MODELLING OF SAND COLUMN COLLAPSE WITH MATERIAL POINT METHOD

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ABSTRACT: The paper shows numerical analysis of sand column collapse. The simulation was performed with the material point method and the results are compared to experiment. The problem considered involves extreme deformations and is difficult to model with more traditional numerical approaches like the finite element method. In the analysis, the sand is modelled with a rate-independent Mohr-Coulomb model. Despite the use of a simple constitutive model, the computed results agree with the experimental observations reasonably well. This agreement is satisfactory both during and after the collapse.

1 INTRODUCTION

The paper models the collapse of a sand pile using the material point method. The analysis aims to reproduce the experimental results of Lube et al. (2007). The material point method is an extension of the FLIP method (Brackbill & Ruppel 1986), and was first developed by Sulsky et al. (1994). In the method, the material points contain all the information required for the calculations, and the problem is solved in an explicit manner. In each time step, the information stored in the material points is transferred to the grid nodes. After solution on the grid, the updated information is returned to the material points, where some additional updates may occur.

The generalised interpolation material point method (GIMP) was introduced by Bardenhagen & Kober (2004). In GIMP, unlike in the original formulation of Sulsky et al. (1994), material points are not just points in space; they have a fixed domain instead (see Figure 1). This corresponds to a fixed grid shape function for all the particles.

As the particle domain (or the grid shape function) is fixed, the material points can still separate from each other once the material deformation is large enough. As the material points interact through the grid nodes, material separation occurs when no part of the two
neighbouring material point domains contribute to a common node. This usually undesirable behaviour is greatly reduced when compared to the original material point method formulation. The more advanced versions of the material point method (e.g. Ma et al. 2006, Sadeghirad et al. 2011) aim to remove the possibility of material separation. The computational cost, however, may be significant. Moreover, due to an increase in their complexity, these more advanced methods may be less robust numerically.

The material point method is particularly suited to problems with very large deformations. That is why it has been chosen for simulation of sand pile collapse. Such a problem would be difficult to solve using a traditional finite element method.

2 SAND COLUMN COLLAPSE EXPERIMENT

The sand pile collapse experiment by Lube et al. (2007) is shown in Figure 2. It consists of a 20 cm deep channel, the release system (adjustable for different column widths) and a table on which the sand can spread after the mechanism is released.

The results of the experiment were filmed through a transparent side of the channel. The particular experiment modelled was performed with a column of initial width equal to 9.05 cm and height 63.35 cm. This experiment was chosen as it is the only one for which evolution of the column free surface during the experiment was given.

The free surface evolution of the collapsing sand pile is shown in Figure 3. These results were obtained by filming the experiment with a high speed camera (120 frames/s). Every fifth frame was taken, leading to a time difference between the lines in Figure 3 of approximately 0.0417s. Note that the initial time $t_0$ is not related to the moment the experiment began, but rather some later moment after releasing the sand.

3 NUMERICAL ANALYSIS

The experiment was modelled with the GIMP version of the material point method using a modified version of the Uintah software developed at the University of Utah. The grid and the initial position of the material points are given in Fig 1. The dimensions of the column were exactly the same as in the experimental setup, i.e. 633.5 x 90.5 mm. The grid cell size was set to 5 mm. In each cell, nine (3x3) material points were placed, so that the simulation was made with a total of 25,920 material points.

The sand was modelled as a Mohr-Coulomb material. This model was implemented using the procedure of Clausen et al. (2006, 2007), which ensures that the stresses are integrated accurately.
The sand used in the experiment was an industrial sand with a grain-size of 1.4±0.4 mm. Unfortunately, Lube et al. (2007) does not provide much more information on the properties of the sand used. Therefore, the friction angle was approximated by the angle of repose while typical values were assumed for the dilation angle, the elastic properties and the density (see Table 1)

<table>
<thead>
<tr>
<th>Material parameters for sand (Mohr – Coulomb model)</th>
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<tbody>
<tr>
<td>---------------------</td>
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<tr>
<td>0.323</td>
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</table>
The release mechanism used in the experiment was not modelled, since little information was given on it. Consequently, modelling the frictional contact between the gate and the sand pile would thus have been rather arbitrary. Moreover, the computational resources needed for modelling the release mechanism accurately would be significant. Instead of modelling the release mechanism, the sand is assumed to be released fully at the beginning of the analysis (i.e. at time zero). This will cause some discrepancies between the experimental observations and the predictions in the first few tenths of seconds of the sand pile collapse (as the release takes around 0.08s).

Lube et al. (2005) (where more details on the test setup is given) suggested that the roughness of the table surface on which the sand spreads has a negligible effect on the experiment results. This can be explained by the fact that the majority of the actual flow generally occurs over the sand already deposited. Therefore rough contact, inherent in the material point method, was used in the analysis.

4 RESULTS

The numerical analysis aimed to replicate the experimental results over the full range of movement, up to an including the final state. However, as the initial data were disturbed by the releasing mechanism, only the data from $t_0+0.125s$ are compared. The correlation between the time counted from the beginning of the numerical analysis and time from the experiment is given in Table 2. As such, the earliest compared experimental result (from $t_0+0.125s$) corresponds to 0.17s of the performed analysis (see Fig 5 left). Further results are given in Figures 7-10. In these figures, the material points are coloured according to their initial position.

Table 2: Correlation between time in the numerical analysis and experiment

<table>
<thead>
<tr>
<th>Analysis [s]</th>
<th>0.17</th>
<th>0.21</th>
<th>0.25</th>
<th>0.29</th>
<th>0.33</th>
<th>0.37</th>
<th>0.41</th>
<th>0.46</th>
<th>0.5</th>
<th>0.54</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment $t_0+…$ [s]</td>
<td>0.125</td>
<td>0.167</td>
<td>0.208</td>
<td>0.25</td>
<td>0.291</td>
<td>0.333</td>
<td>0.375</td>
<td>0.417</td>
<td>0.458</td>
<td>0.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Fig. 5. Comparison of simulation with the experimental results at $t_0+0.125$ to $t_0+0.208$ s.
Fig. 6. Comparison of simulation with the experimental results at $t_0+0.25$ to $t_0+0.291$ s.

Fig. 7. Comparison of simulation with the experimental results at $t_0+0.333$ to $t_0+0.375$ s.

Fig. 8. Comparison of simulation with the experimental results at $t_0+0.417$ to $t_0+0.458$ s.

Fig. 9. Comparison of simulation with the experimental results at $t_0+0.5$ s.
These results indicate a relatively good agreement between theory and experiment. To achieve this good agreement, some additional numerical dissipation was needed in the analysis. This numerical dissipation replicates the loss of energy of the sand upon moving without any change in strain. Such energy loss is observed in reality and is mostly a result of friction when the sand grains rotate during movement.

To compare, some results computed without additional numerical dissipation are shown in Figures 11-13. It can be noted that initially the results are remarkably similar, but at the end of the simulation where no additional dissipation was used, the predicted granular deformation spreads much further than that which is observed in the experiment.
During the calculations, some mesh dependency is expected as certain material points separate. For example, the material points at the tip of the collapsing pile (Figures 7-10) seem to have lost connection with their initial neighbours. It appears that these points were initially close to the bottom of the sand pile (thus their blue colour), but during collapse they were pushed out and stayed at the front of the sand mass. The final result of the simulation with a coarser mesh (150x75) is shown in Figure 14.

To further improve the results, a more advanced constitutive model could be used instead of the classical Mohr-Coulomb model. The Mohr-Coulomb model is a simple one which does not capture some of the more complex facets of sand behaviour (like rate dependency). Still, the predictions agree with the experimental data reasonably well, especially taking into account how simple it is to calibrate the constitutive model used.

5 CONCLUSIONS
The paper shows a material point method simulation of a sand pile collapse. The results obtained are compared to the experimental results of Lube et al. (2005), with show a satisfactory agreement. The calculations were made to confirm the ability of the material point method to model granular media, thus validating its applicability in geomechanics. The material point method appears to be very capable in such problems where extreme deformations and dynamic behaviour are encountered. The simulation proved to be relatively robust and few numerical issues were experienced. In contrast, to solve this problem with the finite element method, very advanced techniques would have to be used and many numerical problems could occur.
6 ACKNOWLEDGEMENTS

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REFERENCES