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On the practical use of the Material Point Method for offshore geotechnical applications

De l'utilisation pratique de la Méthode des Points Matériels pour les applications géotechniques offshore

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ABSTRACT: The Material Point Method (MPM) has been developed as a special finite element-based method for large deformation analysis, material flow and contact problems. When it comes to applications in soil, MPM can provide solutions where conventional FEM faces its limitations. Examples of geotechnical applications include landslides, silo filling and emptying, soil pushing and shoveling, as well as structure-soil penetration and installation problems (piles, anchors). In offshore geotechnics one can find several applications of the latter type where an MPM analysis can provide significant added value, such as for monopile penetration, (suction) anchor installation, spud can punch-through and trenching for pipelines and cables. In order to use MPM on a daily basis in practical applications, several numerical difficulties had to be overcome, such as inaccuracies, (numerical) instability, irregularities in strain and stress, contact formulation, boundary determination (applying boundary conditions), and last but not least, dealing with the required computing power. The latter is relevant, since MPM calculations are far more demanding than FEM calculations with a similar calculation grid. In this paper we highlight important numerical solutions that we have implemented for a practical use of MPM in geotechnical applications. Examples are the use of high-order elements and the Dual Domain Material Point method (DDMP) to smoothen strains and stresses, the use of an implicit integration scheme to stabilize calculations, the use of an augmented Lagrangian formulation to enhance the contact algorithm, and the use of dynamics and inertia to deal with local soil failure. Furthermore, the paper demonstrates a number of practical cases where MPM can provide added value in offshore geotechnical applications.

RÉSUMÉ : La Méthode des Points Matériels (MPM) a été développée comme une méthode spéciale des éléments finis pour l'analyse des larges déformations, de l'écoulement des matériaux and pour les problèmes de contact. Quand il en vient à l'application aux sols, la MPM peut fournir des solutions là où la méthode des éléments finis (MEF) conventionnelle atteint ses limitations. Des exemples d'applications géotechnique incluent le remplissage et le vidage de silos, le remaniement du sol, ainsi que la pénétration sol-structure et des problèmes d'installation (pieux, ancres). Dans la géotechnique offshore se trouvent plusieurs applications du dernier type où une analyse MPM peut fournir une valeur ajoutée substantielle, comme la pénétration monopieu, l'installation d'ancres d'aspiration, la pénétration de caisson de support et les tranchées pour câbles et pipelines. Afin d'utiliser la MPM dans des applications pratiques quotidiennes, plusieurs difficultés numériques ont dû être surpassées, telles que des imprécisions, des instabilités (numériques), des irrégularités dans les contraintes et les déformations, la formulation du contact, la détermination des limites (pour appliquer les conditions aux limites), et enfin pour faire face à la puissance de calcul requise. La dernère est pertinente, puisque les calculs MPM sont bien plus exigeants que les calculs MEF pour une grille de calcul similaire. Dans cet article nous soulignons des solutions numériques importantes que nous avons implémentées pour une utilisation pratique de la MPM dans les applications géotechniques. Des exemples sont l'utilsation d'éléments d'ordre élevé et la méthode du Domaine Dual du Point Matériel pour lisser les contraintes et les déformations, l'utilisation d'un schéma d'intégration implicite pour stabiliser les calculs, l'utilisation d'une formulation lagrangienne augmentée pour améliorer l'algorithme de contact, et l'utilisation de la dynamique et de l'inertie pour faire face à la rupture locale du sol. En outre, l'article démontre un nombre de cas pratiques où la MPM peut fournir une valeur ajoutée dans les applications géotechniques offshore.

KEYWORDS: Material Point Method, Large deformations, Offshore applications, Installation, Penetration, Contact, Second-order.

1 INTRODUCTION

The Material Point Method (MPM) (Sulsky et al. 1994) has been developed as a special finite element-based method for large deformation analysis, material flow, contact, installation and penetration problems. In the last decade, MPM has been further developed for and applied to onshore and offshore geotechnical applications, although it is still primarily used in a research environment. In order to use MPM on a daily basis in the engineering practice, numerical difficulties had to be overcome, such as inaccuracies, singularities, (numerical) instability, irregularities in strain and stress, contact formulation, boundary determination, and last but not least, the strong demand of computing power.

For a theoretical description of the particular MPM formulation as used by the authors, reference is made to some previous publications (e.g. Lim et al. 2013, Brinkgreve & Bürg 2015). This paper briefly describes some measures to overcome the aforementioned difficulties, and it gives some typical examples in the field of offshore geotechnical applications, demonstrating the readiness of MPM for engineering purposes involving large deformations.

2 PERFORMANCE IMPROVEMENT MEASURES

In comparison to the conventional FEM, MPM has two additional calculation phases in each calculation step. As can be seen in Figure 1, MPM has to perform an initialisation phase first. In this phase, the information is transferred from the material points to the background calculation grid. Then, a Lagrangian phase is executed. This is essentially a standard FEM calculation step. Afterwards, the information is transferred from the calculation grid to the material points in a convective phase and the grid is, in principle, restored to its initial configuration.

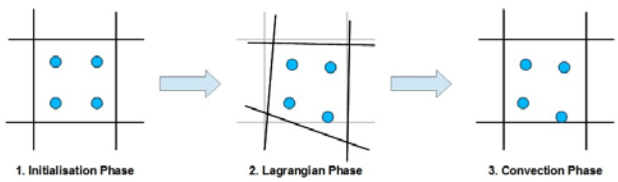

Figure 1. Three phases of an MPM calculation step.

To overcome the numerical difficulties and mitigate additional costs of MPM with the purpose of making it suitable for engineering and design applications in practice, a number of performance improvement measures have been developed and implemented. These measures are briefly described below.

2.1 *Implicit formulation*

An implicit formulation allows for larger time steps (although still relatively small) compared to the maximum time step defined by the CFL criterion as used in explicit formulations. The price to pay is a more complex assembly and solution algorithm, but the benefits are an improved robustness and possibly a faster calculation process due to the use of larger time steps.

2.2 *Second-order calculation grid*

A second-order calculation grid (Bürg et al. 2017) has been adopted to improve the smoothness of the displacement and velocity field. It also enhances the stress and strain distributions. Further, it produces a smoother stress distribution, since the cell-crossing error is less intrusive due to a smaller difference of the gradient at the interface between two cells. This is important for geo-engineering applications considering stress-dependency of soil properties. Moreover, the use of second-order elements helps to prevent volumetric locking and hourglassing.

2.3 *Continuity over cell boundaries*

The original MPM suffers from discontinuities when material points cross cell boundaries, which results in unbalanced forces and stress oscillations. Although the second-order calculation grid from Section 2.1 already reduces this phenomenon a bit, the key to this problem is to provide continuity over cell boundaries by means of B-spline functions (Tielen et al. 2017), C^1-continuity, convected particle domain interpolations (Sadeghirad et al. 2011, Sadeghirad et al. 2013), generalized interpolation MP (Bardenhagen & Kober 2004), DDMP (Zhang et al. 2011) or composite MP methods.

The authors have adopted DDMP as a method to overcome the problems related to boundary crossings. DDMP provides a modified gradient definition which is continuous across cell boundaries. Although this approach as well as all the other solutions mentioned above come with a higher computational cost than the original MPM, the reduction of noise in the stresses is significant and, thus, well worth the effort.

2.4 *Dealing with empty cells*

When all material points have left a cell, the cell has no stiffness or mass contributions in the global matrix. To avoid singularity of the matrix, a small elastic stiffness is added in these empty cells. This procedure is also applied to 'buffer' cells (for example above the soil surface) that are initially empty, but are present to catch material points that are moving above the initial soil surface.

2.5 *Determination of active boundaries*

Since the active domain is formed by the (moving) material points rather than by the calculation grid itself, a special procedure is required to determine the active domain boundaries. This is needed to be able to apply boundary conditions on the soil domain as well as for post-processing purposes. The authors have adopted an enhanced surface integration technique to achieve this functionality.

2.6 *Level-set contact formulation*

Although MPM implicitly accounts for contact when material points meet in the same cell, the contact between soil and structures requires a more advanced contact formulation involving reduced shearing resistance. The authors have employed a robust augmented Lagrangian level-set contact formulation to enable a realistic soil-structure contact modelling. This approach allows to control the shearing resistance by setting some material-dependent contact parameters.

2.7 *Seamless FEM-MPM connection*

In most applications, large deformations do not occur in the entire geometry. In order to obtain a computationally efficient solution, the authors connect the computationally expensive MPM domain (where large deformations occur) to a computational less expensive FEM domain (where smaller deformations occur). Therefore, a seamless connection between a SoilFEM domain (using an Updated Lagrange formulation) and a SoilMPM domain has been developed. Consequently, deformations at the connection boundary result in a 'relaxation' of the MPM calculation grid.

2.8 *Adaptive restoration of the background grid*

One of the contributing factors to the higher computational cost of MPM in comparison to conventional FEM is that the background FEM grid is restored to its initial configuration after each time step (see Figure 1). In addition to causing stress oscillations, this procedure also comes with a certain computational cost, since all calculated variables, e.g., displacements and velocities, have to be transferred from the grid nodes to the material points and back to the grid nodes after the restoration of the mesh has been completed. To mitigate these negative side effects as much as possible, the authors have implemented a mesh quality control such that this grid restoration is only performed once an element gets distorted too strongly.

2.9 *Coupled formulation of undrained behaviour*

In offshore geotechnical applications it is common to assume undrained soil behaviour, which imposes a volumetric constraint. Rather than adding a high (fictitious) bulk modulus for the pore water, the authors use a coupled displacement - pore pressure formulation, avoiding near-singularity of the stiffness matrix and allowing for accurate pore pressure calculations.

2.10 *Quasi-static approach for certain application types*

For applications that do not feature the fall of material, a quasi-static approach can be used to calculate the numerical solution. This simplifies the equations which have to be solved, because the dynamic terms can be omitted.

3 2D OFFSHORE GEOTECHNICAL APPLICATIONS

The remainder of this paper demonstrates a few applications where the use of large deformation MPM analysis is particularly required. Despite the three-dimensionality of the real world, the number of situations where a less computational intensive 2D plane strain or axisymmetric analysis can be used is still plentyful; in particular in offshore geotechnical applications. Examples of axisymmetric applications are (mono)pile and suction anchor installation, spudcan penetration, punch-through and pull-out. Examples of plane strain applications are bearing capacity of mudmats, stability of underwater trenches, seabed slope stability, protection of underwater pipelines and cables. A few such examples are presented below.

3.1 *Pile penetration*

In this example, we consider the penetration of a pile into the seabed. The pile is modeled as linear elastic with a stiffness of E=20000 kN/m^2. The (weightless) soil is represented by a Tresca model with stiffness of 100 kN/m^2 and undrained shear strength of 0.5 kN/m^2. The model setup is depicted in Figure 2.

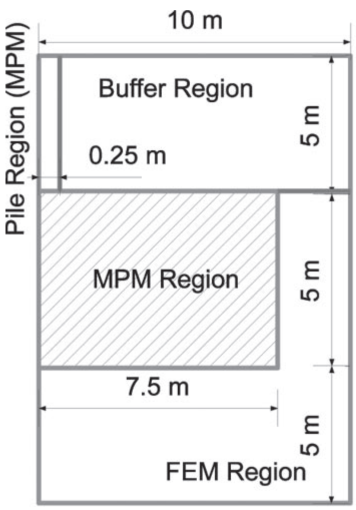

Figure 2. Setup of the geometry of the model

The pile is penetrated into the seabed by 1.6 m. Thus, a MPM region of 7.5 m x 5 m is sufficient to model the area where large deformations occur, whereas the remaining part of the soil is represented by a FEM region. On top of the seabed, we put a buffer region into which material points can flow.

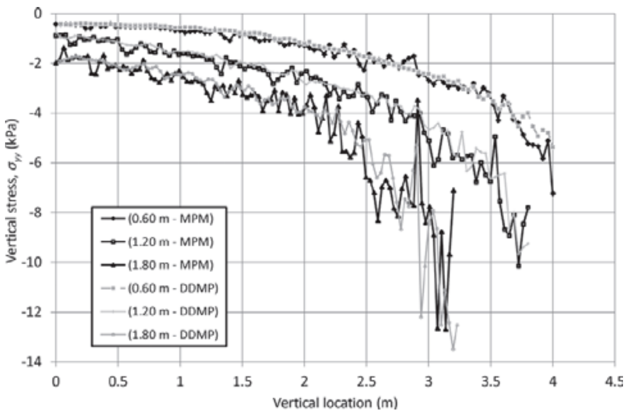

Figure 3. Vertical stress as a function of the vertical pile penetration; comparison between MPM and DDMP results.

Figure 3 shows the vertical stresses in the soil below the pile for penetration depths of 0.6 m, 1.2 m, and 1.6 m. All three cases have been calculated both with standard MPM and with DDMP. One can clearly see how the stresses are oscillating much stronger when standard MPM is used.

3.2 *Pipeline movement*

In (Chatterjee et al. 2011), a large deformation finite element analysis of lateral pipeline movements has been performed. In a first stage, the pipeline is pressed 0.12 m into the soil. Then, it is released such that it stays embedded by self-weight. Afterwards, the pipeline is moved 5.6 m to the right. The soil is modeled by a Tresca constitutive law with the parameters given in Table 1. The pipeline is modeled as an elastic material with a stiffness of 230 MN/m^2 and a submerged unit weight of 6.9 kN/m^3. It has a diameter of 0.8 m.

Table 1. Soil parameters for Tresca model of Section 3.2.

Parameters	*Values*
Shear strength at surface,(kN/m^2)	2.3
Shear strength gradient (kN/m^2/m)	3.6
Submerged unit weight (kN/m^3)	6.5
Young's modulus at surface (kN/m^2)	1150
Stiffness gradient (kN/m^2/m)	1800

In Figure 3, we show the position of the pipeline in the soil at the end of Phase 1 after it has been lowered into the ground. The position of the pipeline after 0.8 m, 1.6 m, 4.4 m, and 5.6 m of horizontal movement is shown in Figure 4. In Figure 5, the vertical position of the pipeline (which results from stress equilibrium) during the horizontal movement is plotted. We can observe that the pipeline pops out of the trench very quickly and then gradually rolls over the heave of soil that it has accumulated at the front. After it has surpassed the soil heave, it sinks back down into soil until equilibrium between the gravity acting on the pipeline and the resistance of the soil has been obtained.

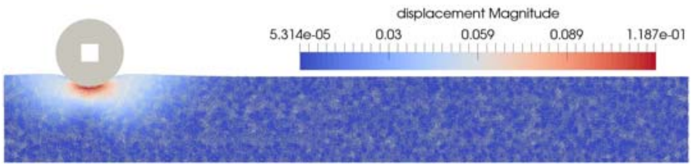

Figure 3. Position of pipeline at the end of Phase 1.

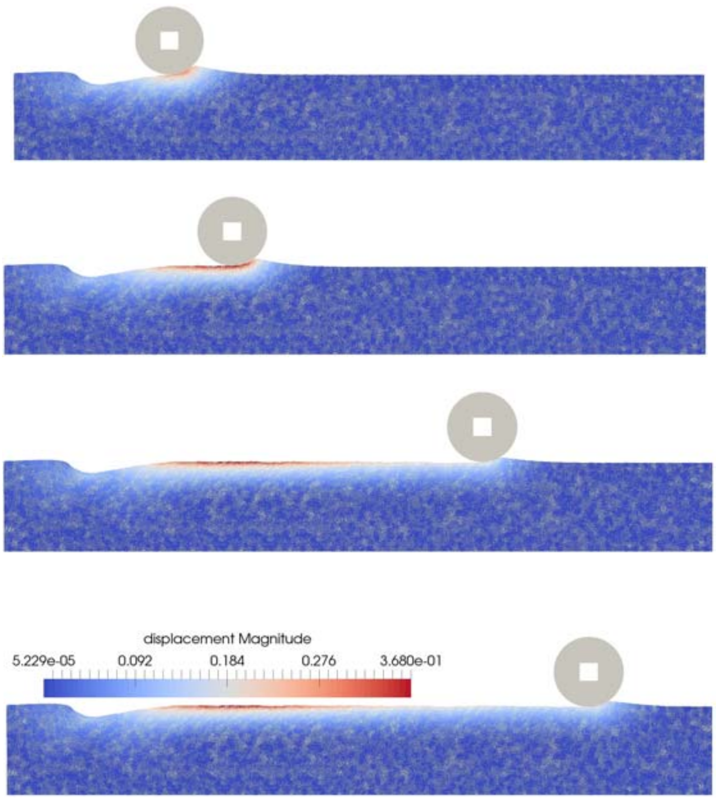

Figure 4. Position of pipeline after (a) 0.8 m, (b) 1.6 m, (c) 4.4 m and (d) 5.6 m of horizontal movement.

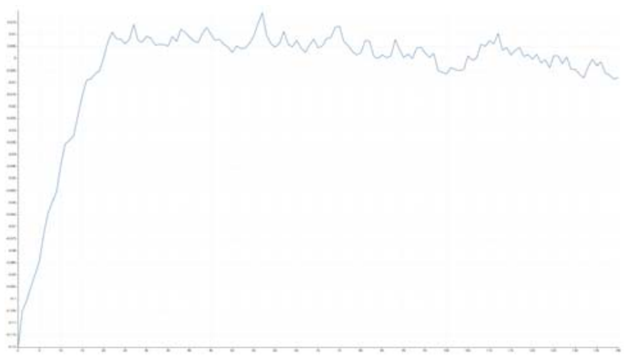

Figure 5. Vertical displacement of pipeline during horizontal movement.

4 CONCLUSIONS

Several offshore geotechnical engineering applications require the use of large deformation numerical analysis. The material point method (MPM) is suitable to deal with such large deformations, material flow, contact, installation and penetration problems, but it suffers historically from numerical issues. Moreover, MPM is much more computational expensive than its ancestor, the finite element method (FEM).

In this paper we have summarized some measures to overcome instabilities and to improve the robustness and efficiency of MPM. In addition, we have shown some typical offshore geotechnical applications that can be modelled using a 2D plane strain or axisymmetric model, which is much less computationally demanding than a full 3D MPM model.

The applications indicate that MPM has become practically applicable in offshore geotechnics and may provide an important numerical tool for analysing the effects of installation effects and the consequences of slope failures.

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