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Solving challenges of operational areas for renewable energy infrastructure

Relever les défis des zones opérationnelles pour les infrastructures d'énergie renouvelable

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ABSTRACT: The renewable energy sector requires new infrastructure for development, prefabrication, storage, installation and operation. Most often, the subsoil conditions of the construction facilities, roads and working platforms are characterised by weak clay, organic soil or sand deposals of low density or a combination thereof. The size of loads from e.g. turbine parts, foundation- or tower segments or cranes for installation are challenging. Resulting loads from e.g. low motion vehicles and crane hardstandings are characterised by high deviator-stresses. Anyhow, only limited differential settlements are accepted. To scope with these issues, a wide range of foundation techniques are used as e.g. floating platforms, dynamic compaction, vertical bearing elements or piling. For all techniques, special attention has to be paid on local bearing capacity on the surface, in combination with total and differential settlement. The paper presents a major project on the example of a large nacelle factory, and addressing requirements on working platforms, making use of the combination of different foundation techniques. The geotechnical design by combining analytic models and numerical analysis are presented and discussed.

RÉSUMÉ: Le secteur des énergies renouvelables nécessite de nouvelles infrastructures pour le développement, la préfabrication, le stockage, l'installation et l'exploitation. Le plus souvent, les conditions du sous-sol des installations de construction, des routes et des plates-formes de travail sont caractérisées par des dépôts d'argile faible, de sol organique ou de sable de faible densité, ou par une combinaison de ces éléments. La taille des charges provenant, par exemple, des pièces de l'éolienne, des segments de la fondation ou de la tour, ou des grues pour l'installation, est un défi. Les charges résultant, par exemple, de véhicules à faible mouvement et de grues sont caractérisées par des contraintes de déviation élevées. Quoi qu'il en soit, seuls des tassements différentiels limités sont acceptés. Pour faire face à ces problèmes, un large éventail de techniques de fondation est utilisé, comme par exemple les plates-formes flottantes, le compactage dynamique, les éléments porteurs verticaux ou les pilotis. Pour toutes ces techniques, une attention particulière doit être accordée à la capacité portante locale de la surface, en combinaison avec le tassement total et différentiel. L'article présente des projets majeurs sur l'exemple d'une grande usine de nacelles, et aborde les exigences sur les plates-formes de travail, en utilisant la combinaison de différentes techniques de fondation. La conception géotechnique par la combinaison de modèles analytiques et d'analyses numériques sont présentés et discutés.

Keywords: Working platforms; dynamic soil compaction; geogrids; case study; renewable energy.

1 INTRODUCTION

The south-eastern port area of the city of Cuxhaven in Northern Germany is being planned as the German Offshore Industry Centre, where several production facilities for offshore wind turbines and other components are based. The development of the south-eastern harbour extension was carried out by pumping sands from the North Sea several years ago. Due to the original topography and genesis, the flushing fields in the area of the harbour extension have special geotechnical features. In the tidally influenced area of the river Elbe, there is a soft to pulpy clay layer with widely varying thicknesses on medium-density tidal sands. This is covered by the approximately three metre thick layer of sand, which is loosely to densely compacted (Figure 1).

The eastern area of the harbour extension is used for a production facility for offshore wind turbines. The high stresses of up to 180 kN/m² from the construction and production in combination with low permissible settlements and a subsoil with a 2.0 m to

3.0 m thick layer of clay made special foundation engineering measures unavoidable. Following the evaluation of the ground investigation, the foundation concept envisaged a foundation for the base slab of the production hall, the office and restaurant building, the outbuildings and the circulation areas on a geogrid-reinforced foundation pad over a columnar ground improvement. Despite the high loads in some areas, the client wanted to do without a shallow deep foundation. The highly loaded column foundations, the crane runways and the sprinkler tank were piled.

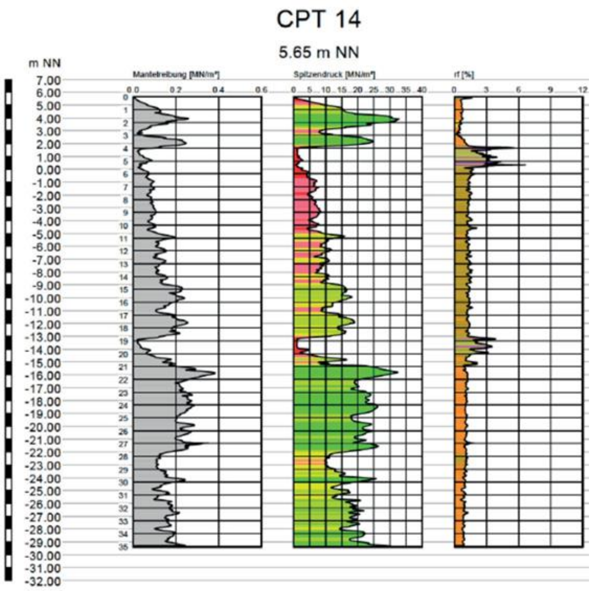

Figure 1. Cone penetration Test Profile, exemplarily.

The columnar soil improvement measure was carried out in the area of the existing access road and the parallel rainwater channel (DN 2,000, GRP material) using vibro-compaction (approx. 200 RSV columns) and in the majority of the area by means of dynamic deep compaction (approx. 5,300 DYNIV® columns) over an area of approx. 130,000 m².

Additional, Cuxhaven is preferred also for monopile production. Monopiles are to be temporarily until they are used in offshore construction. Due to the very large dimensions of the monopiles with diameters of 12 m to 14 m, a length of up to 130 m and a total weight of up to 3,500 tonnes, an economical foundation concept had to be developed for the total available area of just under 330,000 m². In addition to the aforementioned soil conditions of the south-eastern area, the inhomogeneous soil conditions in the area of the formerly approx. 4.00 m deep drainage ditch, which was backfilled in the course of backfilling, required special attention for a floating working area. The surface is to be designed in such a way that it can be driven over by the special transport vehicles for the monopiles.

From a geological perspective, the construction sites are located in the area of Holocene mixed mudflat deposits, which are strongly influenced by their proximity to the water and by the tides. There are Holocene, backfilled sands with a thickness of around 1.70 m to 4.00 m and a very heterogeneous bedding density (very loose to dense).

Below the fill, the subsoil exhibits a typical sequence of Holocene tidal deposits, which can be visualised as follows:

- locally existing lenses of tidal sands with a maximum thickness of 3.50 metres.
- upper clover horizon of varying thickness up to 10.00 m with a soft to stiff consistency. This clay is described as clayey silt with varying degrees of organic content and has low permeability.
- 5.00 m to approx. 17.00 m thick tidal sand layer in loose to medium-dense bedding,
- locally occurring, lower, up to 15.00 m thick clover layer with a soft to stiff consistency,
- From about 18.00 m below ground level, Pleistocene sands in medium-dense to dense compaction.

2 CONSTRUCTION OF NEW PRODUCTION FACILITYS

2.1 Requirements and foundation concept

In total, for the production of wind turbines, an area of 133,000 m² had to be improved. This was divided into six sub-areas, which were differentiated according to their subsequent use. The design load on the individual areas varies significantly between 40 kN/m² and 180 kN/m². Just 60,000 m² of the area is accounted for by the production hall, for which the settlements occurring were to be limited to such an extent that settlement differences incompatible with the structure could be avoided.

The foundation concept envisaged a vertical transfer of the large individual loads in the area of the columns via piles into the Pleistocene layers and a shallow-founded hall base in the other areas. Due to these different foundation systems, large settlement differences were to be expected, which could not be withstood without further geotechnical measures. It was therefore necessary to improve and homogenise the settlement-relevant clays.

In addition to the challenging technical constraints, the time pressure was a decisive factor in this construction project. For this reason, consolidation using vertical drains and ballast fill, which can be used in similar construction projects, was not an option. As the planned construction period fell between the winter months of November and March, downtimes due to weather conditions had to be minimised.

After a variant test, dynamic intensive compaction with a diameter of over 2.50 m and the addition of foreign material was selected.

As part of a calibration field, a grid dimension of 7.00 m was defined in two phases. This results in a centre distance of 4.95 m. Figure 2 shows the corresponding grid scheme.

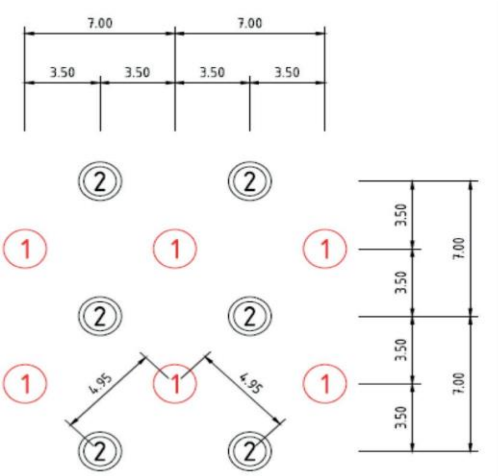

Figure 2. DYNIV® column grid with two offset phases.

Figure 3. Execution of dynamic compaction.

The work sequence provided for the removal of the partially very firm layer of cover sand layer by means of a preliminary excavation and the compaction of the underlying clay with the addition of coarse-grained material. The crater was then backfilled with the pre-excavated material and comparable sand, whereby the installation was carried out in layers. A total of around 5,300 DYNIV® columns were produced, with five machines achieving a peak output of 3,400 m² per day (Figure 3). The amount of material added was adapted to the soil parameters. While between 5 m³ and 10 m³ of crushed stone (base course material with crushed material, 0/32 mm grain size) was usually added to a compaction point, up to 51 m³ of crushed stone was added in areas where high water content was encountered.

2.2 Design of the load distribution layer

In order to ensure optimum load transfer into the compacted columns, a two-layer geogrid-reinforced foundation pad with a total thickness of 75 cm was designed as load and settlement distribution layer. This adaptable, ductile system can compensate for settlement differences resulting from different loads. The design required a long term design yield strength of 1,680 kN/m (per layer) considering creep and installation damage, which could be covered by a biaxial polyester geogrid Secugrid 120/120 Q6 with a short-term strength of 120 kN/m² (md and cmd) to be sufficient to ensure load transfer.

The serviceability verification could not be performed according to EBGEO, as the predefined boundary conditions (significant difference in bedding modulus of rigid column to soft soil > 75) were not met by the DYNIV® columns. Thus, the design was based on the differential equation as provided by Zaeske (2001), documented by Geduhn & Vollmert (2005), taking the column and subsoil stiffness into consideration.

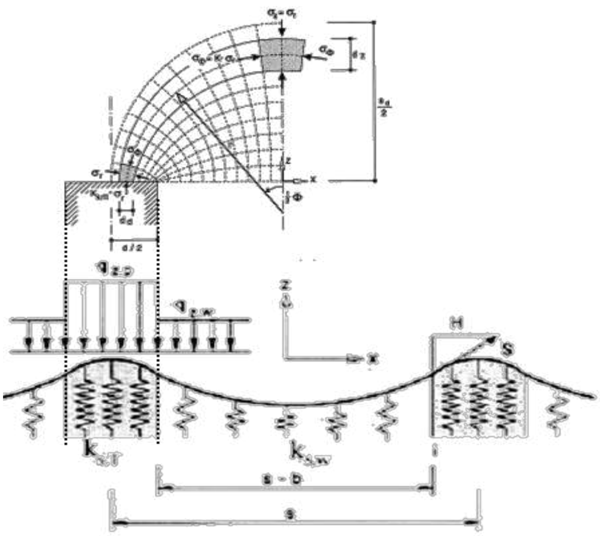

Figure 4. Principle model of the elastic embedded geosysnthetic between vertical bearing elements prone to settlement, arching model according to EBGEO.

Figure 4 shows the model, taking the stiffness of the vertical bearing elements into account. The verification of the static system resulted to a degree of utilisation of 0.54 << 1.0, thus the ultimate limit state (ULS) was verified.

Beside ULS, the serviceability limit state (SLS) had to be focussed, as the allowable differential settlement was limited to less than 1.5 cm. The finite element method (PLAXIS 2D and PLAXIS 3D) was used, taking into account a linear elastic, ideally plastic model with the Mohr-Coulomb failure criterion. Beside taking into account the long-term design yield stiffness, the calculation of the two biaxial geogrids was carried out with a predefined plasticity limit. For other, more powerful material models, with which more realistic deformation predictions would have been possible, it was not possible to determine further material parameters due to the tight deadlines.

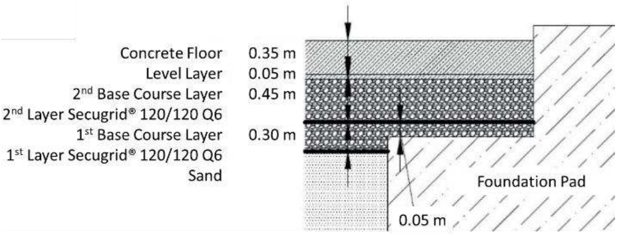

Figure 5. The two-layer, biaxial geogrid in the area of a reinforced concrete foundation (Dr Beuße).

In the area of the hall foundations, the biaxial geogrid layers were arranged as shown in Figure 5, so that notch and shear stresses within the concrete floor are reduced and avoided.

2.3 Installation

Figure 6. Interlocking of base course material and geogrid, compaction with the help of plate compactors (2nd installation level).

During the tender phase, the general contractor had specified Secugrid® 120/120 Q6 from Naue GmbH & Co. KG, as geogrid reinforcement and stabilisation in the first and second layer. Compaction test in a test environment verified the compatibility of the base course material crushed gravel 0/45 mm up to a bearing capacity (plate load test) of 150 MN/m². For this bearing capacity, a compaction of $D_{Pr} \geq 100\,\%$ was verified. The installation guideline required the installation of the base course material by introducing shear forces, so that the geogrid is slightly prestressed and the gravel will be pushed into the open grid structure to ensure proper interlocking of the stiff geogrid structure with the base course grain structure. Figure 6 gives an impression of the interlocking effect.

Figure 7. 1st installation level of the geogrid reinforcement.

The first geogrid layer was laid on the post-compacted sand subgrade (Figure 7). As shown in Figure 8, the second layer of the foundation pad was placed over the individual foundations up to the rising structural elements on a gravel base course.

Figure 8. 2nd installation level of the geogrid reinforcement in the production hall area.

2.4 Safety of construction and transport equipment

The projects in Cuxhaven indicate exemplarily, that weak subsoils covered by relatively thin medium-dense to dense compacted sandy layers are sensitive to differential settlement. Furthermore, the stability of heavy equipment against ground bearing failure as well as against punching has to be ensured. In some cases, especially in large operational areas for the renewable energy sector as Cuxhaven, extraordinary loads have to be considered from the components itself, or transport vehicles to handle components as e.g. offshore tower segments with dimensions of e.g. 130 m length and 15 m diameter. The dimensions can even exceed the example as given in Figure 9, which represents an equalized load of approx. 110 kPa. Loads like these, demand a special attention to consider weak soil layers even in higher depth, as typically needed for road vehicles.

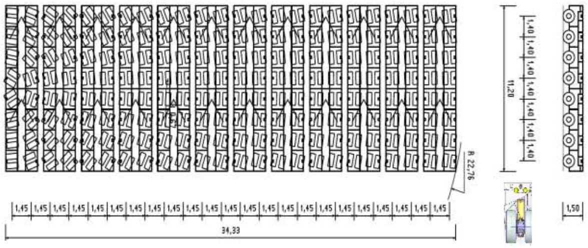

Figure 9. Example of transport vehicle dimensions 34m x 11m with heavy loading up to 120 kPa equalized load.

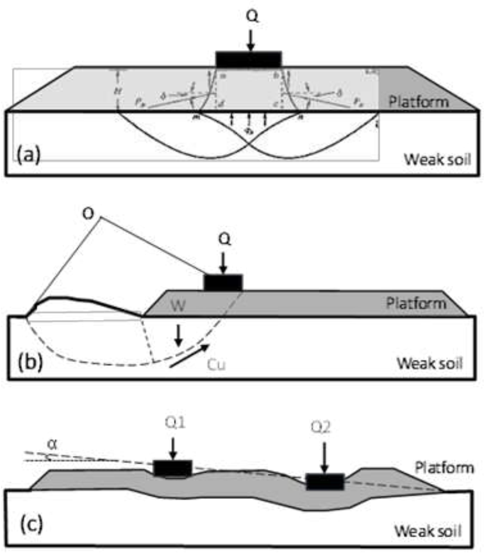

Figure 10. Failure modes to be considered for working platforms as well as for transport devices with large dimensions.

Thus, the punching resistance of the entire structure had to be checked by appropriate measures. Khansari et al. (2023) discussed several aspects of designing operational areas and working platforms, taking thin cover layers and weak subsoil conditions into consideration. Figure 10 outlines the three most relevant aspects, which are considered in design.

Complementing analytical approaches, finite element methods, 2D as well as 3D, allow to calculate the safety level by phi-c-reduction. Therewith, deformation-consistency can be considered more appropriate than using analytical models only. Strain conditions calculated, e.g. on the bottom of asphalt pavements, allow to discuss not only the absolute strain, but also the level of prestressing the system and, comparing with failure strains of asphalt, the tolerance for long term use.

CONCLUSION

Operational areas for renewable energy demand the development of large areas, often placed in locations sensitive to settlements. The presented project has been successfully designed and installed by a combination of soil improvement and stabilized base course layers, reinforced with geogrids of high long term stiffness characteristic. The requirements of the contractor using loads up to 180 kPa could have been met successfully.

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