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A Field Trial Study on Jet Grouting to Improve the Subsoil in Ho Chi Minh City, Vietnam

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Graphical abstract

A Grouting machine

Abstract

This study attempts to fabricate a single Jet Grouting system from used machines and the machines were modified by the authors. The assembled jet grouting system was fabricated to create soil cement mixing by high pressure beams at pressure up to 30 MPa of cement slurry or water plus cement slurry. The two soilcrete columns were created using the above Jet Grouting system at the bank of Nhieu Loc canal, Binh Thanh District, Ho Chi Minh City, Vietnam. The diameters of the soilcrete columns vary from 0.8-1.3 m at the top and larger 0.4 m at the bottom. The lengths of the columns were 12 m and 4 m for the column 1 and 2, respectively. Characteristics of a soilcrete column are appreciably dictated by operating parameters of a Jet Grouting system.

Keywords: Jet grouting; soil cement mixing; soilcrete; deep mixing method; groun

1.0 INTRODUCTION

Jet Grouting technology, a deep mixing method, is a technique improving the subsoil using high jet pressure beams of cement slurry or water plus air (20-60 MPa) to erode, to cut, and to mix the in-situ soil with cement slurry to create soil-cement mixing (soilcrete) columns [1], [2], [3], [4], [5], [15], [16]. Jet Grouting has various applications and advantages such as improvement of diversity soil types from gravel to clay [6], [7], work at limit spacing construction areas, and minimal disturbance effects to adjacent existing structures. Thus, Jet Grouting can be applied at big cities such as Ho Chi Minh City (HCMC) and Hanoi, Capital of Vietnam, which have high population and limit space for construction projects [2], [3], [7], [15], [16], [19], [20]. In addition, Jet Grouting can improve the subsoil and preserve the top soil surface. This application is very useful during construction of tunnels in downtown of the big cities. However, Jet Grouting technology remains little known in Vietnam and has limit applications. High investment of an imported Jet Grouting (around 0.5-1 million US dollars) is one of big hindrances for Vietnamese companies, and a Vietnam code, or specification, or standard to instruct how to apply Jet Grouting technology for ground improvement and reinforcement in detail has not been established yet [15], [16]. In other word, Jet Grouting needs to be further investigated in Vietnam to accumulate experience.

This study attempts to (1) assemble a Jet Grouting - single jet system - from secondhand Jet Grouting instruments modified and combined with domestic parts, and to (2) utilize the assembled Jet Grouting system to conduct a field experiment to create soilcrete columns in Binh Thanh district, HCMC. The assembled single Jet Grouting system was utilized to conduct several field experiments - creating soil cement columns or soilcrete columns at the field. Dimensions and characteristics of field trial soilcrete columns were key data to modify the Jet Grouting system to achieve quality of soilcrete properties for the HCMC's conditions [17, 18]. This investigation analyzed a soilcrete column created by the assembled single Jet Grouting in Ho Chi Minh City to modify operation parameters of the Jet Grouting system to achieve the designed soilcrete characteristics.

2.0 FIELD EXPERIMENTAL IMPLEMENTATING PROGRAM

2.1 Operating parameters of a single Jet Grouting system

A single Jet Grouting system can be used to improve the subsoil having the undrained unconsolidated shear strength, Su, up to 40 kPa, or Standard penetration test (SPT) of 15 (loose sand) or 5 (soft clay) or less [4], [8], [9]. This study is the first field trial to determine appropriate operating parameters of the assembled single Jet Grouting system to create required soilcrete properties in HCMC. Thus, thoughtful comprehension of current knowledge on Jet Grouting in literature is needed to generate primary guidelines how to operate the single Jet Grouting system relevantly.

In general, spoiled materials flows upward along the gap between a jetting rod and a borehole during jet grouting [15], [16]. The spoiled material is replaced by cement slurry and known as an in-situ soil replacement ratio which varies from 30 to 60% and is quite difficult to estimate [4], [5]. A water - cement ratio (w:c) is from 0.6 to 1.2 depending on the required cement content of soilcrete [1], [8], and for this first trial, a w:c of 1:1 was used. For conventional soil cement deep mixing methods, a typical w:c ratio is 0.7:1, that is, cement slurry is more condense than that of this study. In addition, the characteristics of a soilcrete column are influenced by several operating parameters of a single Jet Grouting system such as pressure of cement slurry beam(s), number of nozzles, diameter of a nozzle, rotation speed of a jetting rod, lifting/penetrating speed of a jetting rod, repeating eroding frequency. Table 1 presents a summary of a single jet grouting operating parameters.

Table 1 Summary of operating parameters of single Jet Grouting systems

Operating Parameters	Sources			
	[1]	*[8]*	*[10]*	*[5]*
Pressure (MPa)	30-50	30-55	20-40	20-40
Flow rate (l/min)	50-450	60-150	60-100	
Diameter of nozzle (mm)		1.8-3.0	2.8-3.2	1.2-3.0
Number of nozzles		2-6		
Rotating speed (rpm)		10-30	6-20	20
Lifting/penetrating speed (cm/min)		12.5-33	8-25	

Typical diameters of soilcrete columns created by a single Jet Grouting system are shown in Table 2. In principle, excavation of the top soil layer (≤ 3 m) to expose a soilcrete column head, and drilling cores taking samples for deeper parts of a soilcrete column are the two typical methods for field quality control

Table 2 Typical diameters of soilcrete column created by a single Jet Grouting system

Diameter (m)	[8]	[10]
Typical diameter		0.6 – 1.2
Non-cohesive soils	0.5 - 1	
Cohesive soils	0.4 - 0.8	

Unconfined compression strength (UCS), qu, of soilcrete created by a Jet Grouting system varies with soil types. qu of soilcrete created from cohesiveless soils and inorganic soils is higher than that of cohesive soils and organic soils, respectively [2], [6], [7]. The UCS test is employed to determined qu for soilcrete samples taken at the field, and Table 3 gives typical qu values of several soil types.

Table 3 Typical q_u (MPa) of soilcrete created by Jet Grouting

Soil type	Sources		
	[2]	*[6]*	*[7]*
Gravel	≥ 3	≤ 25	< 9
Sand		≤ 10	< 9
Silt	≥ 1	≤ 5	< 5.5
Clay			< 3.5
Organic soils			< 1.7

2.2 Research Site

The first field trial was conducted at a bank of Nhieu Loc Canal, Binh Thanh District, HCMC to compare with conventional soil cement deep mixing techniques applied to improve the subsoil here [17]. Figure 1 shows the location of the research site.

Figure 1 The location of the research site at Binh Thanh District, HCMC (Google maps)

Three soil layers distribute along a 18-m soil profile with 6-m loose sand at the top, 9-m very soft clay layer underneath, and 3-m soft clay layer at the bottom. The groundwater table locates at -2 m, and fluctuates with the tides of the Saigon River. The key soil parameters are given in Table 4. The first soilcrete column located at a distance of 1 m from a 3-m current concrete well. This setup validates effect of Jet Grouting to existing structures during construction.

Table 4 Key soil properties at the research site – Binh Thanh District, HCMC

Soil type		Loose sand	Very soft Silt clay	Soft clay
Soil classification		SP	CH	CH
Thickness (m)		6	9	3
Clay fraction (< 2 μm)		1%	76.4%	74.2%
g_w (kN/m^3)		18.8	14.6	14.8
w (%)		21.6	87.5	85.5
e		0.70	2.33	2.26
I_P			35.6	32.8
I_L			>1	>1
Friction angle (Degree)	Dry	32°30’		
	Saturated	26°20’		
UCS	q_u (kN/m^2)		28.1	29.8
	E (kN/m^2)		1162.8	1429
Direct Shear	*j* (Degree)		3°56’	3°44’
	C (kN/m^2)		5.7	6.1
SPT (blows)		7	3	4
Organic content (%)		1.1	7 - 8	7.6 - 8.2
pH		7.6	7.2 - 7.5	7.5 -7.6

2.3 An Assembled Single Jet Grouting System

A typical single Jet Grouting system is demonstrated in Figure 2. In general, a Jet Grouting system consists of fixed and movable components [15], [16]. The fixed components are a power supply, a water tank, cement supply, a cement slurry mixer, and a high jet pump. A grouting machine, a moving component, carries a jetting rod with nozzle(s) performing eroding and mixing the in-place soil creating soilcrete columns. The grouting machine operates movements of the jetting rod such as rotation, lifting, and penetrating.

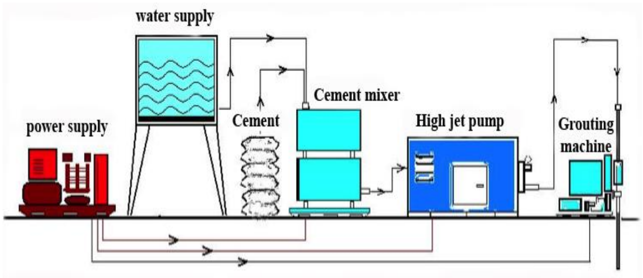


Figure 2 A typical Jet Grouting system [11]

In this study, a secondhand YBM SI-30S grouting machine was used with minor modifications carrying a jetting rod with 72-mm in diameter [17]. The jetting rod is fabricated from 2-m or 1.5-m sections. Two opposite 1.7-mm nozzles were attached at the near tip of the rod. Figure 3 is the grouting machine used for this investigation.

Figure 3 A YBM SI-30S grouting machine employed for this study

A used YBM triple piston high jet pump was modified to operate at a maximum pressure of 30 MPa (Figure 4).

Figure 4 A YBM secondhand high jet pump was modified by the authors

A cement slurry mixer system consists of 3 cylinders of 1.5 m in diameter and 1.1 m in height with motors for mixing that can produce continuously a cement slurry volume of 1800 liters, (Figure 5).

Figure 5 A cement slurry mixing system

A monitoring system - display and storage - operating parameters of the assembled single jet grouting system during jet grouting to create soilcrete columns. A Programmable Logic Controller (PLC) (Figure 6 right) processes signals transmitted from sensors such as a flowmeter and pressure transducers. Field data is stored in a built-in memory and displayed on a 7" touch screen (Figure 6 left).

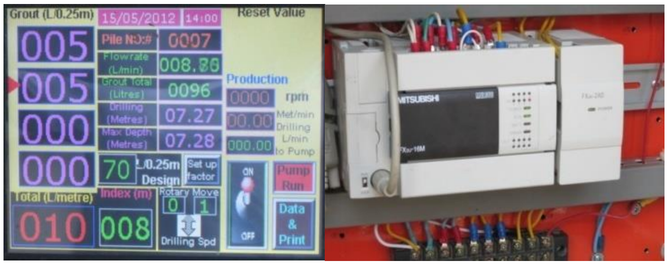


Figure 6 A touch screen displaying operating parameters during the Jet Grouting working

2.4 Testing Materials

A PCB40 cement type was used to mix with fresh clean water to form cement slurry for the Jet Grouting system. Important properties of the PCB40 cement are printed in Table 5.

Table 5 Important properties of PCB40 type

No.	Properties	Result
1	3-day cured compressive strength (MPa), ASTM C109	18.8
2	Normal consistency (%), ASTM C187	28.6
3	Time of setting (min), ASTM C191	140
4	Fineness (g/cm^2), ASTM C204	3470
5	Autoclave Expansion (%), ASTM C151	0.052
6	Density (g/cm^3), ASTM C188	3.09

2.5 Field Experiment Implementing Program

For this field experiment, a drill bit was attached at the tip of the jetting rod to cut and grind the in-place soil during penetrating process of the jetting rod. Low water pressure beams were applied to prevent jam of the nozzles during penetration to the expected depth (e.g., 18 m). At the expected depth, high pressure beams of cement slurry (e.g., 30 MPa) was replaced for the low pressure beams of water. The jet cement slurry beams cut, erode, and mix the in-place soil to form soilcrete columns by movements of the jetting rod (e.g., rotation, lifting, and penetrating). Repeating eroding frequency of the jetting rod was 5, that is, the jetting rod travelled up/downward for 5 times in each meter length of the soilcrete column. The procedure was repeated from the bottom (-18 m) to the top (-2 m) and terminated at a depth of 2 m from the ground surface.

■3.0 EXPERIMENTAL PROGRAM

The field trials were pilot experiments to establish practical guidelines how to apply Jet Grouting technology effectively in HCMC. All operating parameters of the assembled single Jet Grouting system were trial-and-error procedures at the field and modified after each trial.

3.1 Ratio of Water to Cement (w:c)

For convenience, the first trial w:c ratio was 1:1 (w:c = 0.6 - 1.2 in literature) for the assembled single Jet Grouting system [17]. Density of cement slurry with w:c = 1:1 determined in laboratory was 1504 kg/m3. Simply, the density of the 1:1 cement slurry was determined by mixing 1 kg cement with 1 litter water in the laboratory. A typical w:c applied for conventional soil cement deep mixing methods which use metal blades to agitate soil and mix with cement slurry is 0.7:1, which is higher viscous than that of slurry used in this study.

3.2 Laboratory Testing

Several soilcrete samples were made in laboratory to simulate field mixing conditions by an egg mixer. The soilcrete specimens were prepared with a soil replacement of 50%, that is, 50% volume of soil was replaced by 50% volume of cement slurry, equivalently a cement content of 376 kg/m3. Three soil types (loose sand, very soft silty clay, & soft clay) taken from three layers along the 18-m soil profile. The soilcrete specimens (55 mm in diameter and 120 mm in height) were cured by submerging in water to simulate soil layers under the water table. The UCS qu and secant modulus of elasticity, E50, results in the laboratory are displayed in Figure 7 and Figure 8, respectively.

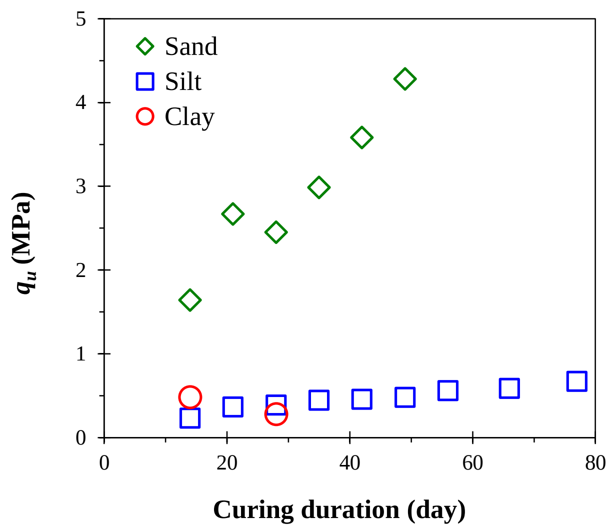


Figure 7 UCS of the soilcrete specimens in laboratory

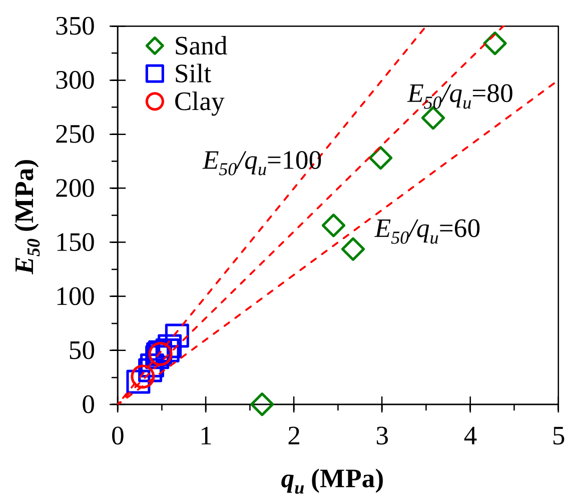


Figure 8 E_{50} versus q_u of the soilcrete specimens in laboratory

3.3 Field Testing

Operating parameters of the assembled single Jet Grouting system were first selected in literature and modified after each field trial. The operating parameters for this study are presented in Table 6.

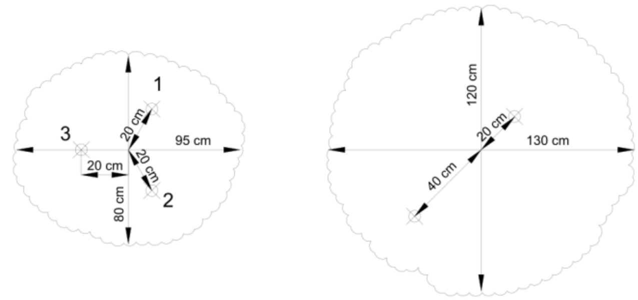
Table 6 The operating parameters of the assembled single jet grouting system used for the field trials in binh thanh district

Operating Parameters	Trial Column No. 1		Trial Column No. 2	
	Initial	*Field*	*Initial*	*Field*
Jet pressure (MPa)	30	27	30	24
Rod rotation (rpm)	10	10	6	6
Rod lifting/penetrating, (cm/min)	33	33/66	20	22/28
Repeating eroding frequency (times)	5	5	5	5
Constructing time (min)	227	200	375	310

Excavation to expose the top part of a soilcrete column for the 3-m top soil and drilling cores in radial directions taking samples varying with depth for deeper parts of a soilcrete column are the two typical methods for the field quality control after field construction about 5-7 days. Figure 9 shows the shape of the first trial soilcrete column after 7 days constructed at a depth of 3 m. The diameter of the soilcrete column was 0.8-1 m.

Figure 9 0.8 m diameter of the trial soilcrete column No. 1 excavated after 7-day construction

The deeper parts of the first trial soilcrete column were drilled to take soilcrete samples and to verify whether the soilcrete is formed or not in deep and in radial. The three boreholes were drilled along 18-m soilcrete length and arranged at 0.2 m in the radial directions (Figure 10a). The drilling results indicate that the soilcrete column was not successfully formed at depth from 14 to 18 m. In other words, the first soilcrete column has a minimum diameter of 0.4 m and a length of 14 m.



(a) Trial No. 1 (b) Trial No. 2

Figure 10 Core sampling locations of the trial soilcrete columns

The second trial soilcrete column was constructed with the modified operating parameters (Table 6) based on the first trial. A diameter of 1.2-1.3 m (excavation) and a length of 7 m of the second soilcrete column (drilling) was formed (Figure 10b). Core samples were all broken after taking at the field at 2-day construction for the both boreholes (0.2 m and 0.4 m in radial directions), but the broken soil cement samples indicate the soilcrete column was created up to 7 m deep in a minimum radius of 0.8 m.

The UCS, q_u, of the 54-day cured soilcrete samples of the first trial column varying with depth is plotted in Figure 11. qu varying from 1.8 to 16.5 MPa is quite higher than that of soilcrete created by conventional cement deep mixing methods (CDM) (e.g., 0.5 MPa).

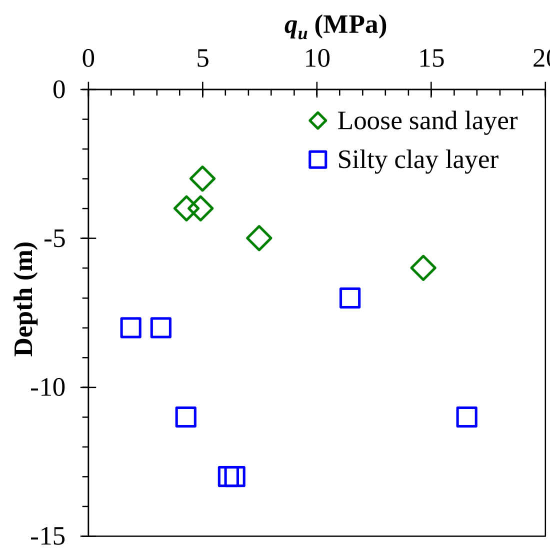


Figure 11 q_u of the core samples varying with the depth of the trial soilcrete column No. 1 at 54-day curing duration

4.0 DISCUSSION

The two trial 18-m soilcrete columns were completely constructed using the assembled single Jet Grouting system at the research site. The operating parameters of the Jet Grouting were initially designed and adjusted after each trial. Excavation to expose soilcrete columns at a depth up to 3 m, and core drilling taking soilcrete samples for parts of soilcrete columns deeper 3 m were utilized for field quality control.

4.1 Performance of the Assembled Jet Grouting System

The single Jet system fabricated by the authors was first tested having several troubles such as the pump broken and nozzles jammed. These problems caused delay of construction process. The nozzles jammed may be due to the minimum diameter (1.7 mm) of a typical nozzle used [5], [8], [10], [12], [13]. The Jet Grouting system worked properly at a pressure of 28-30 MPa, which is the maximum pressure of the system.

Eroding energy per unit length, Ep, can be determined using (1). Eroding energy along the soilcrete length of the two columns is exhibited in Figure 12. It can be seen that the average eroding energy of the column 2 is higher that of the column 1. This result explains why the diameter of the column 2 is larger than that of the column 1. The lower speed of the jetting rod, rotation and lifting speed (Table 6), generated the higher erosion of the subsoil.

$$E_p = \frac{P.Q}{v} = P.Q.t \qquad (1)$$

where E_p - Eroding energy (MJ/m), P - jetting pressure (MPa), Q - flow rate (m^3/min), v - rod lifting/penetrating speed (m/min), t - constructing time (min).

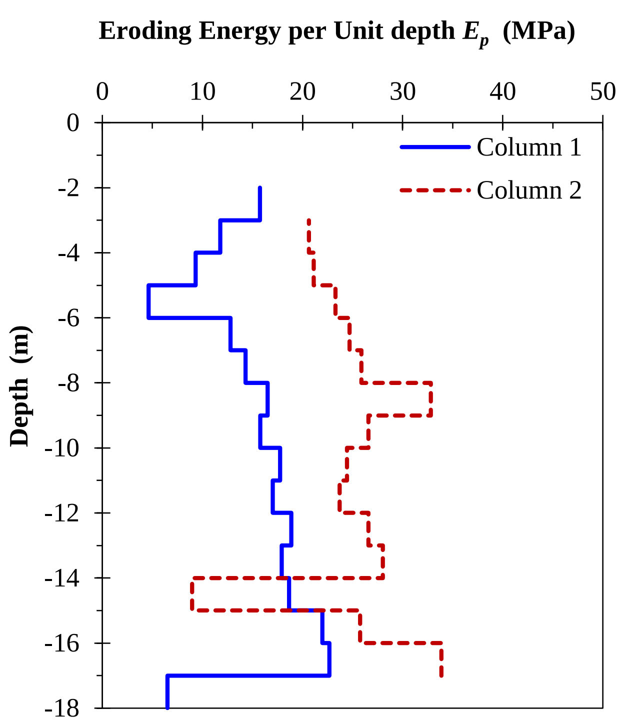


Figure 12 Eroding energy E_p of the trial soilcrete columns with depth

Various surface cracks appeared in a radius of 2 m around the center of the columns during performing jet grouting at a depth of 5 m to the ground surface [18]. Few cement slurry was spoiled throught the cracks. This phenomenon is probably caused by no spacing between the borehole and the jetting rod, and spoiled material has no way to escape to reduce pressure surrounding the nozzles [5], [8], [12].

4.2 Dimensions of the Trial Soilcrete Columns

The soilcrete columns were successfully formed in the loose sand layer from -2 m to -6 m with diameters of 0.8-1 m and 1.2-1.3 m for the column 1 and 2, respectively (Figure 9). The soilcrete diameters are also typical diameters for a single jet grouting system (1 m [8], 1.2 m [6], 1.2 m [12]). The increase diameter of the column 2 (about 30%) is due to increasing in eroding energy generated by decreasing in speed of the jetting rod [4], [13].

However, the soilcrete columns were not uniformly formed or no soilcrete found in the clay layer for the both trials. There were no soilcrete at depth of -14 ÷ -18 m and -7 ÷ 18 m for the column 1 and 2, respectively. The field observation during jetting at the clay layer showed that no spoiled materials were escaped from the boreholes. As a result, the pressure in the spacing surrounding the nozzles was high and diminished capacity of the in-place soil erosion of the Jet Grouting system. Soil cement mixing product could not be formed as expected [5], [8], [12]. Dimensions of a soilcrete column are strongly influenced by operating parameters of a Jet Grouting system, and a diameter of a soilcrete column can be flexibly created. This is a great advantage of the Jet Grouting technology.

4.3 Stress-Strain Behaviour

Figure 9 shows the analysis graph in longitudinal and lateral direction for concrete core. From Figure 9, it can be observed that high-strength concrete with SSTT-type confinement able to provide more ductility and sustain higher ultimate strain than the plain control high-strength concrete columns. The compressive strength for control specimens dropped tremendously right after reaching the ultimate compressive capacity.

On the other hand, as to have a logical comparison solely on the lateral pre-tensioning stresses applied by both techniques, an equalised effective mechanical volumetric ratio of 0.10 of confinement was implemented. The analysis correlates that the specimen with lower lateral pre-tensioning stress (SSTT(HC)) sustains higher ultimate compressive strength enhancement than those confined with higher lateral pre-tensioning stress (SSTT(SS)), however it exhibits low initial (85% of post-ultimate compressive strength) ductile behaviour with a steeper slope decrement after the ultimate capacity. The low lateral pre-tensioning stress needs greater lateral dilation exerted from high-strength concrete to optimally mobilize the pre-tensioned confining materials. The confining materials were only then effectively activated when the high-strength concrete deformed to adequate lateral dilation. This phenomenon can be observed with high longitudinal and lateral strains sustained at 50% of post-ultimate compressive strength for SSTT(HC) confined specimens. In the safety aspect, confinement with higher lateral pre-tensioning stress is more appropriate due to the slow rate of strength losses beyond the ultimate, although it exhibits lower ultimate performance.

4.4 Properties of the Trial Soilcrete Columns

The q_u of sand is higher than those of clay and keep increasing with curing time even after curing 28 days in the laboratory (Fig.ure 7). The laboratory q_u are also higher than those of soilcrete created by conventional CDM. The result indicates that cement content of the soilcrete is higher than the CDM and the mixing process is more uniform in the laboratory than in the field for the CDM [1], [6], [14]. q_u of sand at 28 days was 2.5 MPa close to the experiment result of the Japan Jet Grouting Association (JJGA) (3 MPa), but q_u of clay at 77 days was less than 1 MPa. The low q_u of clay may be high organic content (7%-8.2%) causing low reaction of cement to clay [14]. The secant modulus E_{50} of the soilcrete varies from (60-100).qu which is in a typical range of E_{50} (Figure 8).

q_u of soilcrete samples taken from the soilcrete column 1 varies form 1.8 – 16.5 MPa with a mean value of 5 MPa (Figure 11). These results are typical values published in [2], [4], [8]. The soilcrete quality of the column 2 was good by visual observation because all samples were totally damaged. The soilcrete should have high strength due to the soilcrete stiff enough to resist the tip of the sampling tubes at distances of 0.2 & 0.4 m in the radial directions (Figure 10b).

■5.0 CONCLUSIONS

This study performed the two field trials to create the two soilcrete columns using the assembled single Jet Grouting system at the Nhieu Loc Canal bank, Binh Thanh District, HCMC. The diameters of the soilcrete columns vary from 0.8 - 1.3 m at the top and were not less than 0.4 m. Soilcrete was successfully formed in the loose sand layer, but not uniform or no soilcrete in the clay layer. The qu of the soilcrete samples taken at the field is remarkably higher than typical qu of soilcrete samples made by the conventional CDM. This first field experiment provides the following conclusions:

(1) An single Jet Grouting system assembled by the authors utilizing used machines having similar functions can be employed to improve the subsoil in HCMC, and the authors will keep modifying the system via next field experiments in HCMC.

(2) Diameter of soilcrete columns created by the above Jet Grouting system can be freely adjusted, whereas a diameter of a CDM method is fixed due to a fixed diameter of metal blades.

(3) Soilcrete properties are strongly affected by operating parameters of a Jet Grouting system.

(4) Boreholes need to be constructed and maintained by bentonite slurry before jetting and a borehole should have a bigger diameter than a diameter of a jetting rod. The spacing between a borehole and a jetting rod allows spoiled materials moving upward freely to reduce environment pressure surrounding nozzles.

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