# PMTs and CPTs interacting as design criteria and quality control on a large soil improvement project in Cuxhaven (Germany)

## PMTs et CPTs comme critères pour le design et le contrôle de qualité sur un grand projet d'amélioration des sols à Cuxhaven (Allemagne)

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Abstract: A factory is planned to be built at the mouth of the Elbe River in Cuxhaven, Germany. Soft soils at the site required the use of special construction measures, which included a combination of piling and ground improvement. The short construction timespan of 1.5 years rendered preloading in combination with vertical drains impossible. Since the ground improvement works were scheduled for the cold period between December and March, the use of water and concrete would have been complicated. BVT DYNIV thus opted for the use of Dynamic Replacement columns. The use of both pressuremeter tests and cone penetration tests for quality control allowed for the comparison of test results.

RÉSUMÉ : Une usine devrait être construite à l'embouchure de l'Elbe à Cuxhaven, en Allemagne. Les sols souples sur le site nécessitaient l'utilisation de mesures de construction spéciales, qui comprenaient une combinaison de pieux et d'amélioration du sol. Le temps de construction court de 1,5 ans a rendu la solution préchargement en combinaison avec drains verticaux impossible. Comme les travaux d'amélioration du sol étaient prévus pour la période froide entre décembre et mars, l'utilisation de l'eau et du béton aurait été compliquée. BVT DYNIV a ainsi opté pour l'utilisation des colonnes de remplacement dynamique. L'utilisation de tests de pressiomètre et de tests de pénétration des cônes pour le contrôle de la qualité a permis de comparer les résultats des essais

KEYWORDS: BVT DYNIV, soil improvement, Dynamic Replacement, Dynamic Compaction, survey, Pressiometer, PMT, CPT, correlation

## 1 PROJECT DESCRIPTION

A factory for wind power generators is planned to be built at the mouth of the Elbe River in Cuxhaven, Germany. The principle reason for the choice of this location was that it is close proximity to the North sea, which makes the transport to the offshore sites easier and more cost efficient.

The site occupies a surface area of 170 000 m² and is situated on a hydraulic fill which caracterizes the geotechical conditions of this project.

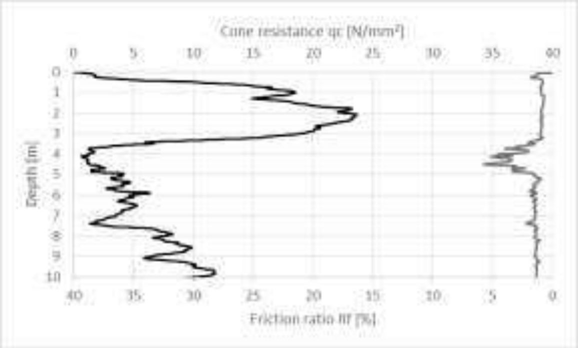

Figure 1. CPT pre-test. A typical pre-test CPT of the project which is characterized by the thick clay layer between 4 and 6 m depth.

### 1 .1 *Geotechnical Background*

The ground at the site is characterized by the following layers from top to bottom:

- A hydraulic fill, roughly 3,0 m thick. It consists of sand of variable density: from medium dense to very dense.
- Below that a layer of clay, up to 3,0 m thick. It also contains some organic material
- Loose to medium dense sandy layer, approximately 15,0 m thick.
- In some parts of the area, a second layer of clay up to 2,5 m thickness have been located at the bottom of this layer
- Finally, the subsoil with a maximum depth of 25 m of well compacted pleistocene sands, which form the base layer for the pile construction.

The stable water table is located at about 5 m deep. On one third of the area a higher artificial water level has been observed.

### 1 .2 *Technical Requirements*

A total area of 133 000 m² required compaction. This area was divided into six different parts which have different design loads ranging between 40 kN/m² and 180 kN/m² depending on future utilization. The factory hall covers approximately 60 000 m². For this area an important design criterion was the minimization of differences in settlement between the base slab and the footings which are founded on piles. The whole construction time was limited to only 1.5 years, too short a period for the use of vertical drains in combination with a surcharge for preloading.

Since the construction period for ground improvement was scheduled in the cold and windy period between December and March, it was important to implement a method that works under difficult weather conditions and can guarantee a high daily production output. BVT DYNIV carried out the ground improvement works for this project, opting for Dynamic Replacement (DR) columns because this method requires no additional water and the use of cable cranes is also possible in high wind speeds.

### 1 .3 *Method description*

Dynamic Compaction (DC) is a technique in which a weight is lifted up by a cable crane and dropped on the ground surface. The ground is compacted by the energy of the drop weight hitting the surface during impact (Ménard,1974). Although the method is relatively simple, it requires a large and intensive quality control in order to guarantee the success of compaction. However, DR was used in this project because the use of DC is restricted to non-cohesive soils such as sands and gravels.

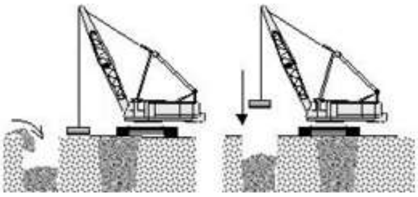

Figure 2. Dynamic Replacement. The soil is compacted and the hole created by the impact is refilled with loose material which is also compacted.

The difference between the two methods is that material is added during DR. The work scheme is shown in Figure 2. The crater created by the impact of the drop weight is filled with gravel or other loose material. The ground is thus improved in two ways: first, through the compaction and drainage of the original soil and, second, through the creation of a soil reinforcement columns of compacted granular fill.

## 2 WORK EXECUTION

An extensive ground investigation program was undertaken during the design phase. This included 100 cone penetration tests (CPTs), 38 exploration boreholes and 18 dynamic probe test. The high data quality and grid resolution enabled the site to be divided into four sections, based on clay thickness.

Before BVT DYNIV commenced works at the site, a trial field for compaction was created. Here, pressuremeter tests (PMTs) were done adjacent to cone penetration tests (CPTs), to allow for a comparison of the two methods and an interpretation of soil stiffness based on CPTs data.

### 2 .1 *Design*

As mentioned above, the site was divided into four zones according to the thickness of the clay. Depending on that, the energy required for compaction works was defined. Surface ponding indicated saturation in an area of approximately 30 000 m². In that place it was not possible for rain water to pass through the clay. Because of that compaction was difficult or even impossible. Here, prefabricated vertical drains (PVDs) were installed.

### 2 .2 *Work description*

Five cable cranes fitted with 20 tons drop weights were employed to complete the compaction of 133 000 m² in the scheduled time. The idea was to work with means of pre-excavation to take out the well compacted sand layer on the top and to penetrate the clay while adding gravel. The compaction was done in two phases in a rectangular grid.

In the areas, where the water level was too high, some PVDs were installed and allowed water to pass through the clay layer and the overlaying sand layer to dry out. The drains also allowed water to escape to the surface, thereby preventing the buildup of excess pore water pressure during compaction.

### 2 .3 *Supporting quality control*

The approval criterion for the ground improvement works was the average soil stiffness. This was tested by comparing the results of PMTs conducted in and between DR columns. In each of the 62 boreholes, a test every meter was carried out to a depth of 10.5 m. Based on these measurements, the average stiffness was determined.

CPTs were conducted in addition to the PMTs. The advantage of using this method was its high speed and low cost in comparison with PMTs. Another benefit of using CPTs was that the results could be compared with the CPT data from the original ground investigation.

The two testing methods were employed in parallel to make use of the advantages of each method. While the aim of conducting PMTs was to measure exact values of soil stiffness, the CPTs were done in order to gain additional information for optimization of the workflow. Since also the pre-tests were done with CPT a comparison could be made very well.

Figure 3. Job site picture. Cable cranes on the site in Cuxhaven in front of the Elb.

## 3 COMPARING THE RESULTS OF PMT & CPT

PMTs and CPTs done at or near the same point provided an opportunity to compare both testing methods and to compare the correlations existing between the cone resistance measured in CPTs and the limit pressure measured in the PMTs. Such a relationship would allow for the estimation of the Young's modulus based on CPT results.

To find an answer on that question the results of the tests were compared. Figure 4 shows the CPT results done at the same point where the CPT shown in Figure 1 was done after compaction. It can clearly be seen that the 2 m thick clay layer was reduced to a thickness of about 0.5 m and that the ground was compacted and improved up to a depth of 8 m.

Figure 5 shows the PMT results from the same point plotted against the CPT results. It is evident that there is a relationship between the values of cone resistance and Ménard modulus.

As written in literature depending on the soil type there is a certain value for the ratio of $q_c$* and $p_l$*(Baguelin et al. 1978 and Briaud 2013). Since the CPT test is a rather destructive test, the investigation of the correlation on this project was mainly focused on the ratio $q_c^*/p_l^*$ not on $E_m/q_c^*$

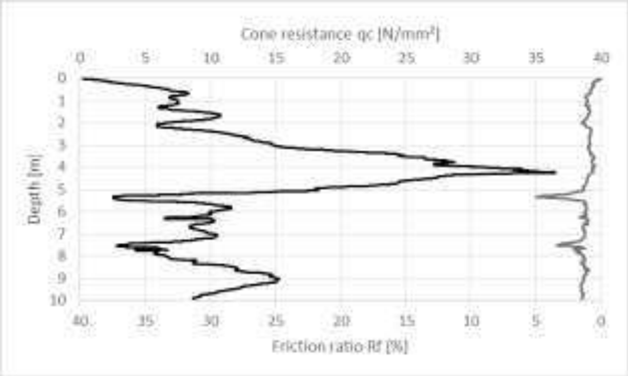

Figure 4. CPT after the compaction works. The layer of clay has been compacted to less than 25% of his previous thickness.

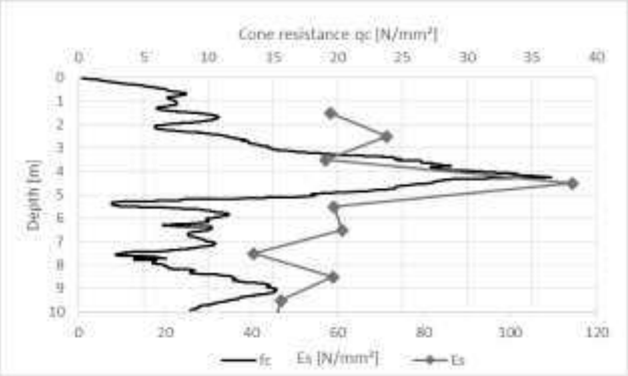

Figure 5. Comparing PMT and CPT.

Since in this project 62 PMTs and more than 100 CPTs in and between the DR-columns were done, a very large amount of data was collected and allowed a closer look on the ration $q_{c*}/p_l$*.

Therefore, the average value of $q_c$* matching the depth where the PMT was done was compared with $p_l$*. This was done with different PMTs which were done close to CPTs. The result is shown in table 1. It can be seen, that the values founded in this project match the values that are mentioned in literature.

The measured values in the hydraulic fill, in the clay and the gravel fitted very well the ones found in the literature. However, the ratio $q_c^*/p_l^*$ observed in the sand below the pillars shows a large variation. Such variations on different soil improvement works have been already reported (Hamadi et al., 2010).

In Cuxhaven, the further analysis of the results of the deep sandy layers concludes that followings reasons could be the origins of the discrepancy:

- Variation of the dissipation of the pore water pressure
- Presence or not of vertical drains
- Presence in few areas of lenses of silty sand

Some PMTs showed that a little increase in $p_l$* within a period of four weeks, after execution of the pillars have been observed, whereas the CPTs performed at the same location showed a large increase in $q_c$*, more than 80 %, for the same period.

It appeared that CPT results seem not to be a reliable piece of device as control for soil improvement works during execution. Even the use of dissipation test CPTU were not helpful for a good prediction of the improvement of the soil parameters, while the decrease of the pore pressure was not uniform. Its interpretations were difficult not only because of the level of the water table but also due to the variation of the applied energy during the DR execution.

Table 1 $q_{c*}/p_l$* ratio, the ratio of $q_{c*}$ and $p_{l*}$ in different soil layers of the project of Cuxhaven compared with the values mentioned in literature

| | $q_c$* | $q_c^*/p_l^*$ Baguelin et al. (1978) | $q_{c*}/p_l$* mean values mesasured in Cuxhaven | Standard deviation |
|---|---|---|---|---|
| **Hydraulic Fill** | > 20 MPa very dense | 5 to 12 | 9.56 | 1,11 |
| | < 20 MPa dense | 5 to 12 | 7.29 | 0,80 |
| **Clay** | 1 < $q_c$ < 2.5 very soft clay | Close to 1or between 2.5 to 3.5 | 2.24 | 0,47 |
| **Gravel** | > 20 MPa dense | 5 to 12 | 9.32 | 1,02 |
| **Sand** | >10 MPa | 5 to 12 | 4,59 | 2,24 |

Some CPTs have been performed during piling, approximately 10 weeks after the execution of the soil improvement works. These results were in accordance with the ones which were already measured with the PMT.

## 4 CONCLUSION

The CPTs can give a quick geological overview of the executed pillars but seem not to be a reliable test for the estimation of the soils parameters at short time during Dynamic Replacement works. Because the works were performed in very little delay, the choice with the PMT as quality control test reaveled to be the best most reliable one. Longterm CPT tests confirmed the PMT results. In relation to large soil improvement works with a short construction period this means that quality control is an issue because CPTs cannot give accurate results in a short time.

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