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NONLINEAR FEM ANALYSIS OF CEMENT COLUMN CONFIGURATION IN THE FOUNDATION IMPROVED BY DEEP MIXING METHOD

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Abstract. In this study, the stress distribution and the deformation in the foundation improved by Deep Mixing Method are analyzed using nonlinear FEM in which the stress-strain relation is elasto-plastic to apply to more detailed specification of the configuration of cement column.
Keywords: Deep Mixing Method, soft soil, cement column, FEM, Simplified Method.

1. Introduction

Main objective of research work is to define a proper design method of DCM column to overcome the limitation of the method, especially for the soft soil such as Mekong Delta soil. There are several methods for designing the DCM column for the soft soil as discussed in the references (Bengt B. Broms, 1999), (EuroSoilStab, 2002) and (Coastal Development Institute of Technology, 2002). In these methods, the settlement of the soil layer is calculated by the consolidation index and the bearing capacity is checked by the strength of the cement column and the bearing capacity of the soil. However, the method to define the cement column properly is not specified.

In this study, the method to define the configuration of cement column, i.e. the dimension and spacing of the cement columns within the soil layers, is proposed. A nonlinear Finite Element Method (FEM), as programmed as commercial ABAQUS software, is used for the detailed consideration. By this nonlinear FEM, the responses and behaviors of the cement column during the stabilizing of soft soil are clearly shown through the distribution of the stress both in the cement column and in the soft soil layers. By this method, the history of settlement for the embankment construction can be displayed.

2. Analysis for embankment

2.1. Model of an embankment

The model to be analyzed is shown in Fig. 1. The model consists of three soil layers, i.e. 11 m soft soil layer, 4 m silty clay and 5 m silty sand, respectively. A 5 m high embankment structure is constructed on soft soil layers. The embankment is planned to pass a transportation highway. Since the model is analyzed in two dimensional, only cross section of the model is given in Fig. 1.

The soft soil layer is one of the typical soft soil layers in the Mekong Delta. The properties of soil are obtained by the tests of the Mekong Delta soils (Engineering Geological Report, 2000) while the dilatancy angle is referred in the literatures (Bengt B. Broms, 1999), (EuroSoilStab, 2002) and (CDIT, 2002).

The traffic load on the embankment is 20 kN/m^2 that is recommended by Vietnamese Standard for Transportation Road Construction (TCVN) (Vietnamese Standards, 2000).

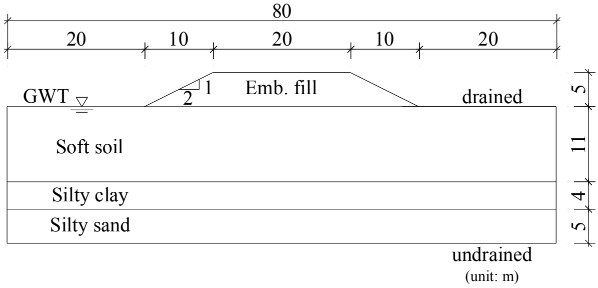

Fig. 1. Cross section of the embankment model

Table 1

Material properties

Parameter	**Soft soil**	**Silty clay**	**Silty sand**	**Emb.**	**DCM**
Saturated unit weight, γ_{sat}, kN/m^3	14.370	18.880	18.510	20.000	15.810
Young modulus, E, MPa	3.048	6.028	7.434	20.000	43.750
Poisson's ratio, ν	0.485	0.439	0.356	0.333	0.333
Cohesion, c, MPa	0.0071	0.0131	0.0024	0.0100	0.1750
Frictional angle, φ (°)	3.25	12.50	26.50	30.00	30.00
Dilatancy angle, ψ (°)	1.625	6.25	13.25	15.00	15.00
Permeability, k, cm/s	10^{-6}	10^{-6}	10^{-5}	10^{-3}	10^{-7}
Void ratio, e_o	2.389	0.705	0.604	1.500	1.532

2.2. Simplified Method

A configuration of cement column generally depends on several factors such as allowable settlement, soil capacity require preventing failure of civil structures such as embankment and dimension of the cement column. The application of the cement column for stabilizing the soft soil is reported in references (Bengt B. Broms, 1999), (EuroSoilStab, 2002) and CDIT, 2002).

The simple method is one of limit equilibrium method where the applied load must equal to resistant of the cement column and soil layer beneath the civil structure, such as embankment. The resistance of the cement column which is analyzed by Terzaghi's equation and settlement is evaluated by using the consolidation theory.

To obtain an optimum configuration, a series of calculation for the settlement of the embankment and the bearing capacity of the improved soil layers are performed by varying size of diameter, spacing and length of the cement column. The optimum configuration is determined by using the smallest replacement area of the cement column in a square meter of the stabilization area and the allowable settlement.

2.3. Nonlinear FEM

The optimum configuration found by the Simplified Method, mentioned above, is investigated by using the nonlinear FEM. For Model-A in Fig. 2, the soft soil layers are not stabilized. The foundation of the embankment is improved by using the cement column for Model-B in Fig. 3.

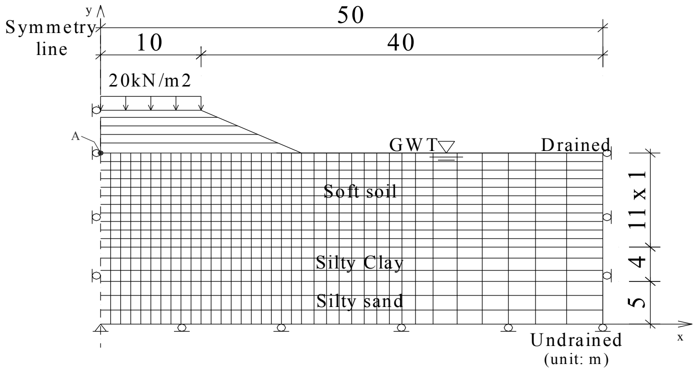

Fig. 2. Embankment without stabilization (Model-A)

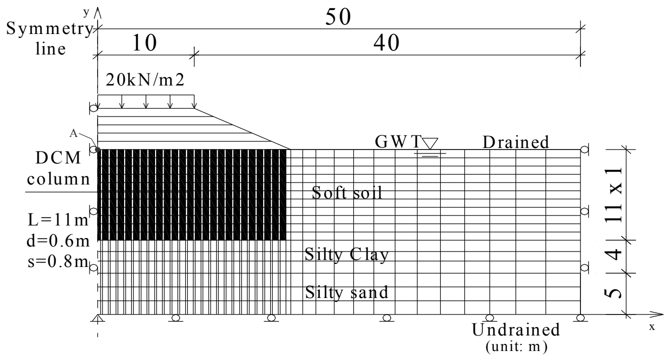

Fig. 3. Embankment with stabilization (Model-B)

ABAQUS program is used to numerically analyze the problem. In the numerical analysis, the cement columns, the soil layers and the embankment are modeled as nonlinearly elasto-plastic materials with Mohr-Coulomb failure criteria. The two-dimensional (2D) numerical model is used for this study. Due to the symmetry of the problem, there is a half of the section modeled to save the computing time. In order to explain more realistic behaviors of soft soil, two phases coupling of solid and pore water and nonlinear of solid materials are taking into account in FEM analysis. The nonlinearity of the material is expressed by Mohr-Coulomb yield criterion.

A finite element mesh is constructed to simulate the sequential construction procedure of the embankment and to calculate the resulting consolidation settlements in the soft soil layer. The mesh includes a half of the geometry because of symmetry. The mesh consists of the part the soft soil layer, silty clay layer, silty sand layer and the five embankment layers. The Model-A consists of 746 elements and 807 nodes, while the Model-B consists of 4828 elements and 6569 nodes. In the Model-B, the 0.6 m diameter of cement column with 0.8 m spacing center to center of cement columns are embedded in the 11 m depth beneath the embankment structure. Since the stabilization problems considering in this study require the information of both soil skeleton and pore water inside the soil mass. The elements are pore water/ stress four node quadrilateral elements (with bilinear displacement and bilinear pore pressure) and appropriate for finite strain analysis.

The cement column in FEM is assumed the continuum element, which the elements can be used to model the widest variety of components. Conceptually, the continuum elements simply model small blocks of material in a component. Since they may be connected to other elements on any of their faces, the continuum elements, like bricks in a building or tiles in a mosaic, can be used to build models of nearly any shape, subjected to nearly any loading.

In both of models, step by step embankment construction is simulated by applied analysis featuring of ABAQUS software, i.e. activate and deactivate mesh of embankment structure in plane stress assumption. The embankment structure is built in 1 m layer by layer construction; totally 5m high of embankment on soft soil layer. The nodes on the mirror symmetrical line are restrained as symmetrical boundary condition, while the nodes on the other sides, are not allowable to move laterally the ground surface which is considered as drained by applied zero pore water pressure during the analysis.

Each step of embankment construction is assumed 2 days. Totally, 10 days for completing the embankment are considered before loaded by external load such as traffic load. In this analysis, 20 kN/m^2 traffic loads are subjected to the surface of embankment as suggested by Vietnamese standard. The models are analyzed for 1000 days after the construction of the embankment to obtain final settlement.

During the analysis, the nonlinear effect of the soil layers is taken into account. For this nonlinear analysis, a Mohr - Coulomb constitutive model is used with a simple bilinear hardening rule. This nonlinear effect is only used for the soil skeleton in the soil mass, while the pore water remains in linear and follows the equilibrium condition with respect to coupling with the soil skeleton.

3. Results of Analysis

The cement column in which the diameter is 0.6m, the spacing is 0.8m and the length is 11m was obtained as an optimum configuration by the Simplified Method. By the optimum configuration 44.2% of replacement area by cement column and 0.169 m of maximum settlement beneath the embankment structure are obtained. The configuration of cement column reduces almost 93% of settlement of the soft soil layers. The flow-chart for the proposed Simplified Method is shown in Fig. 4.

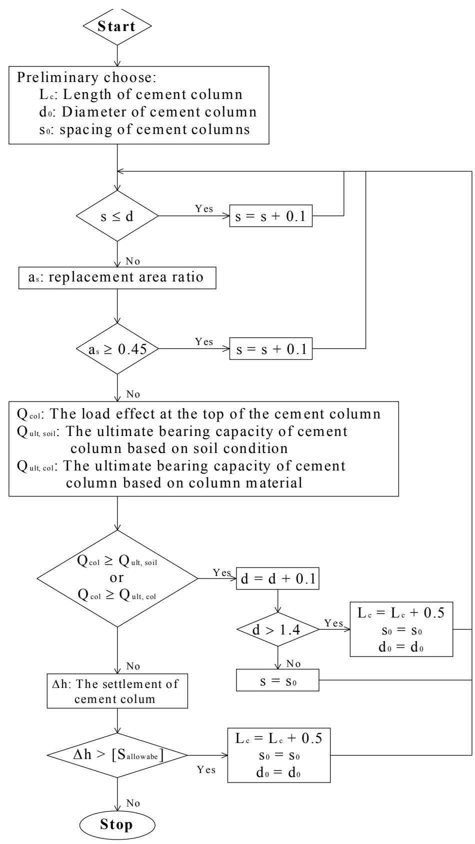

Fig. 4. Flow-chart for the Simplified Method

Fig. 5 and Fig. 6 show the distribution of the settlement of soft soil beneath of the embankment for Model-A and Model-B after 1000 days consolidation analysis, respectively.

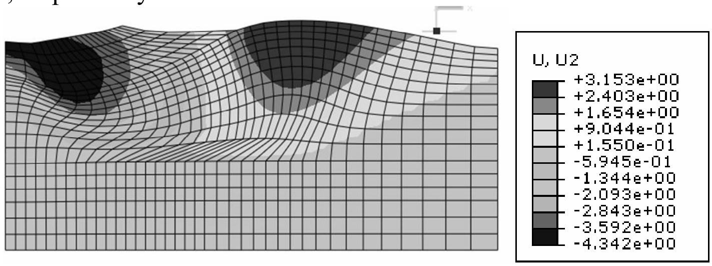

Fig. 5. Settlement distribution of Model-A

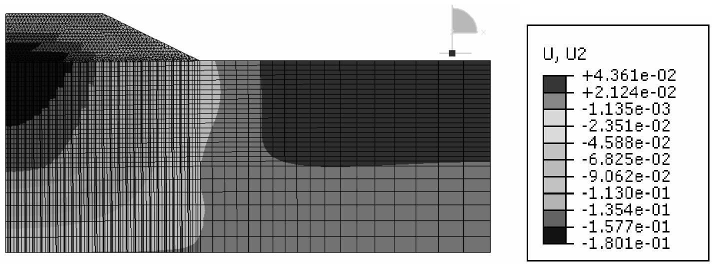

Fig. 6. Settlement distribution of Model-B

The settlement history plotted in Fig. 7 shows the capability of nonlinear FEM for evaluating the settlement of the embankment both with and without stabilization using cement column. These results confirmed with the calculation results using the Simplified Method explained above.

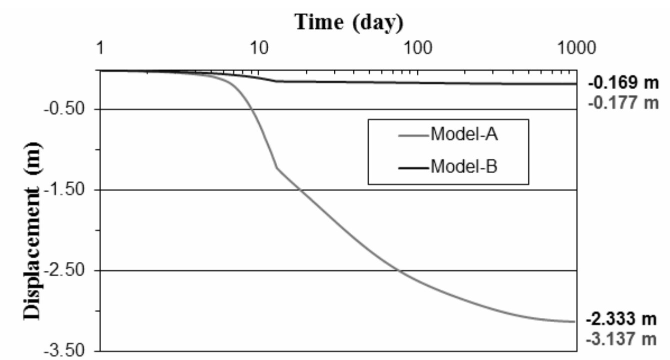

Fig. 7. Comparison of the settlement histories

The distribution of vertical effective stresses of each cement column is plotted in Fig. 8. The stress distributions are divided into three regions, namely region I, II, and III. The region-I indicates the soil mass can bear the applied load. The cement column may not be required in this region. In contrast in the region-III, all applied load are supported by the cement column. The region-II shows that both of soil and cement column bear the applied load. By removing the portion supported by soils, plotted in the region-II, we may reduce the length of cement column proportionally to the removed portion.

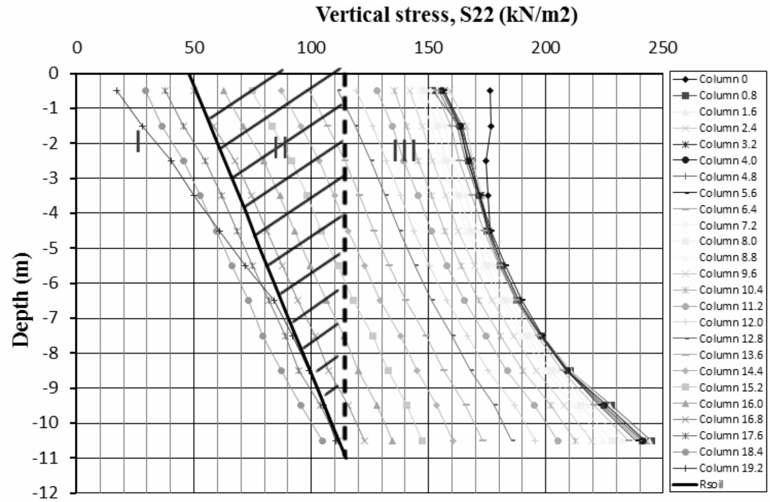

Fig. 8. Response of the cement column

The last FEM model as shown in Fig. 9, Model-C, is analyzed by the load used in the previous models and the result of settlement distribution as shown in Fig. 10. Comparing the maximum settlement occurs on the Model-B and Model-C, as plotted in Fig. 11, the configuration of Model-C is concluded as the optimum configuration for the case in this study.

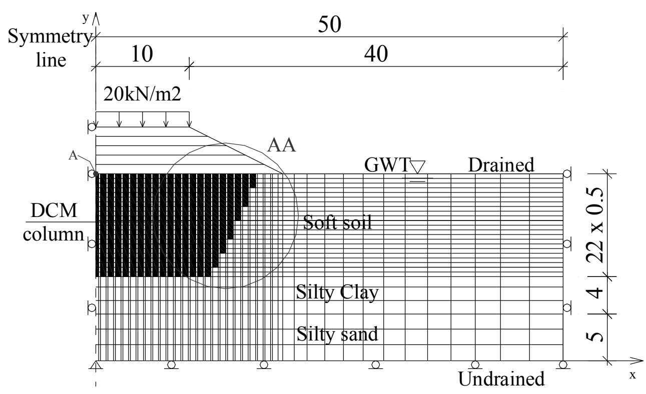

Fig. 9. FEM Model of reduced cement column length (Model-C)

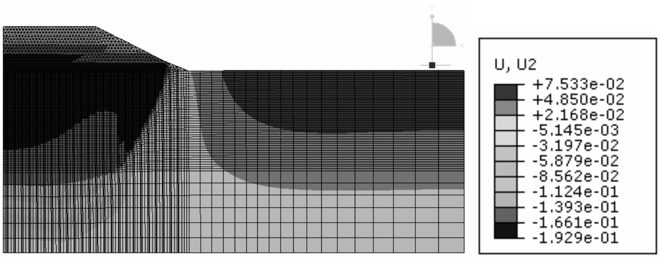

Fig. 10. Settlement distribution of Model-C

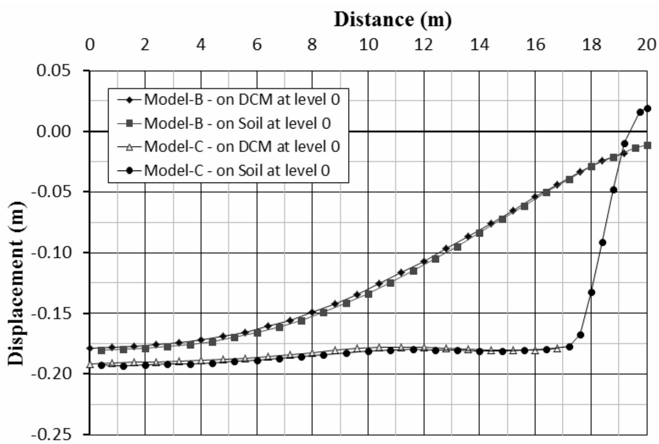

Fig. 11. Comparison of maximum settlement beneath of the embankment structure

4. Conclusions

Based on the analytical study described above, the conclusions of this study are listed as follow:

The optimum configuration of the cement column to stabilize an embankment is determined by the Simplified Method in which the settlement and bearing capacity are estimated by the formula used in the current design. The flow-chart of the method is shown in Fig. 4.

By FEM analysis for Deep Mixing Method using cement column, the stress distribution and the differential settlement are estimated. By the result of the analysis, more detailed configurations of cement column are suggested.

Comparing the results of the Simplified Method and FEM analysis, it is suggested that the stress distribution and the deformation in the foundation improved by Deep Mixing Method are important to determine the optimum configuration of cement column.

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The soil stabilization method, called Deep Mixing Method, is often applied for the soft soil layers in the alluvial plain, such as the Mekong Delta. In this study, the configuration of the cement column for Deep Mixing Method, which is embedded in the soft soil layers, is investigated for the different sizes of diameter, spacing and length of cement column. To obtain the optimum configuration of the cement column, the settlement of the structure and volume of cement are compared. In this study, a new method to find out the optimum configuration using the formula in the current design is proposed as the Simplified Method. The stress distribution and the deformation in the foundation improved by Deep Mixing Method are analyzed by using nonlinear FEM in which the stress-strain relation is elasto-plastic. The stress distribution in cement column and the differential settlement obtained by the FEM analysis are applied to more detailed specifications of the configuration of cement column.

Keywords: Deep Mixing Method, soft soil, cement column, FEM, Simplified Method.

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НЕЛІНІЙНИЙ МСЕ АНАЛІЗ КОНФІГУРАЦІЇ ЦЕМЕНТНОЇ КОЛОНИ В ПІДФУНДАМЕНТНІЙ ОСНОВІ, ПОЛІПШЕНІЙ МЕТОДОМ ПОГЛИБЛЕНОГО ЗМІШУВАННЯ

Метод стабілізації грунту, званий методом глибокого змішування, часто застосовується для м'яких шарів ґрунту в долинах з алювіальними грунтами, таких як дельта річки Меконг. У даній роботі досліджена конфігурація бетонної колони, що вбудовується в м'які шари грунтової основи, поліпшеної методом глибокого перемішування, для різних розмірів діаметрів, довжин колон і відстаней між ними. Для отримання оптимальної конфігурації колони проводиться порівняння витрат бетону. У цьому дослідженні в якості спрощеного методу пропонується новий метод визначення оптимальної конфігурації з використанням отриманих співвідношень. Розподіл напружень і деформацій основи аналізуються з використанням нелінійного МСЕ, в якому залежність напруження-деформація відповідає пружнопластичній моделі. Розподіл напружень, отриманий за допомогою МСЕ, застосовується для уточнення конфігурації колони.

Ключові слова: метод глибокого змішування, м'який грунт, цементна колона, МСЕ, спрощений метод.

Нгуен Нгок Тханг, Нгуен Анх Туан

НЕЛИНЕЙНЫЙ МКЭ АНАЛИЗ КОНФИГУРАЦИИ ЦЕМЕНТНОЙ КОЛОННЫ В ПОДФУНДАМЕНТНОМ ОСНОВАНИИ, УЛУЧШЕННОМ МЕТОДОМ ГЛУБОКОГО СМЕШИВАНИЯ

Метод стабилизации грунта, называемый методом глубокого смешивания, часто применяется для мягких слоев почвы в равнинах с аллювиальными грунтами, таких как дельта реки Меконга. В данной работе исследована конфигурация бетонной колонны, встраиваемой в мягкие слои грунтового основании, улучшенного методом глубокого перемешивания, для различных размеров диаметров, длин колонн и расстояний между ними. Для получения оптимальной конфигурации колонны проводится сравнение расхода бетона. В этом исследовании в качестве упрощенного метода предлагается новый метод определения оптимальной конфигурации с использованием полученных соотношений. Распределение напряжений и деформации основания анализируются с использованием нелинейного МКЭ, в котором зависимость напряжение-деформация соответствует упругопластической модели. Распределение напряжений, полученное с помощью МКЭ, применяются для уточнения конфигурации колонны.

Ключевые слова: метод глубокого смешивания, мягкая почва, цементная колонна, МКЭ, упрощенный метод.

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Нгуен Нгок Тханг, Нгуен Анх Туан. **Нелінійний МСЕ аналіз конфігурації бетонної колони в підфундаментній основі, поліпшеній методом поглибленого перемішування** / Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2018. – Вип. 100. – С. 18-26. – Англ.
Досліджено конфігурацію бетонної колони, яка вбудовується в м'які шари грунтової основи, поліпшеної методом глибокого перемішування, для різних діаметрів, довжин колон і відстаней між ними.
Табл. 1. Іл. 11. Бібліогр. 7 назв.

UDC 539.3
Nguyen Ngoc Thang, Nguyen Anh Tuan. **Nonlinear fem analysis of cement column configuration in the foundation improved by deep mixing method /** Strength of materials and theory of structures: Sci.&Tech. Collected Artcl. – K.: KNUBA, 2018. – Issue 100. – P. 18-26.
The configuration of a concrete column has been studied, which is built into soft layers of the ground base, improved by deep mixing, for different diameters, lengths of columns and distances between them.
Tabl. 1. Fig. 11. Ref. 7.

УДК 539.3
Нгуен Нгок Тханг, Нгуен Анх Туан. **Нелинейный МКЭ анализ конфигурации бетонной колонны в подфундаментном основании, улучшенном методом углубленного перемешивания** // Сопротивление материалов и теория сооружений: науч.-тех. сборн. – К.: КНУСА,, 2018. – Вып. 100. – С. 18-26. – Англ.
Исследована конфигурация бетонной колонны, которая встраивается в мягкие слои грунтового основания, улучшенного методом глубокого перемешивания, для различных диаметров, длин колонн и расстояний между ними.
Табл. 1. Ил. 11. Библиогр. 7 назв.

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