Development of smart and flexible freight wagons and facilities for improved transport of granular multimaterials

Deliverable D4.1
Characterisation of the materials and calibration of the constitutive model
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Abstract: This document describes the experimental characterisation of granular materials. Experimental results are used to calibrate a constitutive model for granular material. A micro mechanical model was used to model granite gravel.

Versioning and Contribution History

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Executive Summary

For granular material flow simulation a constitutive or micro mechanical model is required to obtain a realistic behaviour. This document provides a description of the material characterization and calibration of constitutive models for granular material. Laboratory tests were carried out using a triaxial apparatus in order to characterize the material. Three different materials were tested: fine grained crystalline potash (SMOP), coarse grained compacted potash (GMOP) and salt (NCI). Results from the laboratory tests could be used to calibrate a constitutive model for granular material flow. Granite gravel was successfully modelled with a micro mechanical discrete element method model.

The constitutive testing is completed for granular material flow. Repetition of the reported tests can be desired in the course of the project. This is something that can be performed, but only to ensure that the results are consistent with experimental validation. Triaxial test is considered as the best test for granular material when it comes to find constitutive parameters. This type of testing is extremely time consuming, and some other tests such as Digital Speckle Photography (DSP) could not be included in this deliverable. The results of these tests will be used for the validation of the numerical model in Task 4.2 and therefore will be included in the next Deliverable.
1 Introduction

In this task the mechanical material behaviour of the granular materials is investigated for the calibration of a constitutive model. This is the first fundamental step to build realistic numerical models for the granular material flow study. Three different granular materials and their properties are studied: salt, potash and gravel of granite. A powder material where flow pattern and dusting are interesting to study, grain material where caking and stagnation zones are typical and gravel where abrasive wear is an issue.

The mechanical behaviour is different between material cases and has to be investigated during the characterisation. Static properties are investigated by experimentally measuring the friction angle of the different materials.

The Drucker-Prager model can be a good start for the calibration modelling. The model can use either a linear or a non-linear failure relation. The Drucker-Prager model is commonly used for numerical study of granular material flow. This deliverable gives the first fundamental step to calibrate constitutive models for granular flow behaviour from characterisation (experimental) data. Triaxial testing is an accurate measuring technique for granular material. The method provides accurate data at different loading. This data can directly be used to find parameters to constitutive models.

2 Laboratory testing

2.1 Materials

The experimental work was conducted on samples of the following materials: fine grained crystalline potash (SMOP), coarse grained compacted potash (GMOP) and fine-grained salt (sodium chloride). The more fine-grained potash (SMOP) has a bulk density of 1.11 – 1.15 g/cm³, the angle of repose is 30° and the particle size distribution is given in Table 1.

Table 1: Particle size distribution for the SMOP potash.

<table>
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<th>Tyler mesh</th>
<th>mm</th>
<th>Cumulative retained range (%)</th>
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<td>16</td>
<td>1.0</td>
<td>7-21</td>
</tr>
<tr>
<td>28</td>
<td>0.600</td>
<td>30-55</td>
</tr>
<tr>
<td>48</td>
<td>0.300</td>
<td>66-90</td>
</tr>
<tr>
<td>65</td>
<td>0.212</td>
<td>80-96</td>
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<tr>
<td>100</td>
<td>0.150</td>
<td>85-97</td>
</tr>
<tr>
<td>150</td>
<td>0.106</td>
<td>89-98</td>
</tr>
<tr>
<td>&gt;150</td>
<td>&lt;0.106</td>
<td>100</td>
</tr>
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</table>
The more coarse-grained potash (GMOP) has a bulk density of 1.00 – 1.05 g/cm³, the angle of repose is 35° and the particle size distribution is given in Table 2.

### Table 2: Particle size distribution for the GMOP potash.

<table>
<thead>
<tr>
<th>Tyler mesh</th>
<th>mm</th>
<th>Cumulative retained range (%)</th>
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<tr>
<td>4</td>
<td>4.75</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4.00</td>
<td>4 maxi</td>
</tr>
<tr>
<td>6</td>
<td>3.35</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2.36</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2.00</td>
<td>78-86</td>
</tr>
<tr>
<td>10</td>
<td>1.70</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1.40</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>1.00</td>
<td>99 min</td>
</tr>
<tr>
<td>32</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>&gt;32</td>
<td>&lt;0.50</td>
<td></td>
</tr>
</tbody>
</table>

Granite was used as gravel; the average density of granite is between 2.65 – 2.75 g/cm³.

### 2.2 Triaxial apparatus

The triaxial system used in this study is based on the application of stresses controlled by hydraulic means. The apparatus used in this work is manufactured by GDS Instrument Ltd. and features advanced digital pressure-volume controllers see Figure 1. A schematic of the experimental setup is presented in Figure 2. The mechanism of the triaxial test cell is shown in Figure 3. The hydrostatic stresses are applied using water as pressure medium. A cell pressure controller is used to control the radial stresses. The application of vertical strains to the sample is done by pressurizing the piston in the lower chamber. The pressurization is done by applying water pressure with the lower chamber pressure-volume controller. The pressure controllers are connected to a computer and controlled by a computer program provided by the manufacturer.
2.2.1 Strain and stress measurements

The axial strain is measured indirectly by considering the volume change in the lower chamber. The radial stresses are measured by considering changes in specimen height and volume. The volumetric strains are...
measured indirectly by measuring volume change in the triaxial cell. After a consolidation stage, where the confining pressure is held constant, all the tests were axially deformed 20% of the specimen height.

2.2.2 Testing procedure

The specimens were all tested as consolidated drained triaxial tests. The samples were weighed and put into a membrane, see Figure 3. To enable drainage from the sample, two porous filter stones were placed at both ends of the sample. The sample was fixed to the bottom part of the triaxial cell by unfolding the rubber membrane on the bottom part. To ensure that no water leaks into the sample, two O-rings were mounted on the membrane, tightening it to the bottom part of the triaxial cell. A split mould was used to surround the membrane and to enable some stretching of the membrane in order to reduce local irregularities. With the split mould in place the membrane could be filled by the material. The top cap was then placed, the membrane was mounted to it with two additional O-rings, and the split mould was removed. Use of the split mould was important to avoid disturbance of the sample during preparation and installation.

The triaxial cell was then filled with water, at this stage the open valve, see Figure 3, was left open in order to fill and de-air the cell. When the cell was entirely filled with water the open valve was closed. The sample was then pressurized in order to pre-consolidate it, the confining pressure in the cell was increased to the desired level. Three levels of confining pre-consolidation pressures were used: 30, 100 and 250 kPa. The confining pressure was then kept at the same level for approximately one hour. The axial strains were then applied at a rate of 0.1 mm/min; all tests were subject to axial strain of 20%.
2.3 Results

2.3.1 Stress-strain response

Typical stress-strain curves for the shearing phase of the triaxial test are presented in Figure 5, Figure 6 and Figure 7. Increased confining pressure results in increased axial strains at failure for all tested materials. For the highest confining pressure, 250 kPa, the SMOP potash has a significantly higher failure strength compared to the GMOP potash. For the 100 kPa confining pressure case the SMOP potash has somewhat higher failure strength and for the 30 kPa case the GMOP has higher failure strength. Salt has higher failure strength for 250 and 100 kPa confining pressure compared to both SMOP and GMOP. For the 30 kPa case, salt has lower failure strength than GMOP potash but somewhat higher failure strength than SMOP potash.

The post peak behaviour of salt is quite different compared to both SMOP and GMOP, see Figure 7. With increased axial strain after peak strength is reached the material loses strength very suddenly and then regains some of the strength with increasing axial deformation only to lose it again shortly after. This
behaviour is repeated for further increasing axial strain. The magnitude of the oscillations after peak strength increases with increasing confining pressure.

Figure 5: Material response during axial deformation, SMOP potash.

Figure 6: Material response during axial deformation, GMOP potash.
Figure 7: Material response during axial deformation, salt (NCI).

In Figure 8, Figure 9 and Figure 10 the volumetric strain is plotted as a function of the first invariant of the stress tensor for the three confining pressures. Volume decrease occurs mainly during the consolidation phase, where the confining pressure is applied and held constant. Volume increase during the shearing phase is observed for all confining pressures, the volume increase is larger for lower confining pressures.

Figure 8: Volumetric strain versus first stress invariant, SMOP potash.
Photographs of the sample during the shearing phase are presented in Figure 11 - Figure 14.
Figure 11: Sample of GMOP during axial deformation, the shearing phase of the triaxial test.

Figure 12: GMOP potash after 20 % axial deformation where a shear band can be clearly observed.
Figure 13: SMOP potash after 20% axial deformation showing the formation of a shear band.

Figure 14: Salt (NaCl) after 20% axial deformation where a shear band has developed.
3 Modelling

3.1 Drucker-Prager yield criterion

It is evident from the experimental results that potash and salt are materials where the hydrostatic stress has a strong influence on the failure properties. A failure criterion on the form

\[ F(I_1, J_2) = 0 \]  

(1)

where the influence of the hydrostatic stress is included, is thus required. The simplest possible explicit form of (1) is the following linear relation between \( I_1 \) and \( J_2 \)

\[ \sqrt{3}J_2 + c_1 I_1 - c_2 = 0 \quad c_2 \geq 0 \]  

(2)

where \( c_1 \) and \( c_2 \) are material parameters. The criterion in (2) is the Drucker-Prager criterion, originally formulated by Drucker and Prager (1952). The Drucker-Prager model is a simple model that can be a good start for the calibration modelling. For granular flow this is a commonly used model.

3.2 Material parameters

From the experimental results the maximum value of \( \sqrt{3}J_2 \) is plotted versus \( I_1 \) for the different confining pressures. The three points are used to obtain the Drucker-Prager material constants \( c_1 \) and \( c_2 \) for the tested materials. In Figure 15 and Figure 16 the Drucker-Prager yield criterion is expressed as the best line fit to the three failure points. From the line fit to the experimental results the internal angle of friction can be calculated. The material parameters calculated from the experimental data are presented in
Table 3.

Figure 15: Drucker-Prager yield criterion for SMOP potash.

Figure 16: Drucker-Prager yield criterion for GMOP potash.
Figure 17: Drucker-Prager yield criterion for salt (NCl).
Table 3: Material parameters for granular materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>( c_1 )</th>
<th>( c_2 )</th>
<th>Internal angle of friction</th>
</tr>
</thead>
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<td>-0.625</td>
<td>0</td>
<td>38.5°</td>
</tr>
<tr>
<td>GMOP potash</td>
<td>-0.524</td>
<td>52.386</td>
<td>45.6°</td>
</tr>
<tr>
<td>Salt (NCI)</td>
<td>-0.809</td>
<td>9.036</td>
<td>59.8°</td>
</tr>
</tbody>
</table>

### 3.3 Micro mechanical model for granite gravel

For granite gravel a micro mechanical discrete element method (DEM) model is used. With DEM the material behaviour is determined by an alternation of Newton’s second law of motion and a force displacement law at the contacts. The motion of each individual material particle from body and contact forces is determined by Newton’s second law of motion. The force displacement law is used to update contact forces arising from the relative motion of each contact. In the present study DEM is realized using rigid spheres for each gravel particle. The interaction with other rigid or deformable structures is accomplished with a penalty-based contact algorithm. The material behaviour is governed by normal and tangential contact stiffness, contact damping coefficients and static and rolling friction coefficients. The micro material parameters that were used for granite gravel are presented in Table 4.

Table 4: Micro mechanical material parameters for granite gravel.

<table>
<thead>
<tr>
<th>Material</th>
<th>Contact stiffness</th>
<th>Contact damping</th>
<th>Friction coefficients</th>
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<tr>
<td></td>
<td>Normal</td>
<td>Tangential</td>
<td>Normal</td>
</tr>
<tr>
<td>Granite gravel</td>
<td>0.3</td>
<td>0.01</td>
<td>0.98</td>
</tr>
</tbody>
</table>
4 Conclusions

The presented experimental methodology was successfully used to characterize the studied granular materials and the experimental results were used to calibrate a numerical model. Triaxial characterization tests of three granular materials have been successfully performed. The Drucker-Prager constitutive model has been calibrated against experimental data for potash and salt. A micro mechanical numerical model was used to model the flow behaviour of granite gravel.