Vibrocompaction proposed design guideline for practicing engineers

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ABSTRACT

Vibrocompaction is one of the suitable methods to improve liquefiable sand layer. Due to the relatively young age of this technology in Asia, not many engineers are familiar with vibrocompaction design techniques. This paper aims to provide design guidelines for practicing engineers on vibrocompaction. The paper covers the vibrocompaction working principles, its different types, its applicability to soil types, as well as its design and execution methods. Two case studies are presented. The first case study was the application of vibroflotation to compact reclaimed sand up to 17 m thick in Batam, an island nearby Singapore. The reclamation process caused the upper 3 m of sand above the seawater level reached dense condition inducing difficulty for the vibroflot to penetrate and densifying the loose sand below it. The solution to overcome this difficulty is discussed in this paper. The second case study was the densification of 12m thick loose silty fine sand in East Borneo to prevent differential settlement of a 44 m diameter oil tank to be constructed on the site. On this site, a problem was encountered during backfilling, the backfill material could not flow out of the probe. The solution to this problem, and other problems encountered during execution of the project are presented. Conclusions and recommendations drawn from the case studies are presented.

Keywords: vibrocompaction; vibrofloatation; compozer; liquefaction; design guideline; case history

1 INTRODUCTION

One of the many geotechnical problems in Indonesia is combination of its high seismicity and existence of saturated loose fine sandy soils in many of its coastal region which leads to high liquefaction potential. To mitigate this liquefaction potential, the saturated lose fine sandy soils generally densified by dynamic compaction or vibro-compaction techniques. A design guideline on dynamic compaction for practicing engineers has been presented in the SEAGS and AGSSEA journal (Gouw, 2018). This paper presents the vibrocompaction technique, starting from design, execution, monitoring, and evaluation of the improvement results. Difficulties encountered in execution are also presented through case studies.

2 VIBROCOMPACTION

Vibrocompaction is primarily developed to densify sandy soils, above and below water table, through the insertion of a vibrating probe (Fig. 1), up to the level it can withstand the upper structure with only shallow foundation. This purpose is achieved by increasing bearing capacity, reducing compressibility, and in earthquake prone area mitigating liquefaction potential, of the subsoils. To achieve this objective, in saturated loose sand, the vibration must be fast and intense enough to induce excess pore water pressure to create local liquefaction so as to ease the insertion of the probe into the target improvement depth. Repeated partial extraction and re-insertion of the probe concurrent with the dissipation of created excess pressure will result in the densification of the sandy ground (Fig. 2). In unsaturated condition, the vibratory probe must be strong enough to overcome the soil initial shear strength so that the sand particles can slide one another to a denser state. Whenever necessary water jetting may be used to help the penetration.

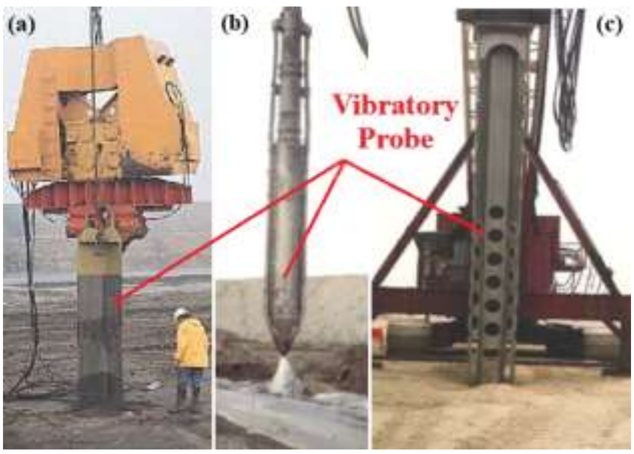

Fig. 1. Vibrocompaction vibratory probe types

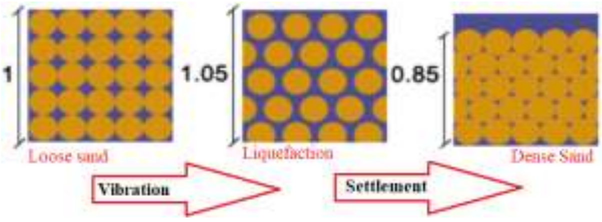

Fig. 2. Densification of loose sand through local liquefaction

Depending on the gradation of the sandy soil, in both cases, well graded and compactible granular backfill material may necessarily be added. Vibration cannot compact cohesive soils, therefore, in cohesive soils the annular space created around the vibratory probe is backfilled with either sand or gravel, to create sand compaction piles or stone column. The clay and the sand piles or stone columns form a composite material with lower compressibility and higher bearing capacity.

2.1 Types and Execution of Vibro-compaction

Based on the vibrator types, vibrocompaction is differentiated into top mounted vertical vibrator (Figs. 1a and 1c) which induced vertical vibration and radial vibrator or vibroflot which induced radial (Fig. 1b). For top mounted vibrator, no water jet is used, therefore, it is known as dry process. The probe can be a close or an open-end pipe, I profile, a rod with horizontal wings or double Y shape probe with holes along it (Fig. 3). It does not remove any in situ soil, instead it pushes the soil sideways and downward to reach its target depth, therefore, it is known as vibro-displacement. Upon reaching the target depth, the probe is repeatedly vibrated up and down at a 30-50cm distance to compact the sandy soils around the tip of the probe. The vibrator amperage is used to control the degree of compaction achieved. The higher the amperage, the denser the sand. Once the compaction is deemed adequate, the probe is withdrawn by 50-80cm, and then the compaction process is repeated until full compaction up to the ground level is achieved. This displacement process is suitable for cohesionless soil that can be compacted without adding backfill material. For cohesive soils, a hollow probe is required to introduce granular backfill material into the ground to form sand compaction piles or stone columns (Fig. 4). This method was first applied in Japan and known as compozer method (Murayama and Ichimoto, 1982).

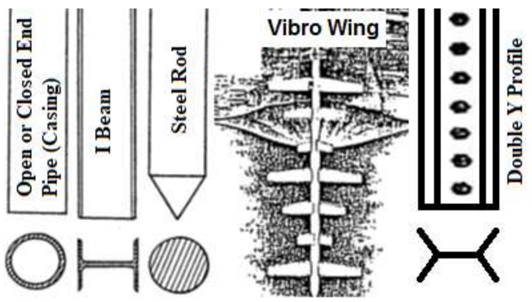

Fig. 3. Top mounted vertical vibrator probe types

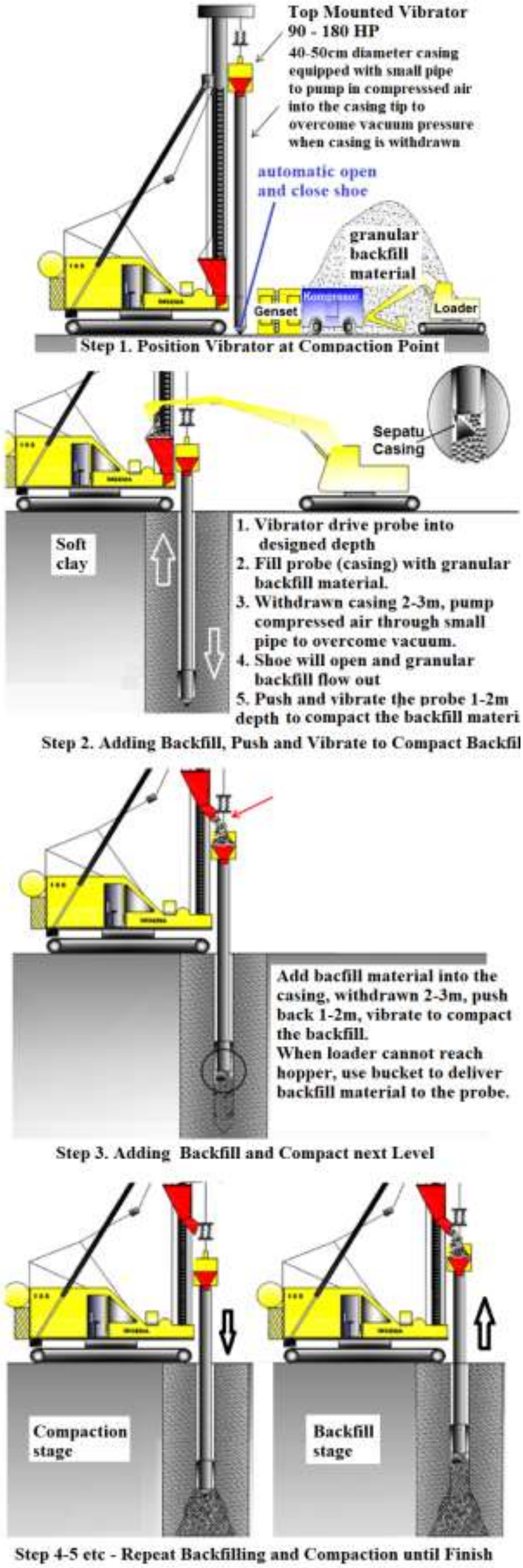

Fig. 4. Vibro-compozer method

Another vibrator commonly used in vibro-compaction is vibroflot. In this case, the vibrator is attached at the tip of the probe as shown in Figure 5. The assembly consists of three main parts, i.e.: the vibrating head or the vibroflot which is a 300-500mm diameter and 2.0-4.5m long tube with a total mass of around 20kN; insulator which isolate the extension tube from the vibroflot vibration; and extension tubes or follower to extend the vibroflot to achieve a greater depth. The radial (horizontal) vibration is induced by the rotation of eccentric mass around its longitudinal axes. The resulting centrifugal force can reach 300 kN or more.

Unlike the top mounted vibrator where the vibration force reduces with depth, since the vibroflot itself is inserted into the ground, the induced vibration force against depth is more uniform, resulting in a uniform compaction. The vibroflot is equipped with water jets system at its tip and at its top. To bottom water jets helps the penetration of the vibroflot to the required depth. The top jets help maintaining the created hole and giving a chance to pour in backfill into the created annular space. Figure 6 shows the compaction process and the formation of stone column by vibroflot. Since water is used in the process, this method is called as wet process vibro-compaction, and also known as vibrofloatation method. This technique can be applied to both cohesionless and cohesive soil, granular backfill material is added to create sand compaction piles or stone columns. Since original soil is removed and replaced with backfill material it is also termed as vibro-replacement method. This method requires a lot of water in its process, hence, it cannot be applied where water is not abundantly available. To overcome this limitation, a newer vibroflot is created with annular space made available at the center of the probe through which the backfill material can be fed into (Figure 7). This technique is known as vibrocat (Keller, 2013).

2.2 Design of Vibro-compaction

Brown, 1977, gave a criterion on the suitability of vibro-compaction based on grain size distribution curve of the soil to be improved (Figure 8). To determine the suitability number, S_n, of the backfill material, a formula is given in Eq. (1), D_{50}, D_{60}, and D_{100} is effective diameter at a certain percentage of passing.

$$S_n = 1.7\sqrt{\frac{3}{(D_{50})^2} + \frac{1}{(D_{20})^2} + \frac{1}{(D_{10})^2}} \qquad (1)$$

Table 1. Suitability number of backfill material (Brown, 1977)

S_n	Rating
0-10	Excellent
10-20	Good
20-30	Moderate
30-50	Bad
> 50	Not Suitable

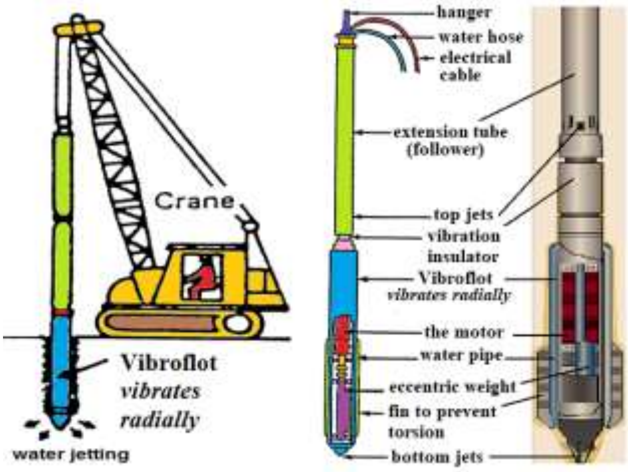

Fig. 5. The vibroflot

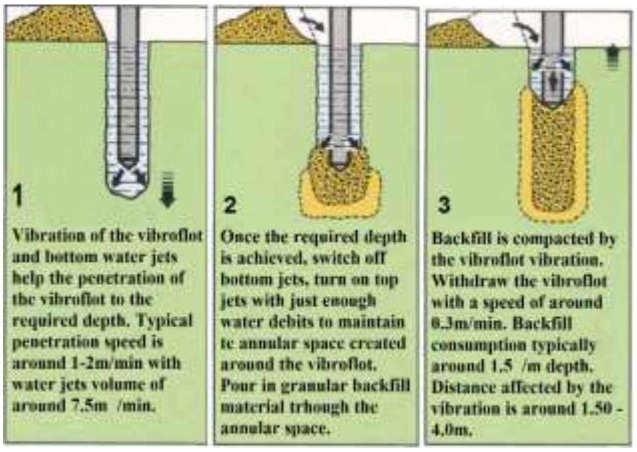

Fig. 6. Vibroflot – stone column formation

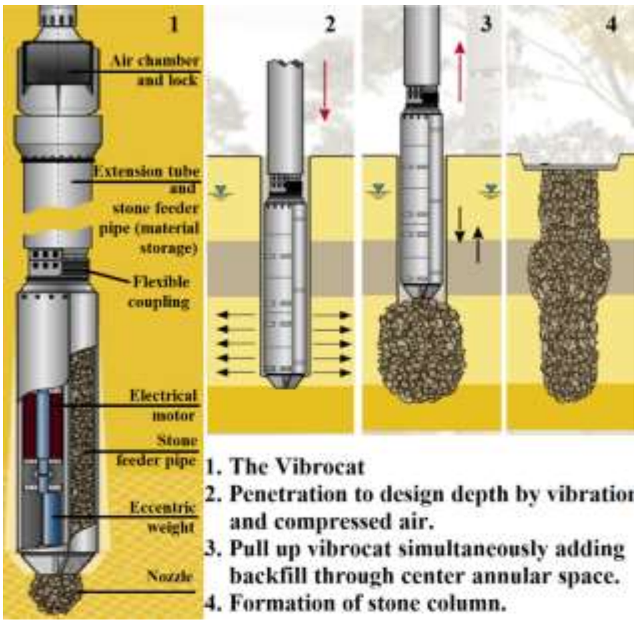

Fig. 7. Vibrocat (after Keller, 2013)

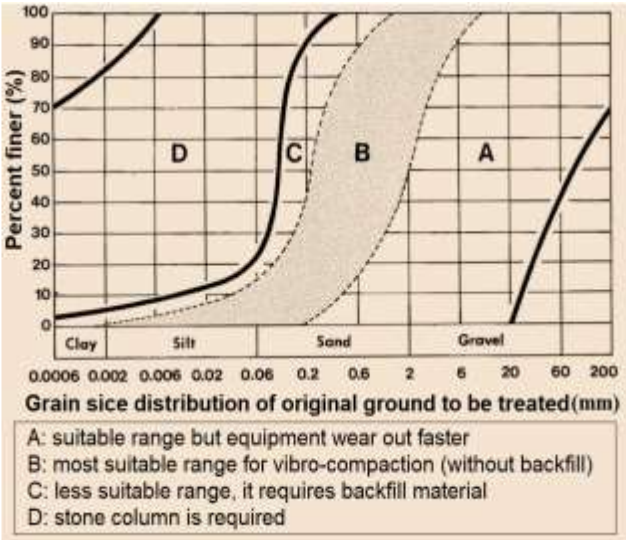

Fig. 8. Suitability of Vibro-compaction (Brown, 1977)

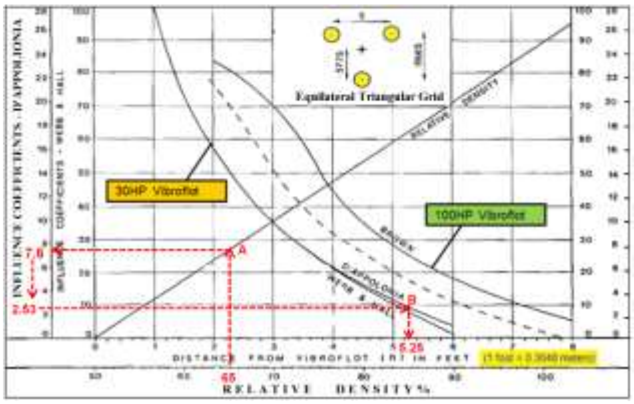

Fig. 9. Spacing of Vibro-compaction Points (Brown, 1977)

D'Appolonia and Brown chart (Glover J.C, 1982) presented in Figure 9 can be used to estimate the spacing of vibro-compaction points. Application example:

- vibro-compaction points: equilateral triangular spacing
- target relative density to be achieved, D_r=65%.
- 30 HP vibroflot
- at x axis from D_r = 65% draw a perpendicular line upward until it reaches the diagonal "relative density" line as indicated by point A in Fig. 9.
- draw a horizontal line from point A to the left toward the vertical axis.
- D'Appolonia influence coefficient is for 30HP vibroflot. Read the influence value, in this case, I = 7.6
- For triangular spacing, divide the influence coefficient by 3, 7.6/3 = 2.53
- Draw a horizontal line from D'Appolonia I = 2.53 until it cross D'Appolonia curve at point B. Draw a vertical line down from point B, and R = 5.25ft is obtained. R is the centroid of influence of the compaction points.
- The spacing of the vibro-compaction point is then calculated as: S=R/0.577=5.25/0.577= 9.1ft = 2.75m.
- If square spacing is used, then I is divided by 4, 7.6/4 = 1.90; from I=1.90 draw horizontal line to D'Appolonia curve followed by vertical curve downward→R=5.6.
- The spacing of the compaction points: S=5.6/0.7071=7.92 ft = 2.41m.
- For 100HP vibroflot, used D'Appolonia influence coefficient and Brown's curve. For the same Dr=65%, the value of I=7.6 → I/3=2.53; from I=2.53 draw horizontal line to Brown's curve, then vertical down, R=7.25 is obtained; S=R/0.577=12.6ft=3.84m.

Figure 10 can also be used to estimate the vibro-compaction points (Mitchell and Katti, 1981). Example: Vibroflotation with a target of D_r = 65%, D/d = 6.8 is obtained; if the column diameter is 50cm, then center to center square spacing is D = 6.8 x 0.5 = 3.4m.

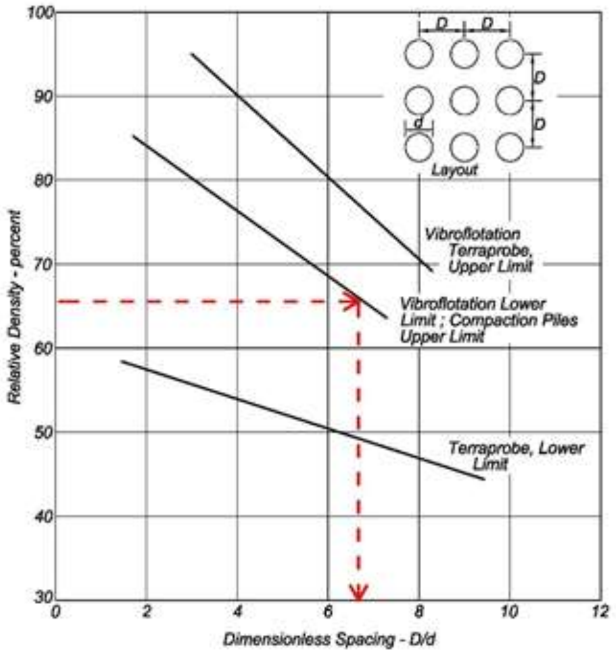

Fig. 10. Vibro-compaction spacing (Mitchell and Katti, 1981)

To determine the relative density, D_r, value through SPT blowcounts, Skempton (1986) formulas presented in Eqs. (2) and (3) can be used.

$$(N_1)_{60} / D_r^2 = 60 \quad (2)$$

$$N = \frac{(N_1)_{60}}{\alpha \cdot \beta \cdot \gamma \cdot \left(\frac{Er}{60}\right) \cdot \sqrt{\frac{100}{\sigma'_{vo}(\text{in kPa})}}} \quad (3)$$

Table 2. SPT correction factors, α, β, γ (Skempton 1986)

Rod length	> 10 m	α	1.00
	6 - 10 m		0.95
	4 - 6 m		0.85
	3 - 4 m		0.75
SPT without lineer		β	1.00
SPT with liner			1.25
Bore hole Diameter	65 - 115 mm	γ	1.00
	150 mm		1.05
	200 mm		1.15

Table 3. SPT effective energy ratio, Er (Skempton, 1986)

Country	Drop System	Hammer	Er (%)
Japan	Automatic	Donut	78
Japan	R&P - 2 turns	Donut	65
UK	Automatic	Donut	60
UK	R&P - 1 turn	Sleeve	60
UK	R&P - 2 turns	Sleeve	50
PRC	Automatic	Donut	60
PRC	R&P - 2 turns	Donut	55
USA	R&P - 2 turns	Safety	50
USA	R&P - 2 turns	Donut	45

Note: R&P refers to rope and pulley

where $(N_1)_{60}$ is SPT blowcounts at effective overburden pressure σ'_{vo}=100kPa and effective SPT energy ratio, Er = 60%; N is field SPT N value; α, β, γ, are the rod length, liner and borehole diameter correction factors of the SPT (Table 2); Er is the effective energy ratio of the SPT (Table 3). Example: for D_r=65%, $(N_1)_{60}=60D_r^2$ = $60\text{x}0.65^2$=5, from this $(N_1)_{60}$=25 the target field SPT blowcounts, N, can be calculated through Eq. (3).

Degree of improvement achieved by vibro-compaction method depends on the existence of fines content. (Figure 11, Mitchell and Katti, 1981).

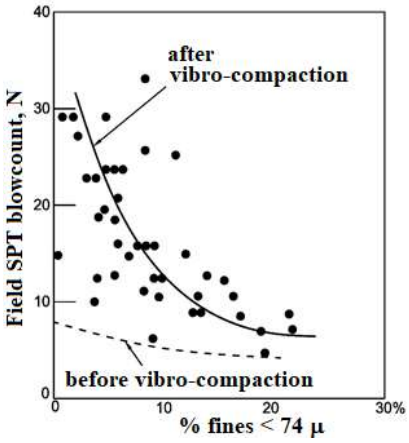

Fig. 11. Degree of improvement (Mitchell and Katti, 1981)

2.3 Design of Stone Column

As cohesive soils cannot be compacted by vibration, granular backfill material need to be added to form composite materials, consist of original ground and stone columns formation. Bearing capacity of a stone column (SC) depends on the shear strength of the compacted granular material and the passive resistance of the surrounding soils.

$$q_{sc\_ult} = \sigma_h' \tan^2(45^o+\phi_{sc}'/2) \tag{4}$$

$$\sigma_h' = k_p\,(\sigma_v'+q) \tag{5}$$

where q_{sc_ult} = ultimate bearing capacity of SC; σ_h' = passive resistance of the surrounding soil, including load effect; ϕ_{sc}' = SC internal friction angle = 35^o~40^o; k_p=passive earth pressure coef.= $(1+\sin\phi_c')/(1-\sin\phi_c')$; ϕ_c' = friction angle of existing clay; σ_v' = effective overburden pressure of existing clay; q = uniform load on the ground surface. Figure 12 shows the working mechanism of the stone columns and their interaction with the existing surrounding soil.

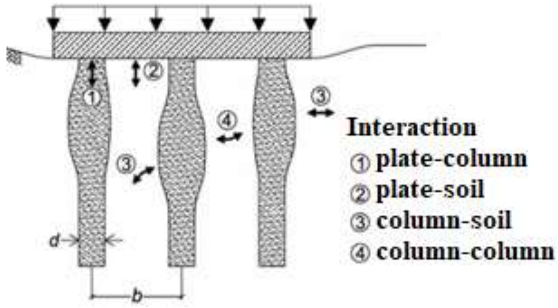

Fig. 12. Stone column work mechanism (Kirsch & Kirsch, 2010)

If SC bulging failure and the surrounding clay fail at the same time, SC bearing capacity is estimated from the clay undrained shear strength, c_u, as in Eq. (6).

$$q_{sc\text{-}ult} = 25\ c_u \tag{6}$$

The bearing capacity of the surrounding clay, $q_{c\text{-}ult}$, can be calculated by Eq. (7).

$$q_{c\text{-}ult} = 5.14\ c_u \tag{7}$$

With a factor of safety, FS=3, A_{sc} = SC sectional area, A_c = clay area, the overall bearing capacity of SC formation, q_{all}, becomes:

$$q_{all} = 0.33\,(q_{sc\text{-}ult}\,A_{sc} + q_{c\text{-}ult}\,A_c) / (A_{sc}+A_c) \tag{8}$$

Group average settlement of SC formation, S_{ave}, can be estimated from Eqs. (9) to (12) or from Figure 13.

$$S_{ave} = \mu\ q\ H / E_c \tag{9}$$

$$\mu = 1/[1+(n-1)a_r] \tag{10}$$

$$a_r = A_c / (A_{sc}+A_c) \tag{11}$$

$$n = q_{sc\text{-}ult} / q_{c\text{-}ult} \tag{12}$$

where μ = correction factor, q = working load, H = improved depth, E_c = clay stiffness, a_r = area ratio, n = stress concentration ratio.

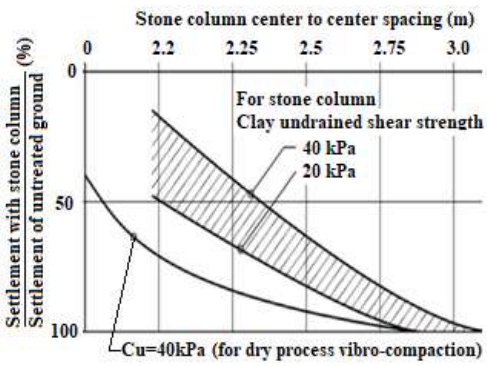

Fig. 13. Stone column settlement (Kirsch & Kirsch, 2010)

Example of calculation:

- Say 10m of clay to be treated, the undrained shear strength, c_u = 40kPa, effective friction angle, ϕ_c=25°, unit weight, γ=16kN/m^3, ground water table at the surface of clay, with existing 1m working platform. Planned SC diameter 60cm. It is for tank foundation of 50m diameter with total load of q = 100kPa.
- k_p = (1 + sin 25°) / (1 - sin 25°) = 2.46
- average $\sigma_v{}'$ = (16-10) x10 / 2 = 30 kPa
- Eq. (5), σ_h' = 2.46 x (30+100) = 319.8 kPa
- Eq. (4), $q_{sc\text{-}ult}$ = 319.8 x tan^2(45+40/2) = 1470 kPa
- Eq. (6), $q_{sc\text{-}ult}$ = 25 x c_u = 25 x 40 = 1000 kPa
- Take the lower value, $q_{sc\text{-}ult}$ = 1000 kPa
- Eq. (7), $q_{c\text{-}ult}$ = 5.14 x 40 = 205.6 kPa
- Note the influence diameter of the SC, D_c, is:
  - For a square grid spacing S, D_c = 1.05 S
  - For a triangular equilateral S, D_c = 1.13 S
- Try center to center square grid spacing of S = 1.8 m
- Influence area of a SC,
  A_{sc} +A_c = 0.25 π (1.13x1.8)^2 = 3.250 m^2
- A_{sc} = 0.25 π 0.6^2 = 0.283 m^2
- A_c = 3.249 – 0.283 = 2.967 m^2
- Eq. (8), q_{all} = 0.33(1000x0.283 + 205.6x2.967)/3.250
  = 105 kPa ≥ (load q = 100 kPa →ok!)
- The estimated settlement is:
  Eq. (12), n = 1000 / 205.6 = 4.86
  Eq. (11), a_r = A_c /(A_s+A_c) = 2.967 / 3.250 = 0.91
  Eq. (10), μ = 1/[1+(4.86-1)x0.91] = 0.22, about similar value if read from Fig. 13, μ = 0.20
  if E_c = 5000 kPa, and improved depth H = 10m,
  S_{ave} = 0.22 x 100 x10 / 5000 =0.044 m = 44 mm.

3 CASE STUDIES

3.1 Vibrofloatation Case Study

The project was a reclaimed land located in Batam island, Indonesia. The sea bed was first dredged to remove the soft marine clay that overlain stiff clay layer. It was then hydraulically filled with sand up to a level of 3 m above the mean sea level. The thickness of the sand fill varied from 4 to 17 m. The upper 3m has a CPT cone resistance, q_c = 5-20 MPa, and from 3-18m depth, q_c = 2-5 MPa. It had to be compacted up to relative density of 65%. Figure 14 shows the grain size distribution of the reclaimed sand. It can be seen the grading is located inside the most suitable range as defined in Fig. 8, therefore, vibroflotation was adopted. 113 HP vibroflot with centrifugal force of 400 kN was used, and a 4m and 2.83m square grid pattern were tried out. Despite its high power, the jetting could not create annular space to fill in backfill material (Fig. 15) as no upper jets was made available and the jetting pump capacity was only 900 liter/min. Very little surface settlement was seen. Comparison of pre and post treatment CPT showed very poor results, practically no improvement was obtained when compacting at 4m square grid, and only 11m depth improvement was achieved when 2.83m grid was tried

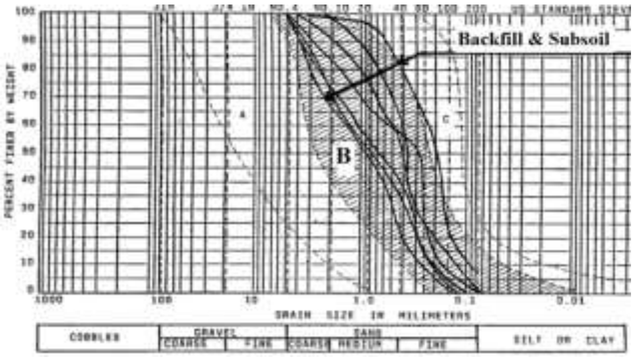

Fig. 14. Grain Size distribution of original ground–Batam project

Fig. 15. Only bottom jets available – no annular space created

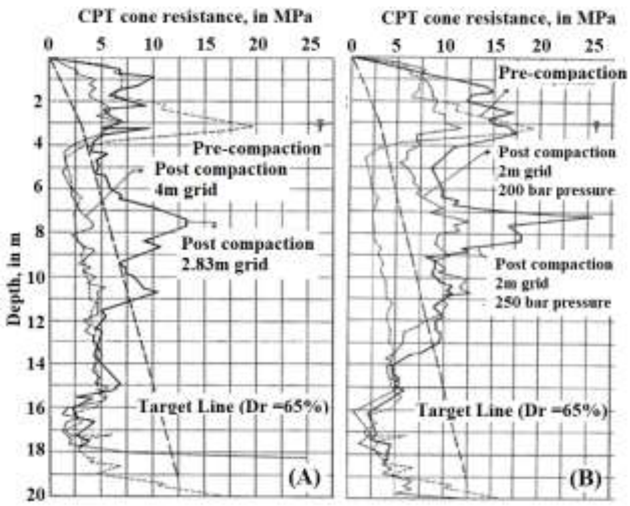

Fig. 16. Pre and Post Compaction CPT

Fig. 17. Field made upper jets was too small

(Fig. 16a). The upper jets were then made available, pump capacity was increased to 1500 l/min, and a grid spacing of 2m was adopted, the compaction could then achieve 13m depth, however, it was still not successful to reach the 18m depth target (Fig.16b). The reason was the field made upper jets was not adequate, it too small (Fig.17), no full length of annular space was created, therefore, backfill added cannot reach full depth.

3.2 Top Mounted Vibrocompaction Case Study

A 44 m diameter oil tank was to be built on a 12 m depth loose silty fine sand at Balikpapan oil refinery. The CPT cone resistance was within 1.5-3.5 MPa. Figure 18 shows the grain size distribution of the subsoil and the backfill material to be added. Dry process vibrocompaction with top mounted vibrator was adopted. The contractor tried to save time by pouring 5-6m^3 backfill material in a one-step feeding method into the hopper and casing (Fig. 19). It was failed, all the material jammed at the mouth of the casing and could not flow out into the ground. Water was added in order to liquify the jamming sand at the casing shoe, the sand compaction piles was successfully constructed. However, heavy backfill and water load causing equipment damages. Finally, after resolving into step by step feeding method (Figs. 20 and 21), the job can be executed smoothly and successfully.

3 CONCLUDING REMARK

This paper is intended as a guideline for practicing engineers on the design and execution of vibro-compaction and stone column. The case studies showed the importance of using proper equipment and proper execution method in order to have a successful execution of the ground improvement work. The authors realized that the write up may not be complete let alone perfect, feedback from readers are most welcome.

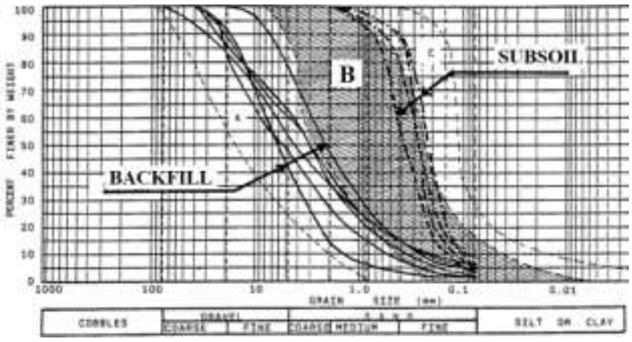

Fig. 18. Grading of subsoil and backfill – Balikpapan project

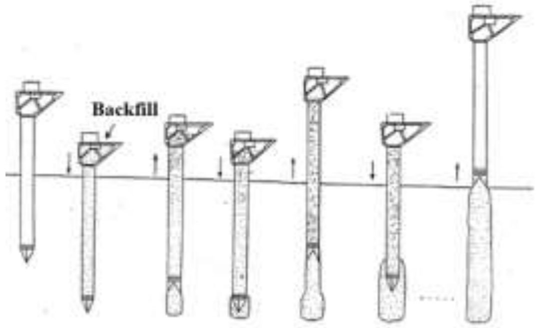

Fig. 19. One step feeding (backfilling) method

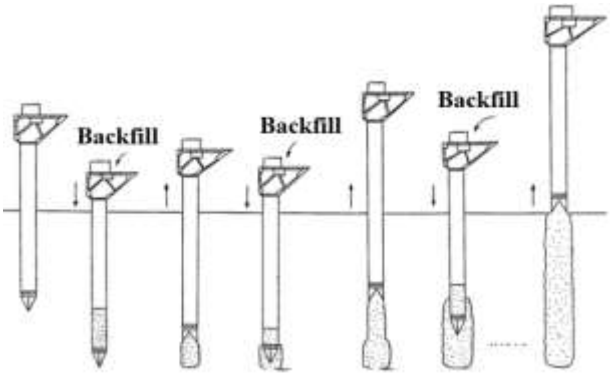

Fig. 20. Step by step feeding (backfilling) method


Fig. 21. Step by step feeding – conventional execution

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