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# Modeling dike failure using the material point method

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**Abstract**

In this study, the material point method (MPM) is used to simulate and analyze the onset and evolution of the failure of a sand dike due to seepage flow. To that purpose, a MPM formulation in conjunction with an elastic-perfectly plastic soil model with Mohr-Coulomb failure criterion is used. For comparison, the onset of failure is also simulated with the standard finite element method. The results show that the double-point MPM formulation can satisfactorily model the essential features of the failure mechanism of the dike.

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## 1. Introduction

The safety of dams, dikes and embankments is an important issue in many areas worldwide. In particular, in the Netherlands the problem has a great impact because three major European rivers (the Rhine, Meuse, and Scheldt) flow through the country protected by over 18000 km of dikes. The failure of a dike may compromise the safety of the country, since approximately 27 percent of the Netherlands is below sea level and in this area over 60 percent of the country's population (almost 16 million people) lives.

The failure of a dike can be caused by several mechanisms, e.g. macro-stability, overtopping, heave, piping, erosion (internal and external) which can be studied by using numerical or analytical methods. Some of these methods are mainly focused to identifying the conditions which lead to the onset of failure. However, nowadays the interest is extended to quantify the risks related to each failure mechanism, and for this reason methods that can fully

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describe the entire failure process from the beginning, where the displacements are small, to the very end after extremely large deformation are foremost important.

This paper describes the failure of a sand dike induced by seepage flow. This is a soil-liquid interaction problem which includes large deformation of soil, possibly together with fluidization and sedimentation of sand. Fluidization and sedimentation occur in the contact zone between soil and free surface water, where the conventional concepts of soil mechanics, based on the existence of a soil skeleton, do not longer apply and there is a transition zone between free surface water and solid skeleton. Such processes may occur in case of erosion of a dike induced by water flow, and the prediction of the final configuration is strongly related to the ability to correctly simulate both the failure mechanism together with fluidization-sedimentation processes.

Hence, the simulation of the entire process cannot be carried out using small-deformation analysis methods. The use of a large deformation analysis approach such as the recent advances of material point method (MPM) that can take into account the interaction of soil and water is rather more appropriate.

The original formulation of MPM was developed by Harlow (1964) [1] for fluid mechanics and then applied to solid mechanics [2] and dry granular materials [3, 4, 5]. Later, the method was extended to handle saturated soils [6] with a numerical approach which uses the velocity of both solid and liquid constituent as the primary unknowns. This formulation was applied to several small and large deformation problems and is able to capture the physical response of saturated soil under dynamic loading. However, only one set of material points is used for both the solid and the liquid phase; therefore groundwater flow and the transition between free surface water and groundwater cannot be captured as well as fluid-like behavior of the soil, which is typical for fluidization and sedimentation problems. Recently, a formulation with two sets of material points (so-called *double-point* formulation) was proposed [7, 8, 9, 10] to overcome such difficulties. Extensions to the original *double-point* formulation were first presented in [11] and then extended in [12].

Since the sand dike failure due to seepage flow is not only a soil-liquid interaction problem which includes large deformation of soil but also involves fluidization and sedimentation of sand, the *double-point* formulation [12] is used in the current study. Concepts of the *double-point* formulation are summarized in the following section.

## 2. Concepts of the double-point MPM

The motion of both solid and liquid material points is described by the system of momentum balance equations, using the velocity fields $\boldsymbol{v}_S$ and $\boldsymbol{v}_L$ for solid and liquid constituents, respectively:

$$\nabla \cdot \boldsymbol{\sigma}'_S + (1-n)\nabla \cdot \boldsymbol{\sigma}_L + \bar{\rho}_S \boldsymbol{g} + \boldsymbol{f}_d = \bar{\rho}_S \frac{D^S \boldsymbol{v}_S}{Dt} \tag{1}$$

$$n(\nabla \cdot \boldsymbol{\sigma}_L) + \bar{\rho}_L \boldsymbol{g} - \boldsymbol{f}_d = \bar{\rho}_L \frac{D^L \boldsymbol{v}_L}{Dt} \tag{2}$$

The terms $\bar{\rho}_S$ and $\bar{\rho}_L$ are respectively the partial densities of the solid and liquid, computed as the ratio of the mass of each constituent with respect to the reference volume; $n$ is the soil porosity, and $\boldsymbol{\sigma}'_S$ and $\boldsymbol{\sigma}_L$ are respectively the effective stress tensor for solid and the stress tensor for liquid. $\boldsymbol{g}$ is the gravity vector. $D^\alpha \boldsymbol{v}_\alpha / Dt$ indicates the material time derivative of $\boldsymbol{v}_\alpha$ with respect to the movement of the constituent $\alpha$.
In equations (1) and (2), $\boldsymbol{f}_d$ is the drag force vector exerted by the liquid on the solid part, and the Forchheimer [12] equation is used to compute it as:

$$\boldsymbol{f}_d = n^2 \frac{\mu}{\kappa}(\boldsymbol{v}_L - \boldsymbol{v}_S) + \frac{F}{\sqrt{\kappa}} n^3 \rho_L \,|\boldsymbol{v}_L - \boldsymbol{v}_S|\,(\boldsymbol{v}_L - \boldsymbol{v}_S) \tag{3}$$

where $\mu$ is the dynamic viscosity of liquid and $\kappa$ is the soil intrinsic permeability. The first term in equation (3) is commonly named the Darcy term whereas the second term describes the additional drop of the hydraulic head