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A numerical study of a pin foundation on hard, rocky seabed

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1 INTRODUCTION

In the offshore renewable industry, sources of natural energy are found in wind, waves and submarine currents which are generated by the tidal sea activity. This paper focuses on the numerical analyses that were carried out for the study of a very particular foundation, which will be adopted to hold a tidal turbine on hard rocky seabed. To place the study in the right context, it is important to keep in mind that it is necessary to have relatively steady water currents and sufficient energies (i.e. speed) to allow the harvesting of energy and achieve sufficient profitability of the machines. In such an environment, the continuous presence of currents makes the sandy and clay seabed uncommon; on the contrary, rocky seabed are the most common case. For the foundation design, this poses several restrictions, mostly related to the fact that a) the drilling to carry out a geotechnical cored borehole is extremely difficult and impracticable; b) the drilling of rock to install any piles or tendons is not convenient, considering the water currents and the metocean harsh conditions.

In this context, today the industry is focusing on the use of gravity foundations where self-weight of the foundation structure is increased by means of ballast. The reduction of the latter and the need to withstand significant horizontal loads to hold the turbine in place both require to increase the grip of the foundation on the rock. In general, the friction coefficient of the steel/rock contact is about 0.7-0.8, which in most cases and for the large offshore tidal turbines is not enough to keep the required ballast weight within acceptable, due consideration of the maximum lift capacity of the vessels available for the project.

Once again, the increase of the global friction and grip on the seabed with a minimized ballast will benefit the overall design.

2 DESIGN AND ANALYSIS

Since the early thoughts about the best suited foundation type to keep the tidal turbines safely in place, the idea of a statically determined, flat triangular structure was developed (Fig. 1a). At the three vertices of the triangle, the structure is lain on the hard seabed by means of so called “pins”, i.e. a pointy base formed by three plates crossed at the center (Fig. 1b), with one of the plates protruding downwards to form the first contact point with the rock surface.

At first sight, such a foundation system should ensure the grip and stability of the entire system. However, if the vertical component of the force under the pin is not high enough to damage the rock and penetrate the seabed, the global friction of the system will not change. On the other hand, if the vertical force is strong enough to fracture the rock, the global friction will be reduced to that of granular soil, knowing that the horizontal load itself will contribute to further fragmentation.

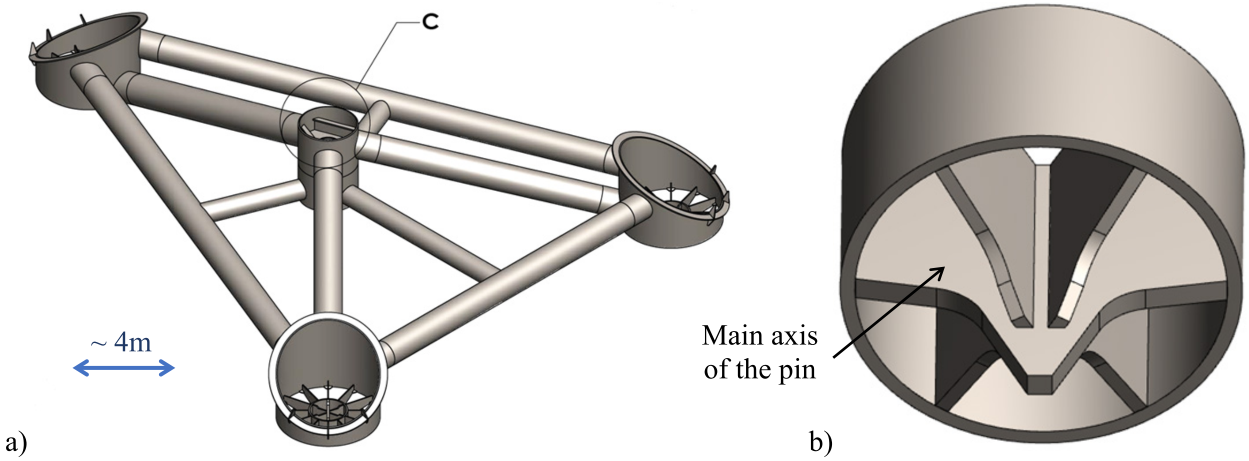

Figure 1. View of the statically determined foundation structure with the 3 pins foundation – after (HydroQuest)

Last but not least, even the interaction with the seabed surface is far from being simple as most of the apexes of the macro rugosity will break due to intense localized stresses; the same behavior can be observed at rock joints for which asperities progressively break and tend to reduce the joint dilatancy and the global friction coefficient.

All these aspects were initially explored by a series of Finite Element Analyses (FEA), in small displacement mode. These first models helped to analyze the pin geotechnical strength and to understand the relationship between the applied vertical force and the maximum horizontal strength. Unfortunately, the FEA did require necessarily to establish hypotheses about the penetration reached by the pin main blade, about the degradation of the rock caused by the penetration itself, both in terms of mechanical parameters of the fractured rock and of the volume which was subject to the degradation.

A new modelling, much more numerically complex, was then performed with the *PFC3D* software (Itasca 2017), with the aim of better reproducing: a) the actual rock mass structural properties (i.e. presence of joint families); b) the fragile behavior of the rock matrix; c) the true scale effect of the pin penetration into the seabed, if any. *PFC3D* is a software which models material in a discrete and discontinuous way, by means of spheres which are connected to each other by elastic, frictional, viscous and/or bonded contact laws (Potyondy et al. 2004). The formulation is fully dynamic (Cundall et al. 1979) and naturally accommodates large displacements. The bonds at the contact can be defined by stiffness, frictional properties as well as tensile and shear strength (Huang et al. 2013).

The modelling phase was divided in two successive phases; in the first phase, the rock mass had to be defined and then the *PFC3D* model built in order to reproduce it. For this, the global rock mass parameters were defined with reference to the Hoek&Brown model (Hoek et al. 2002), on the basis of some basic parameters like the Unconfined Compressive Strength of the rock (UCS, equal to 150MPa), the Geological Strength Index (GSI, equal to 80) and an elastic modulus of the matrix (E=180GPa), which were estimated on the basis of the local geology and rock type (assumed to be basalt). A procedure has been developed which is applicable to real cases, where rock mass properties shall be defined by standard global parameters as above. Three joint families were considered, oriented at about 90±10° from each other, with a mean spacing of 0.5 m. Once the rock mass properties (a flat joint model was used) were calibrated, the numerical model was geometrically built (Fig. 2a) and then the intrinsic joints properties (a smooth joint model was considered) were obtained by back-analyses in order to fit the global propertied defined by the Hoek&Brown model.

Once the calibration phase was completed, the pin geometry, modeled as a faceted wall, was placed at the top surface of the rock mass, as can be seen in Figure 2b. The main axis of the pin (plate axis protruding downwards) was rotated at 20° with respect to the horizontal displacement.

The pin was then vertically loaded until it reached a maximum design value (which cannot be disclosed due to confidentiality). A vertical servo control was activated whereas a constant horizontal velocity was applied to the pin.

The restraint to rotation was imposed to account for the presence of the triangular global foundation structure (see Fig. 1), which at first approximation will not rotate.

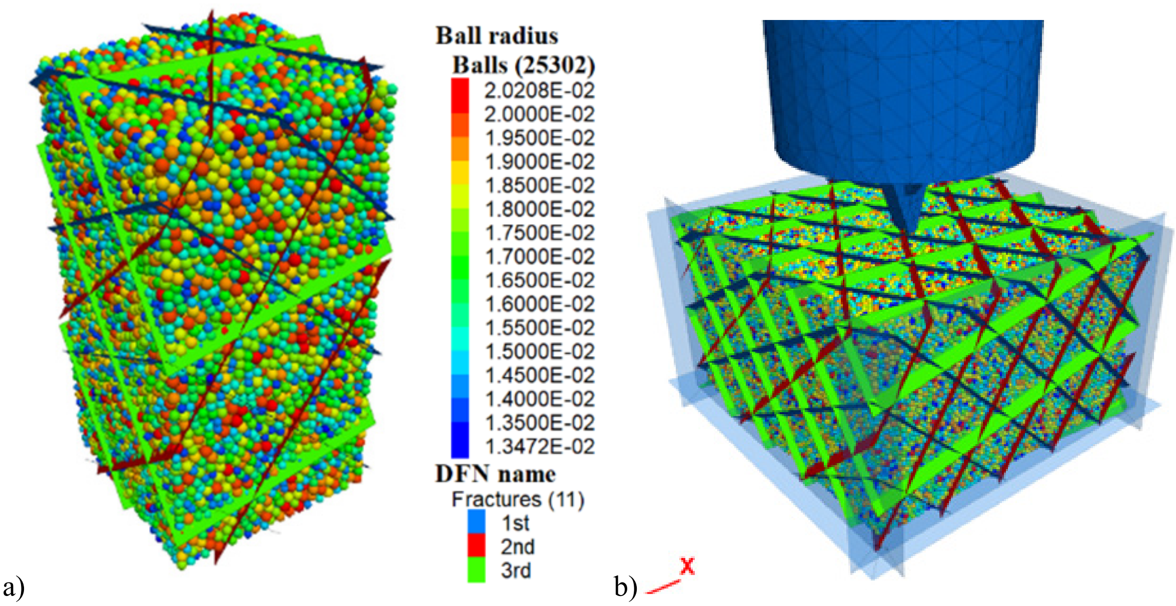

Figure 2. a) Geometry of fractured rock sample 0.75×0.75×1.5m size (about 25,000 particles); b) fractured rock model with pin 2.2×2.2×1.3m (about 200,000 particles).

3 RESULTS AND DISCUSSION

Although we studied seabed rocks, we have decided not to consider the hydrostatic pressure applied to the upper surface of the rock; this was not a simplification as the water pressure will not influence the strength of the rock mass in this case (Helmons et al. 2016). Our main objective here was to set up the best approach to model the pin installation in the rock as well as the procedures for analyzing the rock behavior.

Several load cases were run, by changing for example the pin horizontal velocity, the initial pin position and the direction of the imposed horizontal velocity. In this presentation, we focus on two solicitation cases which show the influence of the pin displacement in relation to the fracture network orientation.

As can be seen from Figure 3, results are indicating that the vertical force is kept constant during shearing (Fig. 3a); except some spikes which are due the uneven pin point contact with the rock when the pin is approaching a highly damaged zone and failing down into a void: nevertheless, the activated servo control on the vertical force component works perfectly since the force immediately returns to its imposed value (no horizontal displacement observed). This is true for both loading cases shown, which only differ in the shear direction: shearing along the X axis then at 90° (along the Y axis).

As shown in Figure 3b, the horizontal reaction force measured on the pin during its horizontal displacement is far more complex and its interpretation is not straightforward. We observe that the rock mass reaction on the pin is erratic and oscillate around a mean value, which corresponds to the pure frictional mechanism between rock and steel (the friction coefficient between rock and steel was set to 0.57).

The reason for the erratic behavior is related in the numerical technique adopted to move the pin: we impose a constant velocity to the pin thus it will move forward “at any cost”, i.e. by overcoming the pin horizontal resistance. This, in elastic-plastic and hardening materials, leads to a “classic” backbone curve since in no case the material will lose resistance. This will not be the case of the rock mass, where after the maximum resistance is reached, a sudden failure happens with loss of resistance. The capability of the model to correctly take into account the brittleness is a key: this implies when the maximum load is reached, the imposed pin velocity will continue to move the foundation and to potentially increase the reaction force (i.e. the solicitation on the rock), so that the rock mass breaks abruptly and the pin loses the contact with the loose particles. The reaction force drops to almost zero until the cumulative displacement is such that the pin touches the rock mass again. For this reason, as the real foundation will be force controlled, the horizontal resistance has been taken as the one corresponding to the highest peaks in Figure 3b.

Changes in the force and displacement of the pin are closely linked. From Figure 3c, which shows the vertical versus the horizontal displacement, it is evident that the vertical penetration is related to the development of the horizontal reaction force: after each horizontal force peak, the force suddenly decreases, resulting in the vertical penetration of the pin. This behavior is related to crack coalescence which results in the formation of rock blocks free to move and tend to detach from the rock mass (which is unconfined on the upper surface).

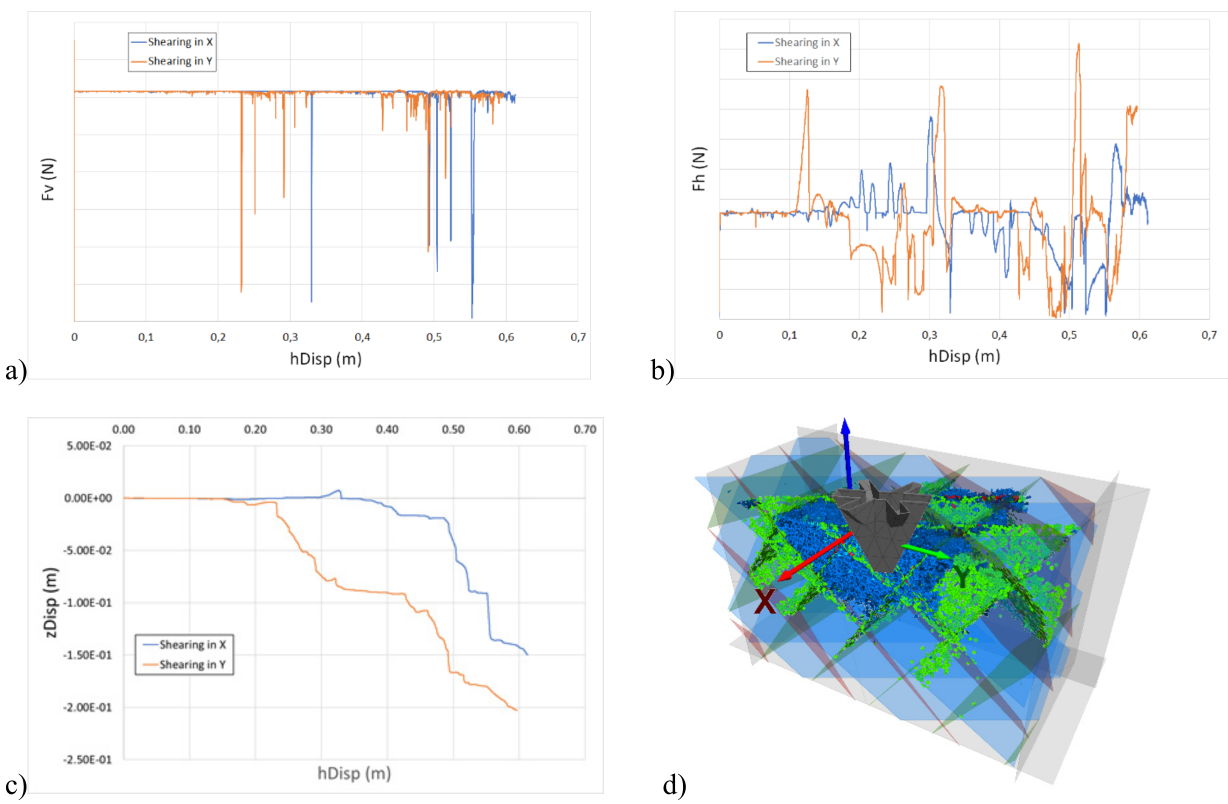

Figure 3. Results of the numerical analysis. a) imposed vertical force; b) calculated horizontal force; c) penetration depth as function of horizontal displacement; d) view of the broken contact bonds in the case “Shearing in Y” (blue in rock mass; green in joints); (values not shown as covered by non-disclosure agreement).

4 CONCLUSIONS

Obtained results show that the overall horizontal resistance of the pin can be higher than 0.7-0.8 (pure experimental friction between rock and steel) times the applied vertical force, even if the rock-steel friction coefficient is prudentially assumed 0.57 in the model. The development of higher friction depends on the penetration of the pin in the partially broken rock mass and in particular on the capacity of the pin to penetrate the rock, and therefore to the vertical load imposed. As well, the horizontal resistance depends on the direction of loading and of the initial placement of the pin, which impacts the way the pin interacts with the rock mass structure as defined by the fracture network. Further research will be necessary to fully understand the impact of all the geometric features, load direction, relationship with the vertical load and the effects of the shape and strength of the rock mass surface. The work also continues by studying the influence of the boundary condition: the fixed horizontal velocity is not suited for understanding this process and should be replaced by a force boundary condition whose magnitude would be derived from the hydraulic currents applied to the structure.

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