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Densification of land reclamation sands by deep vibratory compaction techniques

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ABSTRACT

Loose granular sand deposits formed during the land reclamation process are vulnerable to liquefaction upon imparting seismic forces. These loose granular sand fills could encounter bearing failures or compress beyond tolerable limits under static and dynamic loads. In order to eliminate such failures, loose granular soils require densification to enhance their engineering properties. Deep compaction is the only means to improve these thick deposits of loose sandfill in many foreshore land reclamation projects. Muller Resonance Compaction (MRC) and vibroflotation are deep vibratory compaction techniques, which are suitable to densify thick layers of loose granular fills. This paper describes the applications of deep compaction vibratory techniques in a mega-land reclamation project in the Republic of Singapore where the efficacy of densification was verified by Cone Penetration Tests (CPT) undertaken in a Pilot Test Area. The top sand layer of about 1.5 to 6.0 meters is in the medium to dense state and dilates during shear. In the MRC technique, high vibrating energies are used, which results in the whole mass of soil being rearranged, but a weak point was found at the location of the probing point. In vibroflotation, the densified column of soil was found to form at and surrounding the probe point and the density of the granular soil reduced with distance from the probe point. The aging effect in vibroflotation was found to be significant. vibroflotation was found to have several advantages compared to the MRC technique. Due to the excess water in the pore spaces caused by the high pressure jetting in vibroflotation, the water pressure dissipation further enhances the densification due to the aging effect.

Keywords: Land reclamation; densification; compaction; vibroflotation; resonance; liquefaction.

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Introduction

In land reclamation projects on soft soil deposits at foreshore location, loose granular fill materials are often used. In the Republic of Singapore, thick deposits of soft marine clay are often treated with prefabricated vertical drains and surcharging (Arulrajah et al. 2004; Arulrajah et al. 2005; Arulrajah et al. 2006; Arulrajah et al. 2009a; Bo et al. 2007; Bo et al. 2011; Bo et al. 2012; Choa et al. 2001; Chu et al,. 2009a; Chu et al 2009b). The thick loose granular fills overlying these soft soil deposits require deep sand densification to limit future ground subsidence. Densification methods are used to increase the friction angle and the elastic modulus of granular soil in land reclamation works (Bo et al, 2009; Feng et al. 2013). The bearing capacity of granular foundations is mainly dependent upon shear characteristics such as the friction angle of the soil whilst the compressibility is dependent upon the elastic modulus of the soil.

During land reclamation operations, the granular soil mass can be densified by roller compaction with a certain lift and with specified moisture content (Horpibulsuk et al., 2013). A simple rational method of estimating the compaction curves at different energies has been introduced by Horpibulsuk et al. (2008 and 2009). However for land reclaimed by hydraulic filling at foreshore locations, such shallow densification methods are not feasible. In such land reclamation projects at foreshore locations, deep compaction techniques are required to densify loose sands placed by hydraulic filling. Deep compaction techniques commonly used to densify thick deposits of loose hydraulic sand fills in land reclamation projects include dynamic compaction, vibroflotation and the Muller Resonance Compaction (MRC) techniques. Granular soil specified for these land reclamation projects specify a maximum of 10 to 15% fines.

The dynamic compaction (Menard and Broise 1975; Chow et al. 1994; Ito and Komine 2008; Bo et al. 2009; Feng et al., 2013), stone column (Adalier and Elgamal, 2004; Arulrajah et al. 2009b) and cement stabilization (Aiban, 1994) techniques have been established for sand densification and solidification to mitigate liquefaction and ground deformation. However there has been limited research on deep vibratory compaction techniques such as the MRC (Massarsch and

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Fellenius, 2002) and vibroflotation techniques for sand densification in land reclamation projects in terms of the efficacy of these vibratory compaction techniques. This has been researched in this study with the use of CPT equipment in a Pilot Test area where CPTs were undertaken at the compaction probe points and various distances away from the probe points. The novelty of this work is in terms of field testing with CPT to verify the efficacy of the densification works at various distances from the probe point. In addition, the performance of the MRC and vibroflotation techniques in this project based on CPT testing are discussed and compared.

Materials and Methods

The land reclamation project in the eastern part of the Republic of Singapore included 2000 hectares of land reclamation, which was carried in five phases. A major portion of the site was reclaimed for the future airport runway 3 and future terminal building for Singapore Changi International Airport. The underlying soft marine clay was treated with prefabricated vertical drains with surcharge (Arulrajah et al. 2013; Bo et al. 2014). The granular sand fill for the land reclamation works was sourced from marine borrow sources and transported to the reclamation site with trailer suction dredgers or hopper barges. The granular sand fill for the land reclamation works was deposited within the land reclamation site by means of cutter suction dredgers located at a rehandling pit or directly from trailer suction dredgers. The hydraulic placement of sand fill resulted in reclamation sand being placed in a loose state at cone penetration test (CPT) cone resistance values as low as between 5 and 7 MPa. The hydraulic filling sand in the project comprised of marine sands with a fines content of less than 10% (Bo et al., 2009). An area of 114 hectare was improved by deep compaction methods of 7 to 10 m thickness of loose land reclamation sand fills. Three types of deep compaction techniques were deployed which were dynamic compaction, Muller Resonance Compaction (MRC) and vibroflotation. To satisfy the densification requirements, a cone resistance value of 15 MPa was specified for the runway and 12 MPa was specified for the taxiways, which are equivalent to relative densities of 75% and 70% respectively (Bo et al. 2009).

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The densification requirements for a project were ascertained based on the required magnitude of bearing capacity and allowable magnitude of tolerable settlement. In practice, it is technically impossible to measure the in-situ internal friction angle and also difficult and time consuming to measure the modulus of elasticity of granular soil at various levels along the depth of soil profile. The required degree of densification can however be specified in terms of relative density measured from cone penetration tests (CPT), since this can be well correlated with the friction angle and modulus of elasticity of granular soil (Schmertmann, 1988).

In the MRC technique, a steady-state vibrator is used to densify the soil and this technique does not require application of water for penetration. As a result of vibratory excitation, the friction between the soil particles is temporarily reduced. This facilitates rearrangement of particles, resulting in densification of the soil. A specially designed steel probe is attached to a vibrator, which has variable operating frequencies. The frequency is adjusted to the resonance frequency of the soil, resulting in strongly amplified ground vibrations and thereby efficient soil densification. Two main types of MRC vibrators were used which have a maximum static moment of 1000Nm (MS-100) and 1900 Nm (MS-200) respectively. The probe profile is a “wing” of double Y-shaped flexible plates with openings. The length size of the “wing” as well as the size of the opening can be varied depending upon the soil condition. The procedure of compaction is such that the probe is inserted into the ground at a high frequency in order to reduce the soil resistance along the shaft and the toe. Usually during penetration, the frequency of 23 to 25 Hz is used. When the probe reaches the required depth, the frequency is adjusted to the resonance frequency of the sand layers thereby amplifying the ground response. This is to induce the sand particles to achieve resonance at the same resonance frequency imparted by the vibrators, thus enabling densification of deep deposits of sand fill to occur. The MRC probe is executed in the vertical direction and the vibration energy is transmitted to the surrounding soil along the entire length of the probe. When resonance is achieved, the whole soil layer will oscillate simultaneously. The compaction duration depends on the soil properties and on the required degree of densification. Compaction is usually carried out in

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a square grid pattern of two or more passes. The square grid spacing typically ranges between 3 to 5.5 meters. The monitoring of each probe point is undertaken by the use of an automatic recording device. Triaxial geophones are used to measure radial, vertical and tangential ground vibrations.

The vibroflotation technique is designed to induce compaction of granular materials at depth. The basic principle behind the process is that particles of non-cohesive soils will be rearranged into denser configuration by means of horizontal vibrations induced by the depth vibrator. For non-cohesive soils with natural dry densities less than their maximum dry density, the influence of vibrations will result in a rearrangement of their grain structure. As a result of the vibroflotation process, the void ratio and compressibility of the treated soil will be decreased and the angle of shearing resistance increased. The treated compacted soil is capable of sustaining higher bearing pressures compared to the untreated soil. The essential equipment for the vibroflotation process is the vibrator or vibroflot which comprises a long heavy tube enclosed with eccentric weight and either electrically or hydraulically driven. The motion of eccentric weight inside the vibrator induces effective horizontal vibrations. The combination of vibration and high-pressure water jetting causes liquefaction of soils surrounding the vibrator, which assists in the penetration process. With the inter-particle friction temporarily reduced, the surrounding soils then fall back below the vibrator and, assisted by vibration, are rearranged into a denser state of configuration. This process is repeated back up to the ground level, leaving on completion a column of well compacted dense material surrounded by material of enhanced density. The degree of improvement achieved depends on the type of granular soil being treated, the amount of time spent at each stage of compaction, the distance from the probe point and the effect of vibration. Typically, the zone of influence will have a diameter between 3 to 4 meters. Spacing of probe points is designed to ensure that the zones of influence overlap sufficiently to achieve minimum requirements throughout the treated area. The depression formed around the vibrator or the extension tubes is infilled with granular materials. The monitoring of each probe point is undertaken by the use of an automatic recording device.

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Results and Discussions

For MRC, a higher capacity vibrator (MS-200) requires wider spacing, whereas a lower capacity vibrator (MS-100) requires narrower spacing. The CPT cone resistance at various distances from the probe point for the MRC pilot trial before and after compaction is shown in **Figure 1**. Generally, the CPT cone resistance is lower than 10 MPa for the whole depth except at a depth of about 1.5 to 6 m. As evident in the figure, the densification achieved is significant in the bottom part of the profile as seen by the difference in CPT cone resistance between before and after compaction (dot and solid lines). At the top part of the profile (1.5 to 2.5 m depth), the MRC provides a negative response. The sand changes from dense to loose state after MRC as seen by the significant reduction in CPT cone resistance. This indicates that the dense sand exhibits dilatancy when it is sheared due to the interlocking effect (Terzaghi and Peck, 1967). Similar negative responses are often observed when driving a pile into dense sand (Kishida 1963; Kishida and Meyerhof 1965). The reduction in CPT cone resistance before and after MRC is less than that at the 1.5 to 2.5 depth. This is possibly due to the larger overburden stress, which prevents the dilatancy. The soil natural frequency can be found from spectral analysis (Massarsch 1991). The soil natural frequency was found to be about 12 Hz for the uncompacted sand. Based on this result, the resonance of the MRC works was set at higher frequencies of 20-25 Hz.

Degree of compaction for the MRC type of system is dependent upon capacity of vibrator, spacing of probe points, duration of compaction and the applied frequency. With closer spacing, better ground densification can be achieved. The MRC method compacts the soil mass homogeneously and variation of cone resistance with distance from the probe is insignificant. CPT tests repeated 5 months after MRC indicated that ageing effect is present due to dissipation of residual excess pore water pressure after compaction for the whole depth as shown in **Figure 2**. The ageing effect on the strength gain is clearly observed at the top of the soil layer. Aging effect is seen to be significant closer to the top of the sand layer as this sand layer is originally in a looser state and hence easier to densify as compared to stiffer sand deposits present at deeper depths. However,

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the 5 month strength is still lower than the in-situ strength prior to compaction. The dilatancy effect on strength reduction is noticeably more dominant than the ageing effect.

To access the performance achieved by vibroflotation, post CPTs were conducted at the weakest points (typically at centroid of grid pattern) at the pilot trial to determine the achieved tip resistance with depth in comparison to the specifications. To achieve CPT cone resistance of 10, 12 and 15 MPa of cone resistance with V32 type of vibrator, corresponding amperage of 160 amps, 240 and 260 amp was found to be required. Post CPTs were conducted 7 days after the vibroflotation works to allow the dissipation of excess pore water pressures developed. For the same vibrator, wider spacing produces lower cone resistance. A higher capacity vibrator can achieve the same degree of densification with a wider spacing as compared to a smaller capacity vibrator. The variation of cone resistance with distance from the probe point after compaction is shown in **Figure 3**. It can be seen in the figure that cone resistance is highest at the probe point and lowest near the centroid point of the triangle (CPT point 2 and 4). However, cone resistance at the centroid of the four compaction points is higher than that at points 2 and 4.

The degree of compaction for vibroflotation is largely dependent upon type of equipment, spacing of probes, duration of compaction and the magnitude of amperage achieved. The closer the spacing, the greater the possibility of densifying the whole mass of soil. If spacing is wider than required, some loose pockets can be found at the centroid point. A triangular grid spacing of 2.5 to 3.0 meters was found to be required to achieve a cone resistance of 15 MPa by V32 type of vibroflotation equipment. To achieve a cone resistance of 12 MPa, a triangular grid spacing of 3.0 to 3.2 m is required with the V32 vibrator. For the S300 vibrator, a triangular grid spacing of between 2.4 to 2.6 meters is required to achieve a cone resistance of 15 MPa. However, this is also dependent upon the initial soil condition. **Figure 3** indicates that vibroflotation is more advantageous than MRC in terms of densification. The high pressure water jetting disturbs the dense state to a loose state prior to compaction. Hence, the in-situ dense sand at the top of the sand layer can be improved in that the cone resistances for different locations after compaction are higher

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than those prior to compaction. The ageing effect on the densification gain by the vibroflotation is noted to be more significant than those by the MRC. This is due to the fact that the jetted water increases the water in the pore space between sand particles. The excess water pressure dissipation due to overburden pressure enhances the densification with time after compaction. Ageing effect is evidently quite significant for vibroflotation. CPT tests repeated 4 months after vibroflotation indicated that ageing effect is present and there was a significant increase in the cone resistance 4 months after compaction as shown in **Figure 4**.

Conclusions

In the MRC technique, the type of vibrator, spacing and duration of compaction are found to be of importance. In addition, the selected frequency is also an important factor to achieve an efficient compaction. The selected frequency should be about the soil resonance frequency. If compaction is carried out at the resonance frequency of vibrator-soil-probe, the whole mass of soil would be strongly compacted. The variation of cone resistance at the probe point and away from the probe point is also significant. The vibration causes the dense sand at the top sand layer to become loose. Hence, the MRC technique gives the negative response for the top sand while also improving the deep loose sand layer. The ageing effect after compaction is significant for the top sand layer but not significant for bottom sand layer. Even due to the ageing effect at the top sand layer, the aged cone resistance is still less than the in-situ cone resistance as that for vibroflotation due to the lower magnitude of residual excess pore pressure soon after compaction.

In the vibroflotation technique, the type of equipment, spacing and duration of compaction are found to be of importance. Degree of compaction is found to decrease with distance from the probe point. As such, the spacing of the probe points is of importance. At and around the cylindrical column of the point, the cone resistance is found to be almost constant with depth. Ageing effect is found to be significant in vibroflotation. The high pressure water jetting makes the dense state to loose state before vibroflotation compaction, resulting in the possible improvement in the top dense

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sand layer. Due to the excess water in the pore space caused by the high pressure jetting, the water pressure dissipation enhances the densification after long term of compaction. Vibroflotation was found to be a more advantageous technique compared to MRC for this particular mega-land reclamation project. However, the performance of these vibratory methods are entirely project specific and not necessarily valid for other projects as the performance of the adopted vibratory technique would depend on numerous factors such as type of sand fill, reclamation technique, fines content, shell content, water jetting requirements, staff experience and vibration frequencies.

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FIGURE CAPTIONS

Figure 1. Variation of cone resistance with distance from the probe point after MRC compaction.

Figure 2. Significance of aging effect after MRC compaction.

Figure 3. Variation of cone resistance with distance from the probe point after vibroflotation.

Figure 4. Significance of aging effect after vibroflotation.

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Figure 1

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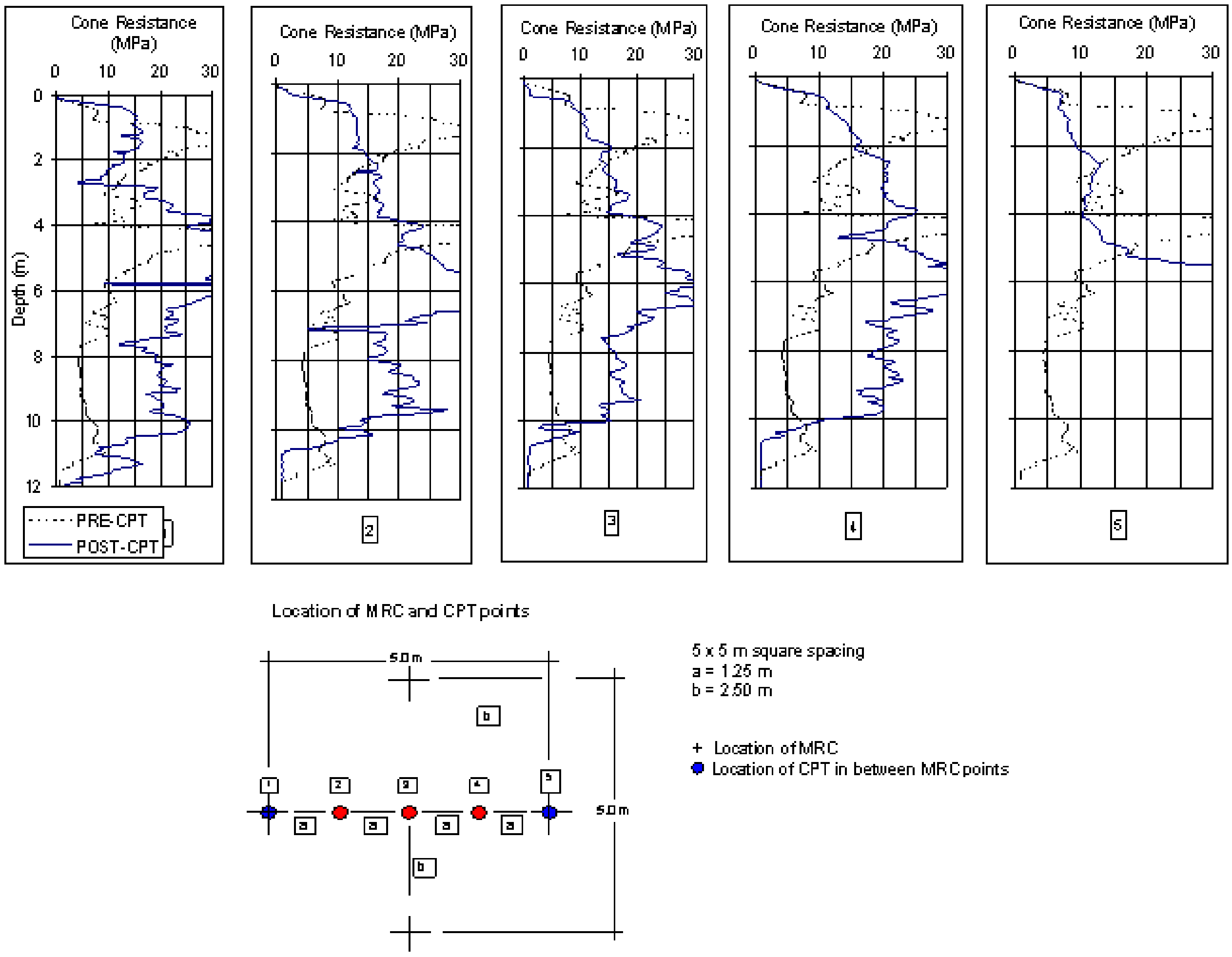

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Figure 2

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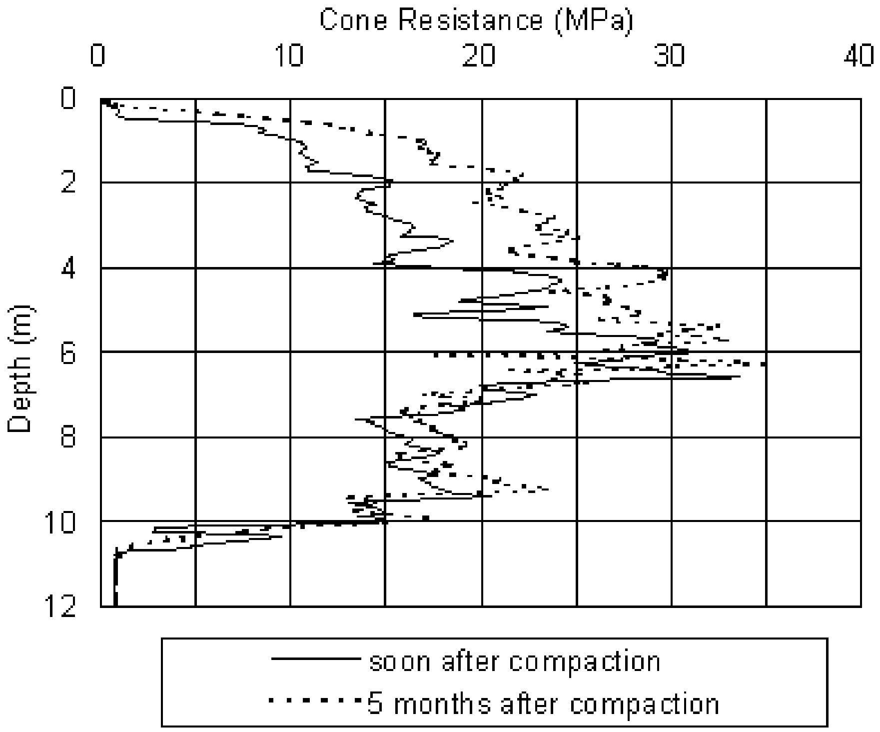

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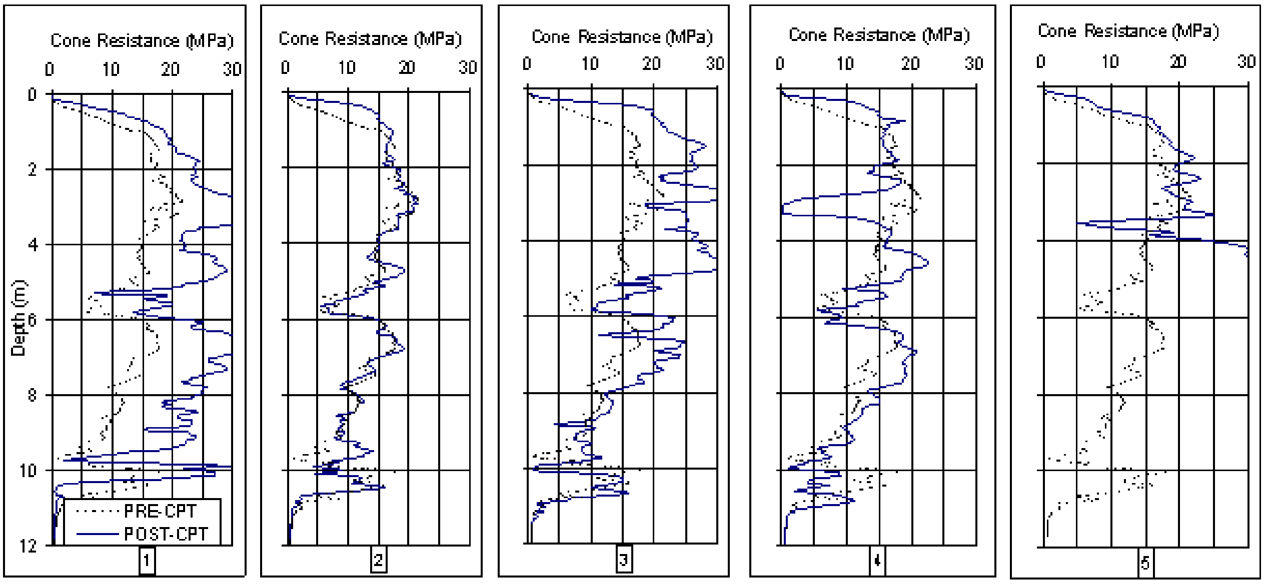
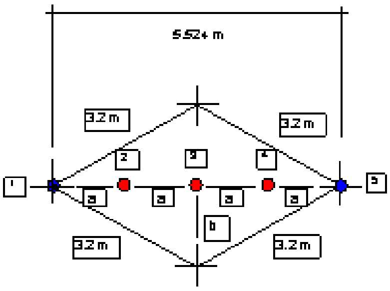


Location of Vibroflotation and CPT points



1. 3.2 m Triangular Grid
2. Duration time - 40 sec
3. Probe type - V32, amplitude - 32 mm, centrifugal force - 460 kN

a = 1.38 m
b = 1.61 m

+ Location of vibroflotation points
● Location of CPT in between vibroflotation points

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Figure 4

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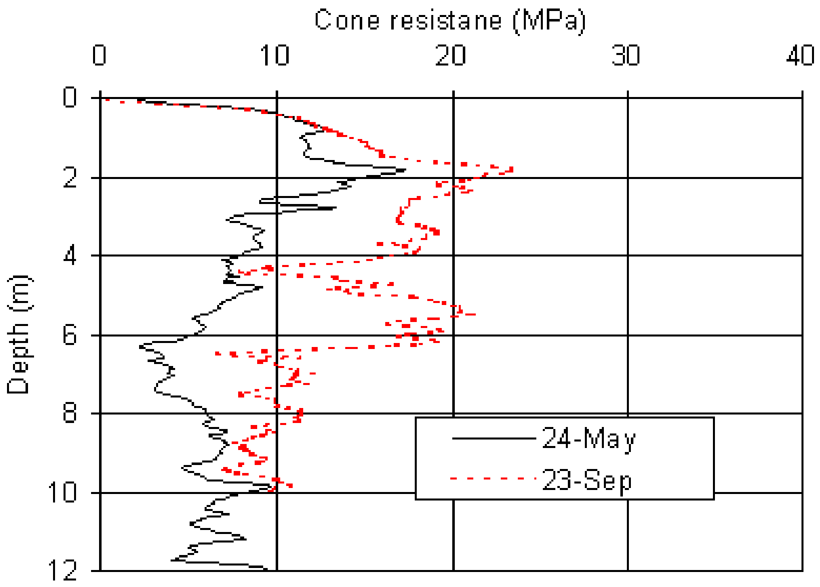

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