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Exploring Optimal Cement Deep Mixing Column Arrangements For Soft Ground Improvement: A Simplified Approach Investigation

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ABSTRACT

The Deep Mixing Method (DMM), a soil improvement technique, is frequently employed to enhance the strength of soft ground in Delta areas. With extensive urbanization and industrialization in soft clay zones, there has been a substantial increase in the design and construction of infrastructure facilities in recent years. Over the past few decades, comprehensive, well-documented reports have been developed at various stages, covering state-of-the-art techniques for improving ground conditions, design methodologies, and detailed records of the adoption of various methods. Among these methods, Cement Deep Mixing (CDM) columns, formed by DMM, emerge as a cost-effective and efficient solution for treating soft soils beneath embankments. This research delves into the configuration of CDM columns embedded in soft ground layers, exploring different dimensions, spacing, and lengths of the CDM columns.
Keywords : Soil improvement, DMM, CDM Columns, Mekong Delta, Simplified Approach

I. INTRODUCTION

In recent years, the design and construction of infrastructure facilities have experienced significant growth, driven by extensive urbanization and industrialization in soft clay zones. The soil in this area is characterized by high water content, low stiffness, a reduced frictional angle, and diminished cohesion. Geotechnically, this type of soil is classified as unstable due to its tendency to undergo substantial settlement under loading, attributed to high excess pore pressure and a reduction in effective stress within the soil mass. The notable settlement observed in embankments, a common civil structure example built on this soil layer, exemplifies the unstable behavior of soft soil under heavy loads.

Various methods are employed to stabilize soft soils, such as those in the Mekong Delta region. A crucial aspect of soil improvement involves rapidly enhancing the strength of treated ground. Bergado et al. (1996) describe the DMM as an in-situ soil treatment and improvement technology. This technique involves blending the ground with cementitious and/or other materials to create vertical stiff inclusions within the soil [1]. These materials often referred to as 'binders,' can be introduced in slurry or dry form and are injected through hollow, rotated mixing shafts equipped with cutting tools. The DMM technique facilitates physical and chemical reactions among cement, clay minerals, and water. These reactions, including hydration, pozzolanic reaction, ion exchange, flocculation, precipitation, oxidation, and carbonation, occur deep below the ground. The result is a rapidly formed high-strength product that continues to strengthen over time. Additionally, the treated ground exhibits lower permeability and compressibility compared to the native soil.

From a chemical standpoint, the CDM method serves to reduce the high water content in the soil mass by absorbing water molecules during the cementation of CDM columns. Mechanically, the CDM method aims to enhance the stiffness of the soil mass through the incorporation of high-stiffness CDM columns. According to CDIT (2022), these methods involve calculating the settlement of the soil layer using the consolidation index. Simultaneously, the bearing capacity is assessed based on the strength of the CDM columns and the bearing capacity of the soil [2].

Anucha W. et al. (2018) conducted a study on the bearing capacity and failure behaviors of floating stiffened CDM columns under axial load [3]. This research aims to elucidate the impact of the length of the stiffened core and the strength of the CDM socket on the behaviors of these columns, focusing on axial ultimate bearing capacity, settlement, and failure mode. To achieve this, a series of physical model tests was conducted as a preliminary investigation. The results indicate that the strength of the CDM socket can be optimized by inserting a sufficiently long reinforced core. This optimization leads to the highest possible load-carrying capacity, suggesting an optimal length for the stiffened core corresponding to a specific CDM socket strength.

Nguyen Ngoc Thang and Nguyen Anh Tuan (2018), Hong-Son Nguyen et al. (2020), and Nguyen Anh Tuan with Nguyen Thanh Dat (2020) have conducted studies on the nonlinear Finite Element Method (FEM) analysis of cement column configurations in foundations improved by the deep mixing method. In this research, the stress distribution and deformation in the foundation improved by the DMM are analyzed using nonlinear FEM. The stress-strain relation applied in this analysis is elastoplastic, allowing for a more detailed specification of the configuration of CDM columns [4, 5, 6].

II. MECHANISM OF CEMENT DEEP MIXING METHOD

1. Load transfer mechanisms

CDM columns are installed as isolated columns, and constructed using single-axis equipment. Depending on the purpose and ground conditions, CDM columns can be configured in typical arrangement patterns such as panels of overlapping columns, cells of overlapping columns, or blocks of overlapping columns. The column type is easily installed separately under square, triangular, or hexagonal grid patterns, with a straightforward construction process. Irrespective of the arrangement of CDM columns, common design procedures incorporate the concepts of area replacement ratio and stress concentration ratio.

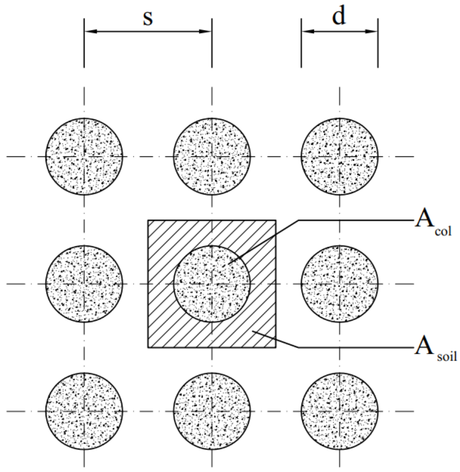

Figure 1. Area replacement ratio

For isolated CDM columns, the area replacement ratio is defined as the ratio between the area of the CDM columns (A_{col}) and the total area (A_{col} + A_{soil}) (refer to Figure 1). Figure 2 illustrates the distribution of load on CDM columns and soft soil under a road embankment.

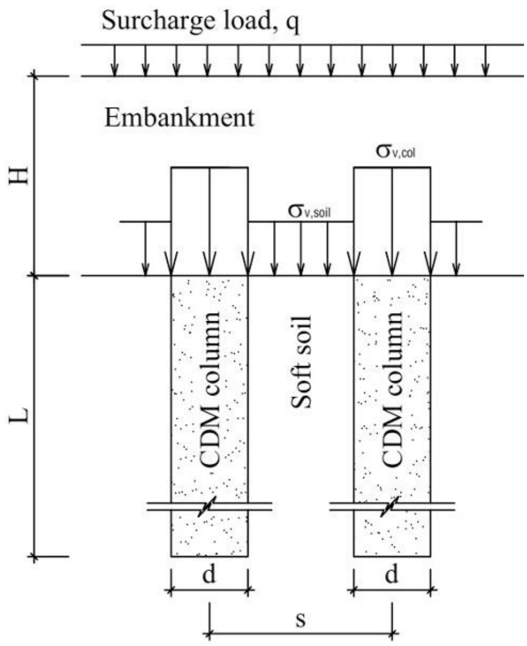

Figure 2. Illustration of load distribution for CDM columns

2. The ultimate bearing capacity of the single CDM columns:

In a comprehensive examination of practical design aspects concerning the stability of embankments stabilized by DMM columns, Bengt B. H. (1999) emphasized precautions against potential failures in DMM columns. These failures, occurring in the form of rupture or collapse due to bending and tilting, underscore the importance of considering the internal stability of DMM columns during the design process [7]. Consequently, evaluating the failure modes of DMM columns beneath embankments under various differential conditions, including bending, shearing, compression, etc., becomes a necessary aspect of embankment design in practice. The ultimate bearing capacity of a single CDM column is influenced by both the skin friction resistance along the column's surface and the end resistance.

3. The undrained compression strength of soil-cement mixture:

The undrained compressive strength of soil stabilized with cement typically surpasses that of the undisturbed soil approximately 1 to 2 hours after mixing. Under favorable conditions, the undrained shear strength of the stabilized soil can reach levels as high as 0.5 to 1.0 MPa, representing a significant 10 to 50 times increase in strength.

III. OPTIMUM CDM COLUMNS CONFIGURATION

The configuration of CDM columns is typically influenced by various factors, including allowable settlement, soil capacity to prevent the failure of civil structures like embankments, and the dimensions of the CDM columns. The simple method, a form of the limit equilibrium method, dictates that the applied load must equal the resistance of both the CDM columns and the soil layer beneath the civil structure, such as an embankment. The resistance of the CDM columns is analyzed using Terzaghi's equation, while settlement is evaluated through the application of consolidation theory.

1. Model of a case study

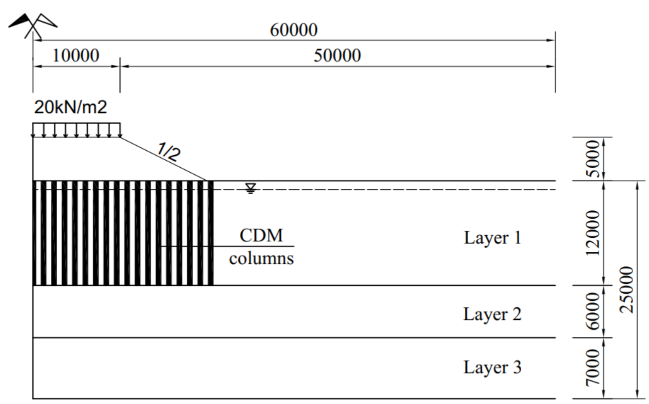

Figure 3. The cross-section of the embankment model

The model to be analyzed is depicted in Figure 3, consisting of three soil layers: a 12 m soft soil layer, a 6 m layer of silty clay, and a 7 m layer of silty sand. On these layers, a 5 m high embankment structure is constructed. The embankment is designed to accommodate a transportation highway. It's important to note that, for simplicity, only a cross-section of the model is presented here as the analysis is conducted in two dimensions.

The soil layer parameters have been established based on a combination of field and laboratory tests conducted on soil samples extracted from the Mekong Delta. These tests were documented in the Engineering Geological Report from Chau Thanh district in Tien Giang province [8]. The specific soil properties utilized in this study can be found in Table 1.

Table 1. Soil properties of soil layers

ID	Soil Parameters	Layer 1	Layer 2	Layer 3	Unit
1	Saturated unit weight, γ_{sat}	17.450	19.680	19.860	kN/m^3
2	Young's modulus, E	3.100	4.290	4.610	MPa
3	Cohesion, c	0.0032	0.0429	0.0461	MPa
4	Void ratio, e_0	2.419	0.685	0.424	-

2. Optimization of the configuration of the CDM columns

The optimization of the CDM columns configuration, using a method, aims to determine the ideal diameter, spacing (center-to-center of CDM columns), and length of CDM columns under an applied load of 120 kN/m^2 beneath the embankment. The optimal configuration must adhere to the allowable maximum settlement of 0.4 m beneath the embankment, as specified by the Vietnamese Standard for transportation roads, TCVN 22TCN 262-2000 [9]. The method is initiated by assessing the bearing capacity of soil layers through the Terzaghi equation. The bearing capacity is computed for the depth of soil layers beneath the embankment structure. At the -12 m level (soft soil layer), the maximum bearing capacity is approximately 150 kN/m^2. This capacity is relatively low compared to the applied load beneath the embankment, set at 120 kN/m^2.

Utilizing the material properties provided in Table 2, the study investigates the minimum ratio of the CDM columns' area to the square of the stabilized area. This investigation considers various dimensions of the CDM columns.

Table 2. Material properties of CDM columns.

ID	Parameter	CDM columns	Unit
1	Saturated unit weight, γ_{sat}	15.270	kN/m^3
2	Young's modulus, E	40.000	MPa
3	Cohesion, c	0.200	MPa
4	Frictional angle, φ	30.00	°
5	Void ratio, e_o	1.432	-

In this study, the method is employed by varying the diameter of CDM columns (0.6 m, 0.8 m, 1.0 m, 1.2 m, and 1.4 m), the center-to-center spacing of CDM columns (0.8 m, 1.0 m, 1.2 m, 1.4 m, 1.6 m, and 1.8 m), and the length of CDM columns (6.0 m, 9.0 m, and 12 m).

According to the results presented in Table 3, the optimal configuration for stabilizing the soil layer in this case indicates a diameter of 0.6 m and a spacing of 0.8 m for lengths of 6.0 m, 9.0 m, and 12.0 m.

Table 3. Values of the ratio of CDM columns area

Length L	Spacing s= 0.8 m	Spacing s= 1.0 m	Spacing s= 1.2 m	Spacing s= 1.4 m
6.0 m	d: 0.6 m a_s: 0.442	d: 1.0 m a_s: 0.785	d: 1.2 m a_s: 0.785	-
9.0 m	d: 0.6 m a_s: 0.442	d: 0.8 m a_s: 0.502	d: 1.0 m a_s: 0.545	d: 1.4 m a_s: 0.785
12.0 m	d: 0.6 m a_s: 0.442	d: 0.8 m a_s: 0.502	d: 1.0 m a_s: 0.545	d: 1.2 m a_s: 0.557

Utilizing the material properties outlined in Table 3 and equations 1 to 12, the study explores the minimum ratio of the CDM column's area to the square of the stabilized area. This investigation encompasses various dimensions of the CDM column.

$$Q_{col} < Q_{ult,col}^{max} \quad (1)$$

$$Q_{col} < Q_{ult,soil}^{max} \quad (2)$$

$$Q_{col} = q_{col} . A_{col} \quad (3)$$

$$q_{col} = \frac{q}{E_{eq}} E_{col} \quad (4)$$

$$E_{eq} = E_{col} a_s + (1 - a_s) E_{soil} \quad (5)$$

$$a_s = \frac{\pi}{4} \left(\frac{d}{s} \right)^2 \quad (6)$$

$$Q_{ult,soil} = \frac{1}{FS} \left(\pi d L_c + 2.25 \pi d^2 \right) c_{u,soil} \quad (7)$$

$$Q_{ult,col}^{max} = \frac{A_{col} . q_{1,max}}{FS} \quad (8)$$

$$q_{1,max} = 0.95 a_s \sigma_{ult} \quad (9)$$

$$\sigma_{ult} = 3.5 c_{u,col} + 3 \sigma_h \quad (10)$$

$$\sigma_h = \sigma_v + 5 c_{u,soil} \quad (11)$$

$$\sigma_v = q + \gamma' L_c \quad (12)$$

where Q_{col} is the load at the top of the CDM column; $Q_{ult,soil}^{max}$ is the ultimate bearing capacity of a single CDM column governed by the shear strength of surrounding soil; $Q_{ult,col}^{max}$ is the ultimate bearing capacity of a single CDM column governed by the strength of the column material; E_{eq} is the equivalent modulus of elasticity of the soil – CDM column; E_{col} is the modulus of elasticity of the CDM column; E_{soil} is the modulus of elasticity of soft soil layer; q is the applied unit load; A_{col} is a cross-section of the column; a_s is replacement area ratio; L_c is the length of the column; d is the diameter of the column; s is the spacing of center of the column; c_{ucol} is undrained strength of column; c_{usoil} is undrained strength of the surrounding soft soil; FS is safety factor; σ_{ult} is ultimate internal bearing capacity of a single column; σ_h is horizontal pressure between the soil and the columns; σ_v is the total overburden pressure; γ' is buoyant unit weight.

The concluding step in this method involves assessing the settlement beneath the embankment after implementing CDM columns. The total settlement after stabilization is the cumulative result of both the settlement of the stabilized soil and the original soil.

$$\Delta h = \Delta h_1 + \Delta h_2 \qquad (13)$$

$$\Delta h_1 = \frac{qL_c}{a_s E_{col} + (1 - a_s) E_{soil}} \qquad (14)$$

$$\Delta h_2 = \frac{h}{1 + e_0} C_c \log_{10}\left(\frac{\sigma_{vz} + q_u}{\sigma_{vz}}\right) \qquad (15)$$

where Δh is the total settlement of embankment; Δh_1 is the settlement of the stabilized soil layer and Δh_2 is the settlement of the soil layer below the CDM column; and q_u is the stress of applied load at the middle of soft soil, below the stabilized soil layer.

In accordance with Equation 15, the overall settlement measures 0.180 m for the scenario involving a column length of 12 m. This settlement falls below the permissible maximum limit of 0.4 m. The ideal configuration for the CDM column includes a diameter of 0.6 m, a spacing of 0.8 m, and a length of 12 m.

IV. CONCLUSION

The analytical study aimed at designing the optimal configuration of CDM columns to stabilize the soft soil layer in the Mekong Delta area has been outlined. In this study, a method, derived from established formulations in soil mechanics, is proposed to determine the initial configuration of CDM columns embedded in the soft soil layer. The identified optimal configuration for CDM columns is a diameter of 0.6 m, a spacing of 0.8 m, and a length of 12.0 m. The total settlement for this configuration is 0.180 m, which falls below the allowable maximum settlement. Determining the optimal CDM column configuration for stabilizing an embankment incorporates estimates of settlement and bearing capacity using formulas applied in current design practices. The outcomes of this approach for identifying the optimal configuration of the CDM column also recommend conducting a comparative analysis of stress distribution and deformation using the Finite Element Method.

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