Post treatment evaluation of ground improvement using vibro compaction

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ABSTRACT

Vibro Compaction (VC) is a widely adopted ground improvement technique to densify loose sand fill, to improve bearing capacity and reduce settlement. Depending on the design purpose, the specification to be achieved in vibro compacted sand layer varies. Normally, the required specification is expressed in terms of a tip resistance (q_c) specification from cone penetration test (CPT) carried out in the treated area after vibro compaction works. Sometimes, a relative density can be specified. Very often, the testing location is chosen conservatively at the zone of least compacted based on the distance from the VC points. This paper presents a comparative study of the actual performance of vibro compacted ground from some projects where post treatment testing location was chosen at the weakest point and at the representative zone. The cone resistance specification to be achieved, results of cone penetration test before (pre CPT) and after (post CPT) VC works, VC spacing adopted and long-term settlement monitoring data from these projects will be presented and discussed. A general guideline on choosing post CPT locations is recommended.

Keywords: ground improvement, vibro compaction; cone penetration test; CPT; testing location; evaluation; actual performance.

1 INTRODUCTION

Land reclamation works have been vital to geographical, social and economic development of Singapore to meet the demands of its ever-rising population. Ever since the early reclamation works in the 1820s, Singapore's land area has increased by about 25% from 578 to 719 sq.km (Tan et al. 2010).

During the 1980s, locally available sand sources were depleted. To meet the rising demand, imported sand is being brought from neighboring countries through Long Distance Sand Supply (LDSS) projects. Even amidst increased demand, sand continues to be a predominant material used in land reclamation works. During the reclamation works, sand is brought in bulk carriers and deposited by activities such as direct dumping, hydraulic filling (rainbowing) and sand spreading (Bo and Choa 2004). Sand thus placed is loose and need to be densified before it is competent to support superstructures or satisfy stability requirement.

2 VIBRO COMPACTION

Vibro Compaction (VC) is a widely adopted ground improvement technique to densify loose to medium dense sand, improve bearing capacity and reduce settlement. This process employs a depth vibrator inserted into target depths of sand layer by self-weight. The sand is compacted bottom-up aided by down and side water jets (Fig. 1). Vibro compaction works are carried out in various grid spacing normally from 2.0 to 4.5m in triangular or square arrangement. The specification to be achieved, the sand property before treatment and the vibrator type decide the grid spacing to be adopted.

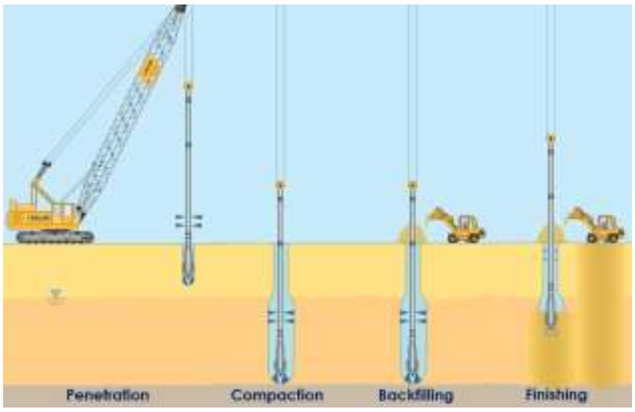

Fig. 1. Vibro compaction process

3 SPECIFICATION AND TESTING LOCATIONS

Depending on the design purpose, such as types of structures to be supported and the bearing pressure on the ground, the specification to be achieved for vibro compacted sand varies. Normally, the required specification is stipulated in terms of a tip resistance (q_c) specification from cone penetration test (CPT) carried out in the treated sand after vibro compaction works, and sometimes a relative density of typically 70 – 80%, is specified. A sample of a vibro compaction specification based on tip resistance and relative density is shown in Fig. 2. Relative density can be correlated to cone resistance using established correlations. The equation by Baldi (1986) as shown in Eq. (1) is widely adopted.

$$q_c = C_0\,(\sigma')^{C_1}\,.\,exp^{\,(C_2\,.\,D_r)} \tag{1}$$

where q_c = tip resistance in kPa; Dr = relative density in %; σ' = effective overburden pressure in kPa and C_0, C_1, C_2 are constants.

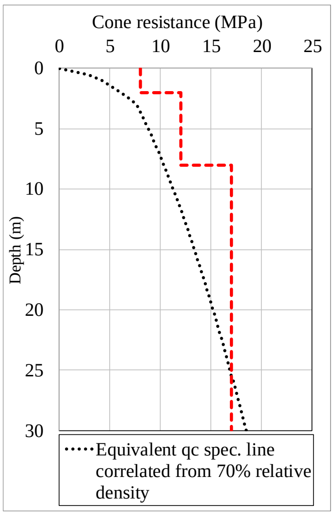

Fig. 2. Typical specification for vibro compaction works

Once VC works are completed, post CPTs are carried out to test the vibro compacted sand block to verify whether required specification has been achieved. Very often, the location of post CPTs is chosen conservatively at centroid of three VC points in case of a triangular spacing and at centre of four VC points for a square spacing. These locations represent the zone of least compacted based on distance from the VC points (Fig. 3).

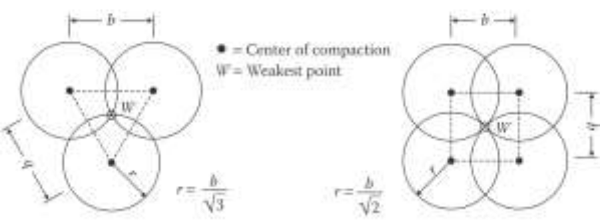

Fig. 3. Location of post CPTs after vibro compaction (from Kirsch and Kirsch 2017).

He et al. (2016) suggested that testing at a representative zone in the vibro compacted ground is more reasonable rather than at the weakest point which may be too conservative and underestimate the actual performance of vibro compacted sand block. This may reduce over densification effort (too close spacing for VC grid) and make the project more cost effective and time saving. Hence testing location of post CPTs is crucial in evaluating the performance of vibro compacted ground.

3 CASE HISTORIES

To illustrate, two case histories are presented in following sections. The verification of acceptance of vibro compaction works using post CPTs and actual performance measured in terms of long term settlement monitoring will be described.

3.1 Case history A - Vibro Compaction for a chemical plant

This case history presents the application of vibro compaction, to improve loose reclaimed sands, for a chemical plant in Jurong Island, Singapore in 2017. Structures supported on vibro compacted ground consists of operation building, substation and utility tank farm. The application of vibro compaction at operations building is described in following paragraphs.

The operation building is founded on a raft with dimension of 60 x 57m. The allowable settlement is 50mm under an average unfactored ground pressure of 70 kPa. Before vibro compaction, PreCPTs were carried out to determine the soil conditions. Loose sandy soils, which required to be densified, was found up to 20m depths underlain by residual clayey and silty soils of Jurong Formation. Based on given loading and settlement criteria, the required design cone resistance (q_c) line to be achieved after vibro compaction is shown in Fig. 4.

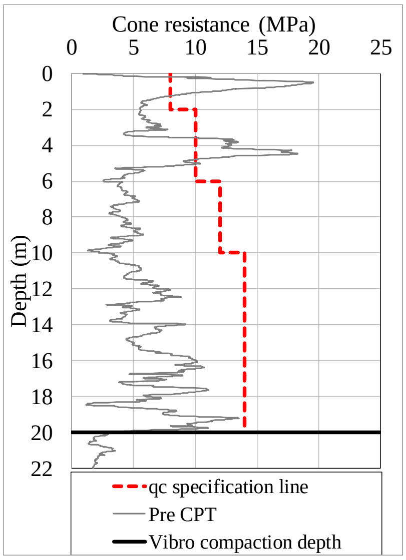

Fig. 4. Typical Pre CPT before vibro compaction and qc specification line

Vibro compaction works were carried out, at triangular grid spacing of 3.0m using Keller depth vibrator, S300, which produces a centrifugal force of 300kN. The quality assurance during vibro compaction works was done with aid of an in-house fabricated “real-time” monitoring M4 system, which records the instantaneous electric current consumption of vibrator and depth of compaction in the ground. The compaction process at every vibro compaction point is documented by a printout, generated at the end of compaction process, which serves as the quality record.

After vibro compaction, post CPTs were carried out in pairs – post CPT A, at centroid of triangular grid and post CPT B at mid-point of two vibro compaction points as shown in Fig. 5 which were chosen by the owner’s representative. The weighted average of a typical pair of Post CPTs is shown in Fig. 6. The settlement performance of the triangular grid, and hence treated ground is calculated by using weighted average of pair of Post CPTs as shown in Fig. 6 and the results are found satisfactory.

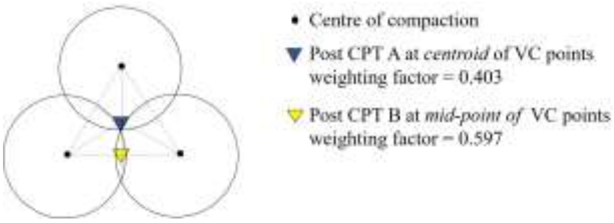

Fig. 5. Locations of post CPTs after vibro compaction

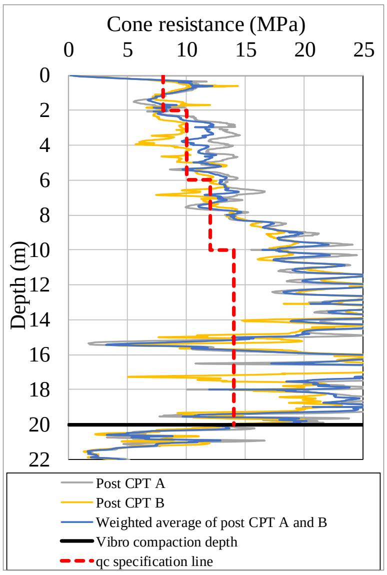

Fig. 6. Typical Post CPTs and weighted average after vibro compaction

Vibro compaction works were completed in February 2017. To monitor the performance of raft founded on vibro compacted ground, settlement markers were installed after casting of raft was completed in Aug 2017. The settlements were monitored once a month during the construction of upper structures and the average settlement till October 2018 is shown in Fig. 7.

The monitoring results showed that raft settlements are increasing through the construction phase, reaching about 16mm after 14 months when most of the load has been imposed on the vibro compacted ground. The stabilized trend of settlements is clearly shown. The final settlements are quite close to the predicted values. It indicates that the weighted average of post CPTs is representative of the overall performance of the improved sand block.

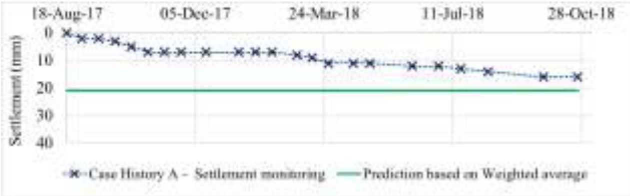

Fig. 7. Settlement monitoring results during construction

3.2 Case history B - Vibro Compaction for a rubber plant

Vibro compaction was used as a ground improvement technique to improve loose reclaimed sands to support shallow foundations of factory-type structure at a rubber plant facility in Jurong Island, Singapore in 2010. The soil conditions consisted of 19 – 23m loose reclaimed sand, followed by a thin layer of marine clay up to 2m thick underlain by firm to hard sandy clay stratum which is residual soils of Jurong Formation. The application of vibro compaction below the finishing building is described below.

The finishing building is supported on raft foundation of 62 x 46m in size. For an average raft base pressure of 107 kPa under the footprint, the allowable settlement is 50mm. To satisfy this allowable settlement, the required qc specification after vibro compaction in sand layer is chosen and shown in Fig. 8. Since the intensity of compaction required was high, vibro compaction using triangular spacing of 3.2m was used to compact the ground. The vibrator used here, S700, can produce a centrifugal force of 700 kN.

After vibro compaction, post CPTs were carried out at centroid of three vibro compaction points within a triangular grid chosen by owner’s representative. Two typical post CPTs after vibro compaction are shown in Fig. 9. Due to intermittent silt lenses, post CPT cone resistance line was marginally lower than the required specification line. However, based on post CPT q_c, the settlement was estimated to be less than the allowable 50mm. Hence the performance of vibro compacted ground was satisfactory based on ground settlement evaluation and not solely by checking with the cone resistance specification line.

To monitor the actual field performance, settlement markers were installed after completion of raft construction in June 2011. The settlements were monitored till June 2012, and also from February 2016 to 2018 as shown in Fig. 10. The average total settlement measured is about 32mm which is well within the allowable settlement of 50 mm.

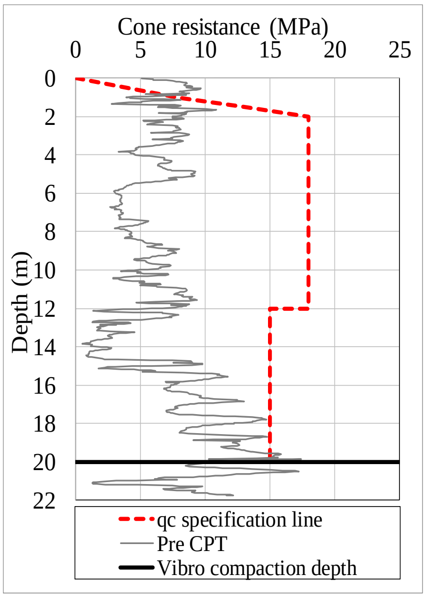

Fig. 8. Typical Pre CPT before vibro compaction and required qc specification line

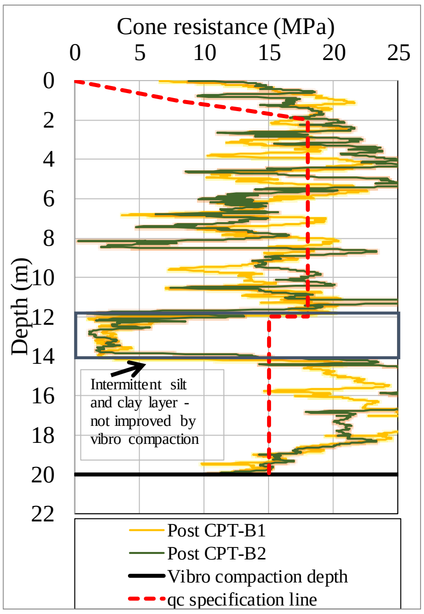

Fig. 9. Typical Post CPTs after vibro compaction

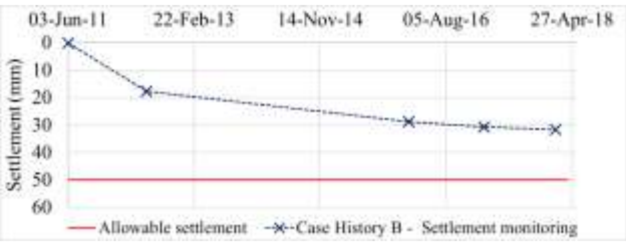

Fig. 10. Long term settlement monitoring

Results from two case studies above show that vibro compaction is suitable to densify loose to medium dense sands to support buildings on rafts with imposed loading of not more than 70 – 110 kPa for an allowable settlement of 50mm.

5 DISCUSSION AND RECOMMENDATIONS

The application of CPTs as quality control tool for evaluating the performance of vibro compacted ground was discussed. Two case histories of vibro compaction projects in Singapore were presented and discussed. The difference between testing location of post CPTs at centroid of a triangular gird (weakest location) and that using weighted average of post CPTs at centroid of triangular grid and at mid-point of vibro compaction points was highlighted. The performance of structures founded on vibro compacted ground in the two projects was found satisfactory based on long term settlement monitoring at the structures.

The specifications for vibro compaction projects are generally mentioned as a minimum required cone resistance rather than the overall performance of the treated sand block. Post treatment testing after vibro compaction is normally conservatively done at the zone of weakest compaction influence which is at centroid of three vibro compaction points in case of a triangular grid. Under such circumstances, a tight grid spacing is required to achieve the target minimum cone resistance specification to minimize occurrences where the post CPT cone resistance falls below the required value. Whereas, when a representative testing location and weighted average of post CPTs are adopted, the vibro compaction grid spacing can be optimized.

As discussed above, the post compaction verification using CPTs at representative locations was found satisfactory and a good measure of the overall performance of the treated ground. Hence evaluation using results at representative locations is recommended for sand compaction projects. With optimized compaction effort, significant costs and time savings can be achieved.

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