Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Pin foundation resistance in rock - Numerical modelling with DEM

A. K. El Haj, E. Nicolini*, I. Terribile
CATHIE Group, Nanterre, France

T. Deglaire
HydroQuest, Meylan, France

**emilio.nicolini@cathiegroup.com*

ABSTRACT: Tidal energy from offshore fields is a powerful source of renewable energy and the first commercial farm offshore France is now at detail design stage. The need of a technical solution that can be installed in short time and with reduced weather standby is leading the industry to consider purely gravity-based foundation structure to bear the turbine. Engineering studies designed such foundation to be placed on 3 so-called "pins", which shall be able to bear the significant horizontal loads applied to the structure with the minimum vertical load on a rocky seabed. The properties of the rock mass were determined via a site investigation, and a Discrete Element Method (DEM) model was calibrated to accurately reproduce the estimated rock mass strength at different confining stresses. Both the peak strength of the rock mass and the residual (crushed rock) strength were provided within the same calibrated DEM model, so that the combined behaviour of the unbroken rock and the crushed one were taken into account in the calculation of the global pin strength. The holding capacity of the foundation to the combined vertical and horizontal loads was obtained, as well as the additional vertical penetration induced.

Keywords: Tidal energy; gravity based foundation; pins; Discrete Element Method (DEM); holding capacity.

1 INTRODUCTION

Tidal turbines are advancing as a promising renewable energy technology, using the consistent movement of ocean tides to produce clean electricity. These turbines offer reliable energy generation while aiming to minimize ecological disruption.

As part of ongoing efforts in tidal energy development, work is underway in France's Raz Blanchard area to establish a pilot farm. The tidal turbines are intended to be installed on tripod foundations, with base 'pins' to be embedded in the seabed to provide vertical bearing capacity and act as anchors, ensuring the necessary horizontal resistance ("holding capacity").

Findings from the geological and geophysical study conducted at the tidal turbine farm site have revealed that the site conditions are globally rocky, with an intermittent layer of gravels/boulders that was found on several turbine's locations; they provided as well the engineering rock mass parameters (UCS, GSI, RQ and spacing of fractures).

This paper focuses on the numerical analysis of tidal turbine foundation on fractured rock mass (gravels/boulders layer not considered in this paper).

The aim is to assess the behavior of the pin foundation and compute the resistance to penetration and the holding resistance against horizontal loading.

2 DISCRETE ELEMENT METHOD (DEM)

The pin-seabed interaction is modelled using Discrete Elements Method (DEM). The method was developed by Cundall in 1971 for application in rock mechanics (Cundall and Strack, 1979). It can be used to analyze stresses, movements, rotations, and separations between particles. This method allows finite displacements and rotations of discrete bodies, including complete detachment, and automatically identifies new contacts as the calculation progresses. DEM is particularly used for simulating systems where discontinuities, such as fractures, cracks, and granular flows, are prevalent. It was thus deemed suitable for the studied problem.

3 FOUNDATION GEOMETRY

The tidal turbine is supported by a three-arms foundation with arms being distributed in plan at around 135°-135°-90° as shown in Figure 1. Each of the 3 arms is above ground level and not supposed to touch it. The connection of each of the arms with the ground happens at one specific point, called "pin", allowing each of the 3 arms to sit on the ground in a statically determined situation.

The pin is supposed to have a very limited rotation around any axis due to the restraints of the global structure and to mainly translate in the vertical and horizontal directions. This avoids including all the global foundation with its 3 pins into the numerical model, but only one pin, with sufficient accuracy from the rock mechanics point of view. The upper part of the pin, connecting and forming the arm part (above the pin top plate) is not modelled. The digital model of the preliminary pin geometry (type .STL) is presented in Figure 1. A half model was adopted in the simulations due to symmetry to reduce the computational effort.

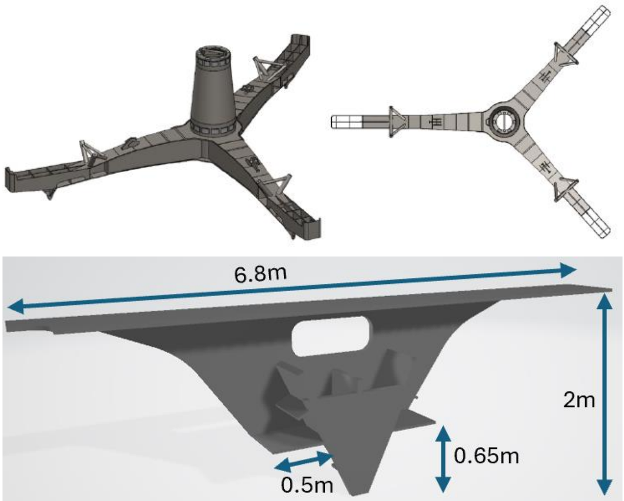

Figure 1. Geometry of the tidal turbine foundation and numerical model of the pin

4 SITE GEOTECHNICAL CONDITIONS

The site conditions are globally rocky (granite), with an intermittent layer of gravels/boulders that was found on some locations. Findings from the site survey indicate a homogeneously fractured bedrock with closely spaced fractures, averaging about 10 cm apart, and fracture orientations in all directions.

The rock mass mechanical properties and failure envelope was obtained by means of Hoek and Brown failure criterion (Hoek and Brown, 2019), based on the input parameters presented in Table 1 and described as follows:

- UCS: the resistance of the intact rock material;
- Tensile strength of the intact rock. This is usually taken into account by the parameter m_i of the H&B that depends on the rock type; numerically, it is equal to the ratio between UCS and tensile strength, both considered on the intact rock (i.e. with GSI = 100);
- D: Disturbance factor;
- GSI: Geological Strength Index;
- E_i: Elastic modulus of the intact rock.

The Hoek and Brown failure envelope of the rock mass, together with the granular material line representing the crushed rock frictional strength, are presented in Section 6.1.

Table 1. Input parameters of H&B criterion

Property	Unit	Value
UCS	MPa	84
GSI	-	55
m_i	-	6
E_i	MPa	26000
D	-	0

5 NUMERICAL MODEL

The Discrete element software PFC3D (Particle Flow Code) from Itasca (Itasca, 2021) was used for the numerical analysis of the pin foundation behaviour.

The fractured rock mass was modeled as a packed assembly of bonded spherical particles of an average size of 10 cm, which represents the average distance between fractures as determined from field surveys. Bonds between spherical grains are assumed to provide rock mass strength before failure.

5.1 Contact model for rock mass

The linear parallel bond model, shown schematically in Figure 2 (Itasca, 2021), was used to model contact between particles. This model provides the behaviour of the particle to particle contact by means of two interfaces: an infinitesimal, linear elastic (no-tension), and frictional interface that carries a force and a finite-size, linear elastic, and bonded interface that carries a force and moment. The first interface is equivalent to a linear model: it does not resist relative rotation, and slip is accommodated by imposing a Coulomb limit on the shear force. The second interface is called a parallel bond, because when bonded, it acts in parallel with the first interface. When the second interface is bonded, it resists relative rotation, and its behaviour is linear elastic until the strength limit is exceeded and the bond breaks, making it unbonded. When the second interface is unbonded, it carries no load. The unbonded linear parallel bond model is equivalent to the linear model. For more details on the model behaviour, one may refer to (Itasca, 2021).

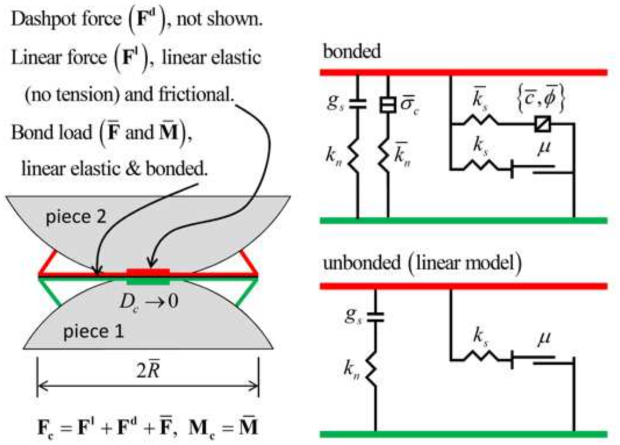

Figure 2. Behaviour and rheological components of linear parallel bond model.

5.2 Rock mass calibration

A calibration was performed on the bonded model parameters in order to match the rock mass properties issued from the site data. Particularly, the Hoek and Brown failure envelope, established based on the site data, was fitted via a series of standard laboratory test simulations. The performed calibration has thus allowed to match the values of the following properties of the rock mass:

- Young's modulus (E_m),
- Direct-tension strength (σ_t),
- Unconfined Compressive Strength (UCS),
- and the compressive strength (σ_c) at different confining stresses.

Three standard rock mechanics laboratory tests were simulated (UCS, confined compression, and direct tension tests), making use of the material-modelling support package “fistPkg7.3” provided by Itasca (Potyondy, 2023). In these simulations, a 1.2m size cubic specimen composed of an assembly of bonded spherical particles, sized between 8cm and 12cm, was created to ensure at least 10 grains across the specimen diameter. The main parameters of the packed assembly and the bonded contact model resulting from the calibration process are summarized in Table 2. The different laboratory test models are illustrated in Figure 3, where specimens at their initial and final states are presented for each test. Fractures tracking was enabled using built-in PFC tools for better visualization.

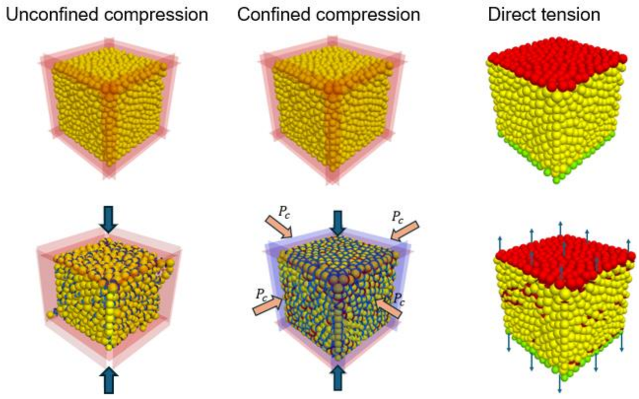

Figure 3 – Simulation of standard laboratory tests

Table 2. Main parameters of the packed assembly and the bonded contact model

Group	Property	Value	Unit	Description
Common group	α	0.7	-	Local damping
	ρ_v	2500	Kg/m^3	Bulk density
	S_g	Balls	-	Grain shape
	T_{sd}	Uniform	-	Size distribution
	$D_{\{l,u\}}$	80-120	mm	Lower and upper diameters
Packing group	P_m	30	MPa	Material pressure
	C_p	Grain scaling	-	Packing procedure
	n_c	0.3	-	Grain-cloud porosity
Linear group	$E*$	1.9	GPa	Effective modulus
	$\kappa*$	2.0	-	Stiffness ratio
	μ	0.6	-	Friction coefficient
Parallel-bond group	g_i	70	mm	Installation gap
	σ_t	0.15	MPa	Tensile strength
	γ	12.0	-	Cohesion to tensile strength ratio
	ϕ	8.0	Degrees	Friction angle

5.3 Pin modelling procedure

Figure 4 below presents the pin-rock interaction model developed in PFC3D.

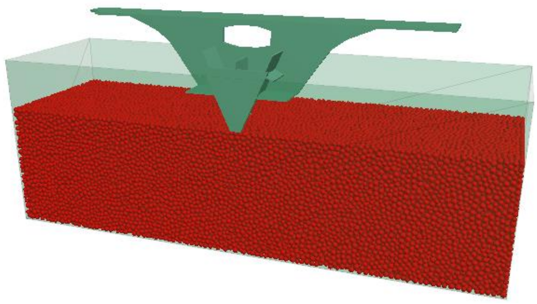

Figure 4 – PFC3D model of pin in rock mass

The modelling steps of the pin in rock may be described as follows:

- a packed assembly consisting of bonded spherical particles sized between 8cm and 12cm. A local damping coefficient of 0.7 is imposed to the model to help numerical convergence in later steps;
- gravity forces are applied to the model, and the model is solved and brought to the equilibrium state. The material is herein assumed to be fully drained, with water not modelled explicitly. The material's total mass density is considered, and a reduced gravity is used, which is more relevant given the dynamic nature of the numerical DEM;
- the pin geometry is imported to the top of the model so that the pin tip is at the level of the rockbed; a friction coefficient of 0.5 is attributed to the interface between the pin and the balls;
- the vertical penetration of the pin is simulated using a controlled constant vertical velocity of 0.1m/s, considered to be low enough to grant accurate results after few sensitivity tests. While penetrating, the resistance offered by the rock to the pin penetration (R_v) is recorded, together with the vertical penetration (δ_v). Several model states are saved during pin penetration at equal intervals of 0.25m;
- from the above saved states, the pin is laterally displaced of at least 1m, by applying a lateral velocity to the pin while imposing a constant vertical force equal to R_v and constraining pin rotation. Several model states are saved at equal intervals of 0.2m.

6 RESULTS AND DISCUSSION

6.1 Rock mass calibration results

Figure 5 and Figure 6 present respectively the results from the unconfined compressive and the direct tensile tests simulation, in terms of deviator stress (i.e. axial stress herein) versus axial strain (all plotted in absolute values). Results from the two tests are summarized in Table 3 and strengths compared to experimental site data. It can be seen that the calibrated bonded model reproduce well the rock mass UCS and tensile strength from site data.

Table 3. Comparison between rock mass properties from site data and calibrated model

Property	Site data	Model
$\boldsymbol{E_m\ (GPa)}$	10.6	10.41
$\boldsymbol{\sigma_c\ (MPa)}$	6.76	6.50
$\boldsymbol{\sigma_t\ (MPa)}$	0.47	0.41

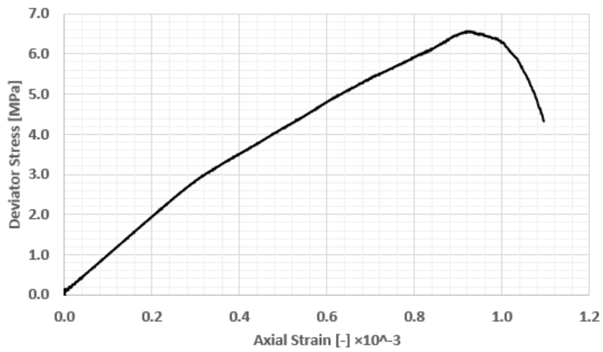

Figure 5 – Unconfined compression test result

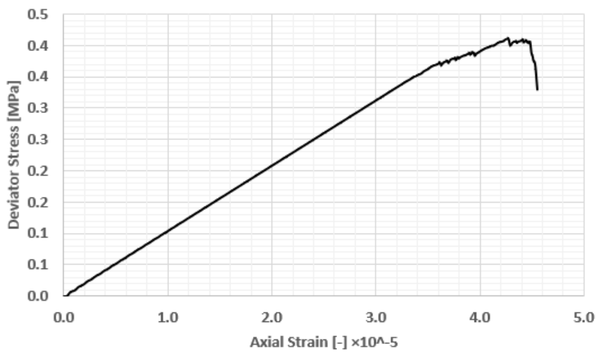

Figure 6 – Direct-tension test result

Besides, a series of triaxial compression tests with increasing confining stresses were carried out. The resulting curves are presented in Figure 7, and the corresponding peak strength values are plotted in yellow points on Figure 10, together with the unconfined compressive and tensile strength values. It can be seen that the ensemble of points fit well the Hoek and Brown curve related to site data.

Additionally, crushed rock (i.e., unbonded particles) behaviour was calibrated within the same model to reasonably match the granular material properties encountered at site, so that the combined behaviour of the unbroken rock and the crushed one was taken into account in the calculation of the global pin strength. The calibration tests of the crushed material were conducted by setting the bond strength parameters to zero and performing a series of triaxial tests with increasing confining stresses. The tests results are presented in Figure 8, and the corresponding peak strength values are plotted in blue points on Figure 10. It can be seen that the resulting trend indicates a friction angle that is aligned with that of the granular material coming from site data.

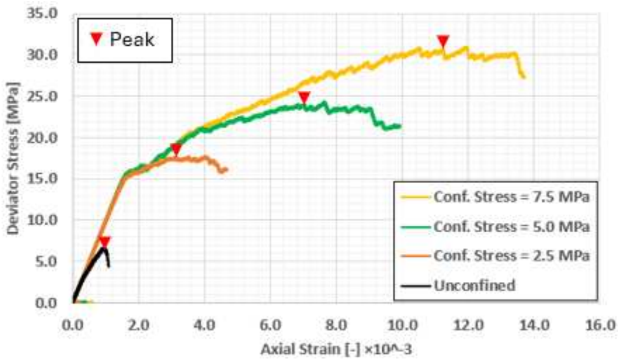

Figure 7 – Confined compression tests on bonded model

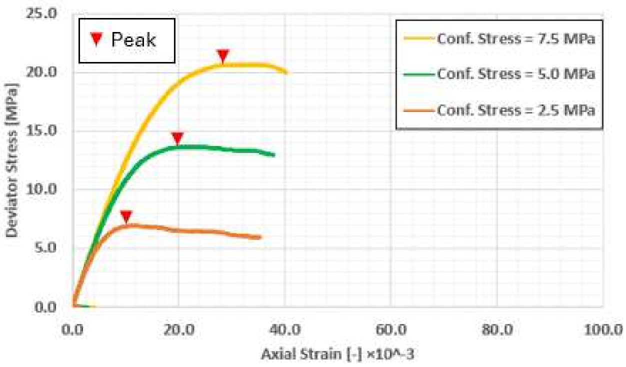

Figure 8 – Confined compression tests on unbonded model

Figure 9 presents extended simulations of confined compression tests beyond 0.2 axial strain, performed on both bonded (i.e. unbroken rock) and unbonded (broken rock) models at a confining stress of 2.5MPa. The figure reveals that the resulting curves from both models align at a certain point after their respective peaks, where all the resisting bonds in the bonded model become broken, to finally converge to the same residual value.

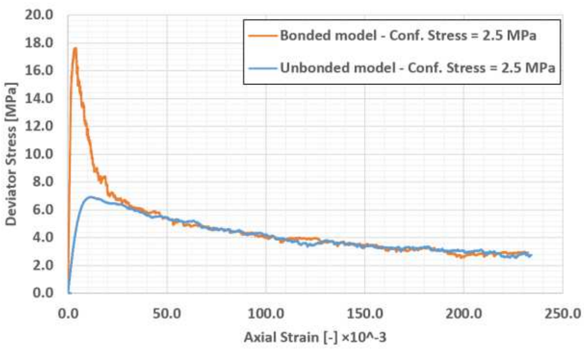

Figure 9 – Confined compression test on bonded and unbonded models (extended)

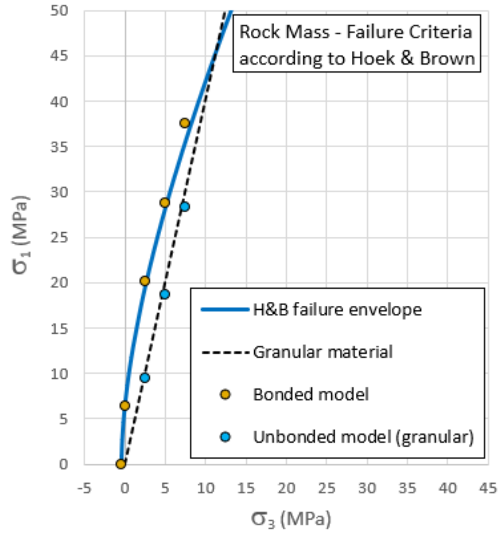

Figure 10 – Hoek&Brown failure envelope

6.2 Pin simulation results

This section presents the results of the simulation of pin penetration in the fractured rock mass, followed by the application of horizontal loading at a certain pin penetration depth with the corresponding vertical force being constantly applied. The simulation time for vertical penetration is approximately 2 days, while for horizontal loading, is about 12 days.

Figure 11 presents the vertical resistance of the pin versus the corresponding vertical displacement. The value of pin weight (632 tons) was indicated on the plot for reference. From this figure, a significant peak resistance is observed at a very small pin penetration. This is explained by the fact that the rock mass is initially broken by the intense loading at the tip, once the pin penetrates into the rockbed. Sufficient vertical resistance is only met once the pin intermediate horizontal plate touches the (fractured and damaged) rock, slightly at smaller depth (~0.5m) than the height of the plate (0.65m) due to the upward movement of the crushed parts during the pin penetration, causing an earlier contact between the plate and the rock parts. The resistance continues to increase with pin penetration.

Figure 12 presents the horizontal resistance curve of the pin at a maintained constant vertical force corresponding to a vertical penetration of 0.5m. This figure also presents the vertical penetration of the pin induced by the horizontal loading. The pin penetration was shown to increase from 0.5m to nearly 0.98m.

Figure 13 illustrate the bond states at various loading steps. In these figures, the bonded contacts between unbroken rock fractures are shown in red. Contacts between adjacent crushed parts are displayed in green if broken in tension, and in yellow if broken in shear. In blue are the unbonded particles that have come into contact with new parts, no longer in contact with their initially adjacent counterparts. It may be seen from these figures that once the pin tip penetrates the rockbed, the surrounding fractures are instantly broken. This corresponds to the first resistance peak observed in Figure 11. As a result of this penetration, a volume of unbonded contacts is formed around the pin tip. This volume gets bigger and bigger with pin penetration and horizontal loading.

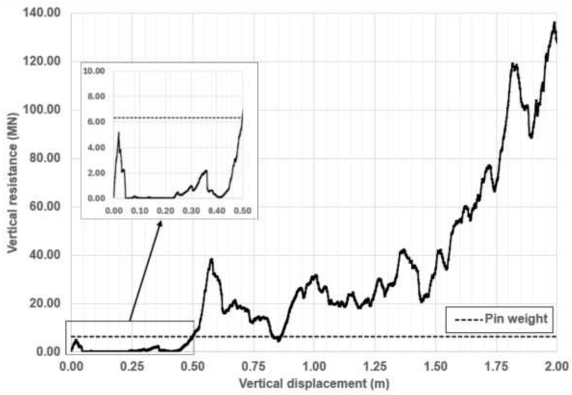

Figure 11 – Vertical resistance to pin penetration

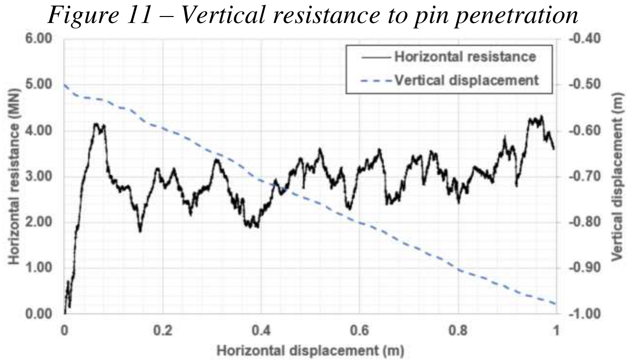

Figure 12 – Horizontal resistance and vertical penetration of the pin under horizontal loading

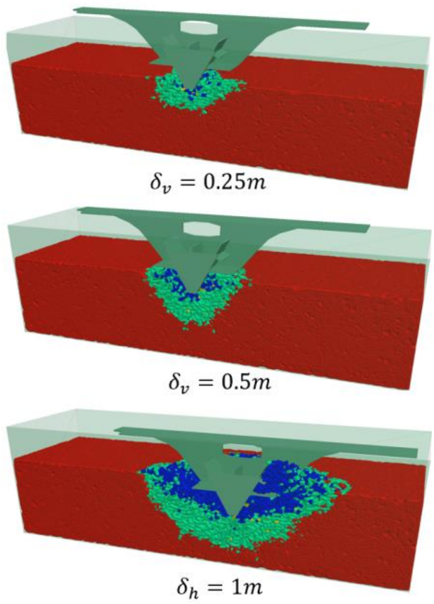

Figure 13 – Bonds state at different loading steps

7 CONCLUSIONS

In this paper, the behavior of a pin foundation under vertical and horizontal loads on a rocky seabed was analyzed using the Discrete Element Method (DEM). The rock mass properties were calibrated based on site investigation data to ensure the model accurately captured rock mass strength at varying confining stresses, including the strength of crushed rock. By considering the combined response of unbroken and crushed rock, the global pin strength was assessed. The study provided insights into the holding capacity of the foundation, as well as the induced vertical penetration. Validation of these results was recommended and will provide additional elements to improve the numerical model. Further improvements might concern the modeling of the post failure behaviour of the resulting granular material.

AUTHOR CONTRIBUTION STATEMENT

A.K. EL HAJ: Data curation, Formal Analysis, Writing- Original draft. **E. NICOLINI**: Methodology, Supervision and scientific lead, Conceptualization. **I. TERRIBILE**: Supervision, Writing- Reviewing and Editing. **T. DEGLAIRE**: Project administration, Writing- Reviewing and Editing.

ACKNOWLEDGEMENTS

We acknowledge that this study was conducted as part of a project assigned by HydroQuest to Cathie. We are grateful for the collaborative partnership and shared expertise, which have significantly contributed to the successful completion of this work.

REFERENCES

Cundall, P. A. and Strack, O. D. L. (1979). *A Discrete Numerical Model for Granular Assemblies. Géotechnique, 29*, pp.47-65.

Hoek, E. and Brown, E.T. (2019). *The Hoek-Brown failure criterion and GSI - 2018 edition*. Journal of Rock Mechanics and Geotechnical Engineering, 11, 445-463.

Itasca Consulting Group, Inc. (2021). *PFC - Particle Flow Code documentation*. Ver. 7.0. Minneapolis: Itasca.

Potyondy, D. (2023). *Material-Modeling Support for PFC [fistPkg7.3]*. Itasca Consulting Group, Inc., Minneapolis, Minnesota, Technical Memorandum ICG7766-L (June 29, 2023).