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Development and Implementation of Practical Constitutive Models for use in Offshore Foundation Finite Element Analysis

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1. Motivation

There have been significant advances in constitutive modelling over the last few decades, with a vast number of advanced "philosopher" models proposed from various research groups. However, industry uptake of such models and use in complex offshore foundation FEA is rare. This is related to: numerical instabilities, slow runtimes, calibration difficulties and lack of availability in commercial FEA software.

Therefore, there is a requirement for simpler "engineer" models which capture only the most salient features of the soil behaviour which will drive the overall response of the specific foundation problem in question.

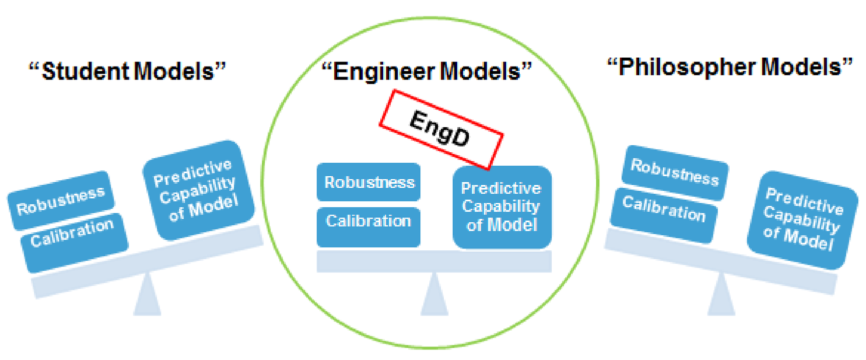


Figure 1.1 Modelling philosophy

2. Implementation

The main function of the constitutive model is to link a given strain increment to a stress increment within an FEA calculation.

All models developed within the research project are implemented as base case code and tested at single element level then developed wrappers codes are used to implement them within commercial FEA packages.

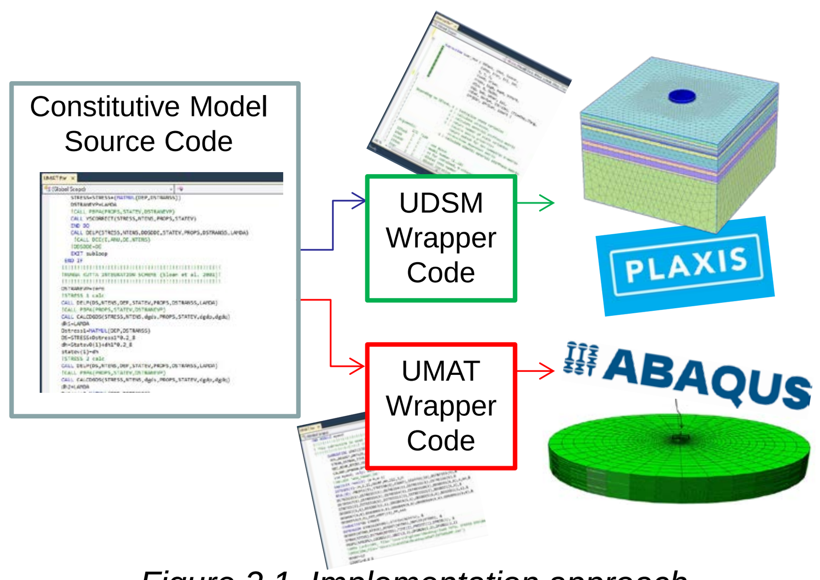


Figure 2.1 Implementation approach

3. Simple Dilational Dense Sand Model

Motivation

Sand is typically treated as fully drained; however, as offshore wind turbine foundations are becoming larger, under typical storm loading rates, the behaviour is likely to be partially-drained to fully-undrained.

The constitutive model used for such FEA in dense sand, even if at the early stage of design, must be capable of predicting the dilational response of the soil reasonably well. Built-in models in commercial FEA software (e.g. Plaxis and Abaqus) are not considered suitable for this purpose.

Model Overview

Simple model with state dependent plastic potential function (*G*) and simple pressure-dependent stationary yield surface (*F*) developed :

$$G = \sqrt{\frac{1}{A\,p'_{cs}}\left(p'_{cs} - p'\right)^{x} + q^{y}} \qquad F = q - M_c g(\theta)(p' + d/M_c)$$

- Plastic potential (G) shape is versatile and is calibrated to fit experimentally observed data;
- Family of plastic potential surfaces change during evolution of p'_{cs} value with plastic volumetric strain;
- Hyperelastic stress dependent formulation within the yield surface;

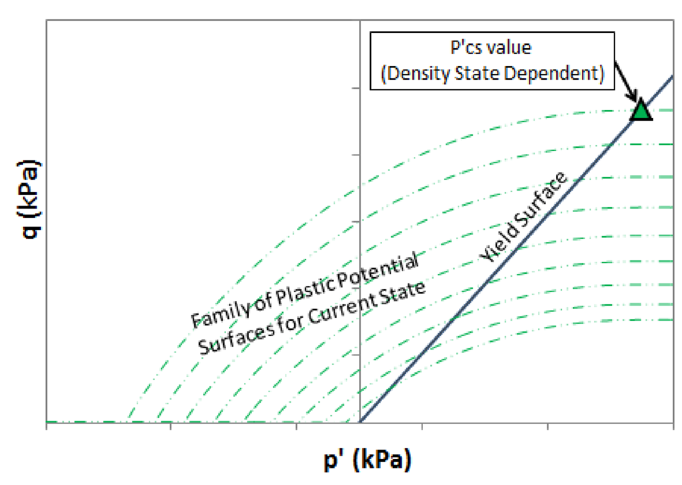


Figure 3.1: Model in p'-q space

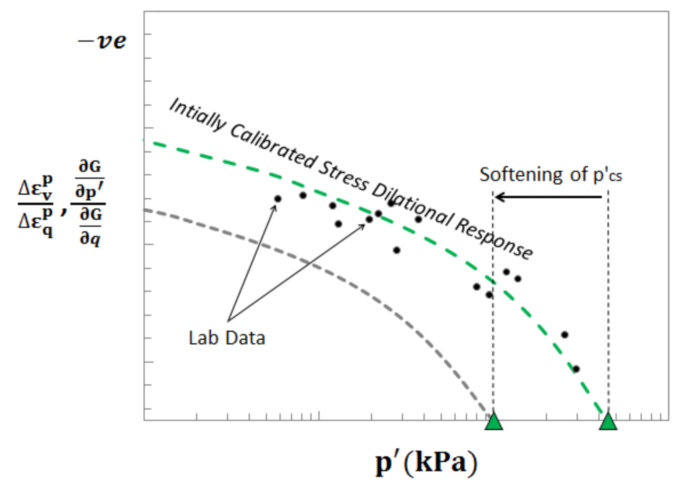


Figure 3.2: Predicted stress dilatational response

Finite Element Analysis of Foundation

- Axially loaded suction bucket FEA results for North Sea site consisting of primarily dense sand are presented;
- The results highlight the potential for drainage induced ratcheting of the bucket out of the ground;
- Planned centrifuge testing to be used to review detailed FEA with different constitutive models.

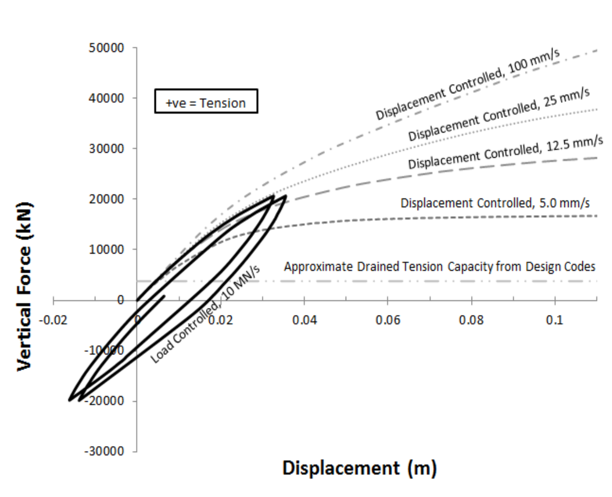


Figure 3.3 Load-displacement results

4. Multi-Surface Total Stress Cyclic Degradation Model

Motivation

The cyclic behaviour of soil is governed by many complex mechanisms. Some effective stress models try to capture these; however, the resulting models are very complex and their use in FEA for foundations is rarely shown in literature.

Given most storm load histories applied to offshore wind turbine foundations can be considered as undrained in clay and potentially even in some sands, a total stress model could be considered suitable to review such cases.

A suitable total stress model with an empirical cyclic degradation rule is currently under development using a library of experimental test data.

Model Overview

Multiple nested stationary Tresca yield surfaces used, each of which bounds an individual component (micro) stress, so that the total global (macro) response results in a hysteresis behaviour as the global stress is the weighted average of the component stresses.

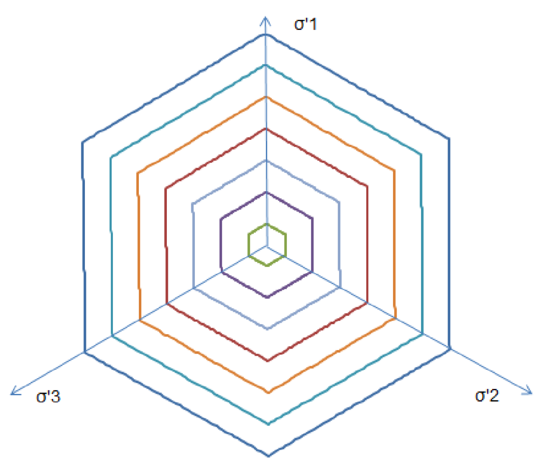


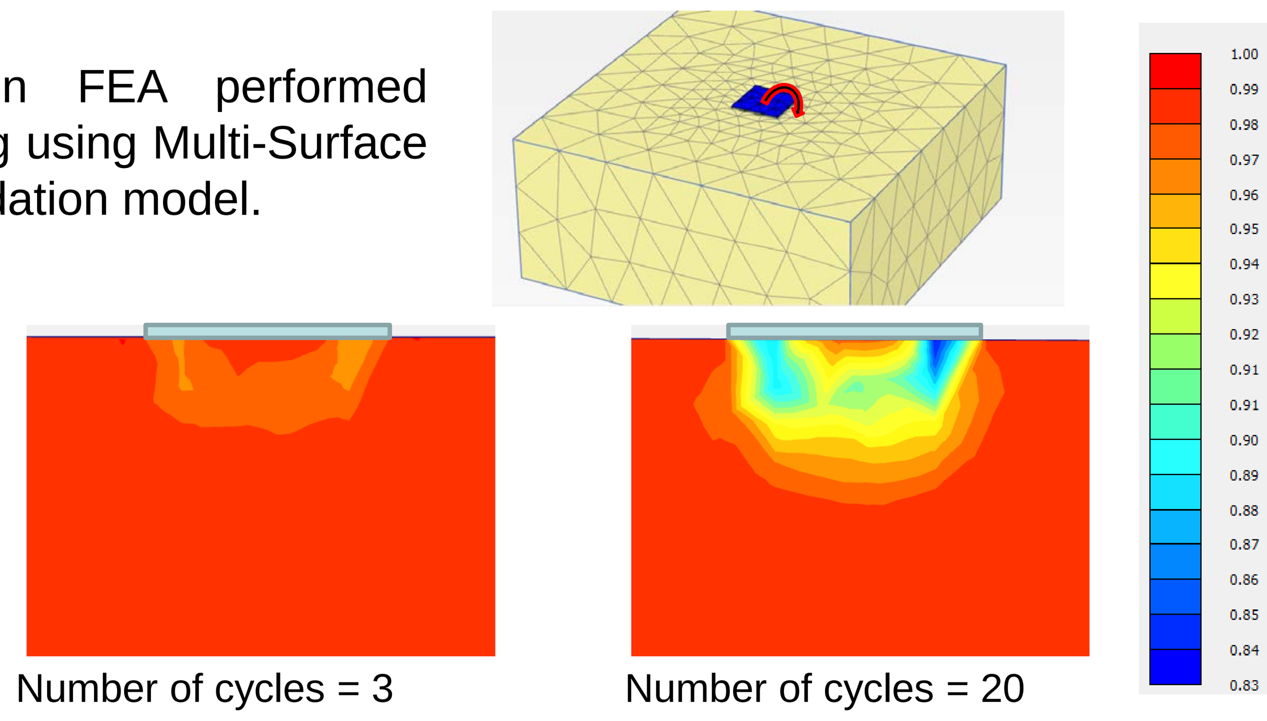
Figure 4.1: Multi-Surface Model

In addition the following is incorporated to capture cyclic degradation:

- Memory surface tracked as state variable to define if cyclic loading occurring;
- Rule implemented which results in higher weighting of strain being added to single "broken spring" component during cyclic loading as a function of the accumulated plastic deviatoric strain (similar approach to Iwan & Cifuentes (1986)).

Finite Element Analysis of Foundation

Shallow foundation FEA performed under cyclic loading using Multi-Surface Total Stress Degradation model.



Number of cycles = 3   Number of cycles = 20

Figure 4.2 Shallow foundation cyclic degradation example

5. CONCLUSIONS & FURTHER WORK

Further development of dilational sand model:

- Extend for multi-surface formulation (in progress);
- Develop plastic potential function further with experimental data;
- Further FEA of wind turbine foundations in sand compared with a number of effective stress constitutive models including SANISAND model;
- Review the drainage response of large diameter monopiles in of dense sand under different loading rates

Further development of Multi-Surface Total Stress Degradation model:

- Develop degradation rule further from laboratory testing results (in progress);
- Review in hyperplasticity framework;
- Further FEA of wind turbine foundations considering storm history;
- Comparison of FEA prediction to centrifuge test results (comparison planned for October 2017)

References

Iwan, W.D. & Cifuentes, A.O., 1986. A Model for System Identification of Degrading Structures. Earthquake Engineering and Structural Dynamics, Vol 14, pp.877–890.

ACKNOWLEDGEMENTS

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