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Ground improvement for wind energy oplants in Germany

Amélioration de sol supportant les éoliennes en Allemagne

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ABSTRACT

More than 21.000 wind energy plants with a capacity of 24.000 MW have been installed in Germany. Last years' general tendency goes towards offshore wind farms, as the average wind speed is usually considerably higher and wind blows more regularly than on land.
The current design of ground improvement for wind energy plants is highlighted and successful examples of wind energy plant foundations are given including vibro compaction, vibro replacement stone columns and vibro concrete columns.
Finally recommendations are given for execution and quality control.

RÉSUMÉ

Plus de 21 000 éoliennes avec une capacité de 24 000 MW ont été installées en Allemagne. La tendance des dernières années est la mise en place de parcs éoliens offshore, du fait que la vitesse du vent y est bien plus élevée, et que le vent y souffle de manière bien plus régulière que dans les terres.
Le dimensionnement actuel des améliorations de sol supportant les éoliennes est ici présenté selon les recommandations et certifications nationales.
Des exemples fructueux de fondations d'éoliennes sont donnés, incluant des méthodes de vibrocompactage, de colonnes ballastées et de colonnes ballastées injectées.
Des recommandations sont enfin fournies pour l'exécution et le contrôle de qualité.

Keywords: wind, ground improvement, vibro compaction, vibro stone columns, vibro concrete columns

1 DESIGN OF WIND ENERGY PLANTS

Wind energy plants exist in different types. They differ in altitude of the hub and diameter of the rotor. To each of these types of wind energy plants a structural standard exists which specifies certain demands for the soil. If the soil does not fulfill these specifications, it is necessary to improve it to meet the specified demands.

The design of ground improvement considers the dynamic oedometric modulus $E_{S,dyn}$ and the dynamic torsional spring stiffness $K_{\varphi,dyn}$ corresponding to the statics of the type of wind energy plant.

The oedometric modulus after Klein (2001) can be determined with the static oedometric modulus based on a conventional settlement computation.

The following diagram shows the ratio between the dynamic oedometric modulus and the static oedometric modulus.

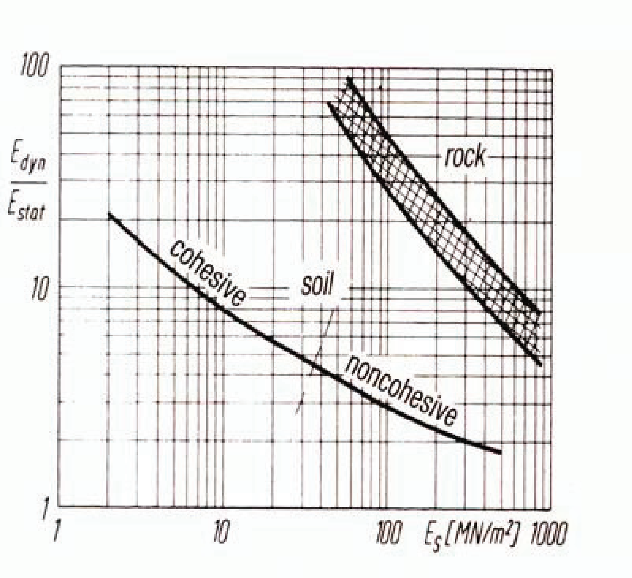


Figure 1. Ratio dynamic oedometric modulus/static oedometric modulus. Klein (2001)

The dynamic torsional spring stiffness is calculated (depending on the shape of the footing) with the following formula:

Square footing:

$$K_{\varphi,\,dyn} = \frac{\alpha^3 \cdot (1 - \nu - 2\nu^2)}{4 \cdot (1+\nu) \cdot (1-\nu)^2} \cdot E_{S,\,dyn}$$

with
ν = Poisson's ratio of the soil
a = side length of footing

Circular footing:

$$K_{\varphi,\,dyn} = \frac{4 \cdot r^3 \cdot (1 - \nu - 2\nu^2)}{3 \cdot (1+\nu) \cdot (1-\nu)^2} \cdot E_{S,\,dyn}$$

with
r = radius of footing

A failure in the year 2002 showed the importance of a sufficient bearing capacity of the soil. A wind energy plant including its concrete foundation in the wind farm Ellenstedt close to Vechta was overthrown during a hurricane. It is assumed that the cause was a foundation problem. The Germanic Lloyd confirms, that the foundation was not built according to the latest engineering standards, TAZ (2002).

The foundation was embedded 80 cm in the ground; a soil improvement hasn't taken place.

Figure 2. Overthrown wind energy plant in the wind farm Ellenstedt without soil improvement

2 WIND ENERGY PLANTS FOUNDATION EXAMPLES

Soil improvement for wind energy plants can be accomplished with different ground improvement methods which are presented hereafter.

1. Wind farm Uelitz: Vibro Compaction (VC), 2005

2. Wind farm Klosterfelde: Vibro Replacement (VR), 2002

3. Wind farm Brauel: Vibro Concrete Columns (VCC), 2002

2.1 Wind Farm Uelitz, Vibro Compaction

The Nordex AG built a wind farm on 3 subareas (Uelitz, Sülte und Lübesse) in 2005 close to Schwerin. The wind farm consists of 17 wind energy plants of the types:

- NORDEX S77/R90 MT (altitude of hub 90m, diameter of the rotor 77 m),

- •NORDEX S77/R100 MT (altitude of hub 100m, diameter of the rotor 77 m),
- •NORDEX N90/R80 MT (altitude of hub 80m, diameter of the rotor 90 m).

Those wind energy plants produce 55.000 megawatt per hour every year, which corresponds to the energy demand of 15.000 households.

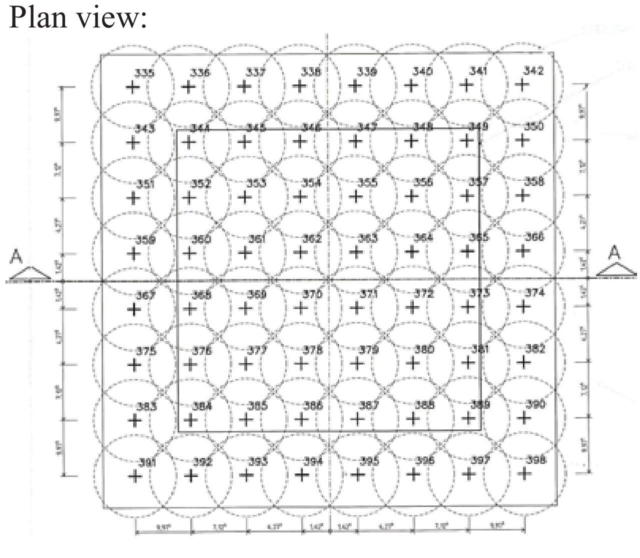
The geotechnical report concludes that the subsoil is similar at the 17 locations. There have been found only non-cohesive soils of fine and medium sized sands. Its bearing capacity did not suffice to carry the weight of the wind energy plants. The ground had to be improved and the settlement had to be decreased. In this case it would not have been economical to excavate the loose sand and compact it in layers. Disadvantageous is the quite high groundwater level. It varies depending on the location in a depth between 2 and 5 m below ground level.

A replacement of the soil would have only been possible with a time consuming lowering of the groundwater.

For the improvement of the foundation at the wind farm Uelitz, the deep vibro technique namely vibro compaction was used. Vibro compaction is used in coarse grained soils, as e.g. loose sands and gravels.

With vibro compaction, the relative density of the soil is increased. Vibro compaction is independent of the groundwater level and provokes a decrease of 5 to 15% of the soil volume.

Plan view:



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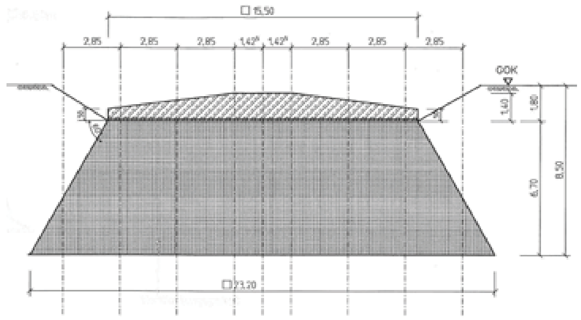


Figure 3. Layout of Vibro Compaction

After the execution of vibro compaction the pit was excavated. Then a redensification of the subgrade with a roller and afterwards the installation of the granular sub-grade for the footing of the energy plant have been done.

The footings possess a square shape with a side length of 15.5 m (NORDEX N90/R80 MT) or a circular shape with a diameter of 14.9 m (NORDEX S77/R100 MT). The thickness of the reinforced concrete footing adds at the border up to 0.5 m (square footing) and 1.67 m (circular footing).

Keller accomplished the soil improvement in the wind farm Uelitz with depths ranging between 4 and 9.5 m. The amount of compaction points adds up to 45 for circular footings and to 64 for square footings. For quality control two static penetration tests for each footing have been accomplished showing a cone restistance of more than 10 MPa which was specified.

2.2 *Wind Farm Klosterfelde, Vibro Replacement*

In the town of Wandlitz close to Berlin, six wind energy plants (ENERCON E-66, altitude of hub 67 m) have been built in the year 2002 between the villages Klosterfelde and Stolzenhagen on an agricultural area. They possess circular footings with a diameter of 16.4 m.

In the geotechnical report (12 borings down to depths to 10.0m and 2 heavy dynamic probings down to depths of 11.0 m) it was stated, that three wind energy plants needed soil improvement.

The soil layers consist of:

- Loose to dense fine and coarse sands as well as sandy fine gravel and silts (DIN 18196: SW, SE, GE, SU) down to -2,5m beneath ground level
- Boulder clay, soft to firm, slightly plastic gravelly, silty, clayey sand as well as silty sand (DIN 18196: ST, SU) between -2,50 m and -5,0 m beneath ground surface
- Underneath there are sands as described above

The water level ranges in each bore hole between 0.9 m and 2.1 m with groundwater occurring in the bottom level of the excavation pit.

To fulfil the foundation requirements of the wind energy plants, there had to be a soil improvement before the installation of the footings.

As this soil consists of fines of more than 5%, it does not admit a sufficient self-compaction. Therefore vibro replacement was chosen instead of vibro compaction. With this method the depth vibrator penetrates the soil in a predetermined grid down to the required depth. As it is pulled upwards in stages, gravel leaves a stone feed tube. During the repenetraton phase, the soil is replaced. In this way a continuous gravel-column from the bottom to the top is installed.

In terms of equipment a vibrocat with a bottom feed vibrator was used. To receive a high shear resistance which leads to high stiffness of the column, as well as a good interlocking with the soil, angular gravel with a grain size of 2 mm to 32 mm was used. The compaction depth ranged between 7.0 m and 8.0 m. For each circular footing 101 vibro replacement columns were built.

A quality control of the parameters (e.g. compaction depth, amperage and vertical activation force) took place at every single column via an electronic digital display as well as by a protocol.

Figure 4. Compaction Example of construction of a Vibro Replacement Column

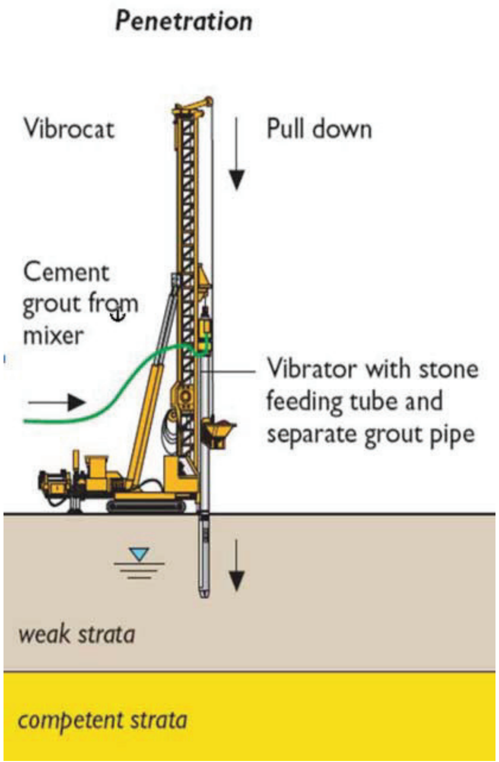
2.3 *Wind Farm Brauel, Vibro Concrete Columns*

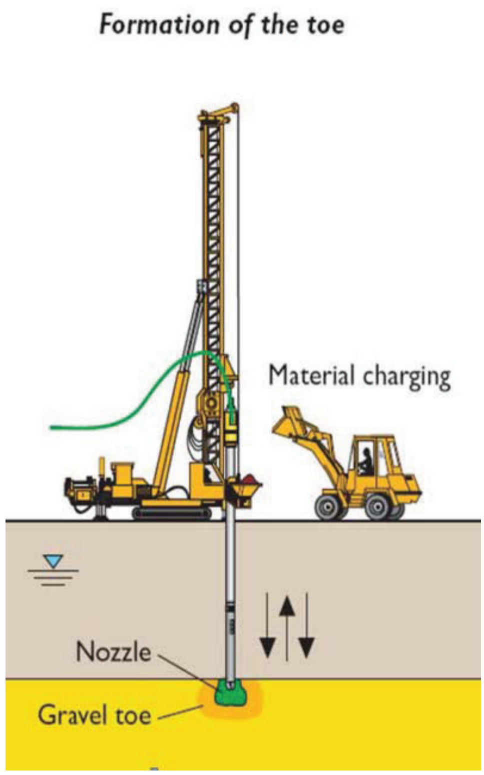
North of the town Brauel, in the district Uelzen (Lower Saxony) four wind energy plants of the type Fuhrländer MD-77 have been built in 2002 with an altitude of 100 m on an agricultural used area. Their capacity was 1.4 MW each. The foundation was made of octagonal footings with outer dimensions of 14 x 14 m. The ground was investigated with 4 borings down to a depth of 7.0 m and 2 heavy dynamic probings down to a depth of 12 m. As a conclusion to these soundings a soil layer of soft boulder clay down to 6 m depth as well as stiff clay was investigated.

In this project ground improvement was performed with vibro concrete columns “System Keller”. Vibro concrete columns belong to the unreinforced pile like foundation elements. They are used within organic soil layers or if the loads are high.

Vibro concrete columns are built in the same way as the columns described under 2.2 with vibro replacements. Instead of gravel a premixed concrete of the quality C 12/15 up to C 16/20 is used.

Under each octagonal footing 68 vibro concrete columns were built.





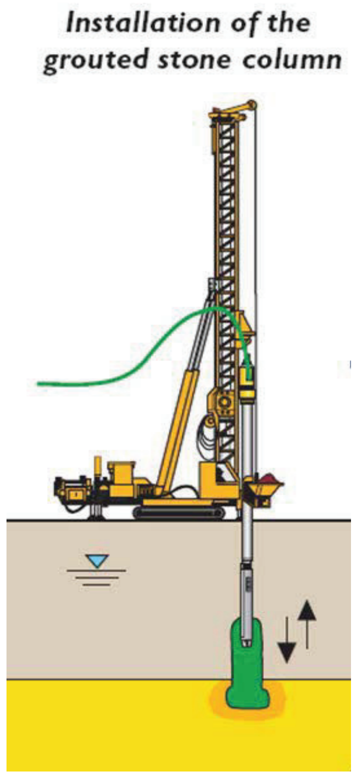


Figure 5. Principle of Installation of Vibro Concrete Columns

CONCLUSION

Wind energy plants in Germany were founded using different types of ground improvement methods which may be a cost effective alternative to piles. However, no ground improvement at all may lead to overturning as shown in fig. 2.

After the current state of the art design was highlighted three successfully completed examples with vibro compaction, vibro replacement stone columns and vibro concrete columns are presented.

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