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SOFT GROUND IMPROVEMENT BELOW BRIDGE APPROACH FOUNDATION USING CEMENT DEEP MIXING COLUMNS COMBINED WITH GEOTEXTILE

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Vehicle load is a dynamic load and embankment load is a static load. These two load types can act simultaneously to accelerate the consolidation rate of the ground under the embankment, which then leads to differential settlement. This differential settlement is dangerous as it can cause sudden bouncing and shock for vehicles on the road. There are also other problems such as the reduction in the exploitation capacity of the construction work due to the reduction in the speed of vehicles going through the positions of settlement. Lower speed increases the waste of means of transport. Excessive settlement can occur from reasons such as improper design or improper construction. This paper uses the finite element method to simulate the construction process of the bridge approach to calculate, and check the stability and deformation of the soft ground under this road. The analysis results show that the settlement of the ground without treatment is quite large at 1.06 m. After reinforcement, the settlement is 0.013 m, and the stability coefficient increases from 1.032 to 2.739. The research results can be applied to reinforce the bridge approach with a system of cement deep mixing (CDM) columns combined with geotextiles to shorten the construction time and limit settlement compensation.

Keywords: bridge approaches, road embankment, differential settlement, soft soil, CDM

1 INTRODUCTION

According to the standard TCVN 9436:2012 in Vietnam, the elevation of most roads, which give access to bridges, is designed to be equal to the pitch of the deck slab [1]. Over a period of operation, under the effects of vehicle load and restoring load, the embankment becomes more compressed. As the roadbed subsides while the bridge deck elevation remains the same, the embankment then appears to be imbalance.

The method of reinforcing the soft ground under the bridgehead road with CDM columns changes the physical and mechanical properties of the soil so that the load carrying capacity can be improved and the deformation of the foundation can be reduced (Bengt, B. H., 1999) [2]. This method uses specialized deep mixing equipment (or Deep mixing method - DMM) to mix soft soil in situ with cement and create strong cement-reinforced soil columns whose shear resistance is below 150 kPa (CDIT, 2002) [3]. These columns replace a part of the soft soil, imposing a constraint on horizontal expansion for the soft soil and creating friction between the CDM columns and the soft soil. The interaction between the columns and the soil can create a foundation whose working principle follows the principle of "complex foundation", which can increase load capacity and reduce settlement of soft ground under external load.

According to the study by Bruce, D. A. (2000), the principle of forming the strength of these columns themselves can be described by the three processes: 1) mechanical compaction, 2) permeable consolidation, and 3) reinforcement which increases increase the strength of the reinforcing columns and the shear resistance of the ground soil [4].

Mechanical compaction process: The reinforcement of the foundation using CDM columns involves a specialized equipment that inserts a quantity of material into the ground in the form of cement-mixed columns.

Consolidation process: In addition to compacting the soil, CDM columns can speed up the consolidation process of the ground soil. As the CDM columns is put into the ground in a dry form, the cement mixture will absorb water in the ground to create a cement slurry, which then turns into a cement stone. The process of making cement slurry releases a large amount of water contained in the pores of the soil, which accelerates the consolidation process of the soil. This process occurs immediately after the reinforcement begins and ends when the ground is completely reinforced. At this point the entire CDM columns becomes a type of concrete. This is a complex physicochemical process which can be divided into two periods: the setting period and the solid phase. During the setting period, the cement slurry gradually loses its plasticity and thickens, but has no strength. During the solidification period, the hydrolysis of the mineral components of clinker mainly occurs. The process of increasing the strength of the CDM columns and the shear resistance of the ground soil: When reinforcing the soft ground with a CDM column, the shear resistance of the column under the effect of external loads is determined according to Coulomb's law $\tau = \sigma tg\varphi + c$, where c is the adhesive force created by the cement bond. The value of c can be determined by a test sample shear test.

Nguyen, A. T. and Nguyen, N. T. (2020) have studied the stress distribution in soft ground reinforced by CDM columns combined with geotextile under embankment works in Tien Giang, Vietnam, using a finite element method (PLAXIS software). In this method, the behavior of the CDM column in the treatment of soft ground is indicated by the stress distribution and settlement of the CDM column and the soft soil layers. The settlement process of the road foundation construction is observed. The simulation results show that the soft soil foundation, which is reinforced by CDM columns combined with geotextiles (which have 0.6m diameter, 11.2m length, and 1m distance), has a maximum settlement of 0.120 m and a stability factor of 1.679 [5]. Nguyen, N. T. and Nguyen, A. T. (2018) analyze the parameters of CDM columns in the reinforcement of the embankment, which include the diameter and length of the columns, and the distance between the columns, using the FEM method [6]. In this method, the behaviors of CDM columns in soft ground treatment are indicated by the stress distribution and settlement of the CDM columns and soft soil layers. The stress distribution in the CDM columns and the deflection settlement derived from the analysis are used to determine an appropriate length for the CDM column. Research results show that the settlement of soft ground reinforced with cement ground can be reduced by 93%.

Kurbatskiy, E. N. et al. (2018) built an experimental model to evaluate the influence of mineral content of Montmorillonite (MMT) on the bearing capacity of soft ground reinforced with CDM columns [7]. An experimental model of 1g was manufactured. Various MMT contents varying from 6% to 15% of the clay base were also established in the experiment to evaluate this change of strength of the soil reinforced with CDM columns. Research results show that for the same cement content, the bearing capacity of the soil decreases as the MMT content increases. The model is also analyzed using the finite element method (FEM) to find out the strength correction coefficient for the strength of the soil-cement mixtures specimen and the strength of the CDM columns.

Nguyen, A. T. and Nguyen, N. T. (2020) used the FEM method in PLAXIS software to analyze the stress distribution on the columns and the ground of the CDM columns system combined with geotextiles in reinforced soft ground under the embankment in Tien Giang [8]. Simulation results for the soft soil foundation reinforced with CDM columns (which have a diameter of 0.6m, a length of 11m, and stay 1m apart from each other), show that the maximum settlement is 0.120m and the stability coefficient is 1.679. Yemi K. A. et al. (2020) conducted a field study for the reinforcement of the roadbed with CDM columns from Papalanto to Sagamu in Ogun State, Nigeria [9]. This road encountered a harsh condition due to heavy trucks causing damage and subsidence. The proposed solution was to use 5% cement content mixed with soil to increase the load bearing capacity of the roadbed. In the current industrial revolution 4.0, Nguyen, H. S. et al. (2020) also studied the integration of information and communication into the soft ground treatment method by CDM columns. The study shows that when the CDM columns are built into the soil, the behaviors of the columns cannot be observed directly in the construction process [10].

Nguyen, A. T. and Nguyen, T. D. (2020) analyzed the application of CDM columns technology to reduce the horizontal displacement of the diaphragm wall of the dug hole by the 2D FEM method [11]. Dario, P. et al. (2020) investigated the settlement between the bridge and the access road [12], where the structure is placed on very weak ground in the Netherlands. The study uses the concept of multi-source information method in geotechnical model monitoring, conventional monitoring techniques, and SInSAR monitoring. Yasrobi, S. Y. et al. (2016) investigated the settlement of the relief floor at the transition from the road to the bridge in the United States [13]. A total of 34 responses from 31 states were obtained from this survey, with some states providing multiple responses and only a few reasonable responses were selected for the analysis. After processing the responses, the last 28 responses were used to determine the cause of the subsidence in the load-reducing floor of the building. Nguyen, N. T. and Nguyen, A. T (2022) had a study on the calculation of deformation of cement deep mixing columns that stabilize soil erosion and landslides on river roads [14]. Toshihide S. and Yuki O. (2021), investigated in fluence of applying overburden stress during curing on the unconfined compressive strength of cement-stabilized clay [15], Thanakorn C., et al. (2022) improving mechanical properties and shrinkage cracking characteristics of soft clay in deep soil mixing [16].

Some other authors have also conducted field studies such as Yihan S. et al. (2022) conducted a study on deflection settlement of bridgehead embankment due to dynamic loading in California [17]; Anand J. P. et al. (2019) designed a causeway system made of lightweight materials to control settlement of road access to bridges in the US [18]. Chengzhi X. et al. (2021) examined the level of damage in the soil mass reinforced with geotextiles at the earth retaining wall at the bridgehead [19]. However, these studies have not addressed the effects of the construction stages on the settlement process of the soft ground beneath the bridge work. This study uses FEM method to simulate the construction process of the bridge work to examine stability and deformation of soft soil under this road.

2 MATERIALS AND METHODS

2.1 Materials

2.1.1 Road surface at a poorly-constructed transition slab

The quality of the pavement layer on the transition slab is influenced by the mix design, environmental factors, material quality, and construction process. The quality of the pavement concrete is not the main cause for deflection settlement, however it can still affect the settlement to some degree.

The deformation of soft pavement is caused by the plastic deformation of the pavement over time, and the asphalt is a material that plastically deforms depending on temperature, age, drainage and pavement. The settlement can damage the road significantly.

2.1.2 Type of abutment and type of support foundation

The type of abutment and the type of support foundation affect the vertical and horizontal displacements between the abutment and the pavement layer at the transition plate.

2.1.3 Filled with soil

To minimize construction costs, contractors often use materials near the bridgehead. When materials such as soft, highly cohesive or sensitive soils, are used, the settlement of the bridgehead will cause a strong fluctuation. In general, with moist soils it is difficult to achieve a satisfactory compaction if the moisture content exceeds the optimum moisture content. The lack of control on the compaction of the embankment is considered to be the main factor that leads to a low specific gravity and a high deformability of the embankment. Unsatisfactory compaction may also be due to limited availability of equipment that is used in road construction near the two bridgeheads. Many projects specify that the fill material must be carefully selected and compacted to achieve maximum consolidation in a short period of time. The compaction method and construction sequence are also very important. On-site supervisor should ensure that the compaction pressure and level of compaction of the material meet the standard requirements during construction. Culverts and abutments are usually constructed before embankment and compaction of the roadbed. This hinders the compaction of the area near the culvert and abutment due to the lack of equipment as most equipment are being used for the construction of culverts and abutments.

In addition to good compaction of the embankment, the lateral stability and shear strength of the embankment are very important factors in the overall stability against the settlement of bridgehead and culvert. For primordial soil, there is a phenomenon of anti-expansion effect in the soil mass, while for embankment, the phenomenon of anti-expansion effect rarely exists. Therefore, the design of slope protection, the selection of embankment materials, and the consideration of the loads acting on the embankment are essential to minimize the final settlement of the roadbed.

2.1.4 Vertical and horizontal displacements of the foundation on the ground

Vertical and horizontal displacements of the foundation on the ground can be the main cause for the settlement of the bridge, especially when the foundation is placed on soft soil layer. The causes of vertical and horizontal displacements are horizontal compression of the soil, consolidation settlement after construction, and failure due to overall instability.

Horizontal compression, or sliding foundation, is the ability of the soft soil layer to move horizontally when subjected to a vertical load that is greater than its shear strength. Weak clays, loose dusts, or organic, silty soils can be pressed horizontally. As the foundation slips, it creates a horizontal load on top of any deep foundation. If the design is not appropriate, the columns can be damaged and the column body can crack due to the effect of lateral loads.

Consolidation settlement after construction: If the ground is cohesive, consolidation settlement may occur due to the weight of the embankment.

Deep sliding instability: The damaged ground can make the slope unstable. Slope instability, or tipping failure, may occur when the shear strength of the ground cannot withstand the applied load. When the ground is weak, the water level difference is large, and the load of the roadbed is large, which can then cause failure.

2.1.5 Poor drainage

A major cause of path settlement is poor drainage in front and behind the abutment, and under the pavement layer of the path. Poor drainage can lead to surface erosion, slope instability, and increased hydrostatic pressure. Several studies indicate that poor drainage management is a major problem for most bridges

2.1.6 Geological conditions at Tan Phu Dong bridge construction area

The work is built on the typical soil in the area of the Mekong low-lying structure. The ground soil is usually modern sediments, with Holocene and Pleistocene age, including loose and soft soils with special status. Regarding geological features of the area, research on groundwater in the region has shown that the stratigraphy of the area from the bottom up is as follows: Pleistocene sediments are distributed throughout the region and they cover the weathered surface of Pliocene sediments directly. Pleistocene sediments are sands containing gravel, interspersed with fine-grained sediments often with thin layered structure.

According to Engineering Geological Report (2020), field observations, soil description at boreholes have been collected to combine with the results of physico-mechanical sample analysis [20]. It was found that survey area is composed of Q_{iy} & Q_{uy} sediments and divided into 05 soil layers from top to bottom as follows:

Layer 1: Cultivated soil is mainly composed of clay and plant root humus. The layer thickness varies from 0.50 m to 0.60 m. The bottom elevation varies from -0.50 m to -0.60 m.

Layer 2: Dark gray clay mud. This class is found in all 3 drills. The layer thickness varies from 10.50 m to 20.20 m, the bottom elevation varies from -11.00 m to -20.80 m.

Layer 3: Dark gray and blue gray clay mud in this layer is found in all 03 boreholes. The layer thickness varies from 7.60 m to 16.20 m. The bottom elevation varies from -27.20 m to -28.40 m.

Layer 4: Dark gray mixed clay, flowing plastic state. The layer thickness varies from 7.40 m to 13.40 m. The bottom elevation varies from -35.80 m to -40.60 m.

Layer 5: Brown-gray clay, semi-hard state. Layer thickness is 4.60 m, layer bottom elevation is -45.20 m.

The author states that the soft soil layer is a dark gray clay layer, flowing state, with a fairly large thickness of 40.6 m near the ground. When constructing the embankment, there will be large settlement and potential instability. The soil layers below are adequate so no treatment is required.

2.1.7 Design requirements

The purpose of the calculation is to determine the main parameters in the absence of treatment, the maximum embankment height of the roadbed that can be achieved, the settlement and the corresponding stability coefficient at that time. Based on the proposed soft soil treatment solution, the author conducts calculations and comparisons for the bridgehead road foundation with embankment height ≥ 3m, vertical slope of about 3%, abutment height of about 5m, width road bed ≥ 9m, road grade IV or higher, thickness in soft soil area of about 12m. Calculation of settlement and stability based on Plaxis v8.2 software. The residual settlement for the bridgehead roadbed is 100mm. Location at the bridge approach embankment: The width of the roadbed is 10m. H of embankment changes along the longitudinal profile and the elevation of the red line, the depth of soft soil layer is H_{mud} = 15m (Fig. 1).

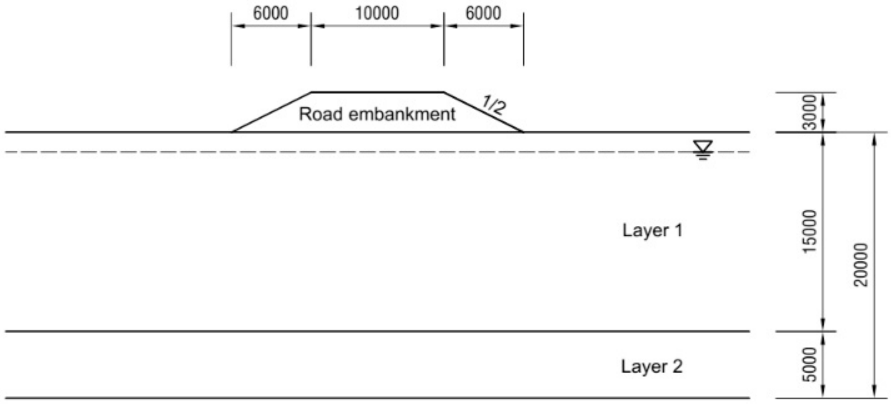
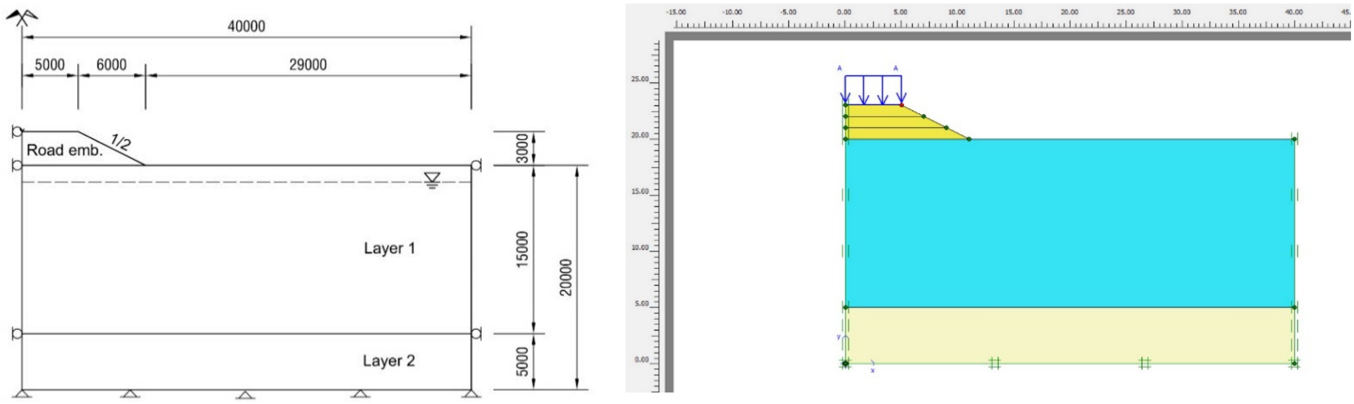


Fig.1. Cross section of the bridge approach embankment model

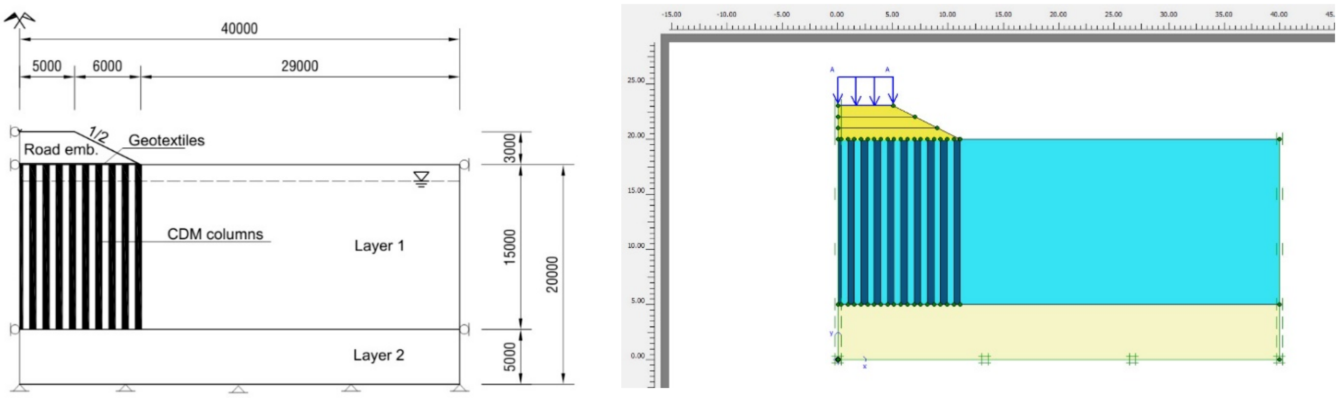
2.2 Method

Based on the geotechnical data of the bridge, the theories presented above, and the relevant references, the author conducts specific analysis and evaluation for the following cases: 1) The first case - The ground is weak and the stabilized solution has not been applied; 2) The second case - The soft ground is stabilized by CDM columns combined with geotextiles. Modeling the analytical problem in Plaxis software is shown in Figs. 2 and 3.



a) Schematic b) FEM Model

Fig. 2. Soft ground below bridge approach without stabilization



a) Schematic b) FEM Model

Fig. 3. Soft ground below bridge approach with stabilization by CDM columns and geotextiles

This model is a generalization of rigid elastic and plastic media with internal friction. Many analytic solutions have been introduced, which compare numerical solutions with exact analytic solutions. This model combines two fundamental theories of modern mechanics: the theory of elasticity and the theory of limit states. The model is described by the common features in engineering geological survey and this background model is used widely in geotechnical problems.

The ideal elastic model is a model that is relatively suitable for the working conditions of the soil. This model does not require complicated laboratory geotechnical experiments as it can be built in standard soil mechanics laboratories. The model can be applied to a number of soil types.

For the problem of calculating the stability of the embankment, the stability of the structure not only needs to be assessed in the long-term period when the work is completed, but also needs to be evaluated during the construction steps.

In the Plaxis stability problem, the factor of safety is defined as follows:

$$SF=\frac{S_{maximum\ available}}{S_{needed\ for\ equilibrium}} \tag{1}$$

where $S_{maximum}$ available is the actual shear resistance of the soil; S_{needed} for equilibrium is the minimum shear resistance at steady equilibrium.

According to Mohr-Coulomb failure criteria, the formula for calculating the factor of safety above becomes:

$$SF=\frac{c-\sigma_n tg\varphi}{c_r-\sigma_n tg\varphi_r} \tag{2}$$

where c, φ are the intensity parameters; σ_n is the total stress at the calculation point; c_r and φ_r are the parameters of the shear resistance falling to exactly the same value at the time of stable equilibrium. This principle is taken as the basis for the Phi-reduction method of Plaxis software to calculate the overall stability of the building. In this application, the adhesion force c and the tangent of the friction angle decrease by the same ratio, and the decrease of the shear resistance parameter is controlled by the total multiplier ΣM_{sf}.

$$SF=\frac{c}{c_r}=\frac{tg\varphi}{tg\varphi_r} \tag{3}$$

This parameter is incremented step by step in the calculation until failure occurs. The value of the factor of safety is defined as the value of ΣM_{sf} at the time of failure. The selection of Phi-c-reduction calculation type in Plaxis software is completed by selecting the tap “Calculation type” in the General sheet.

The analytical process by FEM in the conditions of CDM columns involves: Change in length of CDM columns, L= 5.0 m; 10.0 m and 15.0 m; Change diameter, d= 0.6 m; 0.8 m and 1.0 m; Change the distance of the CDM columns, s= 0.8 m; 1.0 m; 1.2 m and 1.4 m. A total of 18 models were analyzed.

The input parameters of the soil layers and columns in Plaxis model are shown in Table 1. The geotextile is simulated by a Geogrid element with EA=2500 kN/m. To save costs and construction progress, 1 layer is arranged on top of the CDM column, through the geotextile layer, the weight of the embankment causes an arch effect at the ends of the CDM columns.

The calculation model includes: Construction of CDM columns; Construction of geotextiles; making of layer 1st of about 1m thick; making of layer 2nd of 1m thick; making of layer 3rd of about 1m thick; Calculation of long-term stability (10 years).

Table 1. Parameters of soil layers and embankment fill and CDM columns in Plaxis model

No.	Parameters	Symbols	Layers			CDM columns
			2	3	Emb. fill	
1	Material model	Model	Mohr - Coulomb	Mohr - Coulomb	Mohr – Coulomb	Mohr - Coulomb
2	Type of behavior	Type	Undrained	Undrained	Drained	Undrained
3	Unsaturated unit weight (kN/m^3)	γ_{unsat}	17.00	15.80	17	11.15
4	Saturated unit weight (kN/m^3)	γ_{sat}	17.15	15.91	18	12
5	Horizontal permeability (m/day)	k_x	0.001	0.001	0.5	10^{-4}
6	Vertical permeability (m/day)	k_y	0.001	0.001	0.5	10^{-4}
7	Young's modules (kN/m^2)	E	1479	705	30000	75000
8	Poisson's ratio	ν	0.316	0.345	0.3	0.3
9	Cohesion (kN/m^2)	c_{ref}	8.50	6.5	10	120
10	Friction angle (degree)	φ	3^{o}55'	2^{o}15'	30	36
11	Dilatancy angle (degree)	ψ	0	0	0	6

For a more precise analysis on the displacement mesh with 15-node triangular element, the element mesh is selected as a fine mesh, shown in Fig. 4.

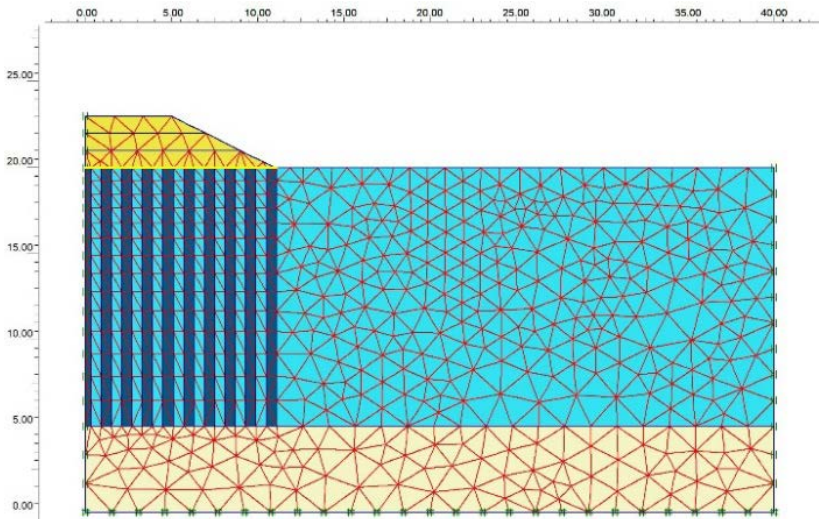


Fig. 4. Deformed Mesh

3 RESULTS AND DISCUSSION

3.1 Results

3.1.1 Soft ground below bridge approach without stabilization

Under the influence of the weight of the roadbed embankment layers and the load on the road, the unreinforced roadbed subsides as shown in Fig. 5, Fig. 6, and slides on the road whose slope is shown in Fig. 7. This kind of roads requires soft ground treatment to be stabilized in terms of bearing strength and settlement.

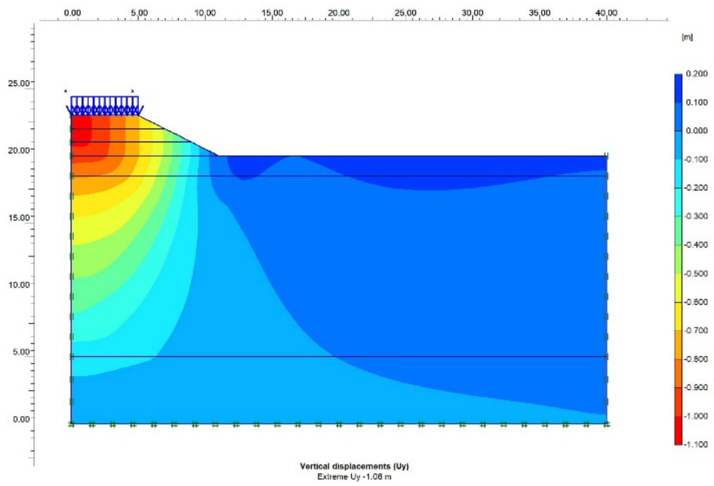


Fig. 5. The vertical displacements of the soft ground without stabilization

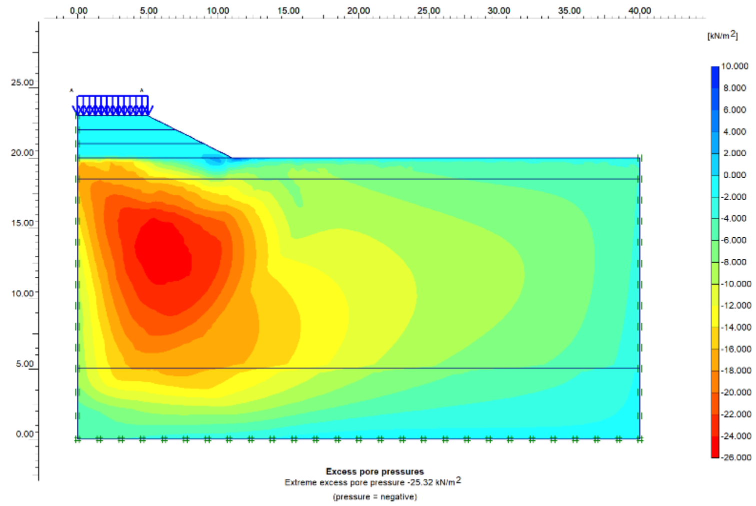


Fig. 6. The excess pore pressures of the soft ground without stabilization

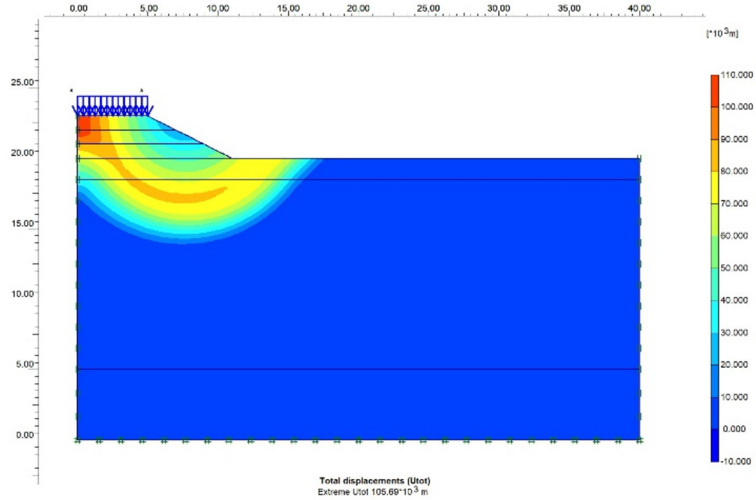


Fig. 7. Stability coefficient of the unstabilized soft ground, FS= 1.032

The settlement of the ground without treatment is quite large (1.06 m) and the stability coefficient is 1.032, which does not meet the requirements according to the standard 22TCN 262-2000 [21].

3.1.2 *Soft ground below bridge approach with stabilization by CDM columns and geotextiles*

When the ground is reinforced with cement soil pillars and combined with geotextiles, the ground below the roadbed has limited vertical settlement (Fig. 8), horizontal settlement (Fig. 9), excess pore pressures (Fig. 10) and stabilizes without slipping of the slope (Fig. 11).

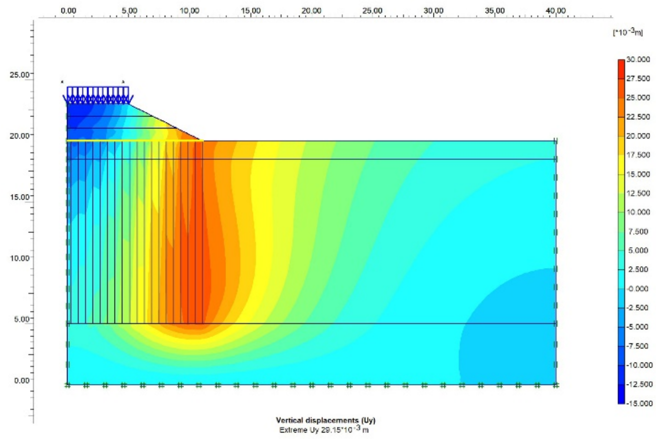


Fig. 8. The vertical displacements of the ground after stabilized with CDM columns and geotextiles

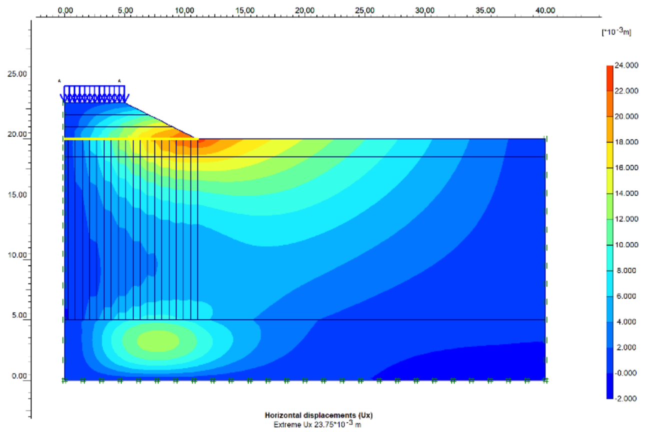


Fig. 9. The horizontal displacements of the ground after stabilized with CDM columns and geotextiles

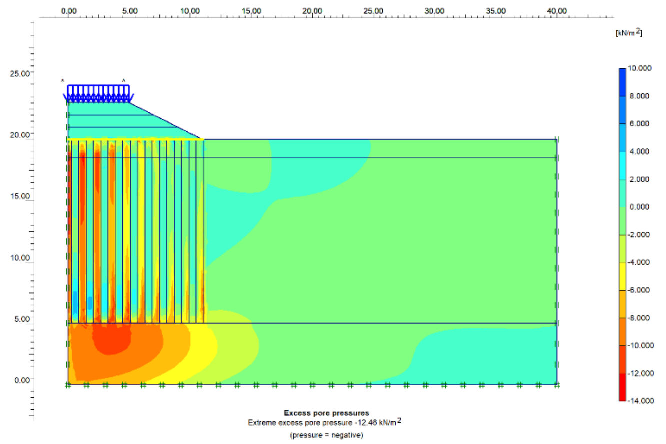


Fig. 10. The excess pore pressures of the ground after stabilized with CDM columns and geotextiles

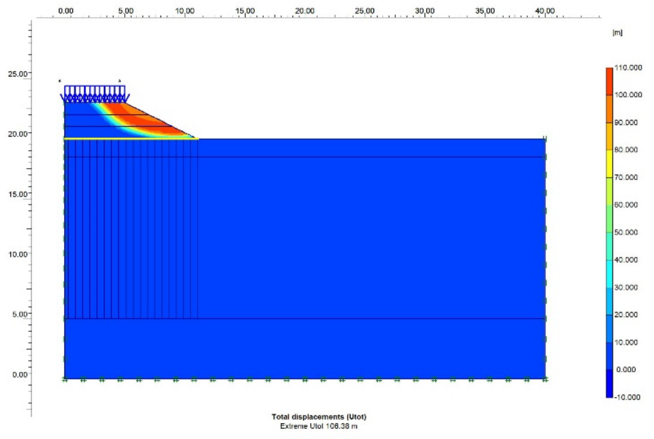


Fig.11. Stability coefficient of the stabilized soft ground by CDM columns and geotextiles, FS= 2.739

To increase the stability of the soil foundation, this area can be combined with other solutions such as phased embankment; building a counter-pressure platform; preloading to speed up settlement; reducing the load of the embankment, or arranging layers of geotextiles at the bottom and in the embankment body, etc. These types of treatment do not affect the natural ground below, but only affect the structure and the process of building the embankment above. For the treatment of soft soil on the foundation of roads that lead to the bridge, along with mastering the geotechnical characteristics of the soft ground to offer specific treatment solutions, it is also necessary to identify the technical requirements of the roadbed. The solution proposes that CDM columns should have a diameter of 0.6 m, a distance of 1.2 m apart from each other, and a length of 15 m. The geotextiles should have a settlement of 0.013 m. For the settlement of the ground after stabilization, the settlement is 0.013 m and the stability coefficient increases from 1.032 to 2.739. This coefficient meets the requirements according to the standard 22TCN 262-2000 [23]. From analyzing the calculation of CDM columns, it was found that this is a feasible method for settlement of embankment embankments on soft soil at the bridge approach. The following requirements for settlement of construction work are met: 1) construction progress is maintained; 2) The use of land is minimal therefore the method does not affect the neighboring construction works. With these superior features, the author proposes to use CDM columns combined with geotextiles to handle settlement of the road foundation on soft soil to achieve high economic efficiency and meet the technical requirements of the urban road projects.

The calculation steps, which are arranged based on the construction sequence, have controlled the distribution of stress and the deformation, and minimized the possibility of settlement and deviation, ensuring that safety standards are met for important work such as aircraft runways, highways, bridge approach and embankments.

3.2 Discussion

The settlement of the ground consists of two main parts, the primary consolidation settlement and the secondary consolidation settlement. The settlement of primary consolidation is mainly due to the static loads of the embankment and vehicular loads, and can be estimated more easily than secondary consolidation. Primary consolidation can be calculated based on the e-logP curve. With P_0 and e_0 being the effective stress due to self-weight and void coefficient of the underlying soil before constructing the roadbed, respectively, when the roadbed load and vehicle load are applied, the stress changes from P_0 to P_1, and then to P_2, and the void factor varies from e_0 to e_1, and then to e_2. The secondary consolidation settlement is usually small compared to the primary consolidation settlement. In practice, it is difficult to distinguish between the secondary consolidation settlement and the primary consolidation settlement.

It is possible to use multiple layers of geotextile placed on the CDM columns system to redistribute the load, and avoid the phenomenon of stress concentration on the top of the CDM columns.

An FEM analysis method is used to calculate for transient plate with axial symmetric stress condition. In the calculation, the soft soil layer is modeled as an elastic material according to the Mohr-Coulomb condition. The loads acting on the slab surface include the self-weight of the pavement layer and the vehicle load. In the analysis of high-speed transport, the conversion from vehicle load to static load is also an issue that needs to be studied further.

4 CONCLUSIONS

The bridge approach is one of the structures that is often damaged. Therefore, it is important to search for a method that can increase the quality of this type of structure. The analysis that stabilizes the path to the bridge on soft ground is necessary to meet the requirements for an effective operation of this structure. New calculation methods such as a finite element can deal with many input parameters, perform complex simulations, and give accurate results. From using the FEM, the article Plaxis software has drawn the following conclusions:

1. From the calculation results of settlement after 10 years of the road leading to Tan Phu Dong bridge, Tien Giang province, treated with CDM columns combined with geotextiles, the column should have a diameter of 0.6 m, a distance of 1.2 m and a length of 15 m. The settlement should be 0.013m, and the coefficient of stability should be 2.739.
2. Based on the design requirements, the research proposes a solution of CDM columns combined with geotextiles as a new direction for positive results, with a reduction in the settlement of the bridge approach, and an increase in operation between road and bridge. In addition, the proposed solution is appropriate given the current lack of construction materials in the Mekong Delta region.
3. When using the finite element method, the designers can analyze many problems with different geometric design parameters and choose the most reasonable design solution.

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