A Case Study on the Young's Modulus of Stone Columns Built in Vietnam

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ABSTRACT

Young's modulus of the stone column is a fundamental parameter in nearly all studies and engineering applications. In addition to the stone properties and construction technology, the elastic modulus also depends on the surrounding soil at the site, necessitating a site-specific study of Young's modulus. The current study presents an investigation of a stone column in the Long Son Petrochemical Project, Vietnam, including a group load test in order to back-analyze the Young's modulus of the stone column. Four stone columns of 800 mm diameter and center-to-center spacing of 2200 mm were installed by Vibroflotation. A full-scale on-site test was carried out using a rectangular group of four stone columns. The properties of the stone were determined in accordance with the Vietnamese standard TCVN 7572. The settlement result of the group load test shows the Young's modulus of the stone column varied from 25 MPa to 40 MPa by back-analysis in the first trial and increased to 70 MPa in the second trial after improving the surrounding soil.

Keywords-stone column; Young's modulus; full-scale test; back-analysis

I. INTRODUCTION

The Young's modulus of the stone column has been extensively studied. In general, the Young's modulus depends on the stone properties, compaction energy, and the properties of the surrounding soil. Authors in [1] back-analyzed the settlements and determined Young's modulus (E_c) to be 72.5 MPa in composite surrounding soils, including sandy silt, clay silt, dense sand, silty sand, firm clay, and stiff clay. Authors in [2] back-analyzed the settlements measured in the preloading phase of large oil tank foundations in Panama, showing the perfect applicability of the homogenization method to a stone column improved ground when an average modulus ratio between the stone column and the surrounding soil of 8 was adopted. The Young's modulus of the stone columns is usually between 25 and 100 MPa, and it also varies with the confining pressure [3]. A number of studies on stone columns used Young's modulus values of 40 MPa, 50 MPa, and 55 MPa as the input data for their study, without indicating the source of the Young's modulus values [4-6]. On the other hand, authors in [7] calibrated their model to determine the Young's Modulus of the stone aggregates using Finite Element Analysis (FEA) and validated it against field measurements obtained from the load test results. Similarly, authors in [8] determined the Young's modulus of crushed stone from the load–load-displacement behavior observed during the unloading phase of a plate load test.

The present paper presents a back-analysis of the Young's modulus of the stone columns on the Long Son Petrochemical project in Vietnam. The proposed back-analysis is suitable under the Vietnamese conditions. Due to the difficulty in reaching the desired vibration pressure of 300 bar required for soil improvement, the study was divided into two trials: Trial 1, where the spacing was kept at 2.2 m and the vibration pressure reached 275 bar, and Trial 2, where the vibration pressure exceeded 300 bar with the same center spacing as the first trial.

The study location, borehole layout, and the typical soil profile are similar to our previous work [10]. The soil profile was prepared in accordance with ASTM D 2487 [9]. The first layer of the soil profile consists of fill soil (SM, SC-SM, SC), clayey sand, silty sand, silty clayey sand, medium dense with Standard Penetration Test (SPT) value *N* over 10 blows; thus, the SPT value (*N*) of 10 blows was used for the calculations performed in the present study. The second layer is filled with silty sand, silty clayey sand, and plastic clayey sand, with SPT *N* being 11 blows. The bottom-most layer is made up of Granite rock, moderately to slightly weathered, hard, and is assumed to be an uncompressible layer. PBH denotes the borehole logs, while PERT refers to the soil resistivity test.

II. SITE WORKS AND PLATE LOAD TEST

Depending on the soil conditions, numerous techniques are available for the stone column construction. One of the most commonly used is the Vibroflotation technique, which utilizes a vibrator poker known as the Vibroflot, as shown in Figure 1. Vibro-displacement stone columns involve the use of a Vibroflot, which comprises a hydraulic or electric-powered eccentric weight assembly enclosed in a heavy tubular steel casing. The typical setup for installing stone columns using vibro-displacement is depicted in Figure 1. A crawler crane or an excavator with a power pack for the Vibroflot is utilized to lift the latter together with the stone hopper and follow-tube. The Vibroflot is suspended from the crawler crane or excavator, whichever is suitable for this project. The nose of the Vibroflot is tapered to aid the penetration of the ground, whilst the vertical fins prevent the Vibroflot from rotating during penetration. Compressed air is used to assist the penetration of the Vibroflot to reach the desired depth. The vibration pressure is reached and kept over 300 bar for the hydraulic motor. The as-built stone column diameter varies with the technique and the soil condition. Generally, the weaker the soil is, the larger is the diameter of the stone column. The stone column installation is terminated when one of the following three criteria is satisfied:

- When the stone column length has reached the specified design length.
- When hard soil is encountered.
- During vibro-displacement by the bottom feed method: vibration pressure reaches 400 bar for the hydraulic motor.
- For vibration hammer with steel pipe: less than 30 cm of penetration is achieved per min.
- When rock is encountered, and no further penetration is possible.

Fig. 1. Dry bottom feed stone column operation at the Long Son Petrochemical Project.

The trial work is typically performed to verify the design prior to commencing with the mass work. In this study, four test stone columns with center-to-center distances of 2.2 m were installed at the site. The diameter of the stone column was chosen based on the construction method and the diameter of the Vibroflot machine. For Vibroflot dimensions of 590 mm × 620 mm, the stone column is typically expanded to a diameter of about 800 mm through vibration. The spacing of the stone column is normally two to three times its diameter [11]. Therefore, the 2.2 m spacing is reasonable in the first trial.

The length of the stone column depends on the soil profile, and in this study, it was approximated to 7500 mm. The approximation was based on the presence of granite rock in 3 layers, which extended to a depth of 9.2 m. The bottom of the stone column was accordingly assumed to be at approximately 9.2 m depth, with the top located around 1.7 m, as portrayed in Figure 2. A load test was carried out on the group of stone columns to verify whether the improved ground meets the design criteria. The layout of the four stone columns and the schematics of the load test are presented in Figures 3 and 4, respectively, while the material requirements are summarized in Table I.

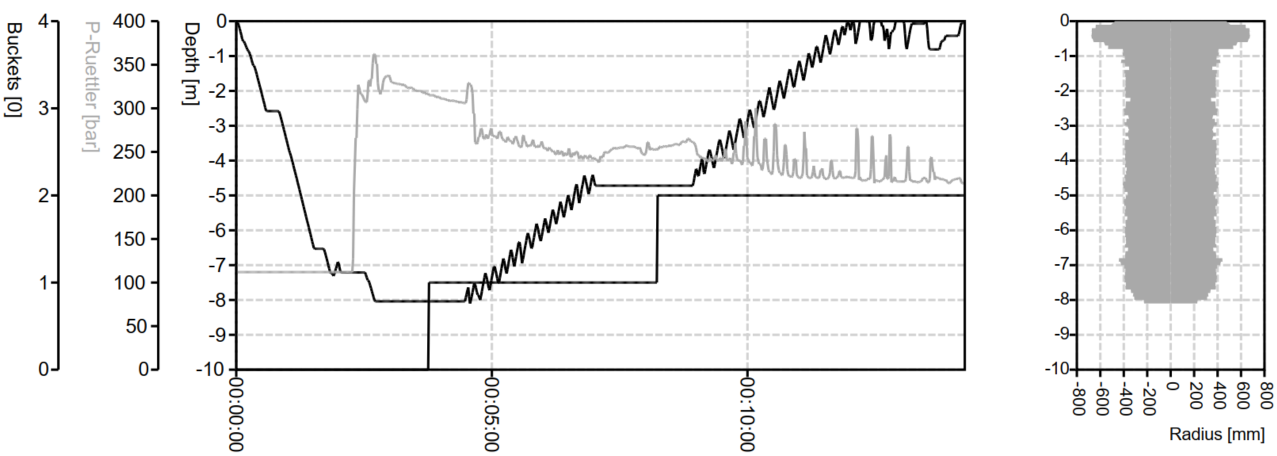

Fig. 2. Sample of recorded data for one stone column point with vibro-displacement using the bottom feed method.

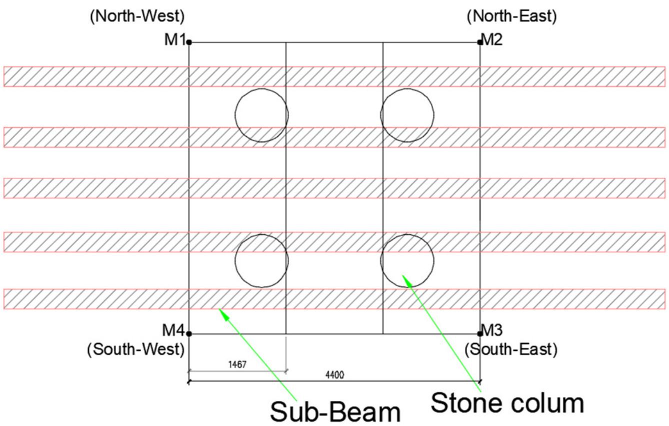

Fig. 3. Layout of trial stone columns.

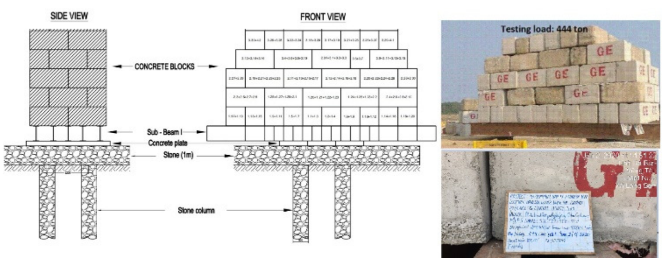

Fig. 4. Loading setup at the test site.

TABLE I. STONE MATERIAL REQUIREMENTS

Property	Standard	Requirements		Field value
Aggregate crushing value in the soaked condition	[13]	< 30%		11.6%
Resistance to degradation by abrasion and impact in the machine	[13]	≤ 40% at 500 rounds		25%
Elongation and flakiness index	[13]	< 30%		17.43%
Grain size	Sieve size	% Passing		
		Max	Min	
	50mm	100	100	100
	37.5mm	100	85	91
	25mm	55	25	27.47
	20mm	20	0	3.10
	14mm	0	0	0

A static load of 300 kPa was applied to a 4.4 m × 4.4 m × 0.2 m plate to measure the settlement of the ground after reinforcement. The counterweight system comprised 1 m × 1 m × 2 m concrete blocks, with the counterweight system placed on the concrete plate through the steel beams. The total weight applied was 5808 kN. The group load test was carried out in accordance with the settlement measurement process. The testing load step and load retention time are presented in Table II. The settlement of the concrete plate was recorded at the time intervals of 0, 60, 120, 240, and 4320 min (3 days).

The test was terminated when the test load reached the maximum. The load settlement curve from the test is shown in Figure 5 with M1, M2, M3, and M4 being the corners of the plate, as displayed in Figure 3. A total station was used to measure the settlement of four plate corners.

TABLE II. TESTING LOAD AND CORRESPONDING LOAD RETENTION TIME

Load step (% of testing load)	% of design load	Testing pressure, *q* (kPa)	Testing load	Time hold (day)
25	31.25	75.0	1452	3
50	62.50	150	2904	3
75	93.75	225	4356	3
100	125.0	300	5808	3

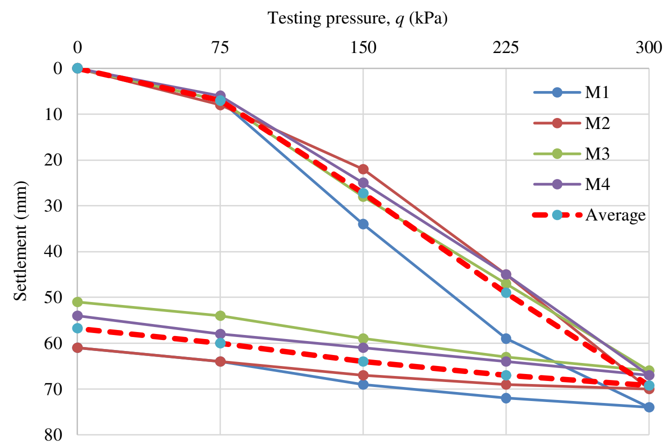

Fig. 5. Load–settlement curve from the plate load test, measuring the surface subsidence of the stone column group.

III. RESULTS AND DISCUSSION

A. *Back-Analysis of Young's Modulus of Stone Column*

With the applied load and settlement recorded during the plate load test, the estimated average elasticity modulus of the soil can be calculated using [14, 16]:

$$E = 0.93q(m.B')(1 - v^2).I_s.I_s/S_{e(rigid)} \quad (1)$$

where q is the applied pressure (kPa), m is the number of corners contributing to settlement. The value of m is taken as 4, 2, and 1, at the center, side, and corner of the footing, respectively. $B' = B/2$, which is half of the foundation width B, v is the Poisson ratio of the surrounding soil, I_S is the shape factor from [15], and $S_{e(rigid)}$ is the average settlement of a rigid footing. I_S is calculated using:

$$I_s = I_1 + \frac{1-2v}{1-v} I_2 \quad (2)$$

where I_1 and I_2 are Steinbrenner influence factors [14] taken from the equations in [12], which suggest that the settlement is reduced when the footing is placed at some depth in the ground, depending on the Poisson ratio v, D_f/B, and L/B. Here, L is the length of the footing and D_f is the depth of the footing.

The average Young's modulus of the soil reinforcement (combined surrounding soil and stone column) is calculated by [3]:

$$E_{ave} = aE_c + (1 - a)E_s \quad (3)$$

where *Ec* is the Young's modulus of the stone column, *a* is the stone column ratio, and *Es* is the Young's modulus of the surrounding soil [17]. The vibration techniques are ineffective in improving the soil density when the fine content exceeds 20% [18]. As a result, in this study, the Young's modulus (E_s) of silty sand and clayey sand was assumed to remain unchanged after the stone column installation.

Authors in [17] proposed an approach for increasing the coefficient of lateral earth pressure (K_0) to address the installation effect of the stone columns. The K_0 values of the soil strata were increased manually, beginning with $K_0 = 1$ and progressing to $K_0 = 2$.

Various formulas have been proposed to determine the Young's modulus of the surrounding soil (E_s) [14, 19]. However, authors in [19] presented a very simple and practical relationship for the sandy soil based on SPT value *N*:

$$E_s = N \quad (4)$$

For the clay soil, Young's modulus of the surrounding soil (E_s) can be calculated by [14]:

$$E_s = 3_{qc} \quad (5)$$

where q_c is the cone penetration resistance.

N was selected as the minimum recorded value at each borehole for a conservative estimation. If the *N* value in a borehole varies 12~16, *N*=12 would be used for the calculation. The above middle-low correlation of the E_s value was applied for a conservative estimation. Using recorded settlements (1) and (2), the average Young's modulus of combined soil and stone columns was computed and presented in Table III.

TABLE III. AVERAGE YOUNG'S MODULUS OF THE COMBINED SOIL AND STONE COLUMN IN LONG SON PROJECT

Test pressure *q* (kPa)	75	150	225	300
Calculated E_{max} (kPa)	38004	20730	15202	14252
Calculated E_{ave} (kPa)	32575	16891	13961	13219
Calculated E_{min} (kPa)	28503	13413	11595	12495

TABLE IV. YOUNG'S MODULUS FOR BOREHOLE PBH-04

Layer	**Thickness *h* (m)**	***N* value (blows)**	**Young's modulus *E* (MPa)**	**Stone column ratio *a***	**Average Young's modulus *E* (MPa)**
Stone layer	0.8		30	-	30
1	4.9	10	10	0.104	12.08
2	2.7	11	11	0.104	12.98
3	0	35	35	-	-
			Average *E*		14.07

The average stiffness of the surrounding soil was calculated using (4) and (5), which were applied to calculate the Young's modulus of the combined stone column and surrounding soil, and the results are illustrated in Table IV. The average Young's modulus of the stone column was 30 MPa, as presented in Table V. The average Young's modulus of the combined stone column and surrounding soil was 14.07 MPa. To account for a 10% variation in the Young's modulus of the surrounding soil, in the present study, the Young's modulus of the stone column was varied between 25 MPa and 40 MPa. The Young's modulus estimated in this study was slightly lower than the values reported in previous research.

TABLE V. YOUNG'S MODULUS FOR BOREHOLE PBH-04

Layer	**Thickness h (m)**	**N value (blows)**	**Young's modulus E (MPa)**	**Stone column ratio a**	**Average Young's modulus E (MPa)**
Stone layer	0.8		70	-	70
1	4.9	15	15.00	0.156	23.57
2	2.7	15	15.00	0.156	23.57
3	0	35	35	-	-
			Updated average E		27.99

B. *Stone Column Quality Improvement in the Second Phase*

To improve the quality of the stone column for mass work, additional stone columns were installed in the center. The layout of the additional stone columns is shown in Figure 6, where "O" represents the first trial stone columns and "×" denotes the second ones. The latter are distributed with the $2.2 \times \sqrt{2} = 3.11$ m spacing.

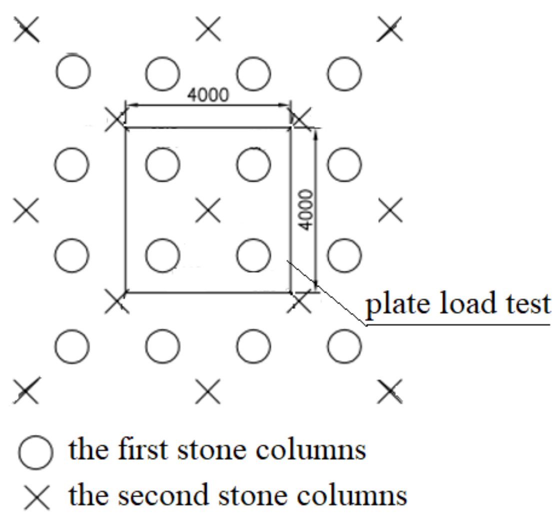

Fig. 6. Layout of additional stone columns.

The quality of the additional stone columns was improved by increasing the vibration pressure, as indicated by the P-Ruettler value shown in Figure 7. The upward P-Ruettler value increased from approximately 275 bar, as depicted in Figure 7(a), to 300 bar, as presented in Figure 7(b), while the downward P-Ruettler value increased from about 110 bar, as seen in Figure 7(a), to 275 bar, as displayed in Figure 7(b). This demonstrates that the soil condition improved in steps, first from the original state to the initial trial work, and then, a further improvement was observed during the second phase.

After the additional stone columns were constructed, the plate load test was carried out again to assess the improvement due to the combined first and second phase stone columns. The plate load test was adjusted to 4.0 m×4.0 m×0.2 m to represent the new Young's modulus ratio of 0.156, as portrayed in Figure 6. The settlement results are shown in Figure 8, with M1, M2, M3, and M4 representing corners of the plate. The second phase of the stone columns significantly reduced the settlement due to load compared to phase one, as depicted in Figure 5, demonstrating the effectiveness of the combined soil and stone columns.

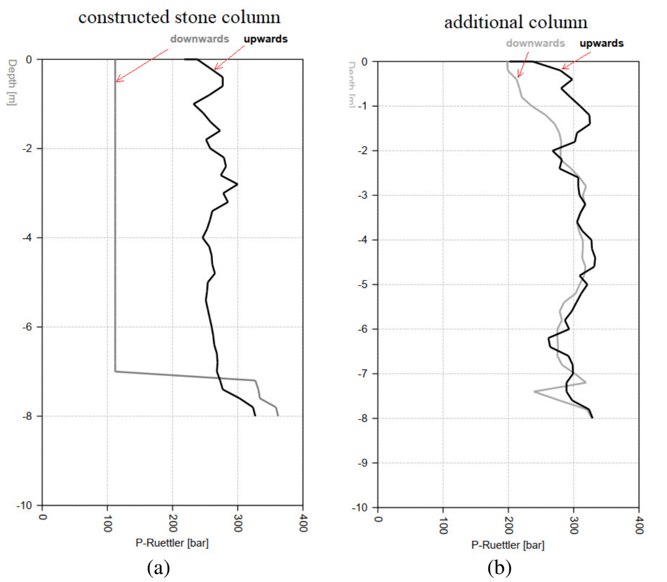

Fig. 7. Plot of the vibration pressure in two stone columns: (a) constructed stone column, (b) additional stone column.

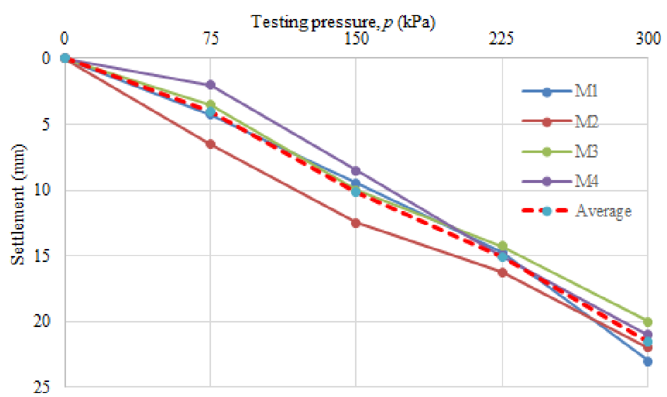

Fig. 8. Load–settlement curve from the plate load test, measuring the surface subsidence of the stone column group after additional stone columns.

The assumption of a middle-low correlation of *Es* for a conservative estimation in part III needs to be revised. The average *N* value for layer 1 was updated to 15 blows for filling soil in the second phase. The average Young's modulus of the stone column was updated to 70 MPa.

IV. CONCLUSION

In this study, a trial stone column and group load test were carried out for the Long Son Petrochemical Project, Vietnam. The construction procedure and the group load tests were conducted to assess and improve the stone column quality. The back-analysis method suggests that the Young's modulus of the stone column varies from 25 MPa to 40 MPa during the first stage of the stone column assessment. The Young's modulus of the stone column was found to be two to five times greater than that of the surrounding soil. However, the modulus ratio between the stone column and the surrounding soil was lower than that reported in previous studies, due to the surrounding soil, which in this study was medium dense, with the Standard Penetration Test (SPT) value of 10-11 blows, and the limitation of Vibroflotation capacity during the first trial phase.

If the Vibroflotation capacity is increased by raising the vibration pressure, the Young's modulus of the stone column can be increased to 70 MPa, corresponding to an improvement in the surrounding soil density to about 15 blows in the SPT.

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