

# STABILITY ANALYSIS OF THE FLOATING OFFSHORE WIND TURBINE SUPPORT STRUCTURE OF CELL SPAR TYPE DURING ITS INSTALLATION

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## ABSTRACT

*The article presents the results of selected works related to the wider subject of the research conducted at the Faculty of Ocean Engineering and Ship Technology of the Gdansk University of Technology, which concerns design and technology of construction, towing, and settlement on the seabed, or anchoring, of supporting structures for offshore wind farms. As a result of this research, several designs of this type of objects were developed, including two stationary types: gravitational and Jack-up, which are placed on the seabed, and two floating types: TLP and SPAR, anchored with tendons and anchors in the form of nailed or suction piles. Below presented is the stability analysis of the new floating CELL SPAR type support structure for offshore wind turbines during its installation in waters with a depth of over 65 m.*

**Keywords:** towing and installation of SPAR platforms, anchoring of SPAR type platforms, calculation of dynamic loads in anchor ropes

## INTRODUCTION

As early as in ancient times, wind energy was used for moving various types of watering devices and mills with the aid of wind turbines, and for driving sailing boats. After inventing electric current generators, in 1888 James Blyth [1] applied a wind turbine with horizontal axis for moving a generator used for home lighting. With time, the designs of wind turbines were improved and their power increased, but until 1973, they were used merely locally to supply individual objects or small groups of them. And only in recent years, rapid grow in wind energy utilisation has been observed, and a large number of wind farms with turbines of several MW capacity, supplying national energy networks, have been built. Due to the limited area of available lands with favourable wind conditions for operation of these farms and the resistance from local communities, mainly caused by the noise emitted by wind turbines, a decision was made by coastal states to build offshore wind farms. Many research centres, including the Gdansk University of Technology,

started design and research projects on this subject. Among other issues, a number of reports and articles were published which presented new designs of turbine tower support structures for different water depths [2], [3], [4], [5], along with methods for their settlement on the seabed [6], or, in the case of floating structures, analyses of their stability and behaviour during towing, installation, and anchoring [7], [8], [9] and [10] and [11]. The first stationary offshore wind farm, with total power of 11x450 kW, was built on the coast of Denmark in 1991, at water depth of 2-4 m [12], while the first floating wind farm, Hywind Scotland, with total power of 5x6 MW and SPAR type foundations, started operation in autumn 2017. [13]. This article presents the structure and stability analysis of a floating platform of CELL SPAR type intended for use with 6 MW wind turbines at water depths of over 66 m.

## PLATFORM STRUCTURE AND EQUIPMENT

In the Polish Exclusive Economic Zone, plots of land for wind farms were firstly allocated in waters with a depth of up to 50 m, as shown in Fig. 1. It is expected that after utilising these areas, more wind power farms will be built in deeper waters, where the use of floating support structures, of TLP or SPAR type for instance, is fully justified.

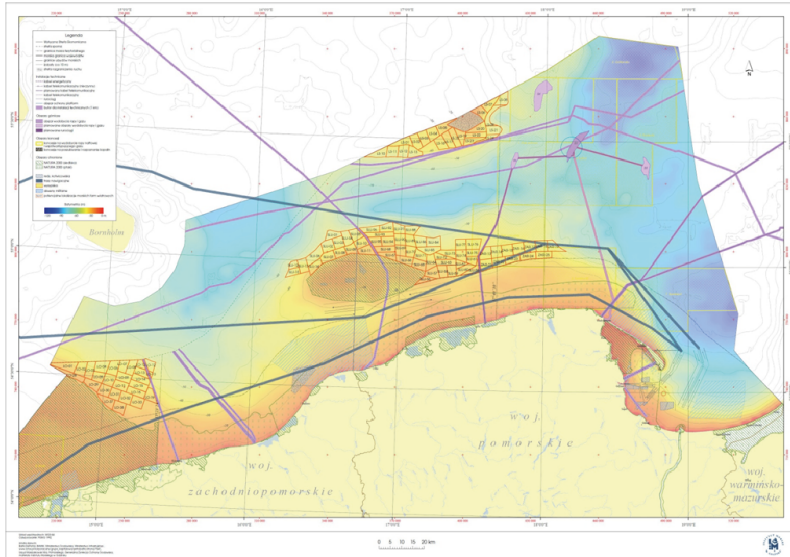


Fig. 1. Planned site of foundation on Baltic area in the Polish Exclusive Economic Zone, north of the town of Leba

When starting the design of a SPAR platform for wind power station with 6 MW turbine, intended to be installed in waters with a depth of over 65 m, the authors had no information about possible installation of the Hywind Scotland wind farm. The main criteria taken into consideration in this design concerned the potential of Polish shipyards to build SPAR platforms and their costs. Therefore, it was considered reasonable for the platform to consist of a set of identical or very similar elements with relatively small overall dimensions, which can be used as air or ballast tanks and, simultaneously, are relatively easy to build. Another requirement taken into consideration was that the platform structure should enable its safe towing and installation.

Fig. 2 shows a simplified view of the platform in four orthogonal projections and axonometric projection, with marked all tanks and chambers.

The designed platform is equipped with a basic ballasting system adapted for cooperation with an external pump unit. It was assumed that during moving the platform from horizontal to vertical position, it is ballasted with seawater and only after its anchoring, the ballast in lower tanks is replaced by pulp, being a mixture of gravel and sand collected from the seabed with seawater. At height of 10 m, the interiors of three columns 8 are separated by horizontal partitions.

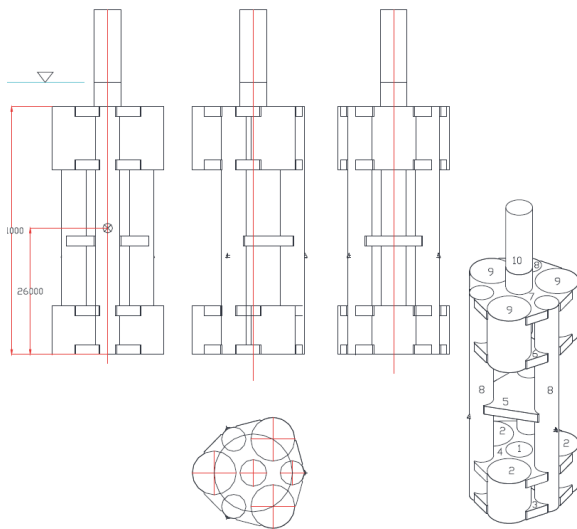


Fig. 2. Simplified view of the platform, with marked tanks and their parameters

1. Lower central tank – 1 –  $D=5,5m, H= 10 m V = 237,6 m^3$ ; 2. Lower tanks – 2 –  $D = 9 m, H = 10 m, 3 \text{ pieces}, V = 1908,5 m^3$ ; 3. Lower chambers – 3 and 4 – 2 pieces,  $V = 2 \times 200 = 400 m^3$ ; 4. Support columns – 8 –  $D = 5 m, H = 51 m, 3 \text{ pieces}, V = 3 \times 1000,1 = 3000,4 m^3$ ; 5. Central column – 10 –  $D = 5,5 m, H = 33 m, V = 784 m^3$ ; 6. Upper chambers – 6 and 7 – 2 pieces,  $V = 2 \times 200 = 400 m^3$ ; 7. Middle chamber – 5 –  $V = 274 m^3$

Other parameters: 1. Platform volume and mass of steel structure -  $V_c = 950,5 m^3, M = 2746 t$ ; 2. Height of centre of gravity of the platform from its bottom,  $X_c = 26 m$ ; 3. Submersion depth of empty platform in horizontal position,  $h_c = 6,5 m$ , and its displacement: 2732 t.

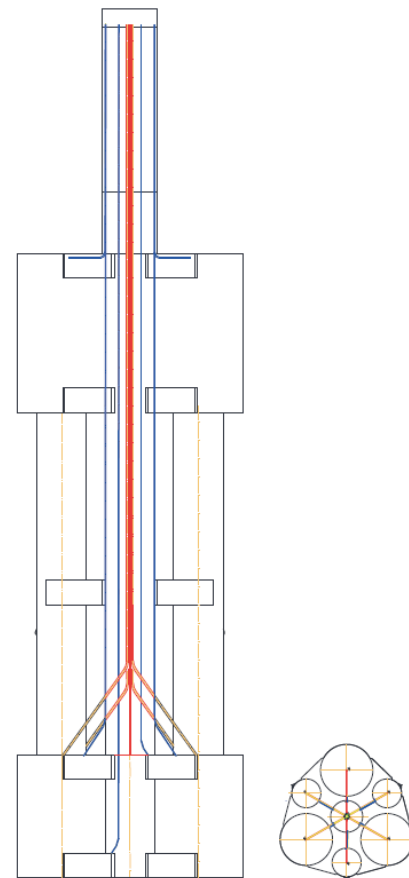


Fig. 3. Distribution of ballast pipelines (orange) and air pipelines (blue) composing the ballasting system.

Upper tanks of these columns can be ballasted with a certain amount of water to provide opportunity for controlling platform submersion, which is indispensable during anchoring, for instance. Two variants of the ballasting system have been developed. In both systems, all valves delivering the ballast water and all air valves are situated on the deck in the upper part of the central column, about 1,5 m below its flange. One of these variants, schematically shown in Fig. 2, assumes that all lower tanks and upper column tanks are connected, via ballast pipelines of larger diameter and air pipelines of smaller diameter, to valves on the central column deck. The ballast valves are situated in the central part of the deck, on the extension of a bundle of vertical pipes symmetrically distributed around the platform axis. The air valves are also distributed symmetrically, but close to the column wall. The unfavourable feature of this system is large number of pipelines, and the resulting problems with uniform distribution of water-gravel pulp to tanks and, in particular, to non-cylindrical chambers. On the other hand, its main advantage is better possibility to control the ballasting process when moving the platform from horizontal to vertical position.

### PLATFORM TOWING

Before starting the towing operation, six polyester anchoring ropes of 240 mm in diameter and approximately 60 m in length, with a loop at each rope end, will be attached to anchoring holders situated on platform's support columns (Item 8 in Fig. 2). These ropes will be tied around the platform circumference and secured against accidental unrolling during platform towing. Small floats will be attached to end loops of the ropes to ensure their floating on water during platform installation. The central column 10 will be covered with a tarpaulin or sufficiently thick foil fixed to the column

flange by screws and, if necessary, metal ring segments. The towing rope holder will be fixed with a number of screws to the lower part of the flange of column 10 (for horizontal position of the platform), or welded to its outer surface close to the flange.

The platform will be towed without ballast in horizontal position and with the column facing forward, as shown in Fig. 3.

### SEABED PREPARATION BEFORE PLATFORM ANCHORING

Preparing the seabed before anchoring the SPAR platform requires a number of identification and research studies concerning: possible ranges of extreme sea conditions (wind, wave, sea currents, temperature changes) [14], structure and strength of the seabed, and the effect of anchoring on natural environment, as well as economic and technical conditions. The present analysis refers to technical and, to some extent, economic aspects, and aims at selecting the best possible devices and technologies.

It was assumed that platform anchoring will be executed using six pre-tensioned ropes, symmetrically distributed in the way shown in Fig. 11. The initial, preliminary assumption was that anchor chains will be used as anchoring tendons. However, numerical analyses of the behaviour of such a chain system in rough sea conditions have revealed very unfavourable dynamic loads of these relatively rigid tendons in the entire range of their possible length changes [15]. That is why a decision was made to replace chains with polyester ropes having the following properties [16]

- material – Polyester
- diameter – 240 mm
- specific weight in air – 43,9 kg/m
- specific weight in water – 11,13 kg/m

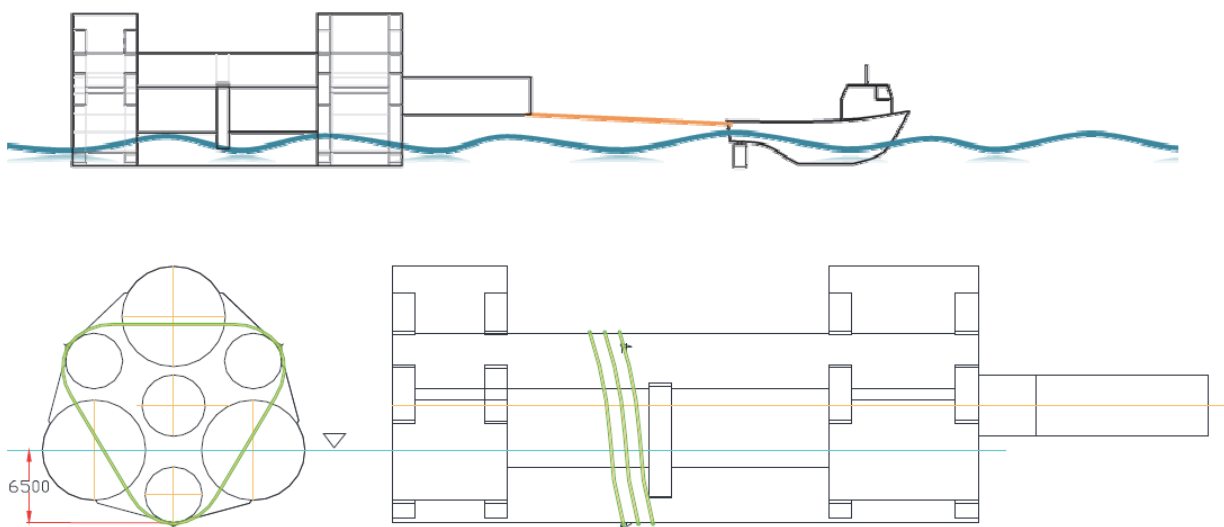


Fig. 4. Simplified drawing of platform during towing, with marked anchor rope attachment. Selected parameters of the towed platform:

- mass of empty platform –  $M_p = 2746 \text{ t}$ ,
- height of centre of gravity –  $Z_o = 10,5 \text{ m}$ ,
- volume of submerged part –  $V = 2726 \text{ m}^3$ ,
- height of centre of buoyancy –  $Z_v = 3,79 \text{ m}$ ,
- moment of inertia of waterplane –  $I_x = 22882 \text{ m}^4$ ,  $I_y = 180036 \text{ m}^4$ ,
- small metacentric radius –  $r_o = 8,39 \text{ m}$ ,
- initial metacentric height –  $h_o = 1,68 \text{ m}$ .

- minimal rope breaking force – 10,268 MN
- maximum elongation at 100% load - 22,5 % for new rope
- maximum elongation at 100% load - 16,5 % for rope in service

These ropes are used for anchoring floating objects. They have significant elasticity, at the same time preserving good mechanical strength, which is of high importance in the analysed case. For the anchoring system with geometric parameters shown in Fig. 11, the maximum forces in ropes were calculated, along with loads applied at rope attachment points to piles or other anchoring elements fixed to the ground in least favourable sea conditions. The calculated loads are the following:

- $F_{max} = 7,418$  MN – maximum force in rope,
- $F_{pmax} = 10,854$  MN – maximum resultant load of a pile or another anchoring element, generated by two loading ropes,
- $F_{max} = 8,49$  MN – maximum horizontal component of pile load,
- $F_{max} = 6,76$  MN – maximum vertical component of pile load.

To provide firm and stable anchoring points for the platform, the anchors will have the form of piles driven into seabed, or suction piles. Based on the preliminary analysis, it was recognised that a more favourable solution is to use suction piles fixed to the seabed symmetrically at intervals of  $120^\circ$  about the axis of final platform position, at an approximate radius of  $R_p = \sim 61$  m, as shown in Fig. 11.

## PLATFORM INSTALLATION

### MOVING PLATFORM TO VERTICAL POSITION

The platform installation operation will be performed using a specialistic ship equipped with a deck crane and suspended platform for people, and with other specialised devices, including pumps and air compressors needed for efficient platform ballasting.

After towing it to the installation place, the platform will be kept in position by tugs. During this time, the column cover will be firstly dismantled. Then, temporary elements which immobilised the end loops of the anchoring ropes during towing will be removed and some floats (buoys) will be attached to them to facilitate rope lifting from water during the platform anchoring operation. Next, the platform service crew with necessary equipment and tools will be transported from the specialistic ship to the open column deck above the water surface, where all ballast and air valves for platform tanks are situated. The distribution of these valves is schematically shown in Figs. 3, 4, and 5. The ballast valves are situated centrally, close to the column symmetry axis, while the air valves are close to the cylindrical wall of the column. Next, an elastic pipe will be passed from the ship to the column. After connecting it repeatedly to successive valves, this pipe will be used for transporting pulp (water with sand) or water for platform ballasting. It is noteworthy that ballasting the platform tanks to move the platform from horizontal to vertical position is the most difficult and most challenging operation, during which large structure accelerations can be generated. Taking this into consideration, the authors performed the stability analysis of platform motion when ballasting successive ballast tanks in the sequence given in



Fig. 6. Changes of platform waterplane during ballasting



Fig. 5. For better clarity, the tanks ballasted in different steps are marked with different colours in the figure.

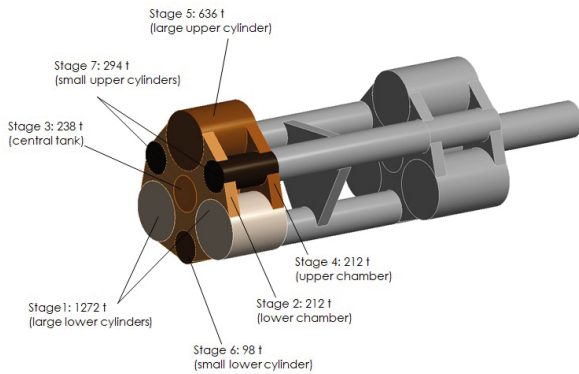


Fig. 5. 3D drawing of the platform in position before ballasting. Different ballast tanks are marked with different colours.

Fig. 6 shows platform waterplane changes during ballasting, starting from the horizontal platform position characteristic for towing, through successive steps of ballasting, up to final vertical position.

The diagram of changes of the platform inclination angle during filling of successive ballast tanks is shown in Fig. 7.

It can be observed that small changes of platform inclination angle, which are characteristic for initial ballasting stages, increase rapidly during the final stage, just before the platform reaches the vertical position.

The ballast introduced to the tanks changes the position of the platform's centre of gravity, which simultaneously results in the change of its centre of buoyancy. The trajectories of these two points during ballasting are shown in Fig. 8.

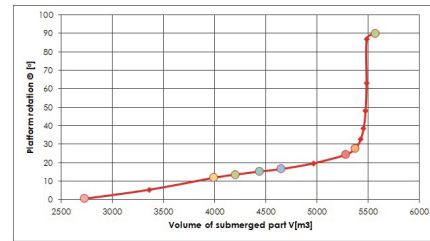


Fig. 7. Changes of platform inclination angle during successive stages of ballast tank filling.

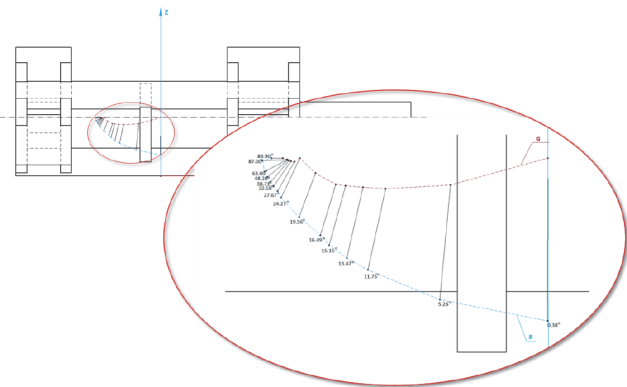


Fig. 8. Position changes of platform's centre of gravity and centre of buoyancy during successive ballasting steps.

The presented data was used for calculating changes of longitudinal and transverse metacentric heights as functions of platform trim. The trajectory of the longitudinal metacentric height of the platform is shown in Fig. 9.

The diagram on the left presents the entire trajectory,

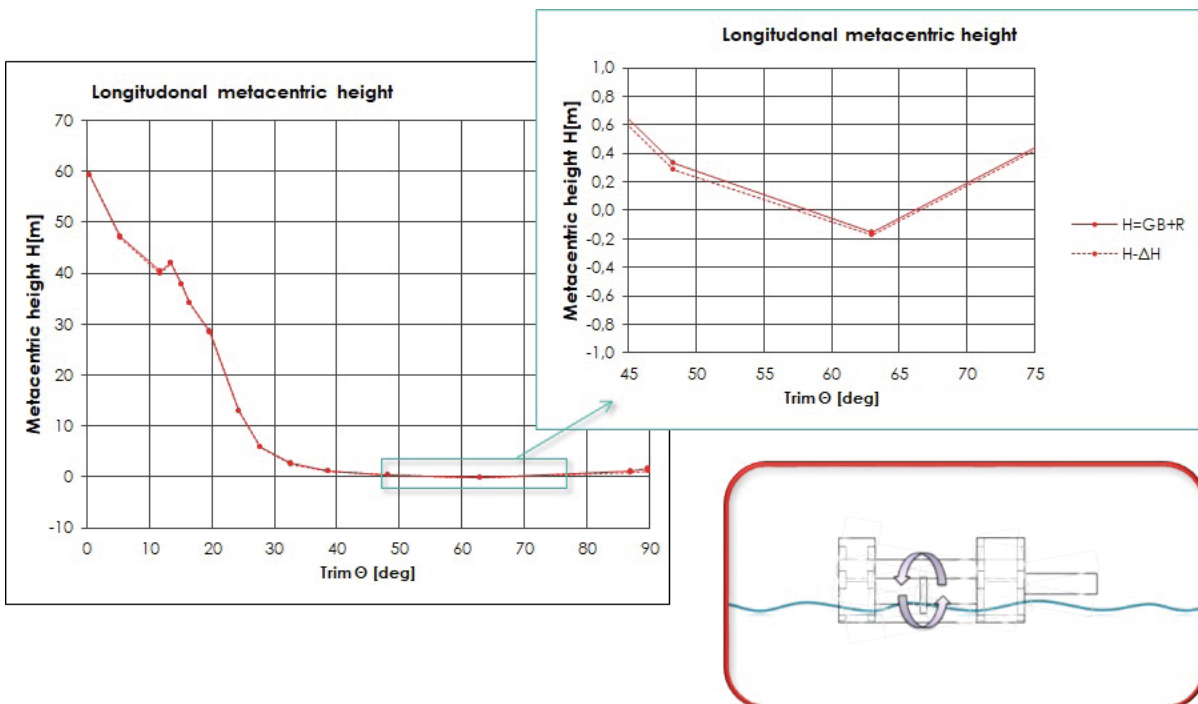


Fig. 9. Changes of platform's longitudinal metacentric height during successive ballasting steps.

while that on the right shows only its magnified fragment, marked as a blue rectangle in the former diagram. The magnified part refers to trim angles at which the metacentric height takes negative values, which may mean loss of platform's stability in the water displacement range of 5480-5550 m<sup>3</sup>. This stability loss may be a source of dynamic behaviour of the platform for angles ranging between 57-67 degrees.

Since for angles between 50-70 degrees, the metacentric height is very close to zero (with the accuracy of up to 0.3%  $GM_L$  determined for  $\theta=0$ ), it is difficult to predict accurately the platform behaviour based on classical methods. A reliable prediction of platform behaviour in this case can only be obtained using CFD methods taking into account the ballast water free surface, or model tests.

The trajectory of the transverse metacentric height of the platform is shown in Fig. 9. This quantity is always positive, which testifies to its stability in the entire range of platform trim angle changes.

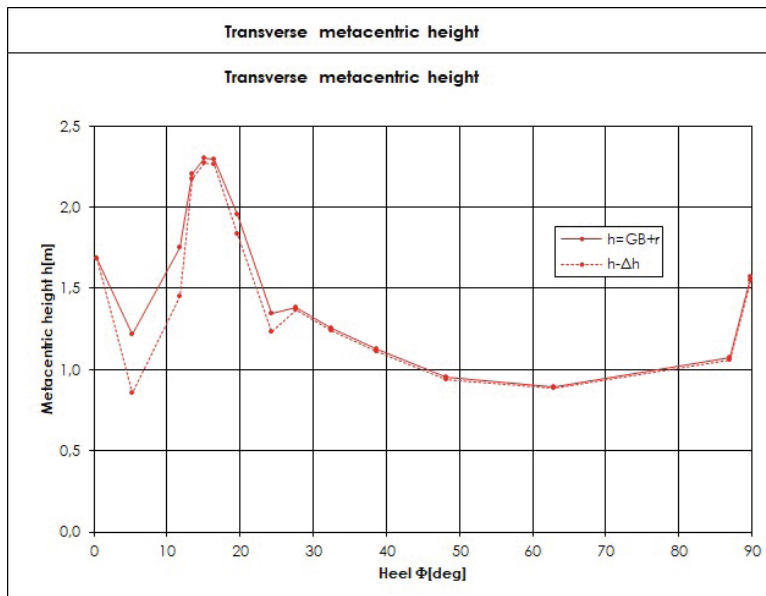
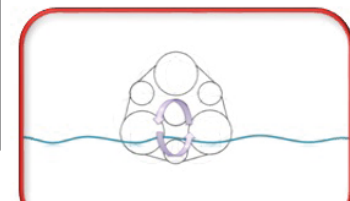


Fig. 10.

of platform's transverse metacentric height during successive ballasting steps



Changes

## PLATFORM ANCHORING

It was initially assumed that the platform anchoring system will be based on suction piles and slightly pre-tensioned polyester ropes. The geometric arrangement and parameters of this system in calm sea conditions are shown in Fig. 11.

Due to the lack of detailed information on the soil structure and characteristics of the seabed on which the platforms will be anchored, a preliminary assessment was made that the calculated loads of anchoring ropes can be carried by suction piles of 5 m in diameter, driven to the seabed soil to the depth of over 20 m. On the cover of each pile, an anchoring bitt will be mounted, which will be inclined in the vertical platform/pile symmetry plane by the angle of ~60 degrees to the horizontal plane, in the opposite direction

to the platform. This bitt will be used for holding loops of two anchoring ropes. The loops on other rope ends will be fastened to the bitts mounted on the platform, at the height of 20 m from its bottom.

Before starting the platform anchoring operation, the crew of the specialistic ship will increase slightly the platform ballast and the resulting draught, for the distance between the pair of bitts on the pile and platform to be slightly smaller than the length of the anchoring rope between the loops. Then the crew will lift floats with the attached anchoring ropes from the sea and move the ship close to the piles driven in the seabed. After that, one rope, with loops already free of floats, will be attached to a specially shaped sling on the crane's lifting cable and dropped on the bitt of the anchoring pile. The same operation will be repeated with the remaining ropes. After checking that all anchoring ropes are properly seated on the bitts, the crew will start partial de-ballasting of the platform, for its draught to reach 20 m at which the

anchoring ropes get a slight tension.

## SUMMARY AND CONCLUSIONS

The presented structural concept of a floating CELL SPAR platform intended for use as a support for a 6 MW wind turbine, along with the method of its towing and installation in water areas with a depth of over 65 m, is a real and relatively cheap technical solution to the problem of installation of offshore wind farms in the Polish Exclusive Economic Zone, at depths of over 65 m.

The proposed platform design takes into consideration the existing infrastructure and potential of Polish shipyards to build platforms of this type. The design underwent

preliminary technological evaluation in the NAUTA Repair Shipyard in Gdynia.

The numerical stability analysis of the platform moved to vertical position via proper ballasting of tanks has revealed that for angles ranging from 50 to 70 degrees (where 90 degrees means that the platform is in the vertical position), the longitudinal metacentric height is close to zero, and in the range of 57-67 degrees takes small negative values, which means the possibility of its dynamic transition to another point of equilibrium.

Determining the platform behaviour during the ballasting operation requires an additional CFD analysis and/or model tests to verify the possibility of appearance of dynamic phenomena and assess their effect on the safety of the platform installation process.

It can be concluded that the presented structural design of the platform and technology of its towing, settlement, and anchoring represent a real solution to the problem of installation of offshore wind farms on the Baltic sea, in the Polish Exclusive Economic Zone.

However, the authors stress that in the case of execution of the presented concept in a given real water area, the real strength and geometric parameters, in particular those referring to the anchoring system, may differ slightly from

the values presented in this article, as they depend on water depth and properties of the seabed soil.

## ACKNOWLEDGEMENT

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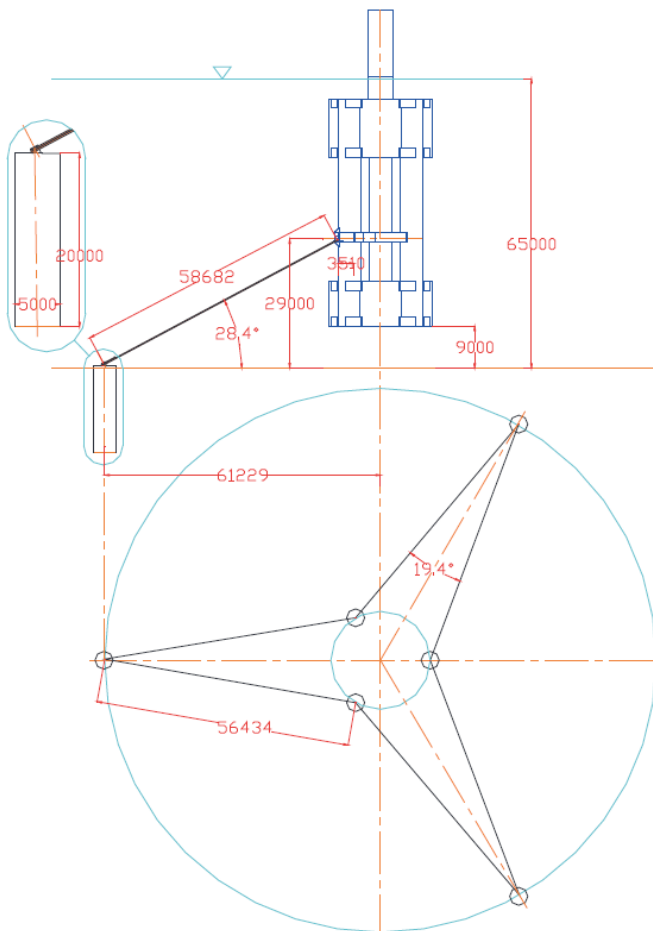


Fig. 11. Scheme of platform anchoring system in calm sea conditions. Suction piles, anchoring ropes, and points of rope attachment to the platform marked black.

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