A numerical study of a pin foundation on hard, rocky seabed
A PFC3D application

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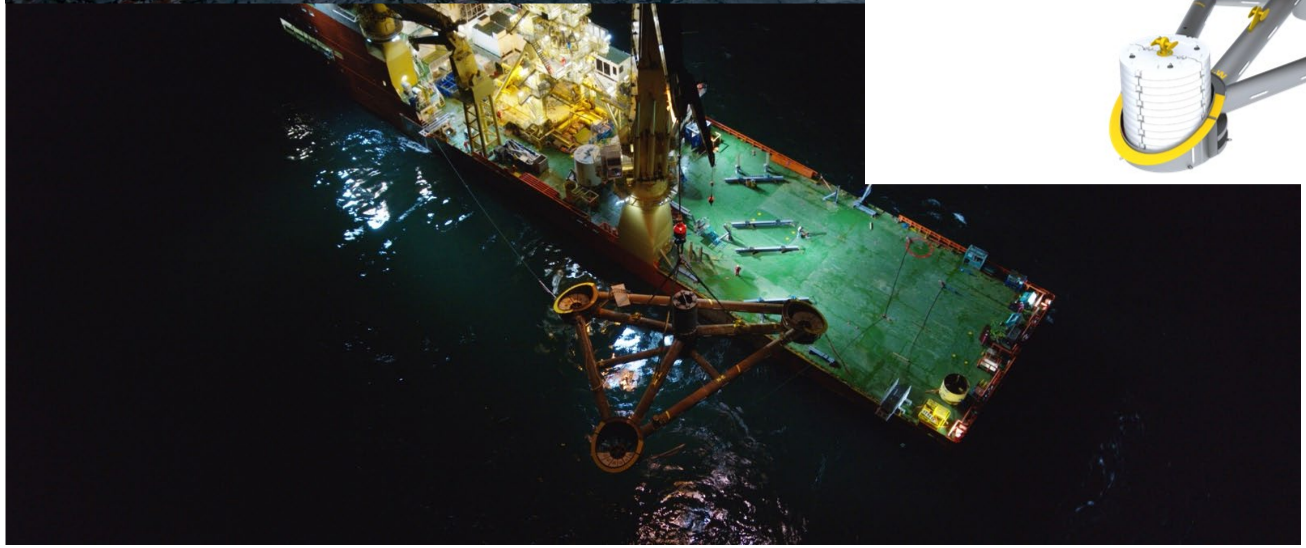
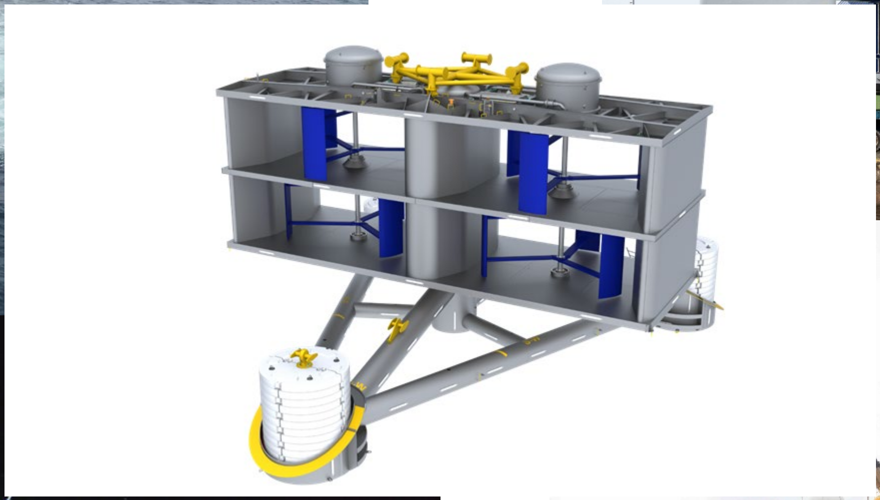
Expertise, Seabed and Below.

Summary of the presentation

- ✓ description of the structure;
- ✓ some insight into the foundation structure;
- ✓ the connection between foundation and the rocky seabed: the pin;
- ✓ general behaviour of the pin foundation;
- ✓ numerical modelling:
    - ✓ determination of PFC3D rock mass parameters from engineering rock mass parameters;
    - ✓ numerical analyses;
    - ✓ discussion of obtained results;
- ✓ conclusions and lessons learnt.

The tidal turbine - photos



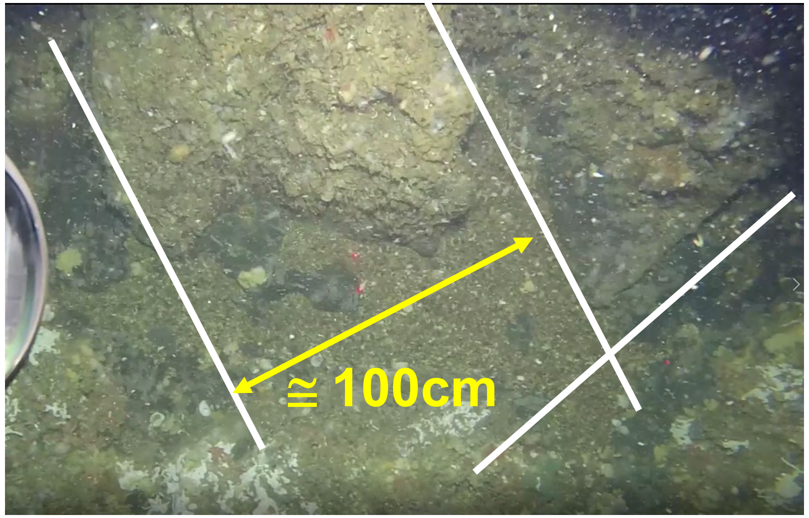


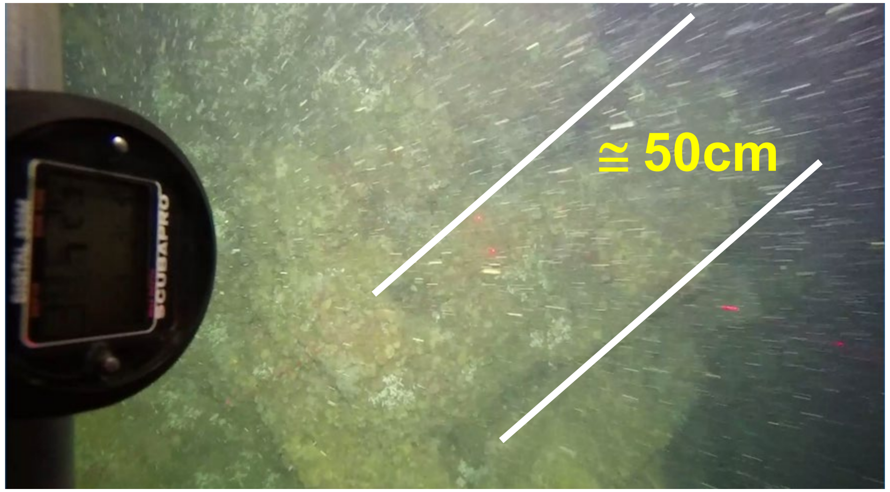
… some element of the global foundation problem…..

- ✓ tidal energy requires a steady current at the seabed;
- ✓ thus, rock is normally present at seabed;

- ✓ rock at seabed and steady currents, frequently associated with tides of several meters have some consequences:
  - ✓ drilling difficult, so cost of boreholes very high;
  - ✓ risk of borehole failure high in any case;
- ✓ for the same reason, drilled and grouted piles or tendons cannot be done (add production in series…..);

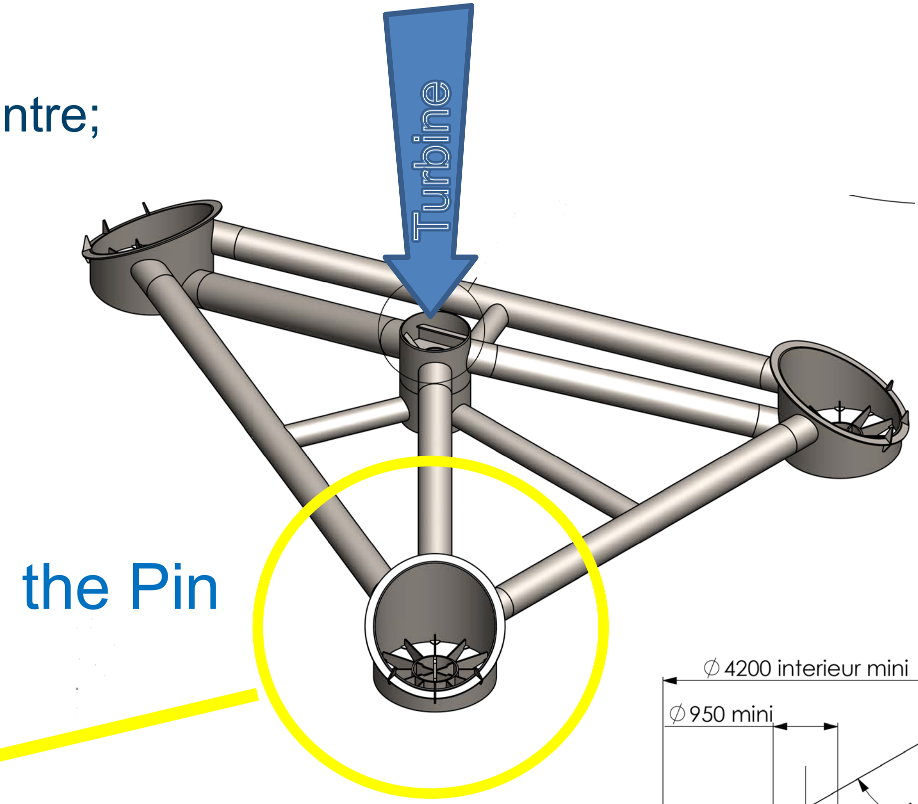
- ✓ in conclusion: very limited information about the seabed ground:
  - ✓ probably hard rock, from geology;
  - ✓ fractured, from camera inspection of the seabed.

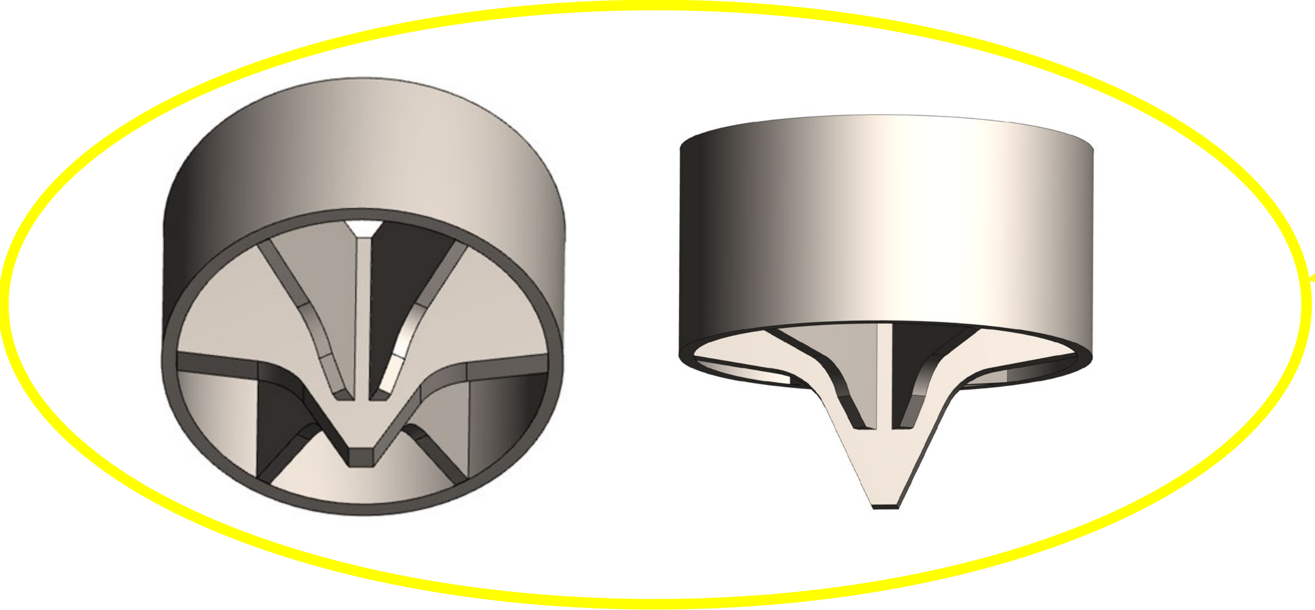


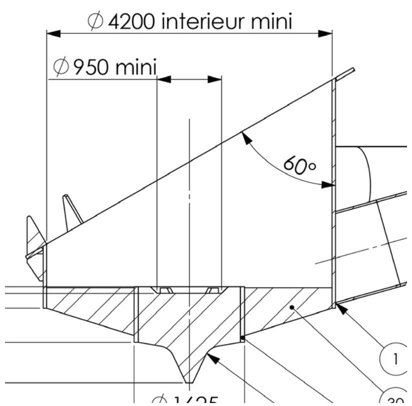


The tidal machine foundation structure and the pin

- ✓ composed by tubular steel members;
- ✓ overall triangular shape, with the turbine connector at the centre;
- ✓ structure touches the seabed at the 3 corners;
- ✓ the contact is made by a “pin”;
- ✓ advantage is that the contact is statically determined.
- ✓ the pin is a steel pointed base;
- ✓ each pin can host a ballast weight.







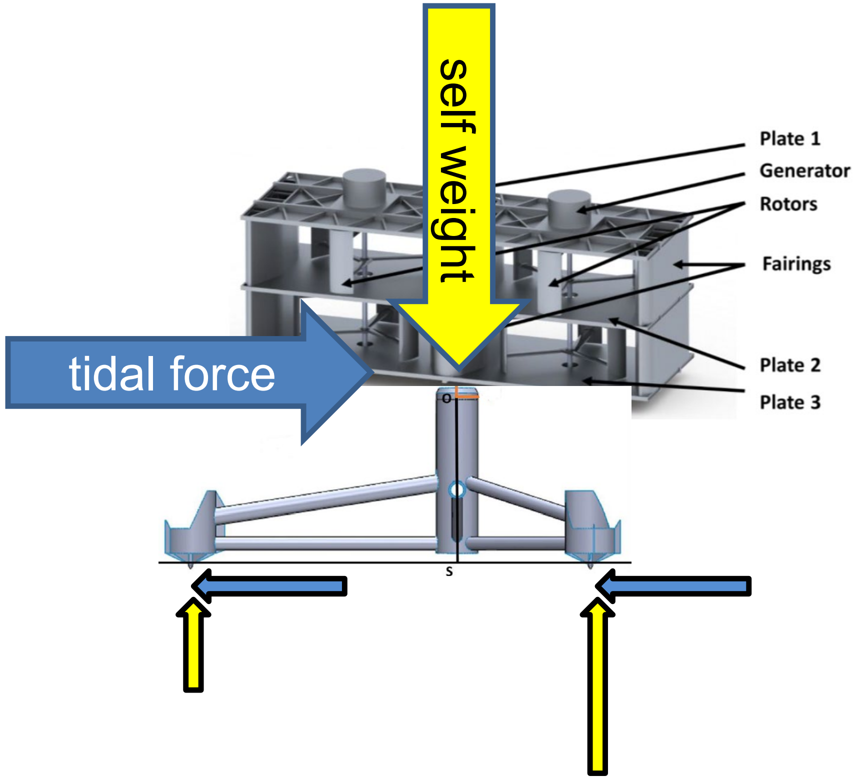
The foundation structure

How can we deal with such ground?

- ✓ to resist to currents, the foundation is required to provide a significant holding capacity (HC), i.e. a large resistance to horizontal loads, say H_{res};
- ✓ as drilling is not possible, the only solution is FRICTION;
- ✓ so, the H_{res} shall come from a mechanism like:

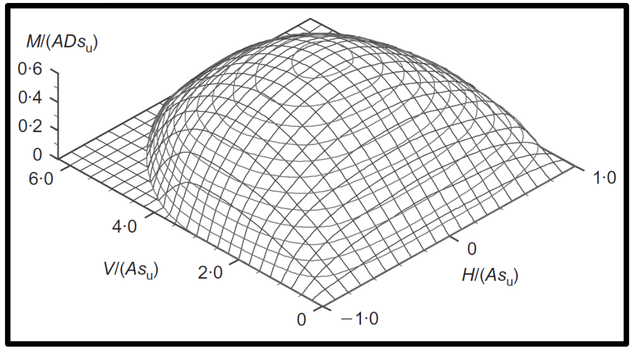
$$H_{res} = W\mu + C$$

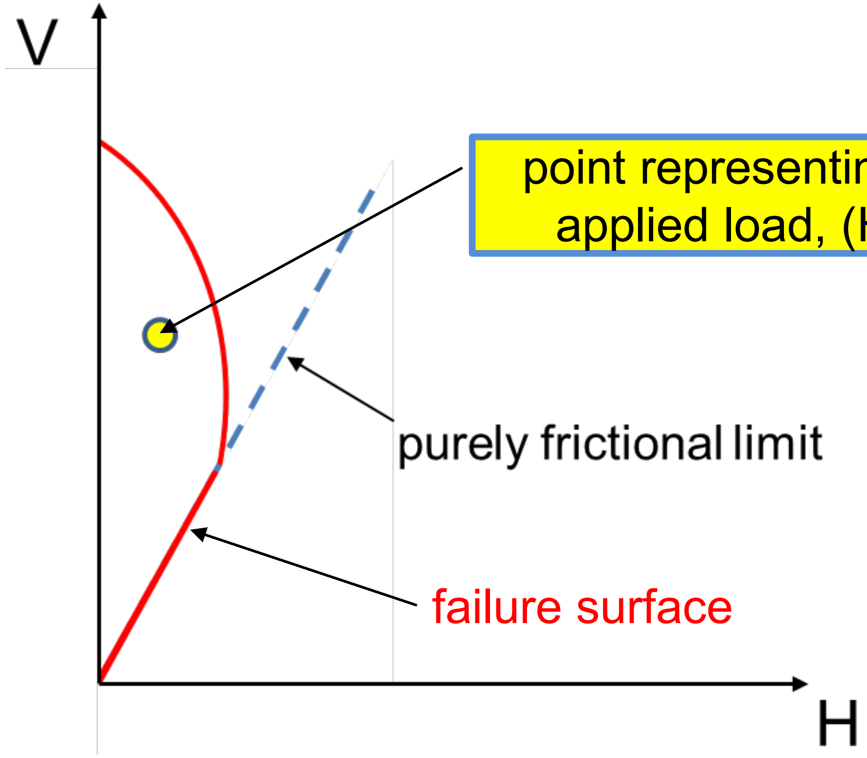
- ✓ where:
  - ✓ W is the global weight on the foundation structure;
  - ✓ μ is a global friction factor;
  - ✓ C is a “cohesive” component of the HC;



The global resistance of pin foundation – basic elements

- the foundation "resistance" depends on the simultaneous action of several forces, usually separated in vertical (V), horizontal (H) and overturning (M);
- failure happens when the VHM forces are in some (complex) relationship;
- if M=0 is assumed (centered load), a 2D envelope is obtained





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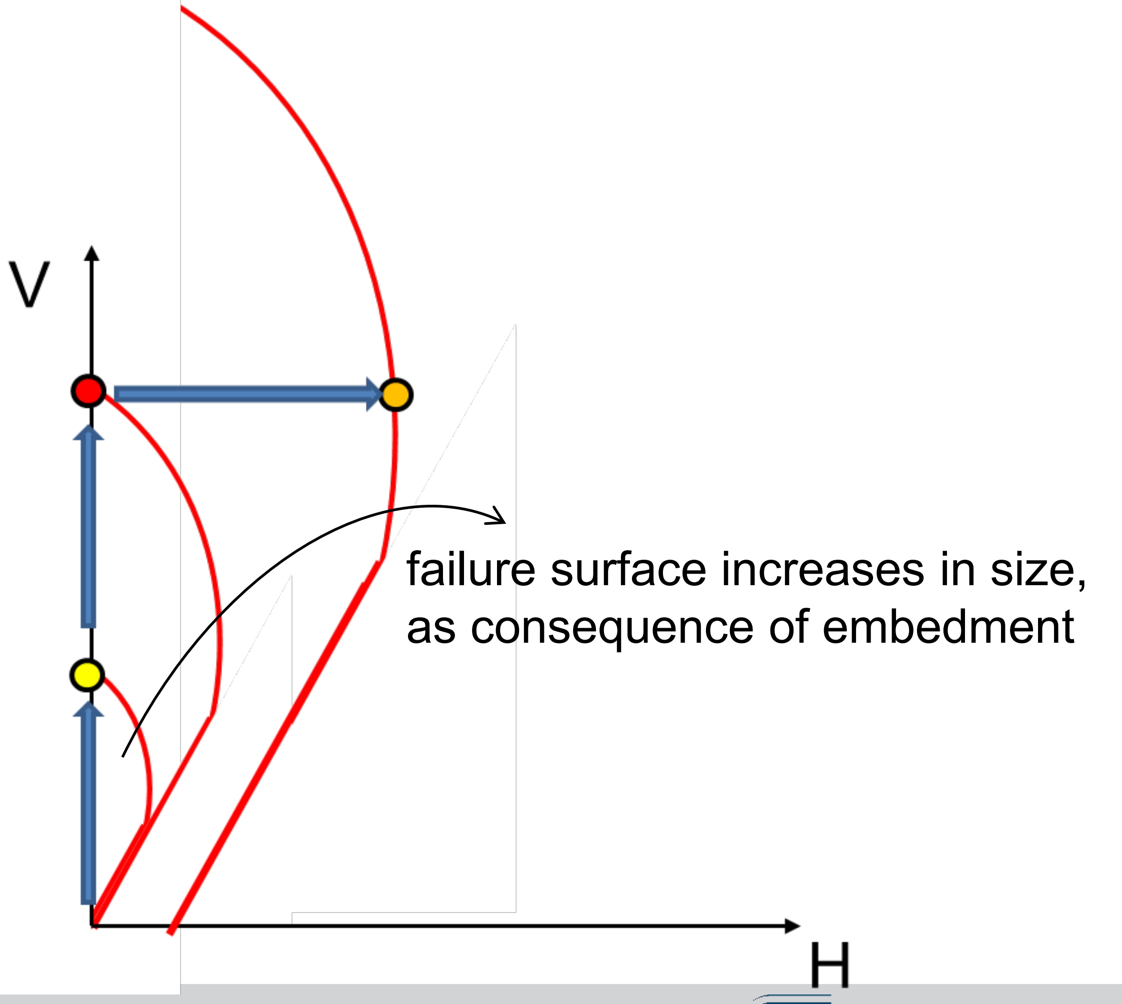
The global resistance of pin foundation – basic elements

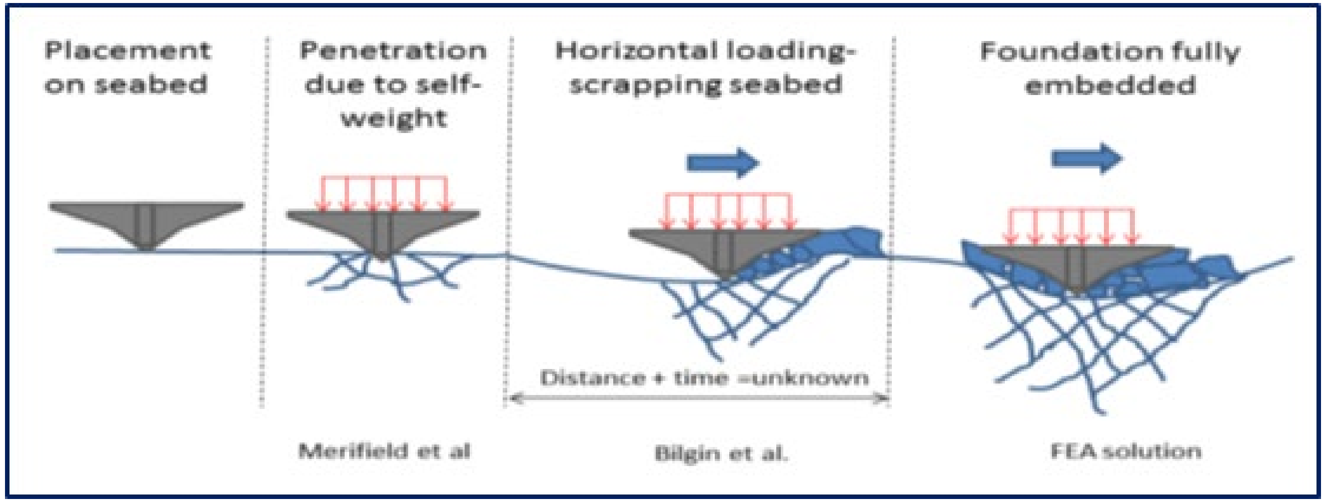
- ✓ for fixed ground parameters, the failure domain depends on foundation geometry, embedment;
- ✓ if failure is reached, equilibrium can still be found if the foundation geometry can change and “inflate” the failure domain;
- ✓ this can happen for example by increasing embedment:
- ✓ i.e. resistance increases at “cost” of further embedment

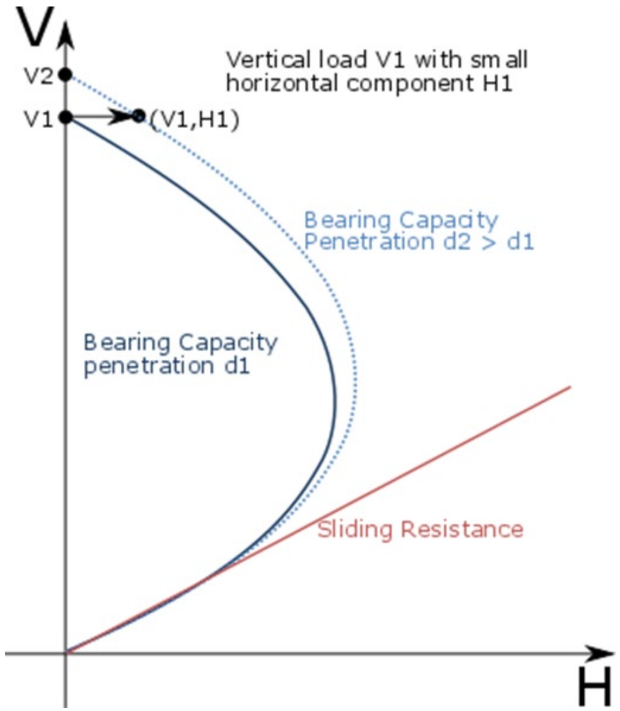


Pin behaviour under horizontal loading - Conceptual model

- ✓ at lay-down, pure vertical load → very limited penetration;
- ✓ with horizontal load → failure and penetration;
- ✓ this will also produce fracturation of the rock mass – decrease of resistance;
- ✓ decrease of resistance compensated by further penetration.

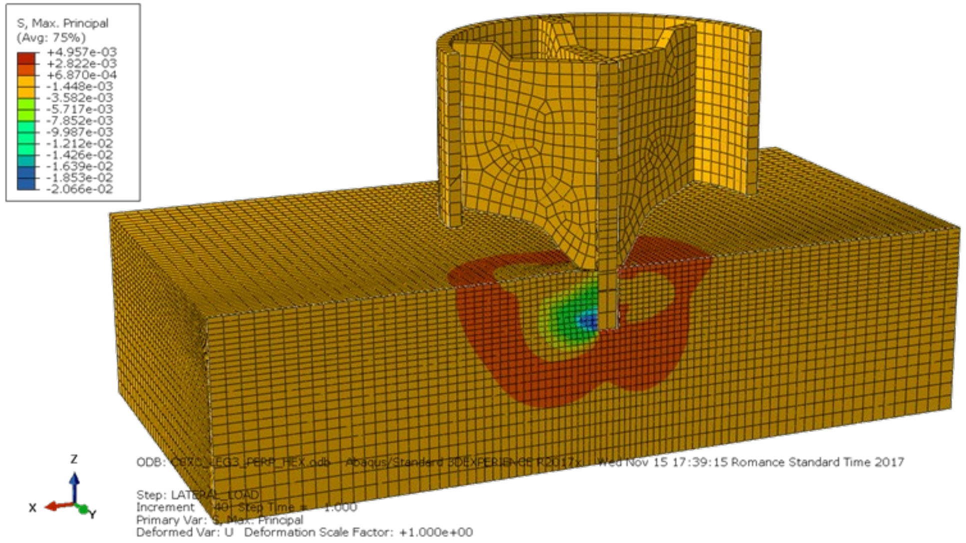
- ✓ How to compute this?

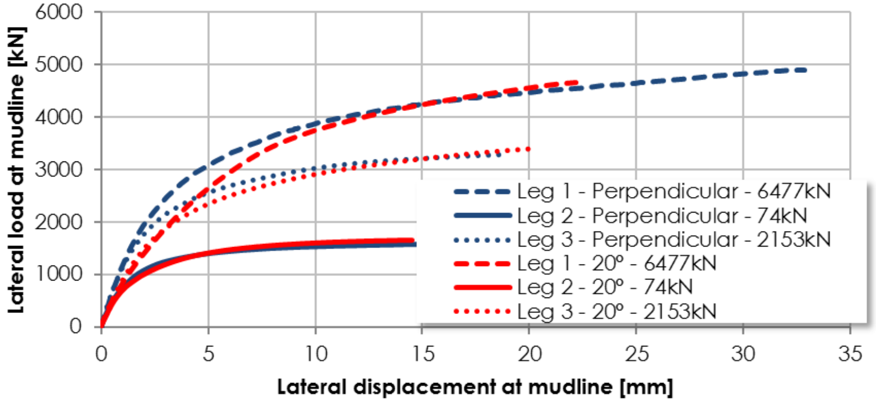




Finite Element Analyses – phase one

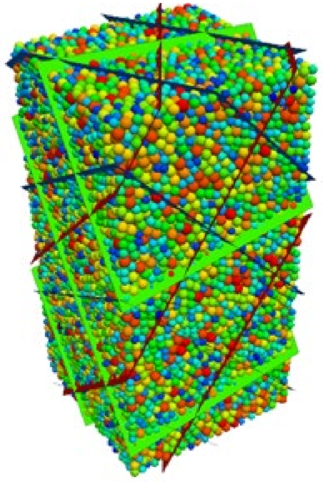
- ✓ “whished in place analyses”;
- ✓ Mohr Coulomb failure: not able to model progressive crushing of the rock;
- ✓ shape and properties of crushed zone are imposed;
- ✓ geometry and penetration fixed at the beginning of the analysis.

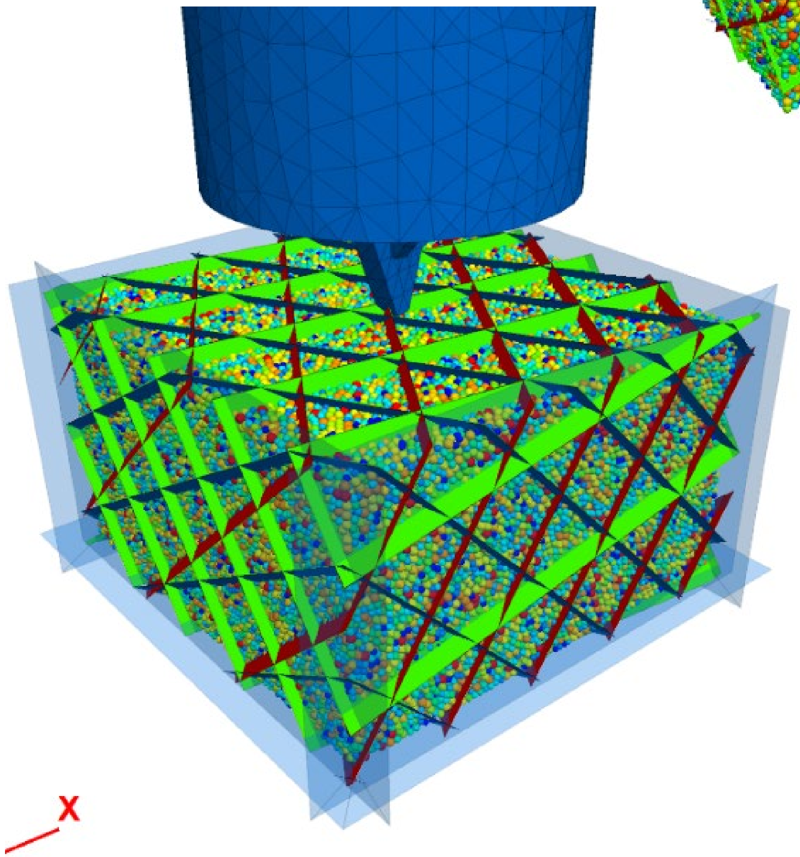




PFC3D modelling of the rock mass and pin

- ✓ The *PFC3D* code was selected as it is able to:
  - ✓ model the rock mass joint families (3 in the figure);
  - ✓ model the crushing of the rock;
  - ✓ take into account of the actual displacement of the pin;
- ✓ we wanted a sophisticated numerical model, but built from sound rock mass model:
  - ✓ rock mass parameters determined to have the mechanical properties defined by Hoek&Brown, based on UCS and GSI;
  - ✓ calibration done for “intact” then fractured rock

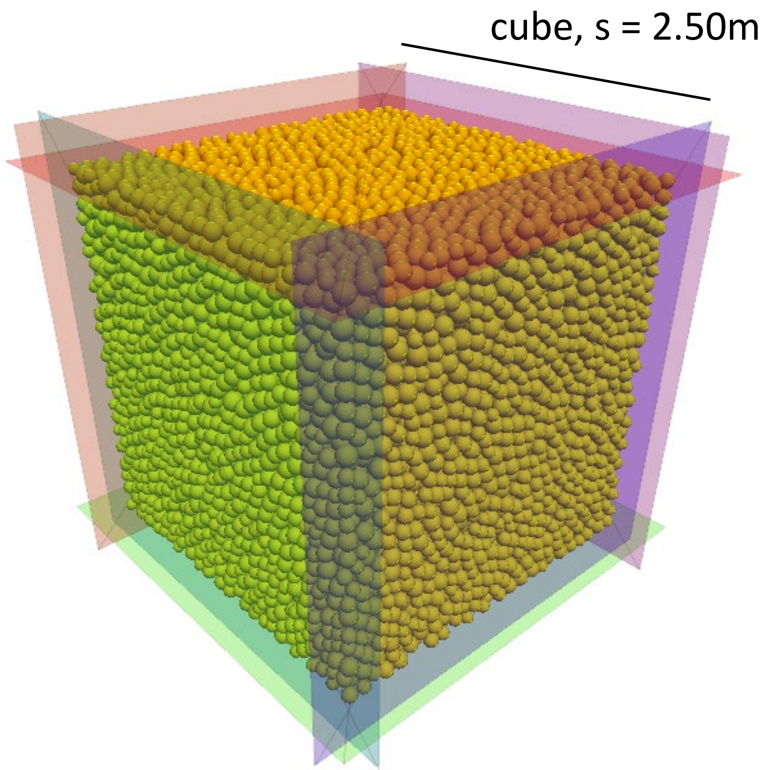


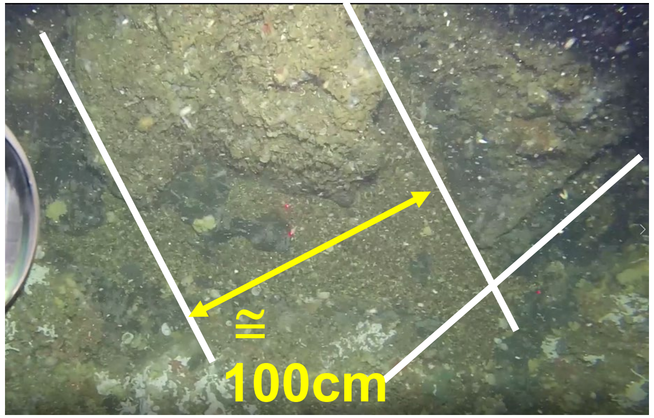


Rock mass model

- ✓ micro-structure of the bonded material is a simplification of the true rock mass structure;
- ✓ so, micro-properties are chosen via a calibration process to match what is deemed to be relevant macro-behaviour;
- ✓ the bonded material micro-properties were chosen by attempting to match:
  - ✓ the Young's modulus and Poisson's ratio;
  - ✓ the UCS (Unconfined Compressive Strength);
  - ✓ the tensile strength.
- ✓ two phases:
  - ✓ intact rock;
  - ✓ fractured rock mass, with joints:
    - ✓ continuous
    - ✓ assumed to be closed and infinite at the model scale
    - ✓ 3 families, 90° to each other; variability of +/-10°
    - ✓ 1 family horizontal, 2 vertical; variability of +/-10°
    - ✓ spacing 0.5m for all families; variability +/-10%

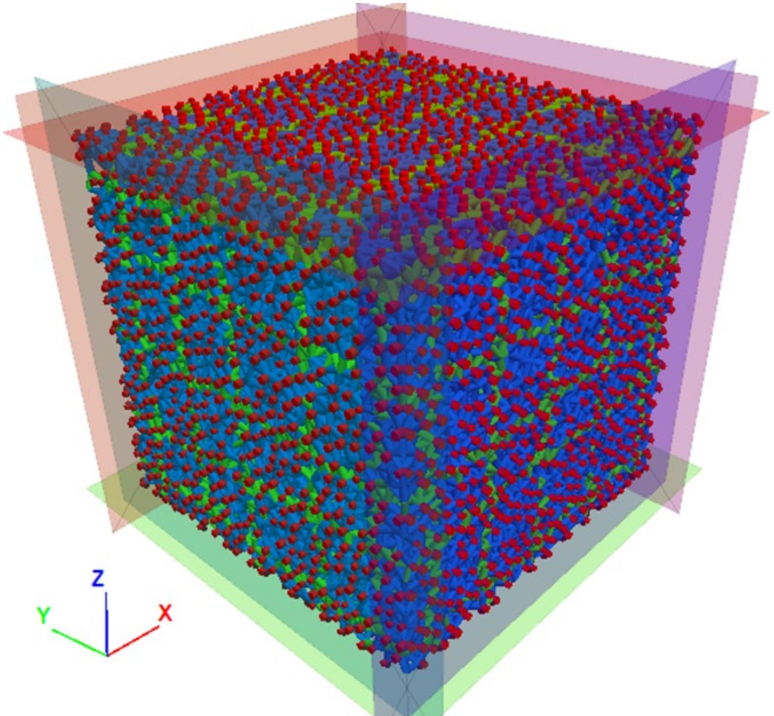
    The geometry of joints was also modified to match the required global rock mass properties.





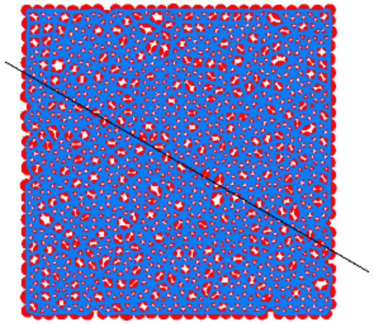
Rock mass model – adding joint families

- ✓ the smooth-joint contact model simulates the behavior of a planar interface with dilation regardless of the local particle contact orientations along the interface.
- ✓ the behavior of a frictional or bonded joint can be modeled by assigning smooth-joint contact models to all contacts between particles that lie on opposite sides of the joint;
- ✓ the model required as well to slightly adapt the joints to obtain the global wished rock mass properties.



Contact model applied at each contact

INTACT



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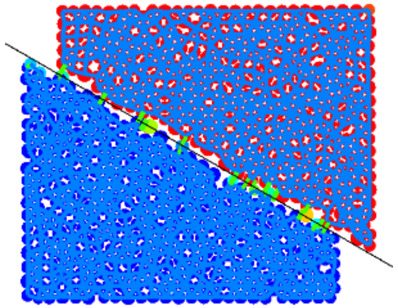
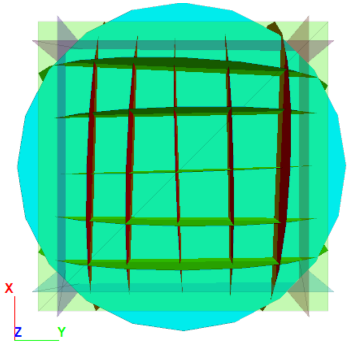
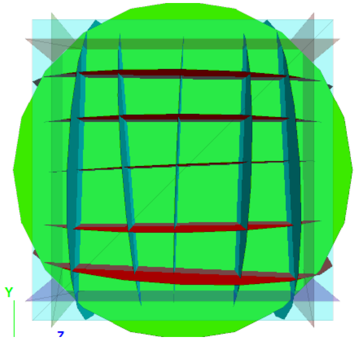


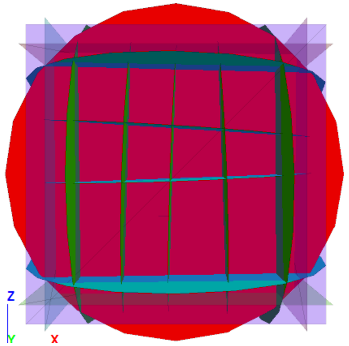
ABOVE



SIDE a

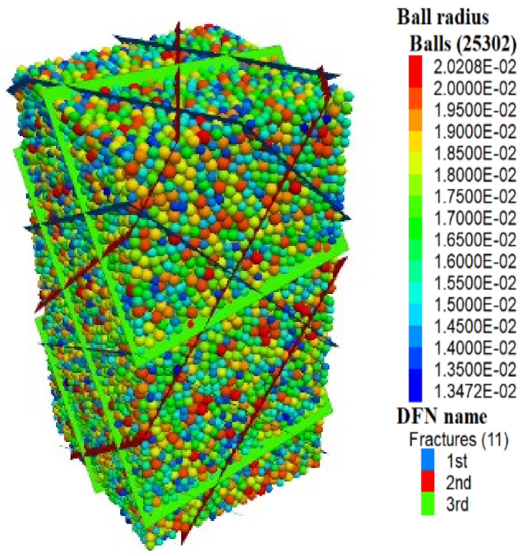


SIDE b



notice variation of orientation and dip of the joints

Rock mass model, with pin installed and loaded



- ✓ initial analyses of the pin revealed not accurate – all model recalibrated by assigning micro-parameters with a random distribution; particle radius variable as well;
- ✓ analyses run at constant vertical load, with imposed velocity to explore the full range of the development of the holding capacity;

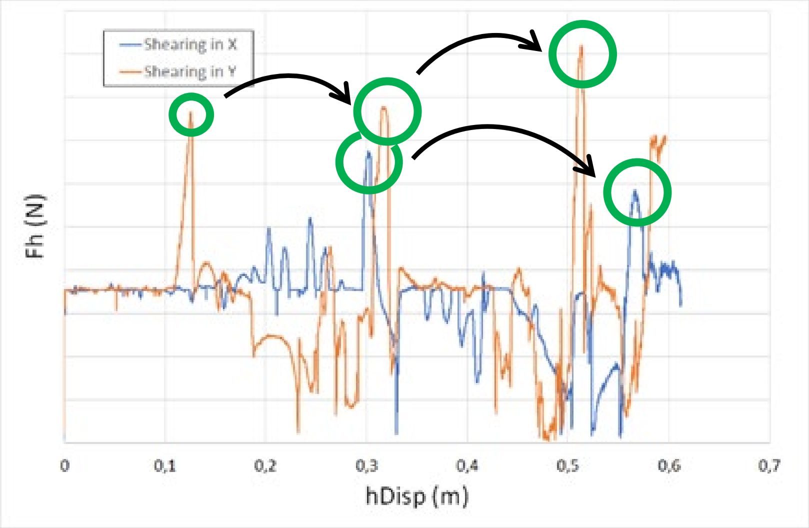
Obtained results

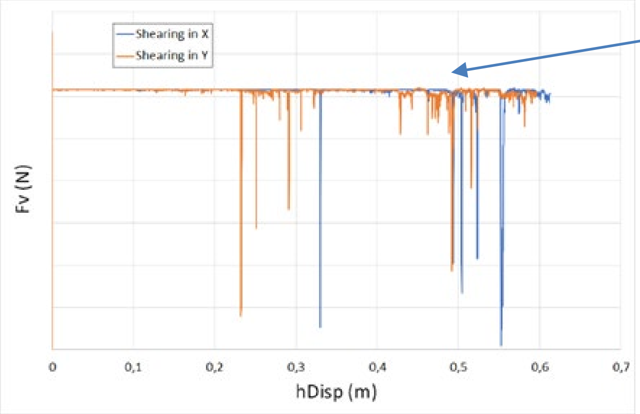
resistance

transition post-failure

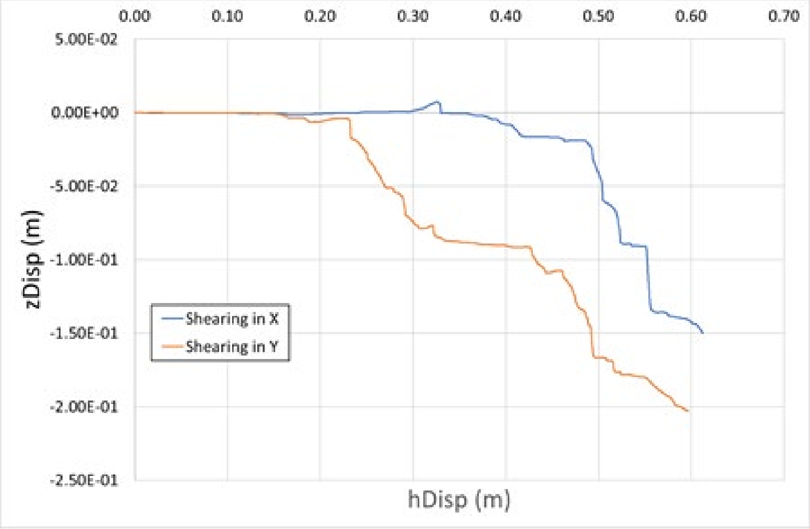
- ✓ vertical force nearly constant during penetration;
- ✓ horizontal force: real resistance at the peaks:
  - ✓ resistance is mobilized, but imposed displacement brings it over failure; failure and remobilization phases observed;
  - ✓ broken rock is pushed away → less resistance → sinkage → displacement;
- ✓ once crushed rock is displaced, new resistance is found;

- ✓ model feature: resistance is different in X and Y!!! anisotropy!!





vertical load constant



Conclusions

- ✓ the rock mass model calibration was complex to set-up, but results were good;
- ✓ implementation of the joints added complexity, but as well, results were good;

- ✓ the behaviour of the pin during horizontal loading under controlled velocity was not as expected, but appears realistic and reliable;
- ✓ test was done immediately before peak (new run), by force controlled and stability was verified;
- ✓ interpretation required some attention, also seen the novelty of the structure-ground interaction.

- ✓ further developments:
  - ✓ effect of cyclic loading, in case horizontal load decreases, then goes up again:
    - ✓ progressive increase of damaged rock?
    - ✓ increase of sinkage of the pin?
  - ✓ effect of geometry of the pin: what happens once the base of the cylinder touches the seabed?

Thank you for your attention

Any questions?

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Expertise, Seabed and Below.