacity and high compressibility will cause excessive settlement of the structure above it**.** Soft soil consists of clay, organic soil, and peat soil. Clay has an organic content of less than 25%, organic soil has an organic fraction between 25-75%, and peat soil has an organic content greater than 75%. Peat is a high-plasticity soil. The Unified Soil Classification System (USCS) classifies silts and clays based on whether the Liquid Limit (LL) is lower or greater than 50 to represent high or low plasticity. If LL is greater than 50%, there is high plasticity.

Several countries have the same problem regarding soft soil, as Bangkok clay is clay with a high-water content close to its liquid limit. The characteristic of soil is its low swelling potential. The researcher [1] found the same phenomenon in Ariake Bay, Japan. In another country, Malaysia [2], soft soils are found in billions of hectares (7.45%) of the country's land area as organic soil or peat. Several problems occurred in the building due to the peat, such as the differential settlement at the foundation of Malaysia's 'leaning tower, Teluk Intan, Perak. The same problem exists in the Mekong Delta in Southern Vietnam, where the central economic areas are on soft soil. It is spread and deep (10–50 m) distributed in this region [3].

A deep in-situ stabilization technique using cement or lime as a binder has been applied to improve soft soils. Binders like cement [4–5] are injected and mixed with the soil using special equipment, well known as deep cement Mixing (DCM). Despite the successful use of these cement columns in the design of highway embankments [6–11], column failures or unexpected deformations occurred in a few cases, even when the design was made with sufficient high safety factors [12–14].

Deep soil mixing (DSM) assumes that the improved soil behaves as a composite soil. The strength and stiffness of the composite soil are calculated using the weighted average of the stiffness and strength of the binder columns and the surrounding soil. Failure should be investigated in terms of internal and external stability. External stability is the global failure of the improved ground without any failure in the columns. Internal failure is the failure taking place in the columns due to their low strength [15–17].

The strength of the soil mixture with a binder is determined by several things, namely the characteristics of the natural soil, the type of binder, the water-to-binder ratio, the scheme or arrangement in the group, and the conditions for implementing DSM in the field [18]. In the design of DSM, it is necessary to know the natural soil data to determine the type and percentage of the binder. The required strength is determined by the maximum loading that will be sustained by the composite material, in this case, the embankment soil and vehicle load.

Several steps need to be taken to avoid collapse. The high natural moisture content (close to the liquid limit) influences DCM design. The conditions will raise the failure potential of DCM-improved soft soil. Further steps will be simulated as arrangement columns by a 2D finite element program to calculate the stability of the embankment structure. The purpose of this study is to investigate the potential risk of a group of single-column DCM of Grati soft soil by investigating failure and proposing to mitigate it.

2. RESEARCH SIGNIFICANCE

DCM is a method that will be applied to improve soft soil in the Grati area, which has a soft soil deposit of a clayey silt type. Several potential collapses occur in the DSM structure, which is investigated to avoid failure after construction, such as single or group failure. Based on soil characteristics and geological conditions in the area, appropriate design steps such as cement content, scheme, spacing, and depth of installation will affect the influence area factor. Recognizing e individual and column group failure is useful in proper design.

3. POTENTIAL SOFT SOIL IN EAST JAVA, INDONESIA

The Ministry of Energy and Mineral Resources of Indonesia, the geology division, issued an Atlas of soft soil distribution that provides information on the location and type of soft soil throughout Indonesia's islands. Soft soils in East Java are found in several places in the northern part of the province [19]. This map is proposed based on an assessment analysis that considers three components, namely:

1. Geology, which includes aspects of lithology (soil or rock type) and the age of the rock,
2. Geomorphology includes morphology and depositional environments. The depositional environment is a site of accumulated sediments. It has been governed by physical, biological, and chemical processes related to the modern and applied to the ancient and lithified into sedimentary rock units.
3. Peatland distribution

Soil compressibility parameters from the soil mechanical laboratory and the ground condition verified the assessment of factors. Other islands, such as Sumatra, Kalimantan, and Papua, have mostly peat soils, whereas Java and Sulawesi have soft clay soils. Mitigation for soft peat and clay silts will require a different method. This study focuses on soft clay soils.

The solution to the soft soil problem for road construction is an urgent response, so the post-construction settlement will not occur beyond the allowable value in the service life structure. The damage will commence with cracks in the road structure, expand over time, and finally result in excessive total and differential settlement. The failure of the embankment slope of the pavement structure is shown in Kuswanda [20]. The design of highway pavements on soft clay soil remains a very challenging issue.

4. SOFT SOIL IN GRATI AREA

The Standard Penetration Test data collected from the location in the Grati area established the thickness of the soft soil at 17 m. The underlying layer, reaching 21.5 m, is clayey silt with a fraction of sand and gravel above silty sand, and the N SPT is 60. The depth of soft soil, which has the potential risk of settlement, should be a consideration for mitigation. The construction of roads to connect regions throughout East Java will face the problem of soft soil, which requires alternative solutions.

Further investigation of the physical and mechanical properties of natural soil by laboratory tests is shown in Table 1.

Table 1 Physical and mechanical natural soil[4]

Parameter	Unit	Value
Liquid limit	%	56
Plastic limit	%	43
Shrinkage limit	%	11
Saturated density	kN/m^3	17.2
Coefficient of permeability	cm/sec	0.00037
Coefficient of consolidation	cm^2/sec	0.001
Coefficient of compression		0.445
Water content (undisturbed)	%	50.5
Compressive strength(undisturbed)	kPa	49.4

The American Association of State Highway and Transportation Official Soil Classification System (AASHTO) classified the soil as clayed soil (A 7-5). The sieve analysis test result performed 92.25% passed of 0.074 mm (#200), whereas it consisted of 26% clay and 66.25% silt. The organic content test based on American Society for Testing and Materials (ASTM) D 2974–87 delivered 3.3%. The amount of water determined the strength of the soft soil. The higher the water content, the less pronounced the shear strength. The water content of natural soil was 50.5%, close to the liquid limit.

5. DEEP SOIL MIXING METHOD

The Deep Soil Mixing (DSM) method is an in-situ improvement technology in which the soil and other materials are mixed. These ingredients are referred to as "binders" and are supplied in dry or slurry form. They are injected through hollow, rotated mixing shafts tipped with the cutting tool. Column diameters usually range from 0.6 to 1.5 m and can extend to a depth of 40 m. The additive material, lime or cement, is often used. The cemented soil material produced generally has higher strength, lower permeability, and lower compressibility than the natural soil, although the total unit weight may be less. The exact properties obtained reflect the characteristics of the native soil, the construction variables, the operational parameters, and the binder characteristics.

The deep mixing method developed in Japan and the Nordic countries has gained popularity in the worldwide construction market. During the past four decades, deep mixing has been chosen by contractors as their proprietary technique, especially in Japan. The Port and Harbor Research Institute (PHRI) of the Japanese Ministry of Transportation initiated research and development of the deep mixing method. The first concept publicized in a technical publication of the PHRI in 1968 was the concept of lime stabilization of marine clays. The application of the deep mixing method exploded after a variety of equipment was established and standard design procedures became available.

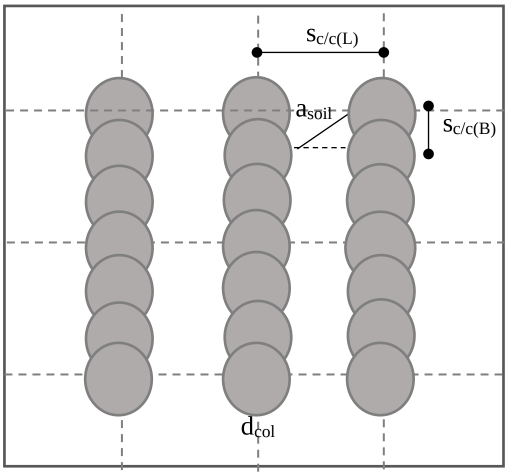

Fig. 1 Scheme DSM panel arrangement

The various schemes of Deep Soil Mixing (DSM) have generated a wide range of treated soil structures, such as single elements, rows of overlapping elements (walls or panels), grids, and blocks. The DSM scheme is one of the factors that affect the strength of the cemented soil, besides the characteristics of the binder, the native soil, the mixing, and the treatment conditions. Figure 1 shows the panel scheme of the DSM and its influence on the strength of cemented soil.

The improvement area is the ratio of a stabilized soil column to the soil area on a column scheme, as in Eq. (1).

$$a_s = \frac{a_{col}}{a_{soil}+a_{col}} = \frac{\frac{1}{4}\pi d_{col}^2}{s_{c/c(B)} \cdot s_{c/c(L)}} \quad (1)$$

Where:
a_{col} : section area of a stabilized soil column
a_{soil} : section area of soft soil

The designed unconfined compressive strength of stabilized soil column should be more than the stress of stabilized soil under embankment as Eq. (2).

$$q_{uck} \geq FS \, \frac{\gamma_e H_e}{a_s} \quad (2)$$

Where:
q_{uck}: designed unconfined compressive strength of stabilized soil (kN/m^2)
FS: safety factor
H_e: height of embankment (m)
γ_e: unit weight of embankment (kN/m^3).
a_s : improvement area ratio

6. FAILURE MODE OF DEEP SOIL MIXING

The first step is to design the deep soil mixing by determining the amount of load that must be sustained by the soil. If the load is embankment soil, then the density and height of the embankment are important parameters to determine the required soil strength. The original soil condition will determine the optimum type and percentage of binder that can achieve the allowable soil strength and the DSM arrangement scheme. The internal and external stability failures of columns in the DSM group are controlled due to soil collapse or the column itself, depending on improvement and ground condition. The failure of DSM under the embankment is shown in Fig. 2.

The internal failure (Fig. 2(a)) is related to the failure of the columns under various patterns such as shearing, bending, compression, and tension. Shear failure will occur along a plane when the shear stress exceeds the strength of the column. The improvement area, diameter column, and overlapping column are effective for increasing internal stability [21]. The shear stress at failure will depend on the normal stress (σ) across the failure plane. If the strength of the group column is satisfied by Eq. 2, then they avoid internal failure [22].

In the external stability (Fig. 2(b)), the possibility of sliding failure is calculated, in which the DM columns and the clay move horizontally on a stiff layer without any rearrangement of columns.

A collapse failure pattern, where the DM columns tilt like dominoes, could take place instead of sliding failure. According to previous researchers [23], the improvement area ratio has some effect, but not considerable, on the external stability of the improved ground. The DSM column diameter improves the external stability of the ground. The overlapping of columns can increase external stability.

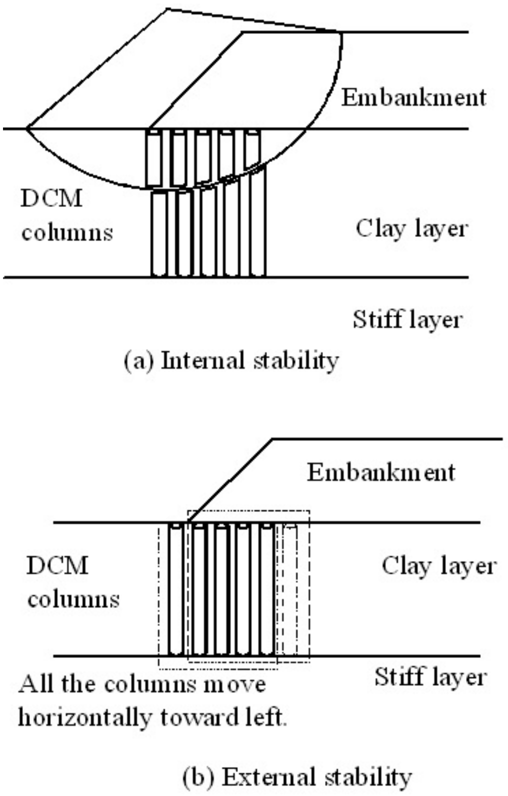

Fig. 2 Failure modes of DSM under embankment [23].

6.1. Small-Scale Model

In previous research [4], adding cement additives to the soft clay of Grati showed significant changes in the physical and mechanical properties of the soil. The high plasticity of clayey silt changed it into silty soil and reduced the clay's properties. The plasticity index decreased significantly, cohesion decreased, and friction angle increased. The optimum fraction of cement was 10% of the dry weight of the material. The undrained shear strength of cement-improved soil is 240.4 kPa.

The small-scale model test was carried out to determine the failure mode of the DCM column. The columns were arranged in the panel scheme after the column was checked for compressive strength. The column sample is composed of 10% cement to the dry weight of the soft soil mixture, with a diameter of 15 cm and a length of 30 cm. The samples were mixed four times in the same composition, and a sample was prepared for a compressive strength test. The loading experiment will be carried out with different panel spaces and a square load of 30 cm x 30 cm. The specimens are removed from the mold and tested after 7 days of curing. Samples are prepared four times, and every sequence contains five samples. The representative sample in every sequence is tested for compressive strength. The average compressive strength for the four samples represented is 70.58 kPa, smaller than previous studies [4], in which the water content of samples was in OMC condition. Meanwhile, the water content of the sample is almost within the liquid limit. The composite material mixture is adjusted to the field moisture content to achieve the allowable strength.

The failure phenomenon of a single column is identical to that of short-column concrete and dependent on material failure (Fig. 3). The column failure was on the entire surface of the column. This condition indicates the column is subjected to uniform loading on the section. The dimensions of the cross-section and the column material determine the amount of loading.

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Fig.3 Failure mode of a single column

The DCM column group in soft soil will sustain loads until failure. The specimen will be loaded using a 30 cm square plate shown in Fig. 4. The loads were subjected gradually and recorded by load cells, which detected the deformation by linear variable differential transformers (LVDT). The compressive strength of different spacing panel schemes is shown in Fig. 5. The panel column spacing will affect the improvement area ratio, which is a very influential parameter on internal stability. The closer the panel column distance, the higher the bearing capacity of the soil. Soft soil was removed to recognize the failure of the column group shown in Fig. 6.

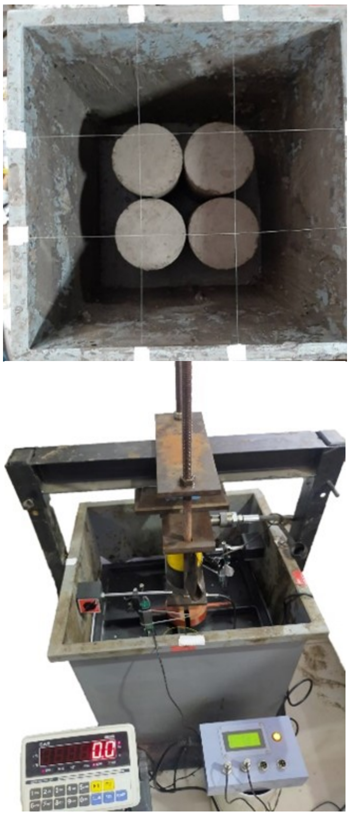


Fig. 4 Small scale model of DCM on loading

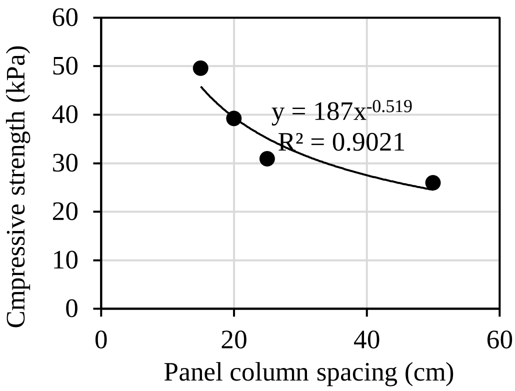


Fig. 5 Influence of spacing of column to compressive strength

The failure mode of the DCM group shows that parts of columns under load in an active shear failure zone were deformed. Another side of the columns that were not exposed will be bent outside. The bending failure of the columns was the same as the rest of the columns in the transitional zone. In the same loading condition [23], but with the spacing of the columns closer, the columns on both sides of the wedge showed brittle bending without any shearing.

The strength of the single column must reach the required load as in Eq. (2). The single column strength, the choice of the scheme, and the space between the columns will influence the allowable load.

(a)

(b)

Fig. 6 Failure mode of the DCM group

6.2 A Case Study of Embankment on Grati Soft Soil

The geometry of the soil layer is described based on boring log data for the soil layer in Fig. 7. Table 2 shows the parameters of each layer. The pavement structure consists of flexural pavement and a 10.2-meter-high embankment on the subgrade layer. The embankment material must not be A6 or A7 according to AASHTO specifications and be compacted to not less than 90% maximum dry density (Table 3). The traffic load was converted to a stress of 30 kN/m^2.

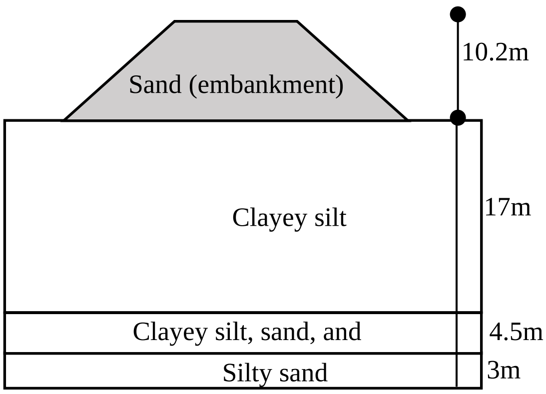


Fig. 7 The geometry of the soil layer.

The clayey silt is modeled as soft soil in the finite element program. This model has the characteristics of stress depending on stiffness, the distinction between primary loading and unloading, the memorizing of pre-consolidation stress, and the establishment of Mohr-Coulomb failure criteria. Soft soil parameters consist of cohesiveness, internal friction angle, modified compression index, and recompression index. The Morh Coulumb method is used for landfill soil layers, as shown in Table 2.

The total embankment width is 74.4 m, and the slope is 1:2. The width of the pavement structure is 27.2 m. Embankment construction on soft soil with a groundwater level of 1 m from the surface will increase pore water pressure. It has six stages of loading with a successive height of 1.7m, and the specifications are in Table 3. Soft soils in undrained conditions take a very long time to dissipate the pore water pressure, and the effective stress remains low. In every step of loading, soil consolidates to spill up excess water pressure for a specific time. Each loading time is calculated to achieve 90% consolidation. After each loading stage, the shear strength increases, so the soil is stable enough to sustain the next loading stage.

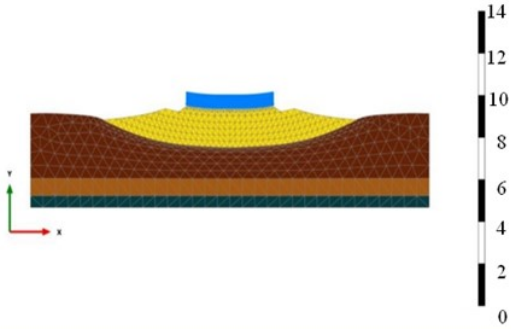
Table 2 Parameters of soil layers

Soil Type	Clayey silt	Clayey silt, sand, and gravel	Silty sand
Depth (m)	0 – 17	17- 21.5	21.5-24.5
Model	Soft Soil	Mohr-Coulomb	Mohr-Coulomb
	Undrained	Drained	Drained
γ_{sat} (kN/m^3)	15.00	18.90	17.30
γ_{dry} (kN/m^3)	8.40	14.30	11.40
c (kN/m^2)	35.00	26.50	15.70
ϕ (^{o})	10.50	17.00	25.00
k_x (cm/day)	0.08	0.86	8.64
k_y (cm/day)	0.08	0.86	8.64
c_c	0.44		
c_s	0.06		
e_0	2.10	0.80	1.30
υ	0.50	0.25	0.30
E (MN/m^2)		28.20	210.0

Table 3 Parameter of landfill

Model	Mohr-Coulomb
	Drained
γ_{dry} (kN/m^3)	17
c (kN/m^2)	10
ϕ (^{o})	30
k_x (m/day)	0.0864
k_y (m/day)	0.0864
E (kN/m^2)	30000

Two-dimensional analysis with the plane strain model was assumed to be the behavior of soft soil. The landfill and traffic loads were applied to the soil to estimate deformation and calculate it with the finite element method. By carrying out the stages of loading until the end of consolidation is achieved, a total settlement of 1.896 m is obtained (Fig. 8). The excessive deformation is in the axle of the road and the landfill.



Deformed mesh [u] (scaled 5.00 times) (Time 3242 day)

Maximum value = 1.896 m (Element 113 at Node 2372)

Fig.8 Deformation of soft soil due to loading

It took 3242 days (9 years) to build a road structure without improving the natural soil. Excessive deformation will occur on the pavement structure continuously after loading (Table 4) when the project is finished early. The project's work might not take a very long time to avoid failure. If the load exceeds the bearing capacity of the soil, an excessive settlement will occur.

Table 4 The settlement of soil at the load stage

Load stage	Settlement (m)	Time of 90% Degree of consolidation(days)
1	0.381	902.9
2	0.757	1562
3	1.042	2051
4	1.28	2439
5	1.5	2760
6	1.685	3023
Traffic	1.896	3242

The safety factor for slope stability after the traffic load is 1.6. The embankment slope is maintained if sufficient time is given for the natural soil to consolidate. However, if the total load is applied directly, failure will occur. A gentle slope is one of the simple mitigations for embankment stability. In this study, the main problem is the excessive deformation of soft soil due to high embankments and traffic loads.

The length of the DCM is 17m to reach the sandy silt layer under the soft soil deposit. The column diameter is 1 m and is installed with group columns in a panel arrangement scheme (Fig. 1) with 1.1m of spacing.

The improvement area ratio $a_s = 0.65$ is presented as the ratio of the sectional area of the stabilized soil column to the ground occupied by the square scheme, such as in a small-scale model. The shear strength of q_{uck} is greater than 375 kPa, which is an allowable value to sustain the embankment and vehicle loads (FS = 1.2). It requires a lot of cement to increase the strength, based on previous research [4] as Eq. (3).

$$q_u = \frac{312.5}{(\omega/p_c)^{0.285}} \qquad (3)$$

Where:
q_u: compressive strength (kPa)
ω: moisture water content (%)
P_c: cement content (%)

In the case of the overlap, the improved soil will increase the area ratio and reduce q_u. If the panel scheme is occupied with $s_{c/c(B)}$= ½ diameter and $s_{c/c(L)}$= 1.1m, then the area ratio is = 1.42. A shear strength of 172 kPa is reached with a 10% cement content. This design is executed in a 2D finite element program.

Geometry modeling for deep cement mixing in FEM applications uses embedded beam row lines or continuous walls [18]. The embedded beam panel thickness in the plane strain case is identical to the column diameter. In the following study, the panel scheme applies to finite element applications. Each loading stage lasts seven days without considering consolidation problems due to changing soil characteristics.

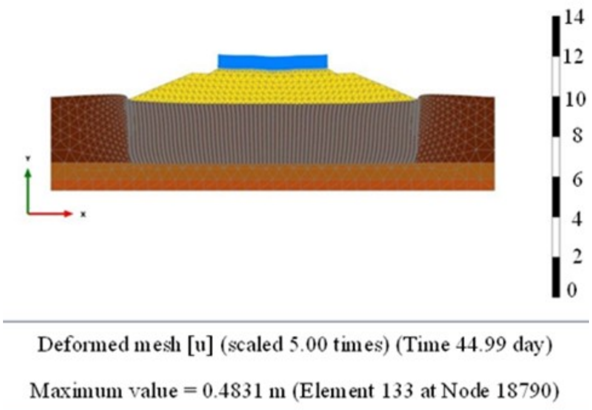


Fig. 9 Deformation of soil after DCM installation

Soil deformation occurred at the final loading stage at 0.4831 m (Fig. 9) after 45 days. There is a very significant reduction in deformation of 1.4 m. The settlement in each loading stage is shown in Table 5. The deviation of deformation for each load increases with higher loads. This contrasts with the case of untreated soil, which takes time to consolidate. This settlement occurs because DCM reduces the risk of excessive deformation by increasing the strength of the subgrade. The columns reached the underlying, hard soil layer. The deformation was recognized as an immediate settlement.

Table 5 Immediate settlement of the embankment

Loading stage	Settlement (m)
1	0.071
2	0.099
3	0.141
4	0.204
5	0.294
6	0.354
Traffic	0.483

The group column type of improved ground is composite ground with an average strength of stabilized soil columns and native soil between them. In the design, two stabilities might be evaluated: external and internal stabilities. For internal stability, the possibility of column failure due to slip circle failure (Fig. 2. (a)). The external one examines sliding failure in the improved ground, in which the stabilized soil columns and the native soil move horizontally, as shown in Fig. 2(b).

Even though the embankment did not collapse, the safety factor decreased (Table 6). The failure area was initially quite deep in the soft soil layer. After the subgrade improved, the slip surface occurred in the landfill. Failure mode delivered a slip circle failure in which the DCM column in the outer groups has a higher displacement than the inner one, as shown in Fig. 10.

Table 6 The safety factor of slope stability

Loading stage	SF of before DCM installation	SF of after DCM installation
1	5.010	3.392
2	3.223	3.026
3	2.618	2.673
4	2.297	2.419
5	1.988	2.179
6	1.822	1.928
Traffic	1.622	1.542

7. CONCLUSIONS

In the case of Grati soft soil, the 10.2 m embankment caused a consolidation settlement of 1,896 m due to the soft soil with Su = 0 kPa. Soil improvements need to be proposed to avoid the failure of toll road infrastructure. The natural water content is almost the same as the liquid limit condition, which influences the strength of the composite material. Several steps must be considered, namely adjusting the addition of cement (more than 10%) to the natural soil moisture content or using 10% cement with an overlapped column scheme to avoid internal failure.

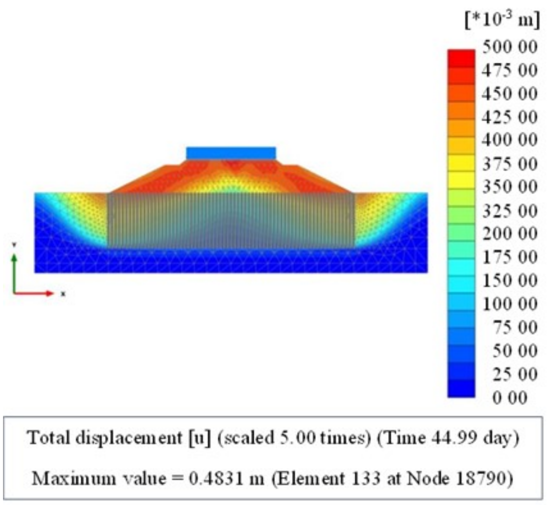


Fig.10 The total displacement of the embankment structure

The internal stability of DCM is dependent on the load and the improvement area ratio to determine the compressive strength of the improved soil. The strength and stiffness of the composite soil are calculated using the weighted average of the stiffness and strength of the binder columns and the surrounding soil. The failure mode of a single column performs as a short column in which the strength of the material and geometry are significant factors.

The improvement area ratio is 1.72 and will reach an allowable compressive strength of 172 kPa. The strength can be achieved with the overlapped panel columns scheme. Internal stability will be satisfied. The closer the spacing between the columns, the greater the external stability. The calculation of external stability through the application of FEM 2D delivers a safety factor greater than 1.5. The results show that the strength of the column is significant for overall stability and the critical failure slope. This study excluded other factors that will influence the composite material's strength in site projects.

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