Finite element modelling of ice rubble

Pavel Liferov. Barlindhaug Consults AS, Norway; NIP-Informatica, Russia

Introduction

A characteristic feature of ice-covered waters is the presence of ice ridges. They are formed by compression or shear in the ice cover and are often found in the shear zone between the land fast ice, i.e. frozen to the shore and the drift ice. A high ridging intensity may also be found in straits and sounds with strong currents. Ice ridges are in general long and curvilinear features. Ridges often exist in combination with rafted ice and this combination is named a ridge field. Ice ridges do in many cases give the design loads for such structures as offshore platforms and bridge piers. They may also cause significant impediment to navigation. When drifting into the shallow waters, ice ridges may scour the seabed and create a serious threat to all seabed installations such as pipelines, cables, wellheads etc. The loads from ice ridges on various structures are not clear, and one of the major deficiencies is that the mechanical properties, in time and space, of first-year sea ice ridges are not well known.

A typical view of the sea ice cover (in the area of high interest with respect to oil and gas exploration) is shown in Figure 1.

A typical section of the first-year ice ridge is schematically shown in Figure 2. A first-year ice ridge consists of the sail, the consolidated layer and the keel. The sail is visible, or above the water surface part of a ridge (ref. Figure 1), similar to that of an iceberg. The keel is a part of a ridge that is below the water surface. The consolidated layer is the uppermost refrozen part of the keel. The keel draught can reach 25 – 30 m.

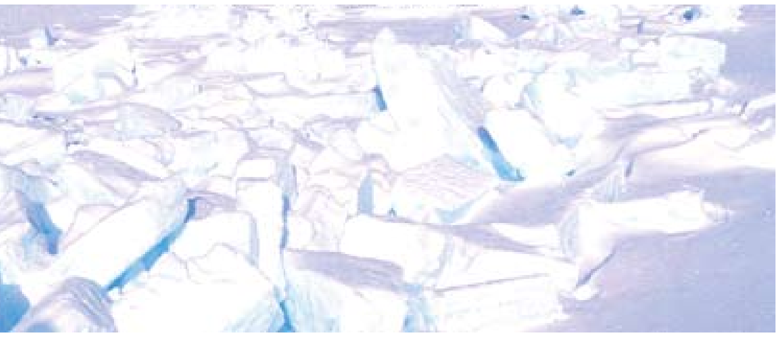

Figure 1: Sea ice cover

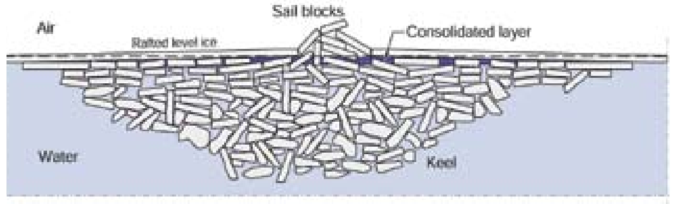

Figure 2: Cross-section of an ice ridge

Loads from sea ice ridges on offshore structures are usually estimated by calculating the loads from the sail, the consolidated layer and the keel separately and adding them at the end. The consolidated layer is often considered to be a thick level ice sheet so that the thickness and the strength (flexural and compressive) become the vital parameters. The sail and the keel are normally called ice rubble and are often treated as a granular material. A number of testing programmes was conducted both in the laboratory and in-situ during the last three decades. Ice rubble was normally described either as Tresca or as Mohr-Coulomb material. The cohesion and the angle of internal friction of ice rubble were, and still are a subject for investigation and discussion. Variation in the above strength parameters was, in particular for the laboratory tests, exceedingly high and there are a number of reasons for this. In contrast with other granular materials, the lifetime of ice rubble within the ice ridge is limited to a few months. During this period the ice rubble constantly evolves throughout the initial, main and the decay phases. Laboratory tests on ice rubble are normally conducted during the initial phase, which is believed to be the most sensitive with respect to the testing conditions. When modelling ice rubble, the thermodynamic similarity is of high significance in addition to geometric, kinetic and dynamic similitude between the prototype and the model. All this, even intending, is very difficult to achieve in reality. Different interpretation of test result with subsequent comparison neither helped to meet the agreement on how to describe the ice rubble strength.

This article briefly descries how PLAXIS was used to simulate some physical tests on ice rubble with respect to derivation of its strength. The developed pseudo-discrete continuum model of ice rubble is also presented as a tool to describe and analyse the characteristic behaviour of ice rubble at failure.

Punch testing of ice rubble

During the design phase offshore structures are subjected to physical model testing. Action from the ice and the ice ridges is studied in ice basins. In the course of conceptual design of the Arctic Shuttle Barge equipped with the Submerged Turret Loading system, the model tests were conducted at the Hamburg Ship Model Basin (TMR Programme from the European Commission through contract N°ERBFMGECT950081) as described in details by Jensen, 2002. The use of the barge concept for export of oil includes the following four major phases: initial approach to the loading facility, final approach and hook-up, loading and departure. During loading the major concerns are related to ice loads on the tanker from ice ridges and mooring/riser interference with ice when the ridges are passing by. Figure 3 shows an illustration of the test with the barge and the STL going through the ice ridge.

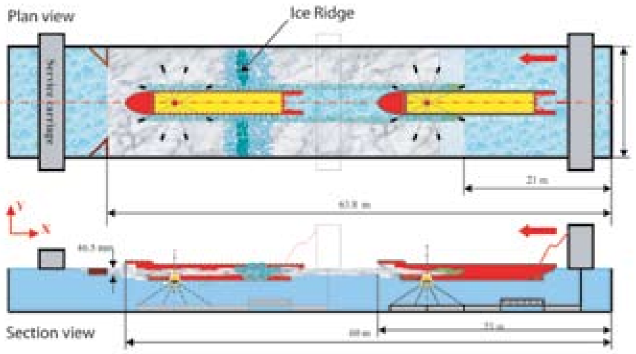

Figure 3: Barge test set-up (from Jensen, 2002)

One of the major problems with laboratory testing is scaling. Gravity forces dominate the problem studied and thus the Froude scaling was used: the gravity field was not scaled and the basic scaling unit was the length (λ). The flexural strength of the ice was scaled, but not that of the ice rubble as there are no standardised methods for ridge production in ice facilities. It was therefore of high importance to conduct separate tests on ice rubble in order to estimate its strength so it could be related to the full-scale values. Two types of tests were conducted and analysed: *plane strain* and *circular plate* punch tests. Figure 4 shows a cross-section along the centreline of the ridge with the corresponding test locations.

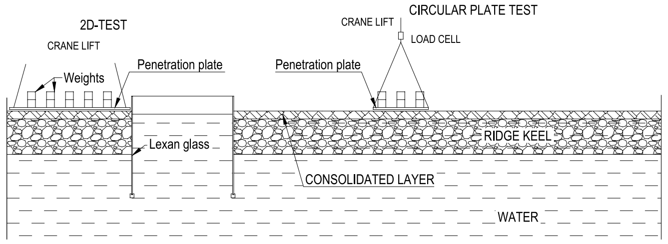

Figure 4: Punch tests set-up

As shown in Figure 4, the plain strain test was performed in such a way that it was possible to observe the failure inside the rubble behind the transparent lexan glass wall. In the circular plate test, the large circular platen with diameter of 0.7 m was loaded by 230 kg of steel weights. Penetration force (*Fz*) and displacements of the platen (*Z1*) and of the surrounding ice (*Z2*) were measured in both tests.

The derivation of the rubble strength from punch tests where boundary conditions are not properly controlled is not straight forward. Two approaches have been used in the past to interpret the test results: analytical and numerical. Among the analytical approaches both the different forms of limit equilibrium method and the upper bound theorem of plasticity were used. The major problem was associated with the use of the two-parametric Mohr-Coulomb failure criterion since tests result in one equation and two unknowns in this case. Simplifications were done and ice rubble was considered either as a frictionless or as a cohesionless material. In the latter case, however, unrealistically high values of the internal friction angle were obtained. As the analytical approaches do not take the complexity of deformation mode into account, they may yield to unreliable results. Numerical modelling of punch tests turned out to be a useful tool for assessment of the ice rubble strength. Finite-element simulations of the physical tests described above were conducted in Plaxis 8 for the plain strain test and in Plaxis 3D tunnel for the circular plate test as described by Liferov et al. (2002, 2003). The finite-element model of the circular plate punch test is shown in Figure 5.

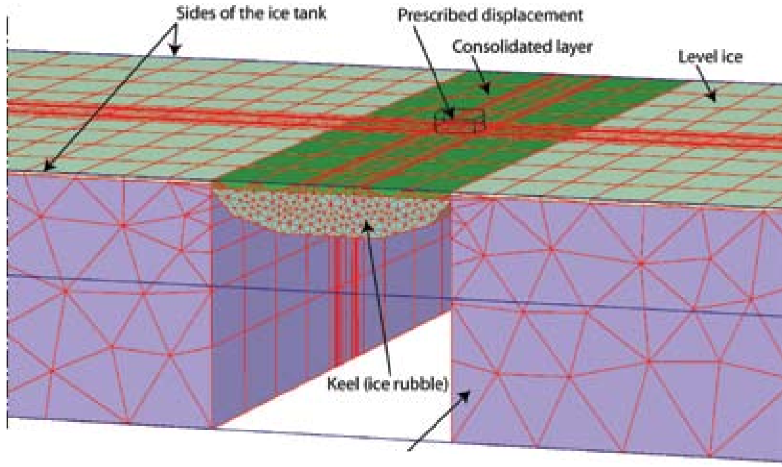

Figure 5: Finite-element model of the simulated punch tests

The quasi-static approach was used in the simulations and the iterative calculations were carried out until the prescribed displacement level was reached. The initial stress state inside the ice rubble was neglected, i.e. the ice rubble was considered as a weightless material. The level ice and the consolidated layer were modelled as an elastic material and their elastic properties were estimated during physical model testing. Ice rubble was modelled as the elastic-perfectly plastic Mohr-Coulomb material. The ice sheet was modelled resting on the underlying elastic layer whose properties were calibrated such that it simulated the water for the particular needs (elastic padding). In the part of the cross-section under the ice rubble the elastic layer underneath was deactivated as it could impose incorrect boundary conditions at the bottom of the keel. In this area the buoyancy force was modelled as an imposed traction load applied to the bottom of the consolidated layer and it was set proportional to the displacement of the ice sheet in *Z*-direction. As the ice became fully submerged, the buoyancy load was set to a constant value. The displacement of the platen was prescribed to a value that was recorded during the experimental testing. The material properties of the ice rubble were then adjusted in order to fit the recorded load - displacement curves *Fz* versus *Z1* and *Z2*. In case of the plain strain test, the failure mechanism observed through the transparent wall was an extra “input” to the curve fitting. An example of the experimental and the simulated failure mechanisms inside the rubble is shown in Figure 6.

The goal of the finite element modelling was to evaluate the strength of the model ice

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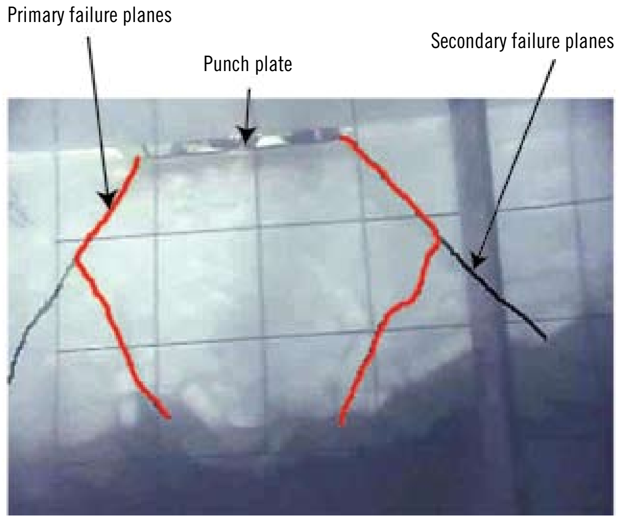
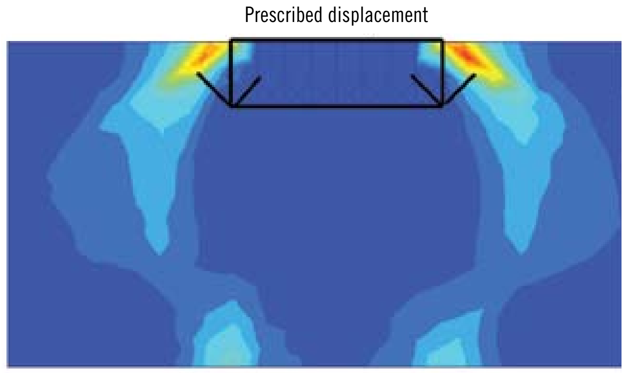
rubble by fitting the experimental curves by the simulated ones. Both the shape of the curves and their ultimate values were fitted. Nevertheless, no particular efforts were put into "refining" of the fitting and the attention was rather focused on the parametric study. Examples of results from the circular plate test simulations is shown in Figure 7 where the experimental (recorded) and the simulated load – displacement curves are shown.

Two stiffness regions separated at about 1-2 mm displacement were obtained as a result of the simulations shown in Figure 7. This coincides well with the experimental records. The analysis of the material state at the transition point shows that in the first high stiffness region the ice rubble fails in tension in the lower part of the ridge as shown in Figure 8 (cross-section taken at the centreline of the plate, prescribed displacement not shown). After that a shear slip surface begins to develop through the keel and a substantial part of the rubble experiences tensile distortion (Figure 9) and the stiffness drops approaching zero at failure (Figure 10).



a: Experimental



b: Simulation (total strains)
Figure 6: Failure mechanism in plain strain test

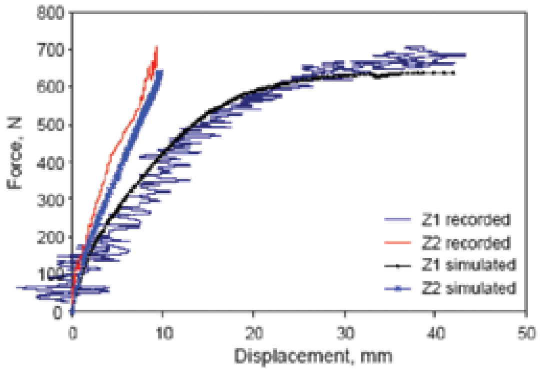
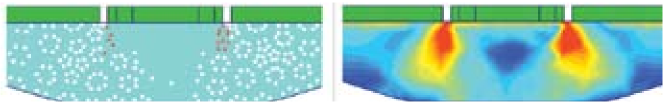
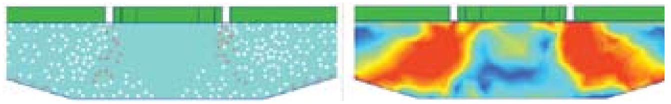


Figure 7: Load-displacement curves, circular plate test (Note: recorded force includes the buoyancy load that is 40 kN at 40 mm displacement).

(a) Plastic (red) and Tension cut-off (white) points (b) Relative shear stresses (red = 1)
Figure 8. Stress state inside the ice rubble at 1.5 mm displacement of the plate.



(a) Plastic (red) and Tension cut-off (white) points (b) Relative shear stresses (red = 1)
Figure 9. Stress state inside the ice rubble at 6 mm displacement of the plate.



(a) Plastic (red) and Tension cut-off (white) points (b) Relative shear stresses (red = 1)
Figure 10. Stress state inside the ice rubble at the ultimate failure.

The simulations revealed that the failure mechanism of ice rubble consisted of the plate bending and the punch through modes. Curve fitting showed that frictional resistance of the ice rubble against the pushing load was minor compared to the cohesive component. It became apparent that the frictional resistance could not be mobilized along the entire failure plane because of the extensive tensile zone in the lower part of the rubble. The parametric study showed that the strength parameters of the material do not contribute independently to the peak load. Basically, it was found that strength of the ice rubble in the punch test is largely dominated by cohesion and tensile strength. The local failure mode is rather complex and depends on combination of the material properties. It was also shown that increase of the friction angle may cause decrease of the attained peak load when the bending of the ice formation is not prevented. It may also be pointed out that the cohesion of the simulated ice rubble could be in order of 0.5 kPa while its tensile strength is about 0.25 kPa. These values correspond to the assumed angle of internal friction of 35° and they provide the best fit of the experimental curves. This corresponds to the full-scale cohesion value of 12.5 kPa that is in a fairly good agreement with what was experimentally measured in the full-scale punch tests in-situ.

Pseudo-discrete modelling of ice rubble

Detailed analysis of the in-situ tests on ice rubble described by Liferov and Bonnemaire (2004) revealed that there exist essentially two failure modes of the ice rubble. The primary failure mode is associated with breakage of the initial rubble skeleton. The skeleton consists of the ice blocks that are fused together by freeze bonds. The secondary failure mode is associated with propagating failure and mobilization of the frictional resistance. Incorporation of these experimentally observed failure modes into modelling of rubble – structure interaction can provide an opportunity to conduct more physically sound simulations and to verify the existing models.

The pseudo-discrete continuum model of ice rubble deformation is a combination of a discrete particles assembly (i.e. ice rubble accumulation) and a FE analysis of this assembly. The primary rational for developing such a model was to produce a tool that would enable a numerical study of the primary failure mode of ice rubble that in many cases can dominate the global rubble resistance. This model, described by Liferov (2004), provides the possibility to simulate contacts between ice blocks and to account for their local failure. The modelling procedure consists of two basic steps. First, the assembly of blocks is generated. A block generator was developed to fulfil this task. In the second step, the generated assembly is used as a geometrical input for the FE analysis to study its behaviour under different boundary conditions. A typical view of the direct shear box FE model is shown in Figure 11.

A series of experiments was conducted to study the variation of the interface strength reduction factor R, the confining pressure p, the angle of internal friction of the parent ice blocks φ and the contact area between the blocks A. Three randomly generated block assemblies were used for each set of the parametric analysis. Figure 12 shows an example of simulation results: the influence of confining pressure p on the rubble shear resistance t. For the range of the present analysis t increased non-linearly with increasing p as shown in Figure 12.

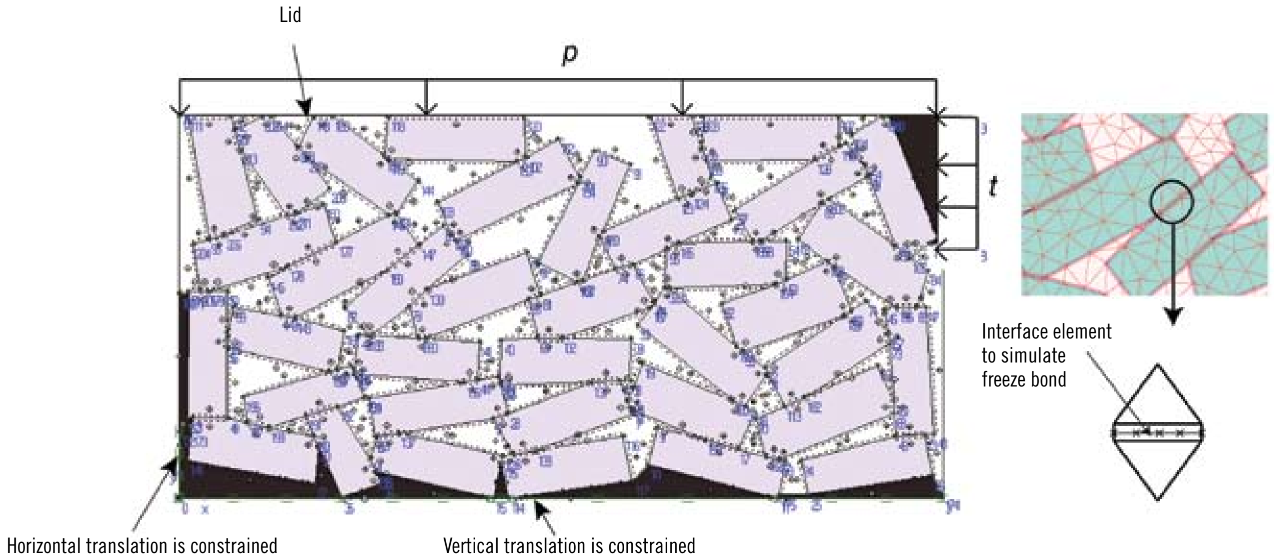


Figure 11: FE model of the direct shear box test

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At the confining pressure *p* of 1 kPa the rubble failed in tension, i.e. the tensile stresses at the contacts between the blocks exceeded their tensile strength. The failure mode changed with increase of p and became a combination of tension and shear modes. Shear failure dominated at $p = 10$ kPa.

A good correlation was found between the interface strength (i.e. freeze bond strength) in the pseudo-discrete model and the equivalent cohesion (i.e. shear strength) in the continuum model. At present, a research project is ongoing to study the freeze bond strength between the ice blocks in-situ. This knowledge would enable to provide better assessment of the ice rubble shear strength, both in time and space, which can then be used in practical engineering applications.

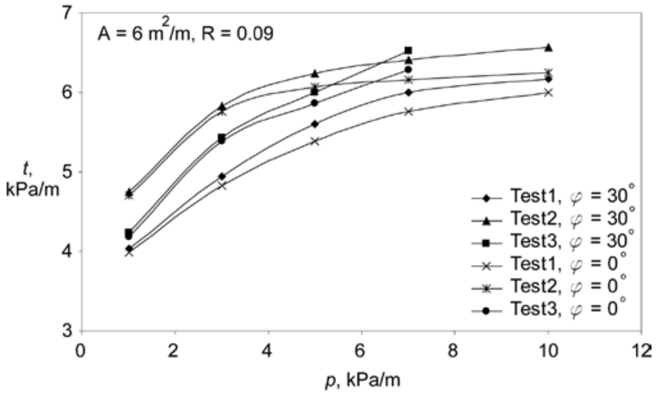

Figure 12: Direct shear box test: t vs. p diagram

Discussion

Mechanical properties of ice rubble is a relatively new item in the engineering ice research. Practical difficulties with conducting both the laboratory and the in-situ tests resulted in a quite approximate description of the ice rubble strength. The numerical tools such as FEM in general and the PLAXIS code in particular are believed to be useful in planning and analysing the non-standard tests as well as performing further applied analyses. Ice rubble resembles granular materials and therefore the soil material models can be used to simulate its behaviour.

References

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Plaxis and GeoDelft

Klaas Jan Bakker

Since GeoDelft and PLAXIS signed their Memorandum of Understanding on further cooperation, much progress has been made.

Among other things, GeoDelft and Plaxis have undertaken the update of their mutual product PlaxFlow. As a first step that will eventually lead to the development of PlaxFlow 3D, an update of the present 2D product PlaxFlow was decided for. The direct occasion to undertake this job was the development of the multi-language user interface for Plaxis 2D, which will eventually enable a Chinese and Japanese version of the Plaxis User interface. This update is in a finishing stage when you read this Bulletin.

Besides that, a new product development line has been undertaken in a mutual project between GeoDelft, Stuttgart University (Prof Pieter Vermeer) and Plaxis. The project is aimed at the development of a new analysis tool for large deformations, such as for cone-penetration and excavation problems, see Figure 1, and most likely for a number of offshore problems such as spud can installation.

The method, known as Material Point Method or sometimes referred to as Particle In Cell method, has shown some major progress in the last decade. Originally some two decades ago, the method appeared in fluid dynamics. Later on the method was adopted by some universities which modified the equations to solve geotechnical problems. Amongst these first geotechnical developers are well-known researchers as Prof Schreyer, University of Albuquerque in New Mexico, Prof. Wieckowski from Lodz University in Poland, and Dr Coetzee from Stellenbosch University in South Africa. With the latter a cooperation and support agreement has been achieved to upgrade his 2D formulation into a 3D version using Plaxis. For those who are familiar with the formulation of the Finite Element Method, the material points in MPM might roughly be compared to moving integration points in a FEM formulation. Therefore it was decided to use the Plaxis 3D source code as a basis for the further development of a 3D MPM code. At this moment Dr Claus Wisser has started working at Stuttgart University IGS with Prof Vermeer, to develop a static version of the code. We are looking forward for his first results in roughly about one and a half years.

Further Plaxis and GeoDelft intend to upgrade the compatibility between the Plaxis and GeoDelft Software by making interactions between a number of Delft Geosystem software products and Plaxis V8. The results of these developments are foreseen in the upcoming year. On the longer term it is decided to match the Plaxis and GeoDelft software range upto a compatible series of software for geotechnial purposes, where Delft geosystem software is aimed at application oriented software products for Geotechnical design and Plaxis is aimed at general purpose analysis software for geo-engineering in 2D and 3D.

Further Plaxis and GeoDelft have decided to increase their cooperation with respect to international marketing by using their mutual international networks and e.g. combining efforts in the case of presence at international conferences and business fairs.

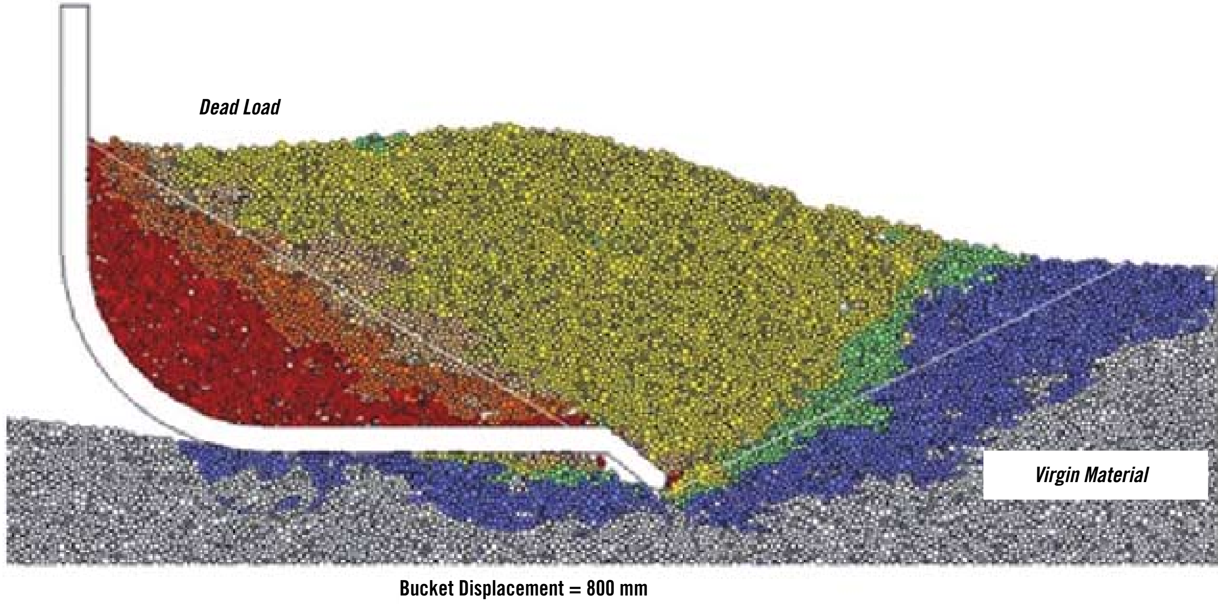

Figure 1: Example of 2D Material Point Method analysis for large deformation analysis, e.g. bucket excavation, by Coetzee