Dynamic compaction of the Baltic basin silty Sand - quality assurance with CPT, DPM, DMT and PLT

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Abstract. Post-glacial evolution of the Baltic basin sedimented Quaternary soils at the great thickness (up to 30 m) in Riga, Latvia. There are present zones of different combinations of post-glacial, alluvial, limnological and dune formations within the metropolitan area of Riga. The geomorphological evolution of this territory is dominated by the Baltic sea former stages, distinguishing these areas as rather complicated. The dynamic compaction was proposed below the warehouse floor of area about 40K m² in Baltic basin silty Sand. The effect of compaction was evaluated to the depth of 10 m and extensive quality assurance using cone penetration and piezocone tests (CPT(U)), dynamic probing (DP) tests, flat dilatometer tests (DMT) and plate loading tests (PLT), was introduced. CPT(U) and DMT results were compared in terms of soil stiffness parameter evaluation prior and after dynamic compaction. The limitation of DP tests were investigated and finally also warehouse test embankment verified by PLT evaluating shallow compaction rates.

1. Introduction
Quaternary sediments in Riga territory are formed both in Holocene and Upper - Pleistocene. Geomorphologically this area covers both Baltic basin sediments, alluvial, limnistic and aeolian soils. Exactly the post-glacial evolution of the Baltic basin has the greatest influence to the accumulation of thick (up to 30 m or even more) Quaternary strata. The older post-glacial sediments are further modified by rivers, lakes and wind, so distinguishing the area rather geologically complex.

Vast areas of thick silty Sand (siSa) Litorina Sea and Baltic Ice Lake sediment layers are governing Riga geology outside both banks of Daugava river, whereas near the waterway the Litorina Sea and alluvial silty Sand (siSa), Silt (Si) and organic Silt (orSi) are dominating (see Figure 1). These Litorina Sea and Baltic Ice Lake Silts, Sands and their mixtures are normally consolidated to slightly overconsolidated and often they are loose, especially at low depth (up to 10 m - 15 m). Moreover, layers of these soils are ununiformly distributed, therefore often being challenging subgrade especially for structures such as building foundations - pads, slabs, rafts, warehouse floors and others.

Deep dynamic compaction (DC) technology involves frequently drop of a weight (special pounder) freely from a height onto the ground surface in order to improve problematic geomaterial to a deep depth. Repeated impacts reduce voids, densify the geomaterial, and induce ground movement [1]. A tamper typically has a weight of 5 – 40 tons and drops from a height of 10 – 40 m, however, there are cases where even 200 ton pounder was used.
The modern DC technology has been developed by the French engineer, Louis Menard since 1960s [2]. The basic mechanism underlying DC in granular soils is relatively well understood nowadays. At the moment of impact with the pounder, the impact energy is transmitted mainly in body waves that consist of compression and shear waves, although surface waves are also generated in the soil [3]. The influence of these shock waves on the soil is dependent on the soil types and the degree of saturation. For dry deposits the compressive and shear waves induced by the impact overcome the interlocking stresses within the loose strata, resulting in a reduction of voids. For a saturated granular deposit the mechanism of densification is quite different. The compressive stresses induced by the DC impact result in a sudden increase in pore water pressure, thereby forcing the soil into a state of temporary liquefaction. The shear waves and Rayleigh waves, which are slower, travel through the soil skeleton. The combination of a temporary loss of contact stresses and dynamic oscillation forces the soil particles to rearrange into a dense state.

The major fields of DC technology can be summarizes as follows [4]:
- Improvement of heterogeneous fill such as construction refusal or even garbage;
- Improvement of rockfill both offshore and onshore;
- Improvement of hydraulic fill and natural sand and silt deposits in order to increase bearing capacity, reduce future total and differential settlements and decrease the liquefaction potential both offshore and onshore;
- Improvement of clayfill above the water table.

Dynamic compaction (DC) has no standard quality control (QC) or quality assurance (QA) measures. A basic QC/QA program for deep dynamic compaction should always include heave and crater depth measurements after each series of tamper drops, settlement measurements after the ground has been leveled subsequent to each pass, dilatometer tests (DMT) and pressuremeter tests (PMT) with combination with dynamic probing tests (DP) piezocene penetration tests (CPT(U)) measurements both before and after the compaction program [4]. The dilatometer test (DMT) and pressuremeter tests (PMT) are deformation tests [5] [7] and provide an accurate prediction of settlement [7] [9]. For ground improvement sites a combination of CPT and DMT or PMT is likely the best solution for quality control and assurance [10]. With site - specific correlations, the CPT can be used to identify areas that are clearly improved enough and areas that are marginal. The DMT or PMT can then be used for the marginal areas to determine the soil stiffness parameters more accurately.

In addition, vibration monitoring should be carried out throughout the compaction program to control construction and avoid damage to surrounding structures. Porewater pressure should be monitored during compaction of saturated soils to ensure the initial soil structure has been broken down and excess pore pressures have dissipated between successive pounder drops [4]. Plate load test (PLT) can be also performed in order to check compaction of top layers by vibro-rollers, where top 1.0 – 1.5 m are loosened after DC.

2. Case study
Dynamic compaction (DC) technology was proposed in Riga, Latvia 2018, in order to increase stiffness and reduce total and differential settlement under warehouse floor in area of 40K square meters. Initial calculations based on CPT(U) data showed that the stiffness in terms of vertical subgrade reaction value is less than the value required ($k_s = 5000 \text{ kN/m}^2$) by the client. Planned warehouse is located in the urban environment in Riga city among Plavnieki, Mezciems and Dreilini suburbs. The closest buildings are existing warehouse 120 m West and 9 floor residential buildings 180 m South from future warehouse.

2.1. Geological description
According to the division of Latvian nature areas, the object of research is located in the Costal lowlands Rigava plain, the so-called Dreilini-Skirotava wavy plain. From a geomorphological point of view, the area is part of the Sandy areas of the earlier Baltic Sea plain. The Quaternary sediments is formed by the Litorina Sea and Baltic Ice Lake silty Sand (siSa) with interlayer of clayey Sand (cLSa) and silts (Si)
(see Figure 3). At the 25 - 30 m depth there is a relatively thin sandy and gravelly Latvian ice age moraine. Underneath the Quaternary sediments, the Upper Devonian weak rocks and clays are encountered. Today’s terrain is relatively flat, with a slight slope towards the southeast. Absolute altitude marks in the area vary within 8 - 9 m of the LAS2000.5. Ground water table measured at 1.5 – 2.4 m below the surface level.

Figure 1. Geomorphological map of Riga metropolitan area

Legend:

- aQ₄ – Alluvial deposits, Holocene (Sand)
- bQ₄ – Mire deposits, Holocene (Peats)
- vQ₄ – Aeolian deposits, Holocene (Sands)
- mQ₃b – Litorina Sea deposits, Holocene (Sand, Gravel, Silt, organic Silt)
- lgQ₃ln₃ – Baltic Ice Lake deposits, Upper - Pleistocene (Sand, gravel, pebble, Silt, Clay)

The Baltic basin (mQ₃b and lgQ₃ln₃) silty Sand (siSa) particle distribution was investigated for 38 boreholes prior the dynamic compaction (DC) (see Figure 2).
Figure 2. Particle size distribution with the susceptibility of DC compactibility

Silty Sand (Sa) investigated from the first 10 m depth is considered as easily compactable with DC technology as it can be seen in figure 2. In general there were made 39 boreholes, 23 piezocone penetration tests (CPT(U)) and 6 dilatometer tests (DMT) prior the start of DC. Soil classification based on CPT(U) data indicate mostly Sand and silty Sand - normally consolidated to slightly overconsolidated.

2.2. Technological assumptions
The compaction process was planned in 3 passes until the required post-treatment relative density has been achieved. The spacing for the first pass of impact points is usually equal to the thickness of the densifiable layer (10 m in this case), in order to allow the impact energy to reach the lower part of the layer. The second pass was made at the centroid prints of the first pass. During each pass, several drops were made at the same point. 17 ton pounder was used for the first two phases. Impact energy needed per point at each stage was defined by calculations [9] and also testing (trial test and heave test). 6 drops from 15 m height and 5 drops from 12 m height was used for the first and the second phase respectively.

There is a maximum number of impacts that leads to the closure of voids in order to achieve the minimum void ratio; after this there is usually no further closure of voids in the treated soil mass. After each pass, the craters created by the dropping pounder were backfilled with surrounding materials prior to the next pass. Finally, an ‘ironing’ pass with a low energy impact and reduced drop height was performed to compact the shallow surface layer in all area.

2.3. Quality control and assurance
The defined requirement within the design was average constrained modulus Em>40MPa within the improved layer of 10 m thickness. Further also the top layer (1.0 m – 1.5 m) compaction effectiveness was tested at the test embankment.

As part of quality control and assurance the following testing scope was introduced:
- DPM (dynamic probing test, medium) at 53 research points (at different work stages);
- CPT(U) (piezocone penetration test) at 108 research points (at different work stages);
- DMT (flat dilatometer test) at 6 research points (at different work stages);
- PLT (plate load test) at 5 research points for test embankment.

The primary way of using DMT results is to interpret them in terms of common soil parameters. The parameters estimated by DMT is compared and checked with the parameters obtained by CPT results. This methodology called, design via parameters, is the current practice in engineering applications [11]. Constrained modulus from DMT and CPT(U) test results was calculated based on approved methodologies and correlations by Marchetti, S. [11][7] and Robertson, P.K. [10] respectively.

Apart from extensive CPT(U) and DMT testing, also DPM was used in some areas at different stages of dynamic compaction (DC), when CPT(U) was not available. On the test field (see Figure 3) five research points were investigated. First, 1.0 m high embankment was build using mineral material from site compacting it with heavy (at least 15 ton) single drum vibro roller and tests executed. Than additional 0.5 m embankment was made and tests executed repeatedly at the same locations. CPT(U), DPM and also one DMT tests were executed to 6 m depth.

![Figure 3. Test field layout](image)

3. Results
The constrained modulus (Em) after dynamic compaction (DC) was calculated from both CPT(U) and DMT results based on soil behaviour type index (Ic) for CPT(U) [10] and combination of horizontal stress index (Kd), dilatometer modulus (Ed) and material index (Id) [11] values to be able to compare the results 6 research DMT/CPT(U) points – No. 1/2/8/10/20/24 (see Figure 4 – 9).
**Figure 4.** Em correlated at test point No 1

**Figure 5.** Em correlated at test point No 8

**Figure 6.** Em correlated at test point No 2

**Figure 7.** Em correlated at test point No 10
It can be seen that not always constrained modulus (Em) values correlated from CPT(U) and DMT have the same drift in these soils. Analyzing these 6 different research points, it was found that constrained modulus values from DMT correlations tend to be lower (in some cases even more than 2 times lower) than obtained from CPT(U). At higher soil behavior index (Ic) values 1.5-1.6< Ic <2.2 for some reason DMT correlations underestimate Em values. It is reported in literature [11], that special care (with Em correlations) should be taken when silty Sands (siSa) or Silts (Si) tested with DMT. However, further research should be taken in order to correct the correlations available for these Baltic basin Sa, siSa and Si. For the project needs the cautious estimate was taken, assuming the lowest Em values from both correlations. Obviously, it is recommended to use two or more parallel in-situ methods and further interpretations yielding to safer estimations of soil stiffness parameters.

The effectiveness of DC was evaluated by comparing constrained modulus (Em) values both from DMT and CPT(U) correlations before and after compaction. It was found that Em increase is greater from DMT correlations than CPT(U) – from 1.2 times at investigation point No. 20 to 2.5 times at research point No. 8. This finding confirms that DMT test is more sensitive to stress history (overconsolidation due to DC) than CPT(U) test also reported in other studies [11].

It was found from CPT(U), DPM, DMT and also PLT measurements on test fields that the top 0.5 m from the first embankment are loose (see Figure 10), and only after placing second layer (0.5 m) the top of previous one getting compacted. This is likely due to low confining pressure at low depth and therefore PLT test do not represent well the mechanism of compaction since the influence depth of this test can be assumed two diameters of loading plate, which is normally only 2 x 0.3 m = 0.6 m. Instead CPT(U) or DPM (or any other modification of dynamic probing) is recommended.

**Figure 8.** Em correlated at test point No 20  
**Figure 9.** Em correlated at test point No 24
Dynamic probing (in this case DPM) tests were also extensively used not only on trial test area, but also for quality control of DC works at different stages. Further DPM test result N10 (number of hits to penetrate 10 cm into soil) was correlated to cone resistance (qc). Even the correlation was existing and it was used successfully, during the analysis of the test field data it was found that the correlation has depth factor due to DPM rod friction (see Figure 11). This factor was further used for correction of DPM test result interpretations.

Figure 10. Correlated Em from CPT(U) and DMT tests at the test field middle

Figure 11. N10 normalized by cone resistance at the test field investigation points
4. Conclusions

Baltic basin silty Sands (siSa) were explored in terms of dynamic compaction (DC) for the specific case study in Riga, Latvia. It was found that this material is rather easily compactable and soil stiffness can be remarkably increased. Special attention to quality control and assurance was paid in order to understand the effectiveness of compaction and finally come up with the results. It is good to use at least two different methods for determining the stiffness parameters (constrained modulus). In this case Em was correlated from CPT(U) and DMT in-situ test results. Even though the results were not always comparable, especially, when soil behaviour index $1.5-1.6<l_c<2.2$, we were able to get realistic Em values. The defined average constrained modulus (Em) was always greater than 40 MPa in layer of 10 m as required in the design. Further research is essential in order to validate the CPT(U) and DMT correlations for these Sands (Sa) in Riga metropolitan area.

It was also proved that PLT is not always the best method for determining soil compaction for Sand at low depth and better to use CPT(U) or even dynamic penetration (DP) test methods. By building the embankment for warehouse and compacting every next layer supposed to compact the previous one by conventional heavy one drum vibro rollers. It was also found that dynamic penetration test (DPM) parameter $N_{10}$ has good correlation to CPT(U) cone resistance $q_c$ at trial test where test embankment was built in two layers. It can also be noted that trial embankment was built on top of improved area, where all three compaction stages were executed. The results from CPT(U) and DMT approved that the all layers from top to bottom are compacted properly and in this case even greatly exceeding design requirements.

References

[1] J. Han, Principles and Practice of Ground Improvement, Hoboken, NJ: John Wiley & Sons, Inc., 2015.
[2] Menard, L., Broise, Y., “Theoretical and practical aspects of dynamic compaction,” *Geotechnique*, vol. 25, no. 1, p. 3–18, 1975.
[3] Bo M. W., Arulrajah A., Na, Y. M. and Chang M. F., “Densification of granular soil by dynamic compaction,” *Proceedings of the Institution of Ground Improvement*, no. GI3, pp. 121-132, 2009.
[4] S. Varaksin, “Recent development in soil improvement techniques and their practical applications,” *Sols Soils*, Vols. 38-39, pp. 7-32, 1981.
[5] U.S. Department of Transportation Federal Highway Administration, “GEOTECHNICAL ENGINEERING CIRCULAR NO. 13 GROUND MODIFICATION METHODS-REFERENCE MANUALVOLUME I&II,” National Highway Institute U.S. Department of Transportation Federal Highway Administration, Washington, DC 20590, 2016.
[6] J. Schmertmann, “Guidelines for Using the CPT, CPTU and Marchetti DMT for Geotechnical Design,” U.S. Dept. of Transportation, Federal Highway Administration, Office of Research and Special Studies, Report No. FHWA-PA-87-023+24, Vol. 3-4, 1988.
[7] S. Marchetti, “In Situ Tests by Flat Dilatometer,” *ASCE Jnl GED*, pp. Vol. 106, No. GT3, 299-321, March 1980.
[8] J. Schmertmann, “Dilatometer to Compute Foundation Settlement,” in *In Situ '86 ASCE Spec. Conf. on Use of In Situ Tests in Geotechnical Engineering*, Virginia Tech, Blacksburg, VA, 1986.
[9] Monaco, P., Totani, G., Calabrese, M., “DMT-predicted vs observed settlements: a review of the available experience,” in *2nd International Conference on the Flat Dilatometer*, Washington DC, 2006.
[10] Kurek, N., Balachowski, L., “CPTU/DMT Control of Heavy Tamping Compaction of Sands,” in *DMT’15 3rd International Conference on the Flat Dilatometer*, Rome, Italy, 215.
[11] R. Lukas, “Dynamic Compaction – Geotechnical Engineering Circular No. 1,” U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1995.

[12] Marchetti S., Monaco P., Totani G. and Calabrese M., "The Flat Diliatometer Test (DMT) in Soil Investigations," International Conference On In Situ Measurement of Soil Properties, Bali, Indonesia, 2001.

[13] P. K. Robertson, “Interpretation of cone penetration test - unified approach,” Canadian Geotechnical Journal, vol. 46, no. 11, p. 1337–1355, 2009.

[14] S. Marchetti, “Some 2015 Updates to the TC16 DMT Report,” in 3rd DMT Conference, Rome, 2015.