Vibroflotation Control of Sandy Soils using DMT and CPTU

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ABSTRACT: Vibroflotation is a typical improvement method for the cohesionless deposits of high thickness. The compaction method was applied to densify sandy deposits in Gdynia Port. Compaction control was verified with CPTU and DMT tests. Some examples of interpretation of soundings in pre-treated and compacted sands are shown. The classification diagrams are given for pre-treated and compacted sand. The stress history of the deposits is analysed. For a given relative density a considerable increase of lateral stress index was recorded after compaction. Some acceptance criteria for compaction control are discussed. The sensibility of CPTU and DMT methods to compaction control is analysed.

1 INTRODUCTION

A set of buildings was designed near the President Harbour in Gdynia Port. Heterogeneous soil conditions – with Holocene sand containing some mud inclusions and recent loose to medium dense sand fills of variable thickness – needed some improvement works to establish more uniform and less deformable subsoil. The vibroflotation method was applied to densify sandy soils by means of electric vibrating unit.

2 VIBROFLOTATION

2.1 *Soil conditions*

The thickness of Holocene sandy deposits in the considered area varied from 4 to 11 m. Below, there is a very dense Pleistocene sand layer. The water table is about 1 m below ground level. Hydraulic fills deposited underwater covers partially the considered area. The preliminary CPTU tests shown that the sandy deposits fulfill the suitability conditions for the use of vibroflotation according to diagrams proposed by Massarsch&Fellenius 2002 and Lunne et al. 1997. The silt fraction in sandy deposits was less than 7% and the uniformity coefficient was in the range from 2.2 to 6.8. The granulometric curves are presented on the diagram (Fig. 1), with the suitability zones for vibroflotation, as defined by Brown 1997. Here, the soil granulometry signifies that the sandy deposit is ideally compactable (B) or compactable (C) using vibroflotation method.

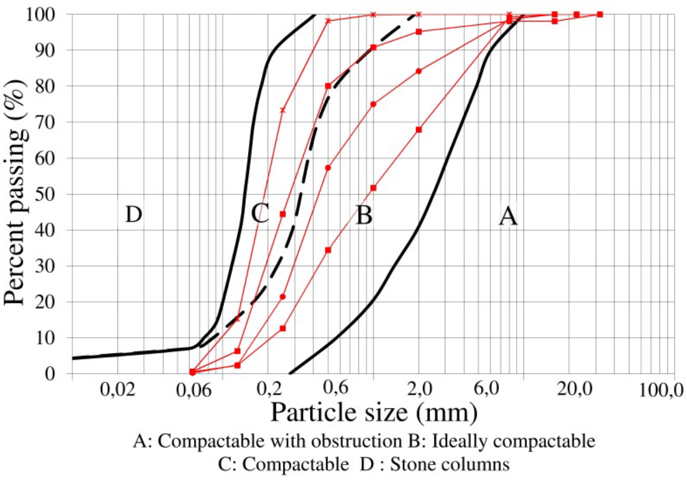

Fig. 1. Compactable zones for vibroflotation and the soil granulometry, Kurek 2013.

2.2 *Compaction works*

Deep soil vibratory compaction with granular material supply from the surface was used. Vibrator with power of 120 kW, frequency of 30 Hz and vibration amplitude about 20 mm was used. Under the influence of vibration in fully saturated conditions the loose sand particles are rearranged into a denser state with simultaneous increase of lateral stress in the soil mass. Additionally, some infill gravelly sand material was supplied from the surface level to reduce the soil settlements. Such action induces an additional increase of the lateral stress within the subsoil.

Some preliminary tests were performed on the trial field to determine the appropriate grid size and vibration time sequences. Finally, the compaction was performed in regular square grid 3x3 m.

2.3 *Compaction criteria*

Compaction effectiveness can be monitored during the works and with penetration testing afterwards. During vibroflotation the input power consumption and surface settlements were measured. The maximum recorded settlement for 8 m thickness of deposits was 49 cm. The consumption of the infill material was also monitored at each point of vibratory compaction. Some CPTU and DMT tests were performed before and after the works midway the vibroflotation points. The tests were executed more than three weeks after the works completion in order to take into account an increase of soil parameters due to aging. The minimum average constrained modulus over the soil profile equal 80 MPa was fixed as an acceptance criterion for the post-treated subsoil.

3. COMPACTION CONTROL

3.1 *CPTU/DMT profiles*

The results of CPTU tests before and after vibroflotation are given on Fig. 2. The control tests were realised from the working platform, so they are shifted about 1.4 m regarding initial ground level. An important, about 3.2 in average, increase of cone resistance is registered within the compacted layers. Only slight sleeve friction augmentation is observed compared to cone resistance. The corresponding normalized friction ratio decreases after compaction, which is consistent with findings of Slocombe et al. 2000 and Debats&Scharff 2009. One should notice that sandy deposits with only very limited fine content can be densified using vibroflotation. As an example, marginally compactable silty interbedding at about 4 m depth are found in the soil profile (see Fig. 2).

Typical DMT tests were performed and standard parameters were derived according to Marchetti 1980 interpretation. The DMT profiles are given for pre-treated and compacted subsoil (Fig. 3). An important growth of the lateral stress index K_{DMT} in post-treated soil was recorded due to soil density increase, soil prestraining under repeatable load and lateral stress increase. The material index I_{DMT}, however, decreases after vibroflotation. Significant increase of internal friction angle determined with Marchetti et al. 2001 correlation was obtained within compacted strata. This uniform distribution of internal friction angle within compacted layer confirms the quality of the compaction works.

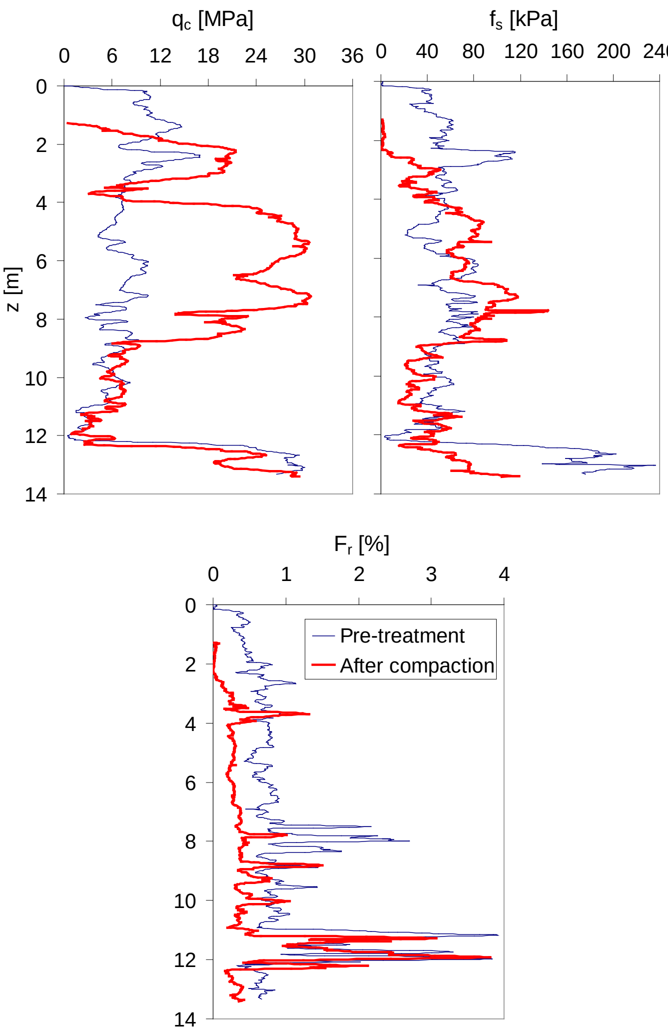

Fig. 2. Comparison of pre- and post-treatment CPTU results, Bałachowski&Kozak 2006.

Considerable augmentation of dilatometer and constrained moduli from DMT is registered. One should notice that the constrained modulus M_{DMT} over the compacted soil strata exceeds by far the acceptance criterion. The post-treatment constrained modulus M_{DMT} is in average 7.6 times higher than before compaction (Fig. 3). It means that dilatometer is more sensitive tool of compaction control that CPTU. The mean increase of the constrained modulus M_{DMT} within compacted sandy layer is about 2.3 times higher than corresponding q_c increase. This result confirms the previous observations of Schmertmann et al. 1986 concerning dynamic compaction and of Jendeby 1992 on monitored deep compaction of sandy fills using vibrowing. They found that after compaction works the constrained modulus M_{DMT} increases more than twice the cone resistance q_c. The acceptance criterion defined in terms of constrained modulus was achieved by far in the compacted strata.

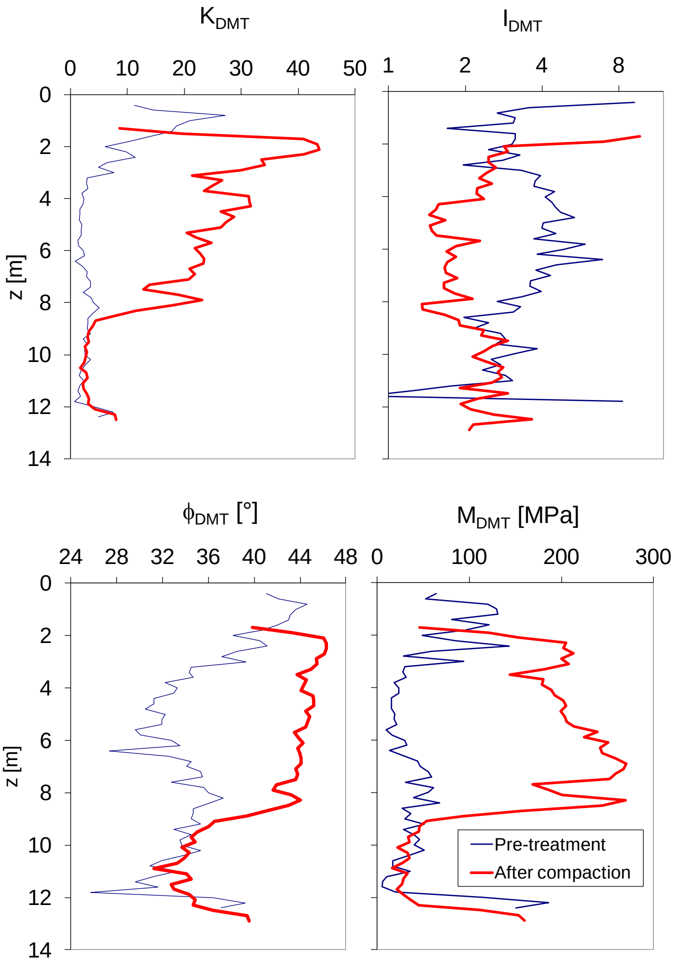

Fig. 3. Comparison of pre- and post-treatment DMT results, Bałachowski&Kozak 2006.

3.2 Classification charts

Robertson 1990 chart was used to present the soil behaviour and the soil classification before and after compaction works (Fig. 4). After treatment the majority of the points on the diagram was translated from area 8 to 9 or 10. While the soil granulometry remains the same after vibrocompaction its behaviour changes from typical for silty sands to be classified as a corresponding to clean sands or even gravelly sands. This shift of the points can be partially attributed to relative density increase. Due to compaction the friction ratio F_R decreases as it was already observed (Fig. 2).

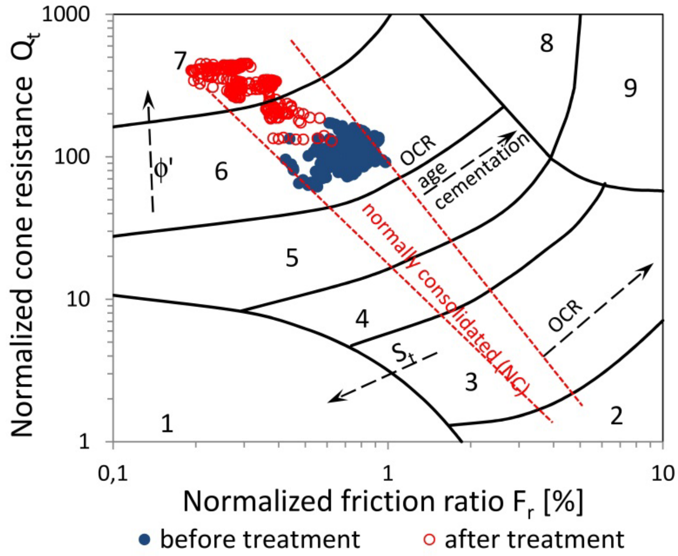

Fig. 4. Robertson 1990 soil behaviour diagram, Kurek 2013.

The soil behaviour based on Marchetti&Crapps diagram is given in Fig. 5. After compaction the material index decreases and the soil behaviour is shifted towards more stiff (compacted) silty sands. This observation is contradictory with changes in soil behaviour classification based on CPTU tests (Fig. 4), where the soil behaviour type is translated towards gravelly sands and gravels. The ratio of p_0 after and before compaction is higher than the corresponding ratio for p_1 (Fig. 6). As p_0 is the denominator in the formula for I_{DMT}, the material index is getting lower after vibroflotation. Thus, it reflects the stiffening effect of overconsolidation.

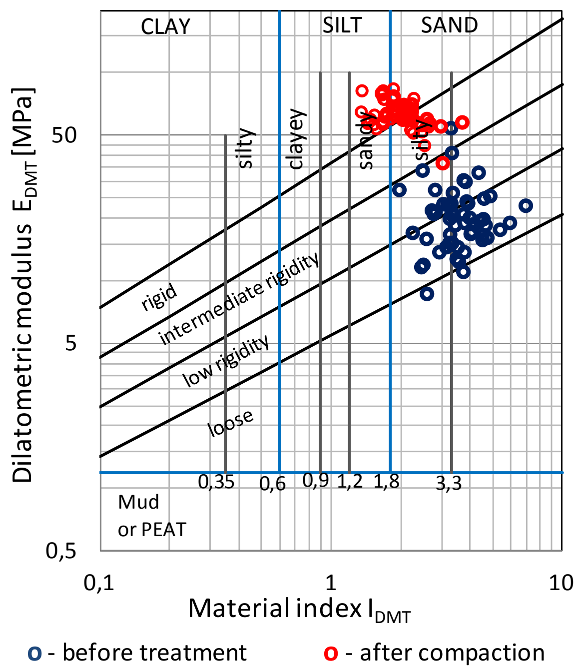

Fig. 5. DMT soil classification before and after compaction using Marchetti&Crapps diagram, Kurek 2013.

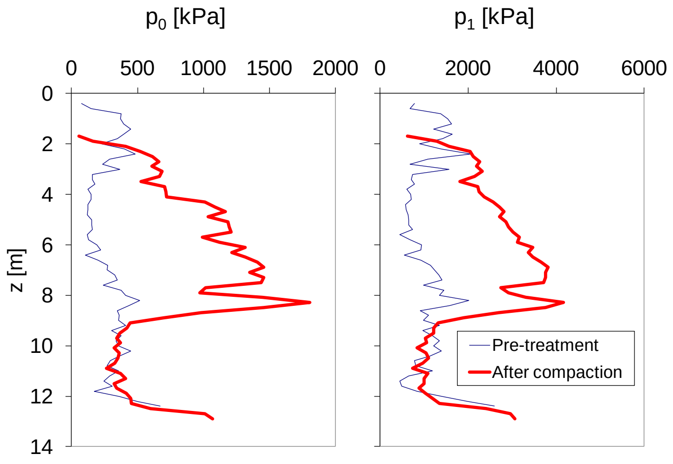

Fig. 6. P_0 and p_1 pressures from dilatometer before and after compaction.

One should also point out the different forms of classification chart for DMT and CPTU tests. According to Marchetti&Crapps diagram the soil behaviour is classified according to I_{DMT} and vertical border lines. In Robertson 1990 chart the soil behaviour is classified due to the soil type behaviour index I_c and circular separation lines, Robertson 2009.

Normalized friction ratio vs. material index before and after compaction is given (Fig. 7), where a similar decreasing tendency is observed for these both parameters. The results in compacted sands are however less dispersed and concentrated in the lower left part of the figure.

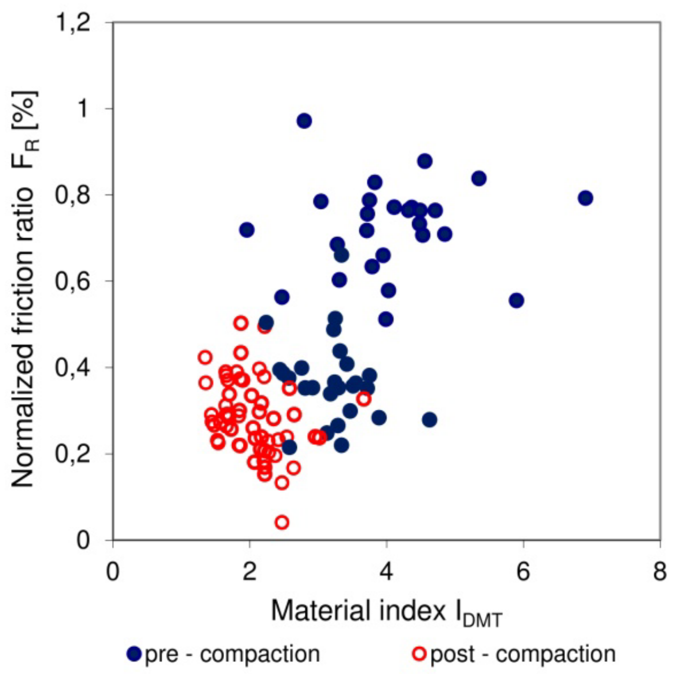

Fig. 7. F_R vs. I_{DMT} before and after compaction.

3.3 Stress history

The overconsolidation ratio of sandy soil was estimated (Fig. 8) with empirical formula proposed by Mayne 2001, Eq. (1).

$$OCR=\left[\frac{1.33(q_t)^{0.22}}{K_{0,NC}(\sigma'_{v0})^{0.31}}\right]^{\frac{1}{\alpha-0.27}} \qquad (1)$$

where:

$$K_{0,NC} = 1 - sin\emptyset' \qquad (2)$$

q_t - corrected cone resistance,

OCR - overconsolidation ratio,

$\alpha = sin\emptyset'$.

While only slight overconsolidation was derived for pre-treated sand, considerable OCR was estimated for compacted deposits. This is consistent with the solicitation path induced by insertion of the vibrator and vibroflotation process, where large lateral strains occur followed by considerable horizontal stress increase as a substitute of overconsolidation. Here, the earth pressure coefficient may exceed 1.

The scheme for such mechanism of overconsolidation was proposed by Handy 2012. The intergranular forces for NC soils and soils with overconsolidation induced by lateral stress increase are shown on Fig. 9. Moreover, such repartition of intergranular forces will counteract the foundation settlements on the compacted subsoil.

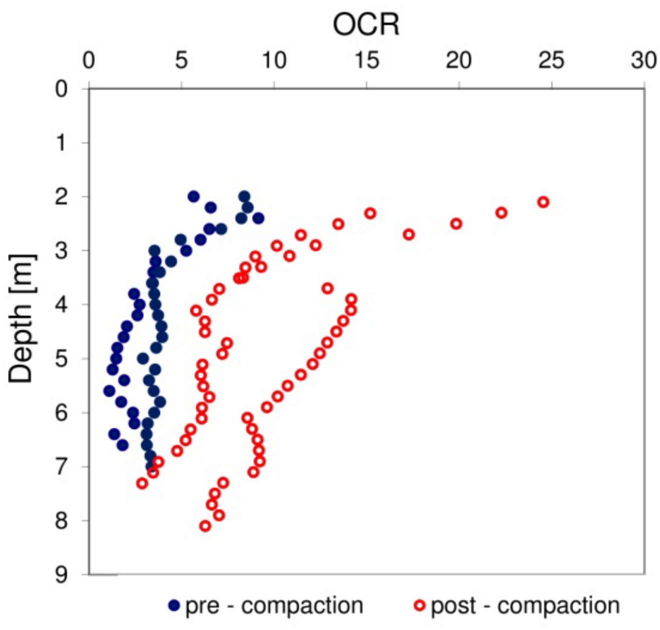

Fig. 8. Overconsolidation ratio in the sandy subsoil, Kurek 2013.

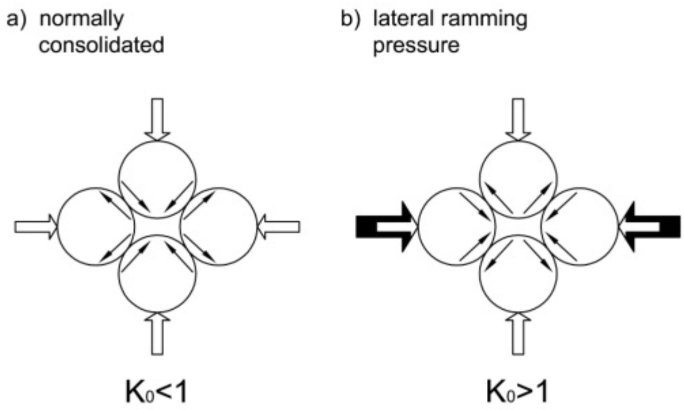

Fig. 9. Mechanism of intergranular forces induced by lateral stress increase, Handy 2012.

The stress history in the subsoil was also checked using the M_{DMT}/q_c ratio calculated before and after compaction (Fig. 10) where typical ranges for NC and OC soils proposed by Marchetti et al. 2001 are plotted. In our case this ratio in compacted sands is slightly lower than that one suggested for OC sands.

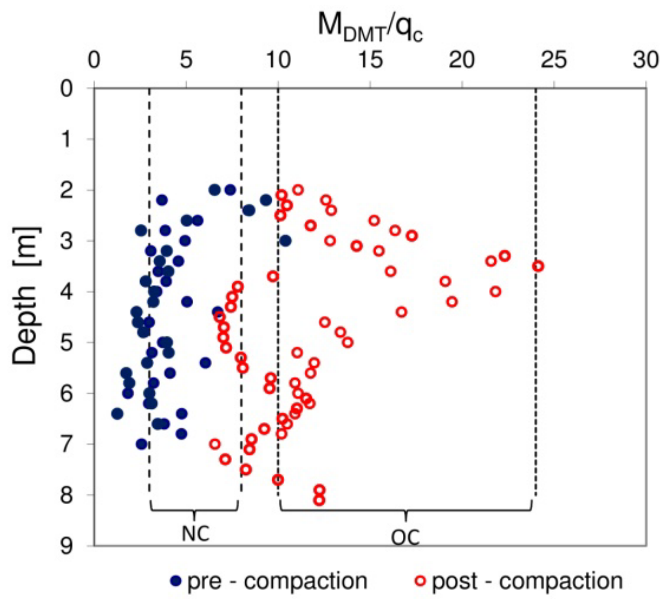

Fig. 10. M_{DMT}/q_c ratio before and after compaction, Kurek 2013.

The lateral stress index is a measure of stress history, Marchetti et al. 2001. The data concerning the sands before compaction (Fig. 11) are situated close to the NC dotted line proposed by Reyna&Chameau 1991, which confirms normal consolidation or slight overconsolidation of deposits. After compaction an important increase of K_{DMT} index is observed. These observations are also consistent with the results of DMT tests in calibration chamber in overconsolidated sands, Lee et al. 2011.

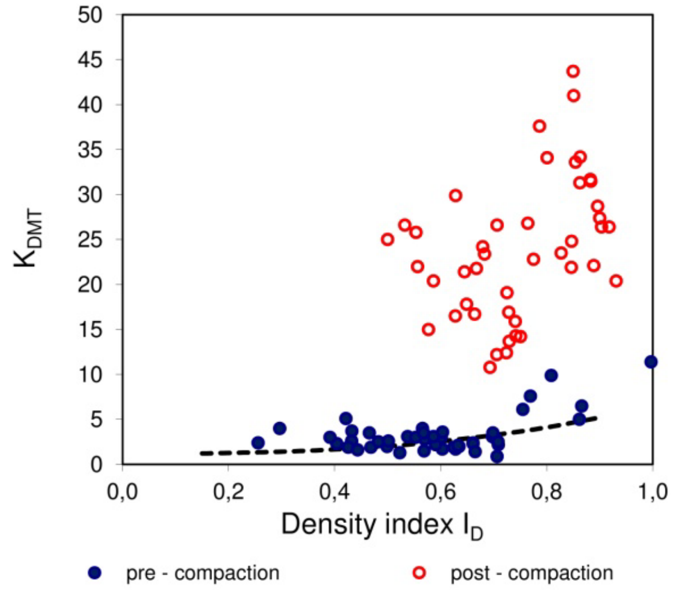

Fig. 11. Lateral stress index vs. density index, Bałachowski 2008.

3 CONCLUSIONS

Quality control of deep soil vibratory compaction was performed with coupled CPTU and DMT tests. Vibroflotation induces an important increase of cone resistance, lateral stress index, angle of internal friction and constrained DMT modulus within the compacted sands. The normalized friction ratio as well as material index decrease after compaction. The mechanism of stress state changes due to vibroflotation works was analysed. Due to vibroflotation process the substitute of overconsolidation is induced by lateral stress increase.

It was confirmed that lateral stress index is very sensitive to compaction of sandy deposits. The constrained modulus from DMT is a good measure of compaction control. Such defined compaction criterion is more complete than typically admitted a fixed value of relative density as it includes the effect of densification and lateral stress increase. The mean increase of the constrained modulus from DMT is 2.3 times higher than the corresponding gain in cone resistance, which is consistent with observations made by Schmertmann et al. 1986 and Jendeby 1992 for dynamic compaction and vibrowing densification, respectively. Further efforts should be done to examine this effect in heavy roller compaction, compaction grouting or microblasting. The use of dilatometer test is thus more beneficial as it is more sensitive to soil improvement control than the cone penetration test is.

The changes in soil type behaviour after compaction are different for CPTU and DMT charts.

While in CPTU classification the data points are shifted towards the soils behaving like gravelly sands and gravels, the DMT classification suggests the soil behaviour corresponding rather to silty sands. These divergences could be partially explained by different construction of these classification charts.

One should also notice that the material index and normalized friction ratio are dependent on stress history. P_0 pressure is more sensitive to horizontal stress and lateral stiffness than p_1. Similarly the cone resistance seems to be more influenced by lateral stress increase than the shaft friction.

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