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Evaluation of displacement of soil cement columns in a dynamic model

Đánh giá chuyển vị của hệ cọc xi măng đất trong mô hình động

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ABSTRACT

This study presents an evaluation of the deformation behavior of the soil-cement column system for ground improvement in a dynamic model with a surface roughness IRI = 2 (based on the research results of [15]) under conditions in Vietnam. The analytical method (according to TCVN 9403:2012 [1]) and the Finite Element Method (FEM) in Plaxis 2D were applied to analyze the effects of both static and dynamic loads on the displacement of the soil-cement column system. The results show that dynamic loads significantly increase settlement compared to static loads, with displacement increasing from 9.8 cm under static loading to 12.3 cm under dynamic loading, corresponding to a 25.51% increase. This clearly reflects the significant impact of dynamic loads on the settlement reduction performance of the soil-cement column system. Furthermore, the study emphasizes the role of road surface roughness and design live load in contributing to increased deformation under dynamic loading conditions. This topic is expected to be a potential subject for future experimental research.

Keywords: Soil cement columns; displacement; dynamic load; soft soil.

TÓM TẮT

Nghiên cứu này trình bày đánh giá biến dạng của hệ cọc xi măng đất trong gia cố nền trong mô hình động với độ gồ ghề IRI =2 (dựa trên kết quả nghiên cứu của [1]) đối với điều kiện ở Việt Nam. Phương pháp giải tích (theo TCVN 9403:2012 [2]) và phần tử hữu hạn (FEM) trong Plaxis 2D được áp dụng nhằm phân tích ảnh hưởng của tải trọng tĩnh và tải trọng động đến sự chuyển vị của hệ cọc xi măng đất. Kết quả cho thấy tải trọng động làm gia tăng đáng kể độ lún so với tải trọng tĩnh, với chuyển vị tăng từ 9,8 cm dưới tải trọng tĩnh lên 12,3 cm khi chịu tải trọng động, tương ứng tăng 25,51%. Điều này phản ánh rõ rệt ảnh hưởng đáng kể của tải trọng động đối với hiệu quả giảm lún của hệ cọc xi măng đất. Ngoài ra, nghiên cứu nhấn mạnh vai trò của độ gồ ghề mặt đường và hoạt tải thiết kế trong việc làm gia tăng biến dạng dưới điều kiện tải trọng động. Chủ đề này sẽ là lĩnh vực tiềm năng cho các nghiên cứu thực nghiệm trong tương lai.

Từ khóa: Cọc xi măng đất; chuyển vị; tải trọng động; đất yếu.

1. INTRODUCTION

Soil-cement columns (SCCs) is one of the most widely utilized ground improvement methods in Vietnam due to its rapid construction process, minimal environmental impact, and adaptability to various soil types and depths without compromising existing structures above [3][4]. Moreover, this method has proven particularly effective in addressing weak soil conditions in the Mekong Delta region [5]. According to [6], when compared to the sand drain method, the SCCs technique meets technical requirements while being more cost-effective and time efficient.

In the Mekong Delta region, weak soil foundations often lead to settlement and differential subsidence near bridge approach areas. To mitigate this issue, SCCs are installed with increasing lengths toward the bridge, improving the elastic modulus in the transition zone between the road and the bridge, thereby this method increases the stability of embankment slopes [7]. However, existing standards for SCCs in Vietnam, such as [2], [8] and TCVN 9906:2014 [9], primarily focus on construction procedures and material specifications without thoroughly addressing critical factors such as local soil behavior, stress-strain states, and post-reinforcement displacements [10]. Furthermore, the effectiveness of SCCs does not solely depend on the cement-soil mixing ratio but is also influenced by other factors, including geometric parameters, pile length, spacing, and differential stress between the piles and the surrounding weak soil, which can induce lateral displacement in the pile system [4]. Ashutosh Kumar Singh [11] found that the stress on Soil cement columns is approximately five times higher than that on the surrounding soil. Incorporating a load transfer platform into the SCCs can increase vertical settlement while reducing lateral displacement. In cases where lateral resistance is insufficient, pile failure may occur. A study conducted in Saga, Japan [12] confirmed that during ground consolidation, applied loads caused compaction and lateral displacement of embankment soil on the SCCs, ultimately leading to ground failure. The strength of the embankment material significantly affects lateral displacement. A decrease in cohesion accelerates lateral movement, reaching approximately 0.2 meters after 200 days. Conversely, higher cohesion limits lateral displacement to around 0.05 meters. Dynamic load effects are critical in roadway foundation design. According to TCCS41:2022/TCĐBVN [13], the design load for road embankments over weak soil is determined by the maximum number of heavy vehicles simultaneously covering the full roadway width.

However, Vietnamese standards have yet to address the impact of dynamic loads on reinforced road foundation design. In contrast, studies have shown that dynamic loads often have a more significant impact on structures than static loads [14]–[16]. Quan [1] emphasized that road surface roughness and vehicle speed are key factors in roadway foundation design. Specifically, the dynamic load coefficient (DLC) and impact force (IF) increase as the international roughness index (IRI) or vehicle speed rises.

This study focuses on evaluating the impact of loads on the displacement behavior of SCCs in the Mekong Delta region, which is characterized by thick layers of soft soil.

2. METHODOLOGY

2.1. Research location

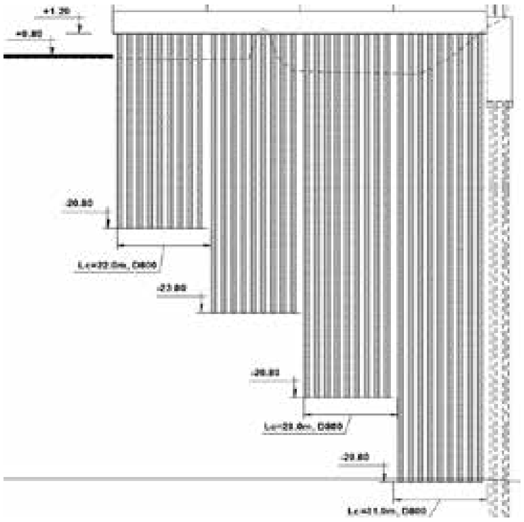


Figure 1. Arrangement of soil-cement columns along the longitudinal axis of the bridge

Figure 1 and Figure 2 illustrate the arrangement of soil-cement columns along the longitudinal and transverse axes of the bridge, showing the length, diameter, elevation, spacing, and configuration of the piles in the ground reinforcement system.

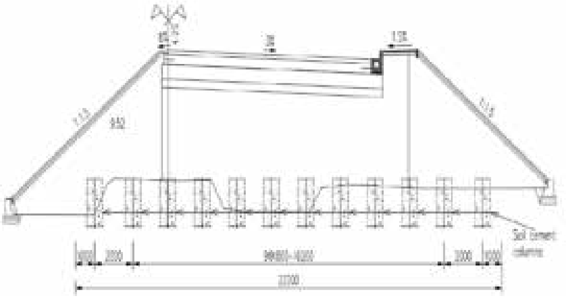


Figure 2. Arrangement of soil-cement columns along the transverse axis of the bridge

Figure *3* illustrates the plan view of the soil-cement column arrangement, where the pile length gradually increases from the road to the bridge to ensure a uniform increase in the reinforcement block's elastic modulus, providing smoother vehicle movement. Additionally, as the soil height at the bridge approach increases, the longer piles help enhance the foundation's load-bearing capacity.

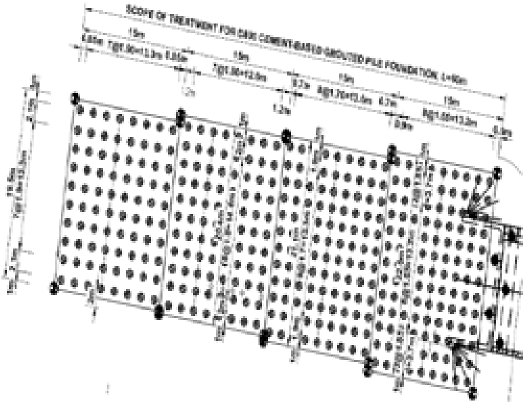


Figure 3. Plan view of soil-cement columns arrangement

2.2. Geological data

The physical and mechanical properties of soil are summarized in below.

Table 1. Geotechnical properties of the foundation soil

Soil Layer	Depth (m)	Unit weight (kN/m^3)	Internal friction angle (°)	Cohesion kN/m^2)
1	0 ÷ - 9.25	14.3	2.302	2.9
2	- 9.25 ÷ - 13.34	17.35	20.27	4.4
3	- 13.34 ÷ - 20.5	19.89	22.3	21
4	- 20.5 ÷ - 28.5	18.96	21.64	16
5	- 28.5 ÷ - 40	18.97	23.82	8.5

The geotechnical data in Table 1 represent typical soil properties of the Mekong Delta, characterized by soft alluvial soils with varying depths, unit weights, friction angles, and cohesion. Incorporating this data is essential for accurately assessing the deformation behavior of Soil cement columns under dynamic loads and design live loads in this region.

2.3. Method for calculating the settlement of SCCs

The methods for calculating deformation of soil-cement columns are currently quite diverse [17]. However, most ground improvement projects using soil-cement columns in Vietnam are designed based on the equivalent foundation concept, which is also the approach outlined in TCVN 9403:2012 [2]. Observational data from actual construction projects have demonstrated that the calculation results are fairly accurate and closely match pratical performance [18]. The overall settlement of the soil-cement columns is calculated as follows.

$$S = S_1 + S_2 \tag{1}$$

Where:

S_1: Settlement of the reinforced block.

S_2: Settlement of the soil beneath the pile toe.

The settlement of the reinforced block S_1 is calculated using the following formula:

$$S_1 = \frac{qH}{E_{tb}} = \frac{qH}{aE_c + (1-a)E_S} \tag{2}$$

The settlement of the soil beneath the pile toe S_2 is calculated using the layer-by-layer settlement summation principle as specified in TCVN 9362:2012 [19].

2.4. Model of dynamic loads

According to [20], the international roughness index (IRI) measured on the Hanoi–Hai Phong Expressway ranges from 1.65 to 1.72. However, for lower-grade roads, surface roughness tends to be higher. Therefore, this study adopts an IRI value of 2.0 to analyze the displacement behavior of Soil cement columns based on the dynamic load model proposed by [1]. To ensure practical applicability in the design process, the quarter-car model (QCM) with two degrees of freedom was employed in accordance with ISO 8608 standards, and the corresponding system of differential equations was established as follows:

$$m_s\ddot{z}_s = -c_s((\dot{z}_s - \dot{z}_u) - k_s(z_s - z_u) \quad (3)$$

$$m_u\ddot{z}_u = c_s(\dot{z}_s - \dot{z}_u) + k_s(z_s - z_u) - k_t(z_u - h) \quad (4)$$

Where: m_s: sprung mass; z_s: displacement of the sprung mass; m_u: Unsprung mass; z_u: displacement of the unsprung mass; k_s: spring stiffness; k_t: tire stiffness; c_s: damping coefficient.

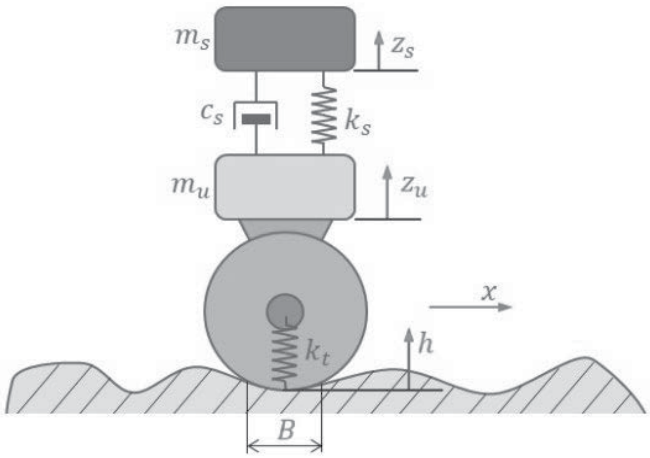


Figure 4. QCM model subjected to road surface roughness excitation [1]

The road surface roughness (RSR), characterized by the international roughness index (IRI) [1] and denoted as h(x), is expressed as a harmonic function as follows:

$$h_x = \sum_{i=1}^{N}\sqrt{3,26K_o\Delta n} \times \left(\frac{n_o}{n_i}\right) \times IRI \times \cos(2\pi i\Delta nx + \varphi_i) \quad (5)$$

Where:

x : horizontal coordinate variable

$N = \frac{L}{B}$: L (length of the surveyed road section); B (Wheel track width)

n_i : discrete spatial frequency

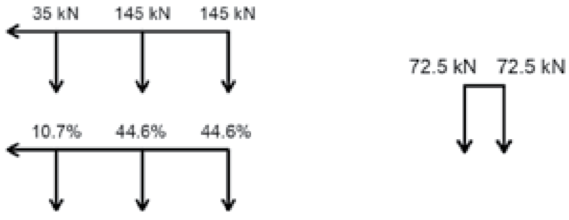
n_0 : reference frequency

Δn : distance magnitude corresponding to n_i

φi : random phase angle

Ko : 10^{-6} m^3.

The calculation of dynamic load is performed by considering both the weight of the vehicle and additional dynamic forces. Specifically, the static load of the entire vehicle is initially determined by the total load of the three axles, which in this case is 325 kN. The dynamic load Ft is then converted to the load on a single wheel using equation (6), in accordance with the finite element model. To determine the dynamic load, the load on the axle carrying the maximum load is used as the reference, and this value is subsequently evenly distributed between the two wheels of that axle.



a) Longitudinal direction *b) Transverse direction*

Figure 5. Properties of the Design Truck

$$Ft_{\text{wheel}} = \frac{44.6\% \times Ft}{2} \quad (6)$$

In which:

Ft_{wheel} : Là tải trọng động của một bánh xe

The dynamic load F(t) is calculated based on two main components: the self-weight of the vehicle and the additional dynamic force. It is expressed by the following formula:

$$F_t = F_d + P = k_t(z_u - h) + (m_s + m_u)g \quad (6)$$

Where: k_t: tire stiffness; H: function representing the road surface roughness (RSR) along the x-direction; Z_u: displacement of the unsprung mass; M_s: sprung mass; M_u: unsprung mass.

2.5. Finite Element Method

FEM (in Plaxis 2D) is applied to analyze the deformation of the soil cement columns in ground reinforcement under the influence of dynamic models and design live loads. The input data are presented in Table 1. The Mohr-Coulomb model in Plaxis is employed to simulate the behavior of soil under dynamic loads.

3. RESULTS & DISCUSSION

3.1. Dynamíc load

From the equation (5), the function $H(x)$, Z_s and Z_u was derived and is presented in Figure 6 and Figure *7*.

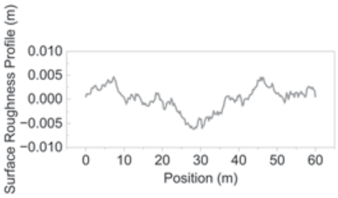


Figure 6. Road surface roughness profile, IRI = 2.0

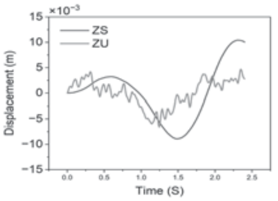


Figure 7. Simulation of vehicle oscillations, IRI = 2

Figure 6 illustrates the road surface roughness profile with respect to the horizontal axis position (m) and the surface roughness profile (m). The curve represents the variation in surface height over 60 meters, with an IRI of 2. For an IRI of 2, the height variation is only around 6 mm, which is relatively small, indicating a smooth surface with minimal irregularities.

Figure *7* displays the simulation of vehicle oscillations with respect to time (s) and displacement (m). The curves represent the displacements of the vehicle body Z_s and the wheel axle Z_u over a time span of 2.5 seconds. With an IRI of 2.0, the results highlight noticeable differences in oscillation patterns between the two components. Although the vehicle exhibits complex oscillations, the amplitude remains insignificant.

Figure 8 presents the dynamic load $F(t)$ over time (s). The curve illustrates the fluctuations of the dynamic load (kN) within the range of 72 to 76.3 kN, exceeding the static load threshold of 72.5 kN - representing the characteristic static load of an HL93 truck according to [21]. With an IRI of 2, the load varies significantly, reflecting the impact of road surface roughness on load intensity over a 2.5-second period. Compared to the static load, the dynamic load is higher by up to 5.3%.

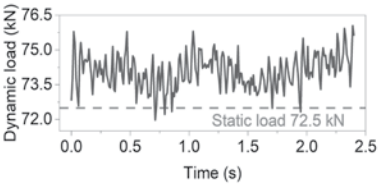


Figure 8. Dynamic load

3.2. Settlement analysis of soil-cement columns under AM and FEM.

Table 2. Displacement analysis results of SCCs under static and dynamic loads.

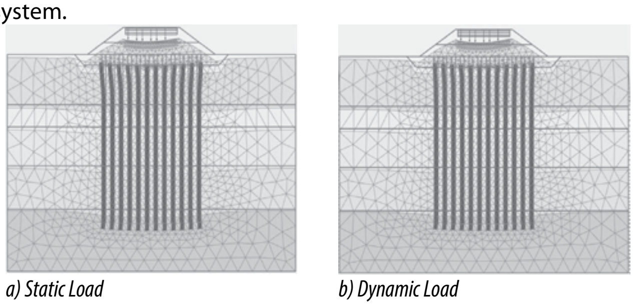
Analysis Method	Settlement (cm)
AM_SL (static load)	8.30
FEM_SL (static load)	9.80
FEM_DL (dyamic load)	12.03

Table 2 presents the settlement analysis of soil-cement columns (SCCs) under static loading, emphasizing the differences between the Analytical Method (AM) and the Finite Element Method (FEM). The AM predicts a settlement of 8.3 cm, whereas the FEM estimates a slightly higher value of 9.8 cm. This discrepancy suggests that the FEM is capable of capturing more complex soil-structure interactions that are typically simplified in analytical approaches.

The consistently higher settlement predicted by the FEM implies that this method provides a more conservative estimation, potentially offering greater alignment with actual field behavior. This indicates a possible safety advantage of using FEM over AM in practical applications. Overall, the observed differences underscore the significant influence of modeling techniques on prediction accuracy, making direct comparisons between AM and FEM challenging.

3.3. Settlement analysis of soil cement columns under static and dynamic loads

The displacement distribution of soil-cement columns based on FEM simulation under static and dynamic loads is presented in Figure 9. The results indicate that the maximum displacement is primarily concentrated in the central area, mainly due to the impact of embankment loads and vehicle traffic. Therefore, appropriate settlement compensation measures should be implemented in this region to ensure the stability and performance of the foundation system.



a) Static Load *b) Dynamic Load*

Figure 9. Displacement of the Soil cement columns Based on FEM

Table 2 also presents the displacement analysis results under static and dynamic loads, showing a significant difference in settlement. Under static loading, the soil-cement columns (SCCs) experience a settlement of 9.8 cm. However, under dynamic loading, the settlement increases substantially to 12.3 cm. This result emphasizes the considerable impact of dynamic loading on the deformation of the pile system, particularly under the influence of road surface roughness and design live loads

Compared to static loading, dynamic loading causes a settlement increase of approximately 25.5%, demonstrating the significant impact of dynamic loads on the settlement of the foundation system.

4. CONCLUSION

This study evaluates the deformation behavior of soil-cement columns under dynamic and static loads. The key conclusions are as follows:

(1) Dynamic loading significantly increases settlement compared to static loading, highlighting the importance of considering dynamic factors in ground reinforcement design.

(2) The FEM method provides safer design results, especially under static loading conditions, reflecting the real-world behavior of the system more accurately.

(3) Road surface roughness and dynamic loads must be carefully considered to ensure the effectiveness and durability of soil-cement columns.

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