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Material point modelling of releasing geocontainers from a barge

Fursan Hamad [a, *], Dieter Stolle [b], Christian Moormann [a]

[a] Institute of Geotechnical Engineering, University of Stuttgart, Pfaffenwaldring 35, 70569 Stuttgart, Germany
[b] Department of Civil Engineering, University of McMaster, Hamilton, Ontario, L8S 4L7, Canada

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ABSTRACT

Numerical modelling of thin structures combined with history-dependent material under large deformation is challenging for the traditional methods of analysis. The material point method (MPM), in which the continuum is represented by material points, is a Lagrangian–Eulerian procedure suited for granular material and geomechanical simulations. The releasing process of geocontainers within a barge is simulated, in which the split barge is modelled via boundary particles with prescribed angular velocity. Various frictional contact coefficients between the barge and geotextile material are considered. Moreover, the influence of adding wrinkles to the bottom of the container that follows practice is evaluated and the predictions are compared to that of a non-slack geotextile. The effect of soil properties on the geotextile forces are also examined.

1. Introduction

An important application for geosynthetic materials is the use of *Geotextile Sand Containers* (GSC) for shore protection. Owing to economical and ecological advantages over conventional materials, the use of GSC is becoming increasingly popular for reinforcement of existing threatened coastal barriers and structures (Oumeraci et al., 2003). Studying the stability, interaction and failure of sand containers has been investigated by numerous researchers (Hornsey et al., 2011; Recio and Oumeraci, 2007). Another application of geotextiles is the construction of a *geocontainer unit*, which consists of prefabricated geotextile placed in a split barge and filled with sand or slurry up to several hundred cubic meters. Thereafter the container is closed by sewing and is subsequently dumped from the scow bed into the desired position. Such units are used for underwater structures such as breakwaters and disposal of contaminated sludges. See, for example (Pilarczyk, 2000; TenCate, 2007) for more applications.

Numerical modelling provides a flexible tool to analyse the physical phenomena associated with geocontainer applications and to investigate the effects of the controlling parameters. Through a better understanding of the physics, better and more economical experiments can be developed to both validate our models and better tailor geosynthetic products for specific applications. Numerical models based on the distinct element method have been developed to simulate the releasing and dropping process of geocontainers (Palmerton, 2002). The coupling between the *discrete element method* (DEM) and *finite element method* (FEM) has been used to model the interaction of grains as well as soil–geogrid interaction (Tran et al., 2013, 2014; Wang et al., 2014). In spite of the capability of DEM to model the interaction of grains, it is limited to small scale problems and the selection of model parameters is difficult to achieve in a reliable way. As a result, continuum models such as the FEM are usually preferred over discrete representations. Classical finite element methods have drawbacks when large deformation takes place. As an alternative, the *Material Point Method* (MPM) provides a convenient framework for handling large deformation. The *Particle–In–Cell* (PIC) method developed by Harlow (1957) for fluid mechanics is regarded as the origin of MPM. The method was introduced for solids by Sulsky and Schreyer (1993) and their co-workers in New Mexico. The weak formulation of the MPM is provided in terms of a finite element methodology by Sulsky et al. (1995). For geomechanical applications involving geosynthetics materials, where the membrane effects are important, the thin structures and soil material often develop large displacements and large deformation.

York et al. (1999) introduce a membrane element to the MPM formulation for two-dimensional problems. They modify the MPM algorithm by considering the in-plane membrane effect of a single layer of material points. Hamad et al. (2012) propose an alternative formulation, in which the membrane is treated as a FEM structure

* Corresponding author.
E-mail address: fursan.hamad@igs.uni-stuttgart.de (F. Hamad).
URL: http://www.uni-stuttgart.de/igs

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inside the MPM framework. By taking into account FEM–MPM coupling they apply this model to study the releasing of geocontainers from split barges. A detailed comparison between the two membrane approaches shows that the coupled approach more accurately predicts stresses with coarser discretisation (Hamad et al., 2014). Various geotechnical applications using the two membrane formulations are given by Hamad et al. (2013).

As a continuation of studying the dropping of geocontainers (Hamad et al., 2012, 2014), the objective of this paper is to advance the MPM model. For this purpose, the influence of adding wrinkles to the bottom of the container that follows practice is evaluated and the predictions are compared to that of a non-slack geotextile. The influence of barge–geotextile friction coefficients and soil properties on the tensile forces along the thin membrane as well as the deformations of the geocontainer are examined. Section 2 provides a brief overview of the MPM formulation combined with the discrete form. Moreover in this section, the non-zero kinematic condition is presented where the procedure of defining prescribed particles displacement in MPM is elaborated. An application of soil column collapse, where excessive deformation is taking place, is examined in this section. Section 3 is dedicated to outlining and presenting the two approaches to model geotextiles in MPM, where an evaluation of these methods is given at the end of this section. More attention is given to the application of releasing geocontainers from a split barge in Section 4. The effect of adding slack to the geotextile on the tensile forces is examined. Additional cases having various soil and frictional properties are included in this section. Section 5 illustrates the interaction of two geocontainers by dropping one on top of another. The development of the tensile forces due to the dynamic installation is discussed and compared to the final residual values. Section 6 contains the concluding remarks.

2. Brief review of the MPM algorithm

MPM is a modified finite element method, that employs two levels of discretisation: the Lagrangian discretisation, in which a continuum body is represented by *material points* (particles) that are tracked during the computation; and a *computational mesh* to solve the momentum equation. Whereas, the material points are tied tightly to the elements for FEM, they are allowed to move in MPM from one element to another in an Eulerian fashion such that the state properties remain with the material points. Fig. 1 illustrates the two levels of discretisation. This paper follows the original MPM framework (Sulsky and Schreyer, 1993; Sulsky et al., 1995), in which a body is defined in terms of collocated material points that contain the properties and state variables, such as density, stress and strain. More recent implementations of MPM use subdomain procedures to better capture gradients, although at added computational expense. These extensions are not adopted herein.

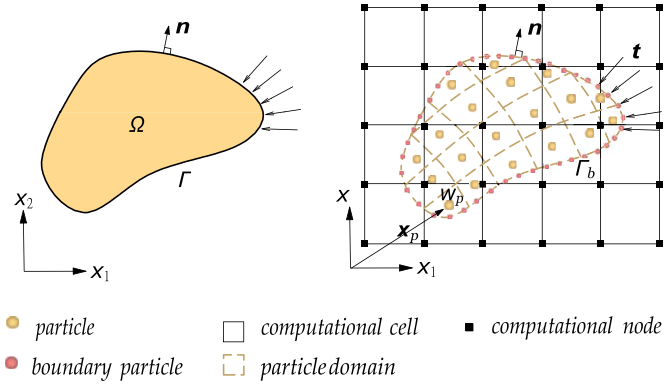

Fig. 1. Continuum body (left) discretised with MPM (right).

The important variables for the class of problem addressed in this paper appear in the momentum balance

$$\rho\ddot{\boldsymbol{u}} = \boldsymbol{L}^T\boldsymbol{\sigma} + \rho\boldsymbol{g}, \tag{1}$$

and its virtual work equivalent, which is used to develop the MPM equations that include the boundary conditions

$$\int_V \delta\boldsymbol{u}^T\rho\ddot{\boldsymbol{u}}\,dV = -\int_V \delta\boldsymbol{\varepsilon}^T\boldsymbol{\sigma}\,dV + \int_V \delta\boldsymbol{u}^T\rho\boldsymbol{g}\,dV + \int_{S_t} \delta\boldsymbol{u}^T\boldsymbol{t}\,dS, \tag{2}$$

where $\boldsymbol{\sigma}$ is the Cauchy stress tensor, ρ is the mass density, $\boldsymbol{g}$ is the gravitational acceleration vector, $\boldsymbol{\varepsilon}$ is the strain tensor, and S_t denotes part of the surface S of volume V on which traction $\boldsymbol{t}$ is specified. The superposed double dot above displacement $\boldsymbol{u}$ implies a double time derivative, with $\boldsymbol{L}$ being the linear differential operator as given in the finite element literature; see, e.g. (Zienkiewicz and Taylor, 2005). The symbol δ represents a virtual quantity and bold implies a vector or matrix. All variables are a function of position $\boldsymbol{x}$ and time t. Since we are following the motion, there is no need to include the advection term for acceleration.

2.1. Discrete form

Following the original MPM description, a body Ω shown in Fig. 1 is discretised into subdomains, where the mass of the subdomain is concentrated at the location $\boldsymbol{x}_p$ of the material point p such that the density is given by

$$\rho(\boldsymbol{x}) = \sum_{p=1}^{n_p} m_p\delta(\boldsymbol{x}-\boldsymbol{x}_p), \tag{3}$$

in which m_p is the mass of the material point p, n_p is the number of material points, and the Dirac delta function δ is defined as

$$\delta(\boldsymbol{x}-\boldsymbol{x}_p) = \begin{cases} 0, & \boldsymbol{x}\neq\boldsymbol{x}_p \\ +\infty, & \boldsymbol{x}=\boldsymbol{x}_p \end{cases} \text{with} \int_{-\infty}^{+\infty} \delta(\boldsymbol{x}-\boldsymbol{x}_p)d\boldsymbol{x} = 1, \tag{4}$$

Referring to Fig. 1, Eq. (3) does not apply to particles that are only used to define the boundary Γ. Similar to the standard finite element method, the value of a variable inside a computational element depends on the nodal values and the corresponding shape functions. For example, the displacement vector is written as

$$\boldsymbol{u}(\boldsymbol{x},t) = \boldsymbol{N}\boldsymbol{a} \quad \text{with} \quad \delta\boldsymbol{u} = \boldsymbol{N}\delta\boldsymbol{a}, \tag{5}$$

where $\boldsymbol{N}$ is a (3×12) matrix containing the shape functions corresponding to the tetrahedral grid as given in Appendix A and $\boldsymbol{a}$ (12×1) contains the nodal displacements, which are a function of time. Using these definitions and making use of Eq. (5), the discretised momentum takes the form

$$\boldsymbol{M}\ddot{\boldsymbol{a}} = \boldsymbol{F}^{ext} - \boldsymbol{F}^{int}, \tag{6}$$

in which $\boldsymbol{M}$ is the consistent mass matrix, $\ddot{\boldsymbol{a}}$ denotes the nodal acceleration vector, and $\boldsymbol{F}^{\mathbf{ext}}$ and $\boldsymbol{F}^{\mathbf{int}}$ are the external and internal nodal force vectors, respectively; see for example (Jassim et al., 2013; Więckowski et al., 1999). In practice, the lumped mass matrix $\boldsymbol{M}_l$ is preferred over the consistent mass matrix as it simplifies the computations due to it being diagonal, albeit at the expense of introducing a slight amount of numerical dissipation (Burgess et al.,