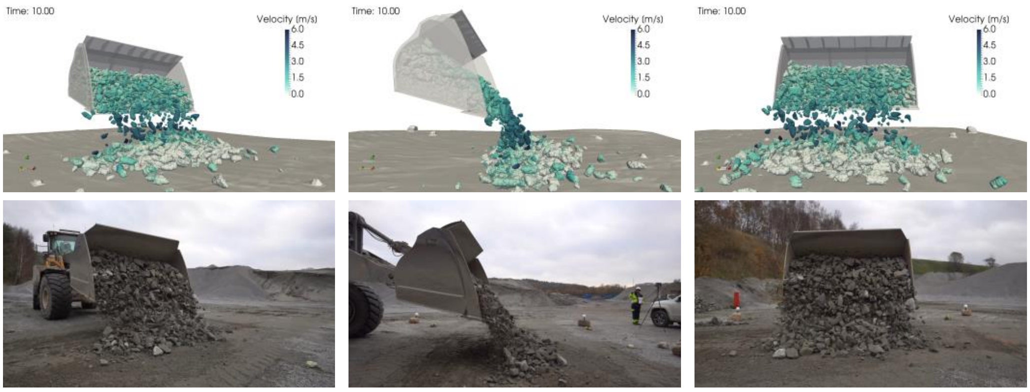
ID: 13638

SEGREGERING AV BERGMATERIAL VID AVLASTNING

Fullskaliga försök för DEM validering och undersökning av segregering



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FÖRORD

Forskningsteamet vill rikta ett stort tack till SBUF (Svenska Byggbranschens Utvecklingsfond) för bidrag till SBUF projekt 13638. Projektet stöds av NCC med Pär Johnning som den formella projektledaren. Författarna vill också tacka för alla idéer, kommunikation och återkoppling på rapporten från Per Murén och Kristofer Hofling, också vid NCC. I projektreferensgruppen ingår också Erik Liljeby, Skanska och Peter Martinsson, Swerock (Peab). Projektgruppen vill tacka referensgruppen för goda diskussioner och återkoppling.

Den experimentella delen av studien hade inte kunnat genomföras utan insatsen från personal och operatörer vid NCC täkten i Stenungsund. Ett stort tack till alla operatörer och speciellt Mikael Date. Jonatan Berglund från Visinator AB kontrakterades för att utföra all 3D-skanning under testkampanjen och point cloud-postbearbetning. NCC-laboratoriet i Hisings Kärra utförde siktanalys för alla prover med utmärkt professionalism och omsorg. Stort tack till laboratoriechef Mats Fehrm och alla medarbetare vid laboratoriet.

Denna rapport har skrivits av Johannes Quist och granskats av Franziska Hunger och Klas Jareteg. Modelleringen och simuleringarna har huvudsakligen utförts av Johannes Quist och Franziska Hunger och DEM-simuleringsprogramvaran Demify ™ som används för studien har utvecklats med Klas Jareteg som ledande programmerare och utvecklare.

Detta projekt utförs inom ramen för Vinnova InfraSweden2030-projektet 2018-00606 DigiRoad, detta stöd är också mycket tacksamt mottaget.

Om du som läsare har ett intresse av att granska material från projektet som t.ex. experimentellt eller simuleringsvideomaterial som inte är möjligt att visa i en rapport, vänligen kontakta författaren. Rapporten är fortsatt skriven på engelska. Om du som läsare önskar en version på svenska, vänligen kontakta författaren.

Johannes Quist (PhD), December, 2019
Fraunhofer-Chalmers Centre

Preface

The researchers would like to acknowledge the support from SBUF (Svenska Byggbranschens Utvecklingsfond) through project grant ID:13638. The project is supported by NCC with Pär Johnning as the formal project leader. The authors would also like to acknowledge all the ideas, communication and report feedback from Per Murén and Kristofer Hofling, also at NCC. The project reference group also includes Erik Liljeby, Skanska, and Peter Martinsson, Swerock (Peab). The project team would like to thank the reference group for good discussions and feedback.

The site personnel at NCC Stenungsund is also greatly acknowledged for the contribution, interest and dedication during the experimental campaign, especially operator Mikael Date. Jonatan Berglund from Visinator AB was contracted to perform all 3D scanning during the test campaign and point cloud post processing. The NCC laboratory in Hissings Kärra performed all size distribution sieving tests with excellent level of professionalism and care. We would like to thank Mats Fehrm and all his colleagues at the lab.

This report has been written by Johannes Quist and reviewed by Franziska Hunger and Klas Jareteg. The modelling and simulations have mainly been performed by Johannes Quist and Franziska Hunger and the DEM simulation software Demify™ used for the study has been developed by Klas Jareteg as the lead programmer and developer.

This project is performed under the scope of Vinnova InfraSweden2030 project 2018-00606 DigiRoad, this support is also greatly acknowledged.

If you as a reader has an interest in reviewing material from the project such as e.g. experimental or simulation video material not possible to display in a report, please contact the author.

Johannes Quist (PhD), December, 2019
Fraunhofer-Chalmers Centre

Sammanfattning

Följande rapport ger en detaljerad redogörelse av aktiviteter och resultat från SBUF-projekt 13638. Projektet har genomförts inom ramen för Vinnova InfraSweden2030-projektet DigiRoad (2018-00606). Digiroad-projektets syfte är att undersöka storlekssegregeringseffekten i materialhanteringsprocessen och vid kompaktering av obundna granulära material (UGM) vid vägbyggnad. För detta används beräkningsmetoden diskret elementmetod (DEM). En viktig aspekt av Digiroad-projektet är att genomföra fysiska experiment för att validera simuleringsmetoden på olika skalor, från laboratorium till industriell skala. SBUF-projektet som presenteras i denna rapport har inriktats mot att utföra experiment i industriell skala i en bergtäkt där avlastning från två olika maskiner studeras. Resultatet av projektet kan klassificeras i tre kunskapsdomäner: metodik för experiment i industriell skala, DEM-modellering och simulering av bergmaterial vid avlastningsprocesser, samt segregeringseffekter som uppkommer under avlastning och vid den resulterande högbildningen.

Det finns ett antal utmaningar kopplade till validering av simuleringsmodeller. Det utförda experimentet måste dokumenteras tillräckligt så att modelleraren inte gör ett misstag eller gör antaganden som leder till en diskrepans mellan systemkonfigurationen i testmiljön och motsvarande simuleringsinställningar. Det bästa sättet att minimera sådana avvikelser är att personerna som modellerar deltar i eller utför testerna själva. Detta kräver emellertid erfarenhet och kunskap om både hur man utför modelleringen och hur man utför väl genomförda experiment i fält. Därför har samarbetet mellan FCC och NCC varit en så unik projektstruktur.

Mätningarna har utförts vid NCCs bergtäkt i Stenungsund. Ett testområde på 6x6 meter bereddes och referens-sfärer för 3D-skannings placerades. Sfärerna används för registrering av varje 3D-punktmoln till samma globala koordinatsystem. Avlastningsprocessen studerades för en Volvo L180H hjullastare utrustad med Gjerstad 5000L skopa samt en Volvo FMX bergflaksbil med en lastplattform från SLB Övertorneå AB. Tre Sony RX0-kameror användes för synkroniserad videoinspelning vid 50 fps från tre synvinklar betecknade som iso-, front- och sidovy. Fyra fraktioner av olika storlek testades: +22/-90 mm (A), +0/-90 (B), +22/-250 (C) och en binär blandning av +8/-11 & +22/-90 (D). För att fånga start- och sluttillståndet 3D-skannades maskinerna före och efter varje testsekvens. Efter att maskinen tagits bort skannades även högen från tre positioner. Fem materialprover togs från varje hög betecknad som Front, Back, Left, Right and Top, där Front definieras som den sida varifrån maskinen lastar av.

DEM-simuleringar har utförts med den vid FCC internt utvecklade DEM-koden kallad Demify™. Partikelpopulationen byggs upp av tio 3D-skannade verkliga stenformer, modellerade som multisfärer med 40 sub-sfärer i varje partikel. Storleksfördelningen har baserats på den experimentella siktanalysen och en validering har utförts för att säkerställa kongruens mellan simulerad och experimentell fördelning. Kinematiken för maskingeometrin härleddes från start- och sluttillståndet samt genom motion capture baserat på videoinspelningarna. Dessa rörelser översattes till en uppsättning translationer och rotationer, tidsjusterade så att rörelsen matchar experimentet. Både den experimentella och simulerade analysen av partikelstorleksfördelning av högarna visar en signifikant segregeringseffekt för alla test-serier. Data-setet för den experimentella storleksfördelningen i serie C verkar lida något av provtagningsproblem relaterat till de grova storlekar som testades. För serie C genomfördes provtagning med hjullastaren och siktanalysen genomfördes medelst manuell sortering och storleksklassificering med kvadratiska tolkar.

Jämförelsen mellan simulering och experiment visar en mycket hög grad av kongruens. För att statistiskt kunna utvärdera kongruensen bättre behöver fler tester genomföras så att variansen för avlastningssekvensen och högbildningen kan beräknas.

Executive Summary

The following report provides a detailed account of the activities and results from SBUF project 13638. The project has been conducted under the scope of the Vinnova InfraSweden2030 project DigiRoad (2018-00606). The scope of the Digiroad project is to investigate the size segregation effect in the materials handling process and compaction of unbound granular materials (UGMs) in road construction using the discrete element method (DEM). A vital aspect of the Digiroad project is to conduct physical experiments in order to validate the simulation methods on different scales, from laboratory to industrial scale. The SBUF project presented in this report has been framed around performing industrial scale experiments in a quarry on the unloading process from two different machines. The outcome of the project can be classified in three knowledge domains: industrial scale experimental methodology, DEM modelling and simulation of rock aggregate unloading processes, segregation effects during unloading and in pile formations.

There are a number of challenges linked to validate simulation models. The performed experiment needs to be documented well enough so that the modeller doesn't make a mistake or have presumptions leading to a miss-match between the system configuration of the test environment and the corresponding simulation setup. The best way to minimize such discrepancies is that the modeller takes part in or performs the tests themselves. However, this requires experience and knowledge regarding both how to perform the modelling and how to conduct well executed experiments in the field. This is why the collaboration between FCC and NCC has been such a unique project configuration.

The measurements have been performed at the NCC quarry in Stenungsund. A test area of 6x6 meters was prepared and 3D scanning reference spheres were positioned. The reference spheres allow for registering each 3D point cloud into the same global coordinate system. The process of unloading was studied for a Volvo L180H wheel loader equipped with Gjerstad 5000L bucket, and a Volvo FMX aggregate truck with a loading platform from SLB Övertorneå AB. Three Sony RX0 cameras were used for synchronised video recording at 50fps from three view angles denoted as iso, front and side view. Four different size fractions were tested: +22/-90mm (A), +0/-90 (B), +22/-250 (C) and a binary mix of +8/-11 & +22/-90 (D). In order to capture the start and end condition of the test the machines were 3D scanned before and after each test sequence. After the machine was removed the pile was scanned from three positions. Five material samples were extracted from each pile denoted as Front, Back, Left, Right and Top, where Front is defined as the machine side of the pile.

DEM simulations were performed using the in-house DEM code developed at FCC, called Demify™. The rock particle population is built up by ten 3D scanned real rock shapes, modelled as multispheres with 40 sub-spheres in each particle. The size distribution has been defined by the experimental sieve analysis and a validation has been performed in order to ensure congruence. The machine geometry kinematics was derived from starting conditions and motion capture analysis based on the video recordings. These motions were translated to a set of translations and rotations, timed so that the movement matches the experiment.

Both the experimental and simulated particle size distribution analysis of the piles demonstrate a significant segregation effect for all size fractions tested. The experimental size distribution data does seem to suffer slightly from sampling issues as the extracted sample masses were constrained by the feasibility of handling the total amount of samples from the experiments. The coarse +22/-250 were hand sorted and sized on site.

The comparison between simulation and experiment display a very high level of congruence. However, in order to statistically evaluate the congruence, more tests would need to be conducted so that the variance of the unloading sequence and pile formation could be calculated.

Content

1 INTRODUCTION

The Fraunhofer-Chalmers Centre (FCC) has in a series of research projects together with NCC, studied rock material, its behaviour and interaction with machine geometry in road construction processes. This is realised through the use and development of software based on the discrete element method (DEM). The goal is to provide a world-leading simulation software for unbound rock materials. Potential users are, for example, designers and performers of infrastructure, machine manufacturers, academic and industrial research practitioners and more. Today, the DEM technology is very capable and is heavily used in many industries, but not as widely used in the rock material industry. What is needed specifically in the ballast and infrastructure industry is that the method is validated on an industrially relevant scale to achieve an increase in TRL levels from 4-5 to 6-8. This type of successful TRL increment and implementation can be considered a concrete innovation process. In order to reach these higher TRL levels, novel methods and measurements are needed for full-scale rock material experiments that are adapted for validation comparison between experimental and simulation data. The challenge is partly to measure and quantify the particle bulk flow behaviour of the rock material, and partly to measure the segregation effect. While this challenge/problem may be regarded as a specific rock material related difficulty, there is a general lack of industrial scale validation cases for DEM described in the literature. The authors believe there are at least three main reasons:

- Several knowledge and competence domains are needed. Experienced people are needed from the computational modelling, the measurement/experimental as well as the industrial operations domain.
- Industrial processes need to be made available. This requires a project with industrial partners included as active stakeholders and where the specific objective and long-term value of model validation is prioritised and understood.
- The actual sampling and measurements are challenging to perform. The industrial setting does not naturally provide the controlled environment normally provided by a traditional laboratory. Therefore, it is difficult to control sampling variance and test conditions.

In this project, these challenges are targeted by a collaborative project with stakeholders from the relevant knowledge domains. An experimental methodology has been developed and tested at the NCC quarry in Stenungsund. The physical experimental setup has further on been built up in a virtual twin DEM environment and the results from each respective domain are finally compared.

1.1 Related projects

The DIGIROAD project is carried out within the framework of Vinnova's SIO InfraSweden2030 and aims to model and simulate the handling and function of the unbound aggregate material in the road body. The proceeding project was a feasibility study conducted within the Chalmers Area of Advance program Building Futures, where the results showed a strong relationship between size distribution and bed stiffness and segregation effects in handling and propagation of unbound rock material. The coordinating part of the project is the Fraunhofer-Chalmers Centre (FCC) and industrial partners are NCC AB, Volvo CE and Dynapac. The Department of Industrial and Materials Science (IMS) at Chalmers is also an academic partner. After completion of the project, the goal is that a world-leading and industrially validated demonstrator is developed for simulation of unbound granular materials in base and sub-base layers and its interaction with the subgrade. With this type of tool, engineers and designers are expected to be able to analyse and create optimal flexible road structures in terms of material volume, resilient stiffness, packing density and rigidity (cost and performance).

1.2 Aim

The primary purpose of the project is to develop a methodology as well as a full-scale experimental dataset for the validation of simulation models for rock material and its interaction with machine geometry. The secondary purpose is to investigate the segregation effects of rock pile formations from loading and unloading processes.

The following points exemplify how the project is intended to target SBUF's stated goals:

- Customer added value - Increased product quality through reduced variance in size distribution due to segregation effects during loading and unloading.
- Favourable conditions for innovation & technology development - Digitalization through validated simulation technology provides a virtual test environment for the development of new machines and processes at significantly reduced costs in relation to physical experiments and prototypes.

The project results have an intrinsic value as a documentation of the experimental methodology and through the experimental results. Through the direct link to the DIGIROAD project, the methodology can be managed directly. The project is expected to benefit companies linked to the Swedish rock material industry through the availability of validated simulation models in the form of software. The project results are also expected to quantify as well as provide insights regarding good handling of rock material to avoid quality degradation due to segregation effects.

1.3 Specific objective of this study

The specific objective of this experimental campaign is to perform full scale unloading tests from an aggregate truck and a wheel loader. The complete sequence should be measured with 3D scanning, video, photography and rock material samples in order to analyse the segregation effect and to generate a validation dataset for DEM comparison.

2 METHODOLOGY

In this section the experimental methodology to perform these tests is presented. The simulation method DEM and how it is implemented in our in-house code is also briefly discussed.

2.1 Experimental configuration

The machines used for the tests were a Volvo L180H wheel loader equipped with a Gjerstad 5000L bucket and a Volvo FMX 4-wheel aggregate truck equipped with a 20.5 ton loading platform from SLP Övertorneå AB.

In preparation of the experiments a methodology document was developed that can be found in appendix A. The method includes the preparation of the ground and the setup of cameras and 3D scanning reference spheres. The preparation steps are listed below:

1. Measurement of a 6x6 [m] square area and positioning of corner stones
2. Measurement and spray marking of centre and side-centre positions
3. Placement of four rocks (as large as possible) for 3D scan reference spheres
4. Epoxy gluing of 5 steel washers used for the magnetic reference sphere holders
5. Measurement and placement of camera tripods
6. 3D scanning of the empty test area

The camera tripods were placed to capture the front, side and ISO view, see Figure 1. The final configuration of the test area including the first A1 test can be seen in Figure 2. Two example images showing the loading of the truck and wheel loader unloading can be seen in Figure 3.

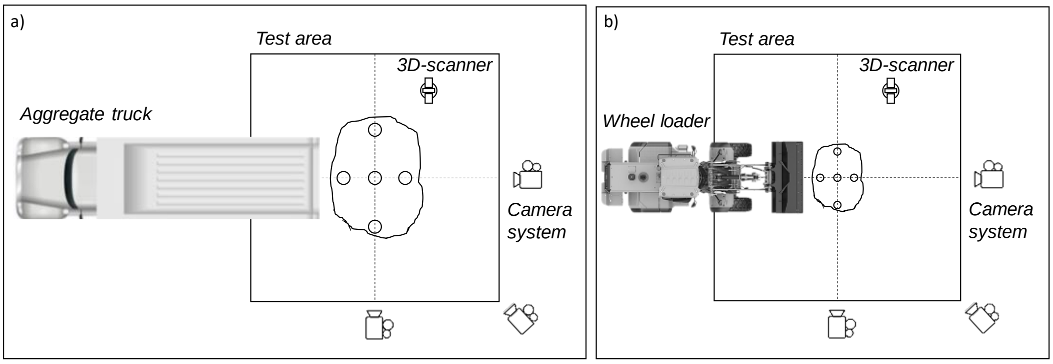


Figure 1. Schematic illustration of test area with 3-point camera system and 3D scanner a) Aggregate truck b) Wheel loader.

Figure 2. Test area setup (6x6m) in the NCC Stenungsund quarry showing the camera system, 3D scanning reference spheres and the A1 pile formation.

Figure 3. Left image showing the wheel loader loading the aggregate truck. Right image showing the wheel loader position after the unloading sequence from sample.

The tests were performed at the NCC Stenungsund quarry during two days of otherwise normal operation. The wheel loader machine and operator were dedicated to the project for the full two days. The aggregate truck with operator was called in when the project team was ready to perform a test. It was critical to minimize the time span of the test so that the normal production of the quarry was not affected. The general procedure of each test is listed below:

1. Order material from aggregate truck
2. Operator positions the machine aiming for unloading on the centre
3. Start condition is 3D scanned with one scan
4. Camera system is activated
5. Test name sign is presented visible to the camera
6. Test leader signs to the operator to start the unloading sequence
7. The operator keeps the machine in the final tilted position
8. 3D scanning of final position of machine
9. Machine leaves test area
10. Marking of material sampling positions on pile using spray paint
11. Photography of pile sampling positions
12. 3D scanning of pile from three positions
13. Material sampling (front, left, right, back, top)
14. Wheel loader removes pile
15. Test area manually cleaned/restored using a board and a rake
16. Test completed

A summary of the performed tests can be seen in Table 1. Four different size fractions were tested. The table also includes measurements of air temperature and humidity. After each test the repose angle on the left and back sides of the pile was measured using a wooden board and a universal spirit level tool. The final angle of the truck platform and wheel loader bucket was also measured. The size fraction in the D-series was created by blending approximately 10% of +8/-11 material into a sample of +22/-90 material. This was done in order to evaluate an extreme case of segregation. It was difficult to blend and homogenize the material before testing since all actions performed tended to in cause segregation in itself.

Table 1. Measurements of environmental conditions and pile properties.

Test	Size fraction	Final angle	Air RH	Air temp.	Repose angle side	Repose angle back	Total mass
		[deg]	[%]	[C°]	[deg]	[deg]	[kg]
A1	+22/-90	40	74.5	8.6	28	39	10260
A2	+22/-90	46	74.5	8.6	35	38	5760
B1	+0/-90	50	74.5	8.6	28	35	7960
B2	+0/-90	40	74.4	11.9	38	36	4650
C1	+22/-250	50	74.4	11.9	34	34	8150
C2	+22/-250	43	74.4	11.9	28	30	5990
D1	+22/-90 & +8/-11	28	74.4	12.1	37	40	8420
D2	+22/-90 & +8/-11	33	74.4	12.1	30	37	4000
E1	+22/-90	50	76.8	11.5	31	35	8400

In Table 2 the sample masses for all piles are presented. Sampling of coarse rock material is difficult since a very large sample is needed in order to achieve statistical significance. However, for practical reasons it was only possible to handle one bucket for each sample. Otherwise logistics of handling and transporting the samples to the laboratory would not have been feasible. The actual sampling in the pile was done by marking a 70x40 cm square and using a shovel and hands to extract material inside the sampling square. The sieving and size distribution analysis has been performed by the NCC laboratory in Hisings Kärra according to relevant standards and protocols. The moisture content of three different samples were measured the day after the experiments were completed. The +0/-90 mm sample contained 1.89 wt%, the +8/-11 mm sample contained 0.93wt% and the +22/-90 sample contained 0.28wt% water.

Table 2. Sample masses from each test.

Test	Size fraction	Left	Front	Right	Back	Top	Total
		[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
A1	+22/-90	22.6	23	20.74	23.14	22.9	112.38
A2	+22/-90	21.65	20.8	20.6	21.4	21.7	106.15
B1	+0/-90	19.8	22	20.6	21.4	23.54	107.34
B2	+0/-90	15.12	17.64	16.1	13.26	13.92	76.04
C1	+22/-250	-	-	-	-	-	0
C2	+22/-250	385.91	218.58	-	-	-	604.49
D1	+22/-90 & +8/-11	16.22	17.4	15.12	15.46	15.2	79.4
D2	+22/-90 & +8/-11	14.92	15.48	17.02	16.5	14.6	78.52
E1	+22/-90	13.68	13.24	15.8	14.3	14.7	71.72

Figure 4 shows the result from the 3D scanning of the empty test area. The point cloud displayed has been cropped from a larger point cloud of the fully captured surroundings from several scans. In order to arrive at a complete coverage without dead view spots several 3D scans have to be performed. The reference spheres are used in the scan post-processing software to register the scans to a global coordinate system. The same methodology is used to generate complete point clouds of the scanned piles as well.

Figure 5 and Figure 6 shows the scanning from step 3 and step 8 from the test procedure respectively. In Figure 7 all of the scans are shown in the same view in order to display the initial and the final position of the wheel loader bucket.

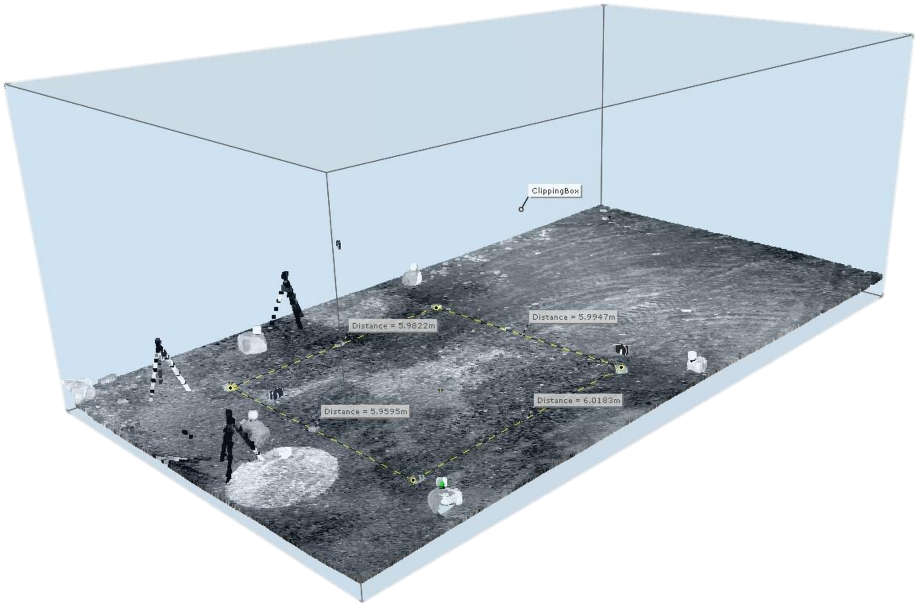


Figure 4. Cropped 3D point cloud showcasing the virtual lab environment.

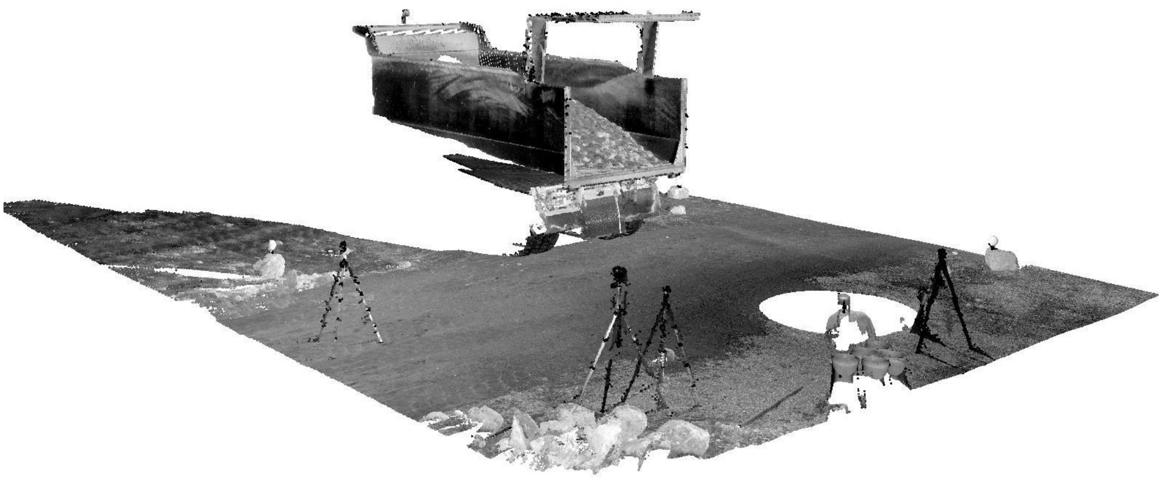


Figure 5. Example 3D scan of the initial position of the truck before unloading.

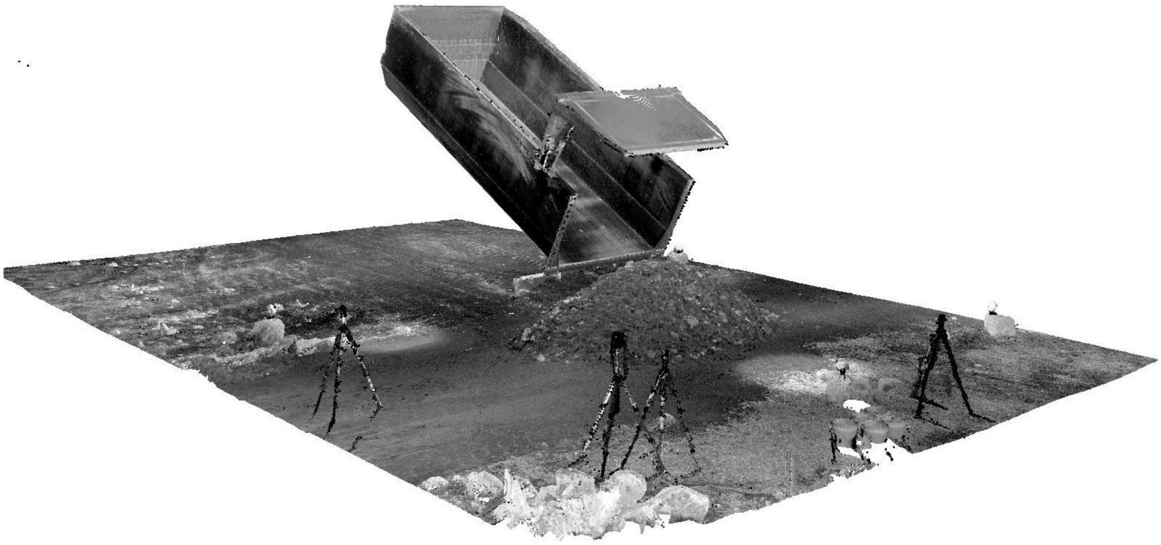


Figure 6. Example of the 3D scan of the pile and final position of the truck platform after unloading.

A specific difficulty of reproducing the experiments with simulations is to match the machine kinematics. The idea before performing the test campaign was that the combination of 3D scanning and video recordings from known positions would enable analysis to reproduce the kinematic pattern. In Figure 8 it can be seen how the open source software Tracker (Tracker, 2019) is used to trace two key positions, providing X and Y coordinates, velocity and acceleration. By combining the motion tracking with the information of the boundary start and stop states it was possible to define a set of linear kinematic translation and rotation functions matching the experimental movement.

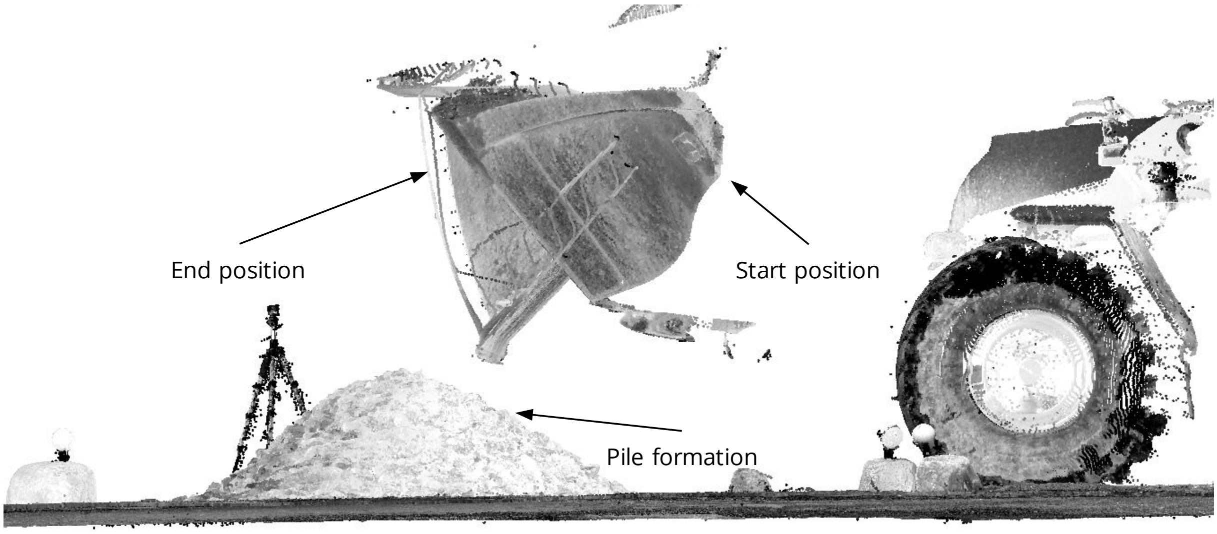


Figure 7. 3D point cloud of the pile formation, start and end position of the wheel loader bucket for the A2 test.

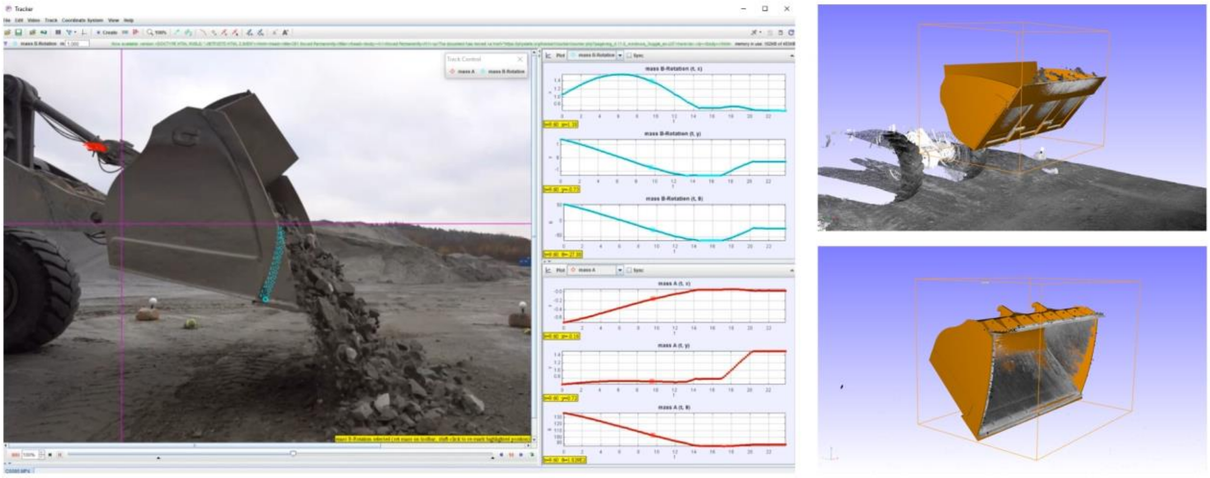


Figure 8. Left image showing a screenshot from the motion capture software used to analyse the bucket motion based on the video recordings. Right images showing the matching of the bucket CAD geometry to the 3D scan data of the start and end positions.

2.2 Discrete Element Modelling

The DEM modelling and all simulations completed in this project have been performed in the in-house DEM solver, developed under the working name Demify™. The discrete element method is a numerical method for simulating particulate matter and was first proposed by Cundall and Strack (1979). The scope of this report is not to provide a comprehensive description of the general methodology of DEM nor the details regarding the implementation as done in Demify™. However, in order to be able to describe the simulation results and make necessary arguments understandable a very brief description is provided below.

In DEM, particles are commonly modelled as spheres or clusters of spheres called multispheres, see Figure 9. The strategy of using the sphere as the base shape is practical due to the straight forward way to track particle collisions and to calculate the overlap between objects. This overlap is further on the quantity for calculating the interaction forces based on Hertzian contact mechanics. When all forces acting on a particle has been calculated the particle position and velocity is updated incrementally based on Newtonian mechanics.

It should be noted that the methodology includes all of the particles in the system and calculates the complete particle system. The difference between simulation and experiment can hence be linked to very specific details in e.g. the micro-mechanical model of force interactions or how machine objects move. In this sense it is a very precise approach and the improvements from the validation process can be carried forward for future applications in a generic manner.

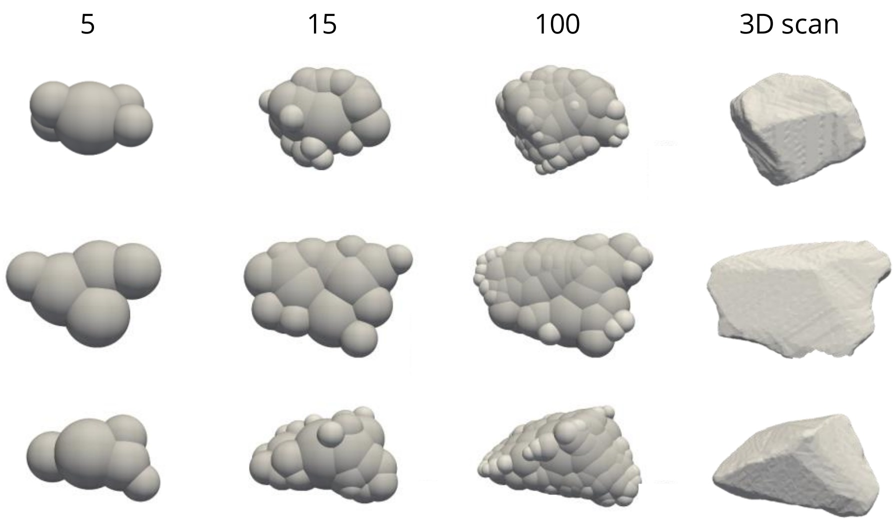


Figure 9. Particle shape representation using the multisphere approach. The illustration shows three levels of resolution where sub-spheres are positioned and sized to optimally match the 3D scanned rock shape.

When modelling rock particles, it is critical to represent the irregular and non-convex shape. In the performed simulations 10 different 3D scanned rock shapes have been included with a sub-sphere resolution of 40.

The simulation settings for the two main cases C1 and C2 can be seen in Table 3. The C1 and C2 case with the coarsest +22/-250 mm gradation was selected as the initial development case. The other cases will be simulated in a later stage and will be of great value in the continuation of the DIGIROAD project.

Table 3. Simulation parameter and material property settings.

Parameter	Detail	Unit	Value
Friction	particle-particle	[-]	0.7
	particle-steel	[-]	0.6
	particle-ground	[-]	0.85
Restitution	particle-particle	[-]	0.3
	particle-steel	[-]	0.2
	particle-ground	[-]	0.15
Youngs modulus	Rock	[Pa]	1.0e8
	Steel	[Pa]	200e8
	Ground	[Pa]	1.0e7
Poisson's ratio	Rock	[-]	0.25
	Steel	[-]	0.3
	Ground	[-]	0.25
Density	Rock	[kg/m^3]	2717.7
	Steel	[kg/m^3]	7800
	Ground	[kg/m^3]	2717.7
Library of rock shapes	# of 3D rock models	[#]	10
Multisphere resolution	# sub-spheres	[#]	40
Time-step		[s]	1.0e-6
No. of particles	C1_T12	[#]	377280
	C2_T5	[#]	303360

3 Experimental results

In this section the data from the performed unloading experiments will be presented. In order to minimize the length of the report we focus on showing and commenting on the size distribution curves. The reader should notice, as described in the methods section, that all piles have been 3D scanned. Photos were also taken from each material sampling position for all piles. The synchronized recordings from four view-points are not possible to include well in a report format, however some frames from these recordings are presented in the upcoming Validation section. If a SBUF member company reader is interested there is hence a possibility to review both the 3D scan data, videos and photos since they might unveil additional details and understanding.

3.1 Size distribution of all tests

In Figure 10 the total size distribution for all experimental pile formations are shown. Here, the total size distribution has been calculated based on all five sample positions for each pile. For the C-series where a very coarse +22/-250 gradation was used the sampling was done by the wheel loader, hence it was only possible to reach the “front” and “left” sides of the pile without moving the cameras and 3D scanning reference spheres. The sizing of the coarse samples was done by hand sizing every particle using stainless steel squares. This was a labour-intensive process that also limited the feasible sample mass. Despite this, 604 kg (Left: 386 kg, Front 2019 kg) of rock was sampled from the C2 pile. Due to limited time on site it was decided not to sample the C1 pile at all.

Another detail in the plot that should be highlighted is the difference between the A1 and the A2 curves where the A1 gradation is significantly finer. Under perfect conditions these curves should align however there is a distinct difference. This difference/variance may have several sources. The main two reasons are probably; the segregation variance from the stockpile transferred via the ad-hoc loading by the wheel loader, and the variance due to the sampling procedure in the pile itself. What is interesting is that the A1 test was repeated due to a too high total mass. The repeated test named E1 aligns almost perfectly with A2.

The B-series (+0/-90) curves also displays a deviation where the B2 test shows a substantial lack of fine material. As for the A-series this might be due to both stockpile sampling variance and the test pile sampling variance. From the video recordings it can be seen for the B-series that fines dependently are present in the bulk flow. These videos reveal how the fine material, both in the case of the truck and the wheel loader, is unloaded preferentially in approximately the first 60% of the flow process. In the final stage of the unloading the coarser particles seem to fall on top and create a covering layer of coarse material. When performing the material sampling from the surface layer of the pile this effect may cause the total distribution to appear as coarser than the actual pile distribution really is (i.e. sampling and performing sieving analysis on the entire pile material sample which is unfeasible). In a real experiment it would be difficult to perform a sample in the middle of the pile. This is however not a problem in the simulation environment indicating that simulations should be used to better understand the phenomena.

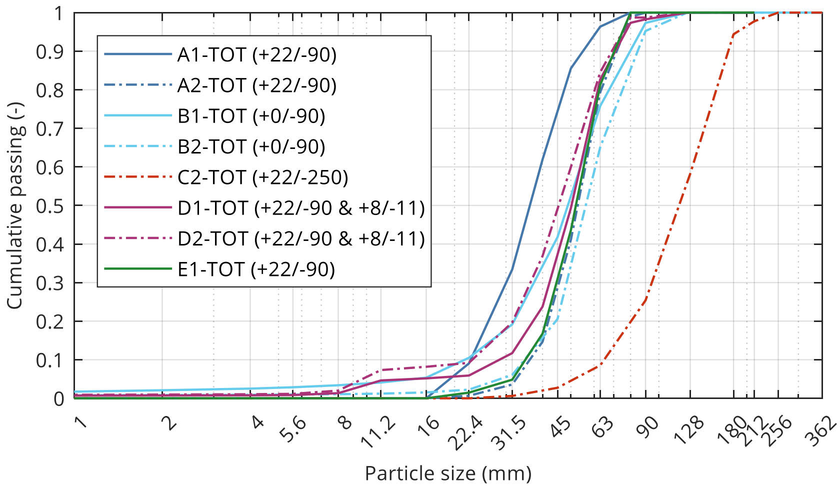


Figure 10. Total particle size distribution for all test piles.

3.2 A-series +22/-90 mm

The first test performed during the campaign was the A1 where a +22/-90 mm gradation was used. Initially the plan was to test approximately 10 tons of material for the truck unloading. During the initial run of the A1 test, it was obvious that the mass was too large since the entire material sample didn't leave the loading platform. The truck had to move forward in order for the remaining material to be unloaded. This created an unnecessarily long total time of the test with poor repeatability. Even so the A1 test was still completed with all scanning and sampling but may be regarded as a dry run learning experience. The test was repeated as the last test the day after and named E1. The five-point sampling size distributions for the A1 test can be seen in Figure 12. The data suggest a distinct difference in gradation between the sampling positions where the finer material accumulated preferentially at the back and top positions which is not according to the hypothesis of the typical behaviour (most fines in the front position). The unloading process clearly influence the segregation. The result for the repeated test E1, shown in Figure 13, displays a more distinct segregation behaviour as anticipated. As seen in Table 1 the mass loaded onto the truck was reduced from 10 260 kg (A1) to 8 400 kg (E1). The difference in pile formations and volume can be seen in Figure 11. It may be noted that it is difficult to define a single regression line on the slope of the pile that corresponds to a representative repose angle.

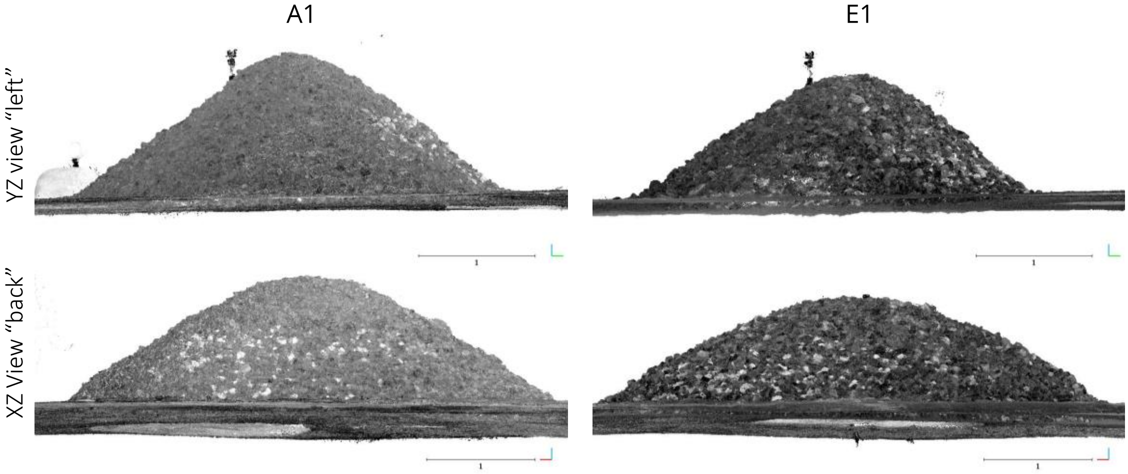


Figure 11. Comparison between the point cloud for A1 and E1 pile formations. (The vertical object in the top images are the camera tripods)

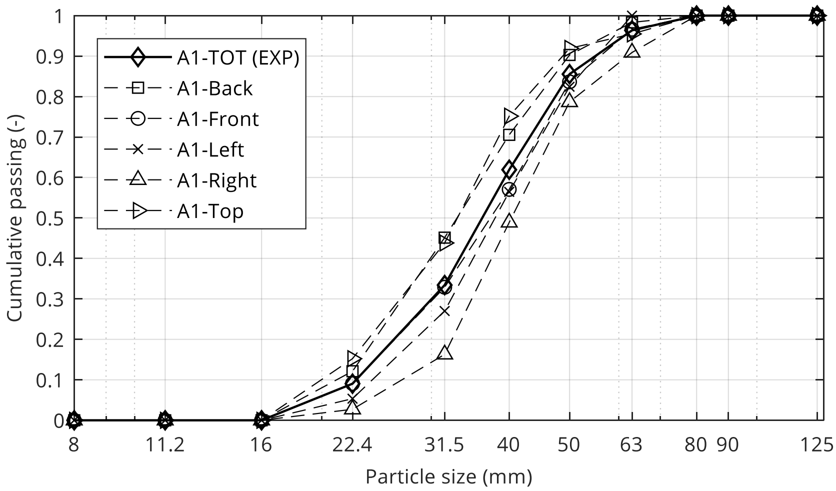


Figure 12. Particle size distribution for the A1 truck unloading test (+22/-90 mm).

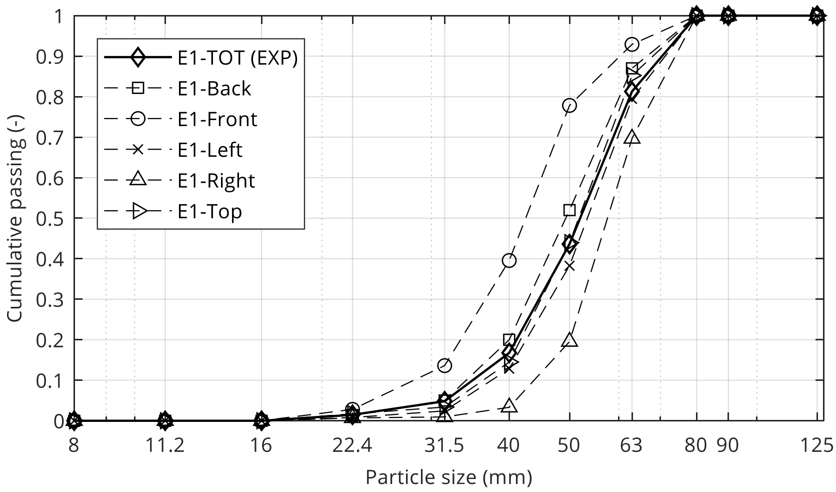


Figure 13. Particle size distribution for the E1 truck unloading test (+22/-90 mm).

The size distributions for the A2 wheel loader test is displayed in Figure 14. This test shows a relatively low variance between the curves which indicate a relatively low segregation effect, at least on the surface layer (~0-150mm depth) of the pile.

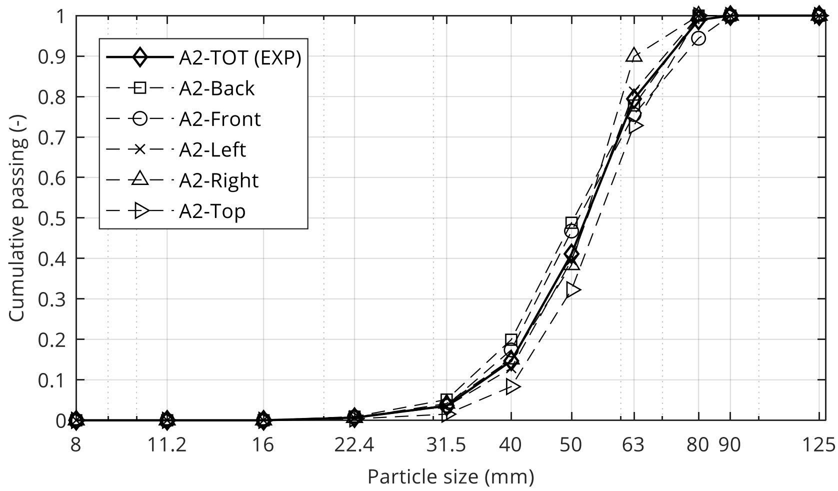


Figure 14. Particle size distribution for the A2 wheel loader unloading test (+22/-90 mm).

3.3 B-series +0/-90 mm

In Figure 15 the size distribution for the B1 test is shown. The segregation effect is distinct with finer material reporting to the front/top sections of the pile and coarser material accumulating at the left section of the pile. As a visual reference this can also be seen from the photos of the sampling positions shown in Figure 16.

In contrast the pile formation in the B2 case displays the opposite outcome with the coarser material reporting to the front and the fine material accumulating at the left and top sections, see Figure 17.

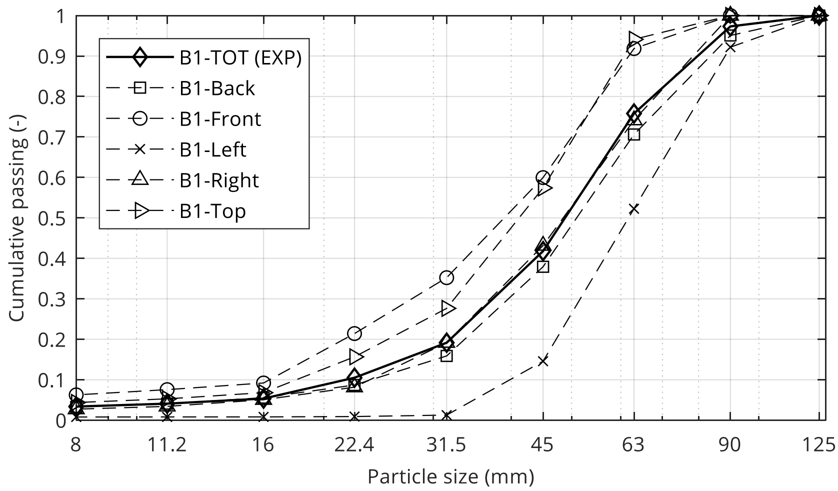


Figure 15. Particle size distribution for the B1 truck unloading test (+0/-90 mm).

Figure 16. Photos of sampling positions for the B1 pile. Left image: Front section. Right image: Left section.

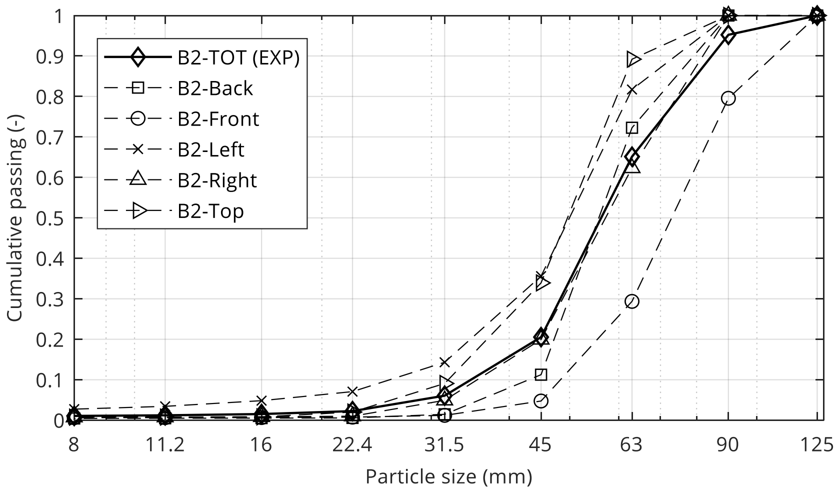


Figure 17. Particle size distribution for the B2 wheel loader unloading test (+0/-90 mm).

Figure 18. Photos of sampling positions for the B2 pile. Left image: Front section. Right image: Left section.

3.4 C-series +22/-250 mm

The size distribution measured for the C2 series can be seen in Figure 19. The curves indicate that the Front section is slightly coarser than the Left section. However, as seen in Figure 20 a larger amount of material was sampled for the Left section. The combined total sample is probably large enough to be statistically significant, however the front section sample seems to be a too low sampled mass. The manual histograms created during the sizing were first made as an amusement, but they actually demonstrate the distribution rather well in a practical sense. It can also be seen by the colour that the finer material holds more moisture than the coarser particles.

The C1 pile was not sampled, however the images of the pile in Figure 21 provides an indication that the front section is finer than the other sections. In Figure 22 the C2 pile is displayed with three different views as well as an image of the sampling process of the Front section using the wheel loader.

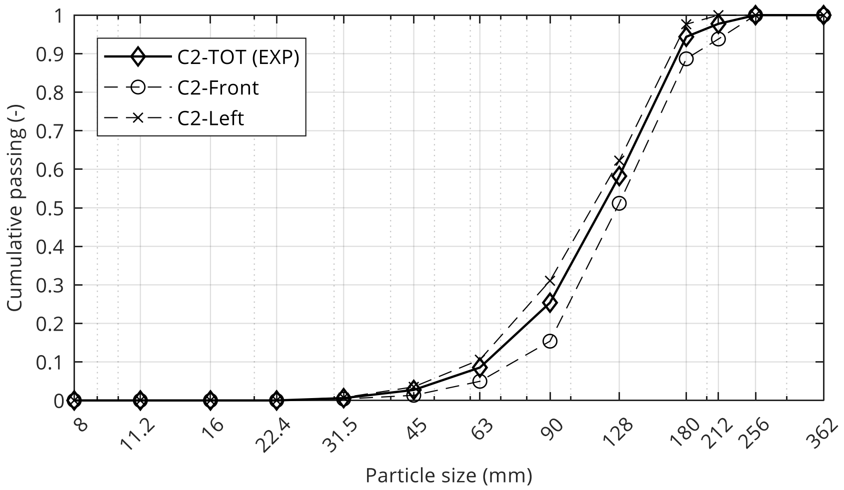


Figure 19. Particle size distribution for the C2 wheel loader unloading test (+22/-250 mm). Only two samples where extracted due to the manual labour effort of sizing the coarse material.

Figure 20. Manually arranged histograms visualizing the size distribution of the +22/-250 mm samples.
Left image: C2 Left section. Right image: Front section.

Figure 21. Images of the four different sections of the C1 pile.

Figure 22. Images of different sections of the C2 pile.

3.5 D-series +22/-90 & +8/-11 mm

The size distribution for the D1 test is displayed in Figure 23. The 10% blending of the finer +8/-11 material creates a very apparent segregation effect. In the D2 case however, the fine material instead accumulates at the sides of the pile as seen in Figure 24. As seen in Figure 25 the pile formation follows a typical topographical pattern that differs between the aggregate truck and the wheel loader. This difference in characteristic pile shape can be seen for all test series.

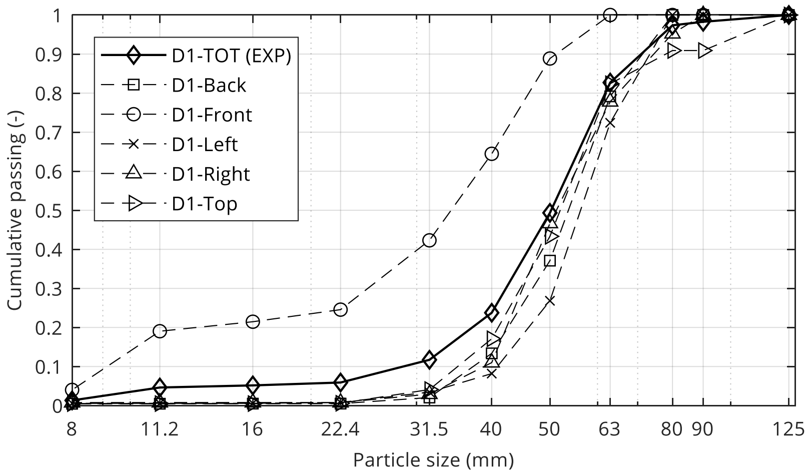


Figure 23. Particle size distribution for the D1 truck unloading test (+22/-90 & +8/-11 mm).

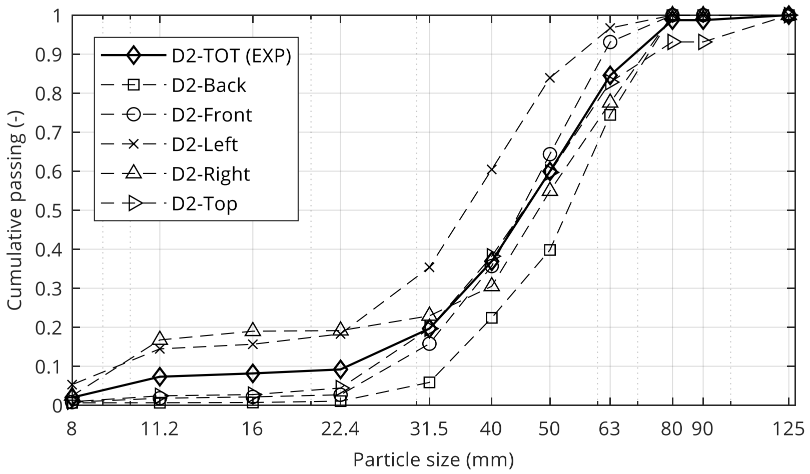


Figure 24. Particle size distribution for the D2 wheel loader unloading test (+22/-90 & +8/-11 mm).

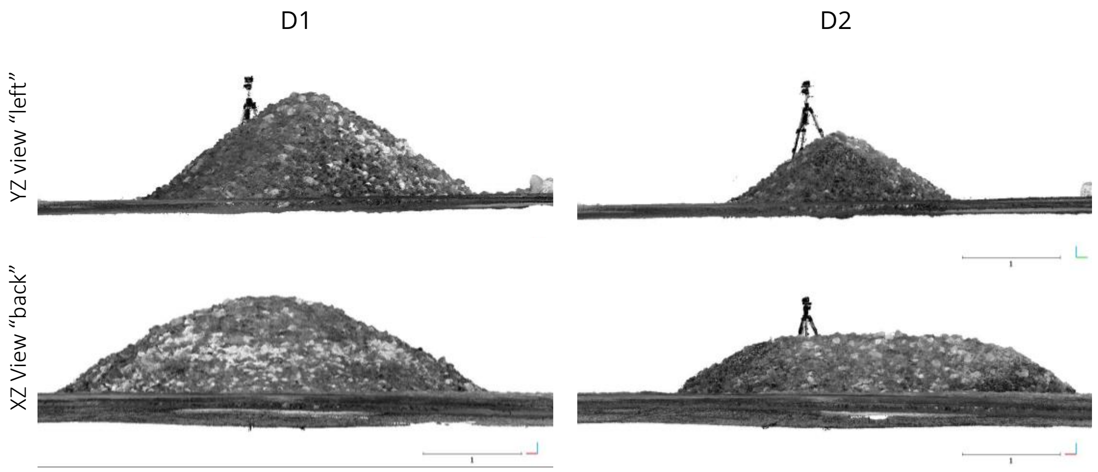


Figure 25. Comparison between the point cloud for D1 and D2 pile formations.

4 SIMULATION RESULTS

The cases C1 and C2 have been the subject of simulation in this project. The other cases will be further investigated in the DIGIROAD project. The size distribution for the different pile section can be seen in Figure 26 and Figure 27. In both the C1 and C2 case there is a strong segregation effect with the finer material reporting to the front section. The size distributions for the simulated piles are based on a virtual sampling procedure where the pile is divided into a grid. This means that all of the material in the sampling domain will be included in size analysis. The large sampling domain allows for much higher total sample masses than what is feasible to analyse experimentally. This generates a substantially better statistical basis for determining the distribution when compared to the experimental data-set.

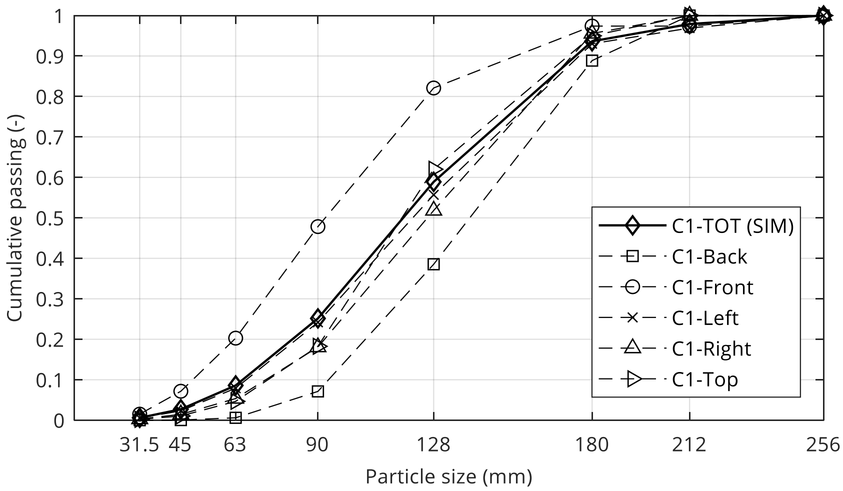


Figure 26. Particle size distribution from simulation of the C1 truck unloading test.

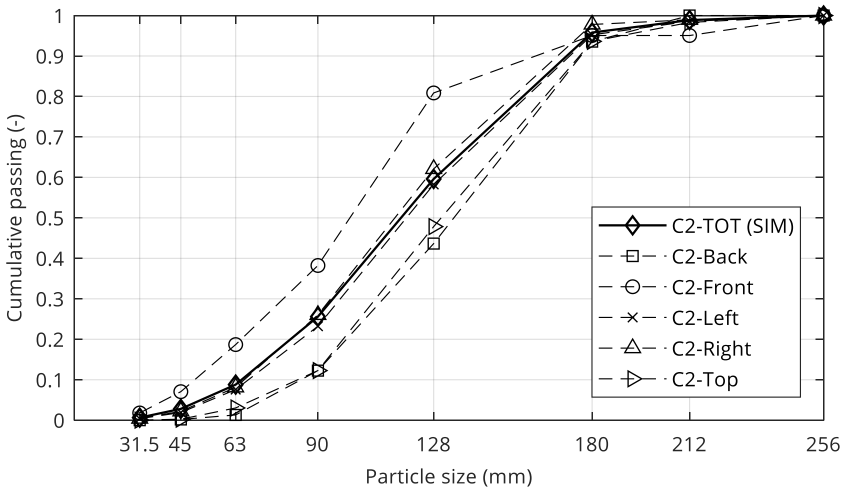


Figure 27. Particle size distribution from simulation of the C2 wheel loader unloading test.

In Figure 28 the two pile formations are displayed from three different viewpoints. The colouring reveals a distinct segregation effect which is in alignment with the size distribution curves presented above. The larger particles have a higher kinetic energy and momentum to travel further away from the machine geometry during the dynamic process of pile formation. The small particles are able to stratify and fall between larger particles preferably ending up in the section closest to the machine. The behaviour is similar for both machines however with a characteristic difference in the topography of the resulting pile.

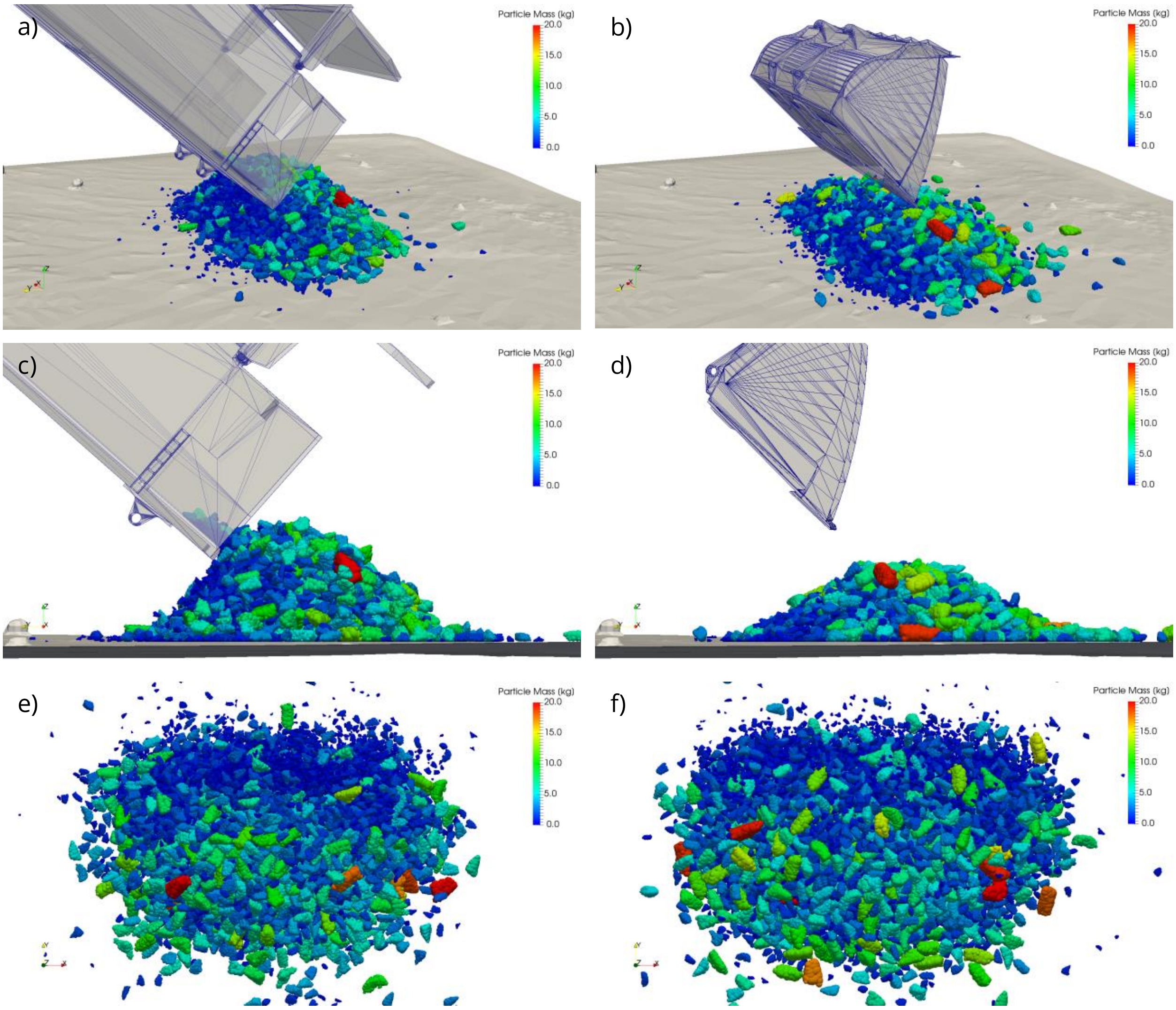


Figure 28. Particle mass distribution for C1 and C2. Warm colours are related to large particles. a) C1 ISO back view b) C2 ISO back view c) C1 +X side view d) C2 +X side view e) C1 -Z top view f) C2 -Z top view

The segregation effect is sequential in the sense that the size distribution outcome is dependent on the configuration of the preceding material bed. It should also be noted that the specific pile formation is a consequence of a combination of stochastic and non-stochastic physical phenomena. In order to quantify the stochastic variance on the operation, repeatability experiments could be conducted where the same unloading sequence is performed multiple times. Preferably the unloading should then be done with external kinematic control of the machine in order to minimize the effect of the operator.

5 Validation comparison

In this section the simulation results are compared to the experimental data. The comparison is presented as snap-shot images from simulations as well as post-processed data comparisons of size distribution and pile formation.

5.1 Aggregate truck C1 +22/-250

In Figure 29 the simulation and experimental snapshot at T=24 s is shown. The visual congruence may be regarded as high. When comparing the videos side-by-side

Figure 29. Comparison of C1 aggregate truck experiment and simulation with three different views: ISO, Left, Front displayed at time=24s.

The total mass for each experiment was recorded by the wheel loader operator based on the machine load cell. This mass was used as input to each test. In the C1 simulation it was found that not all of the material was unloaded from the truck as it is in the experiment. Hence the total simulated mass was reduced. Even so, some material is still left on the truck as can be seen in the comparison between the final pile formation in Figure 30. The total mass problem might stem from either a calibration error in the wheel loader load cell system, or there is a modelling error in terms of achieving the correct packing density of the pile. If the packing density is too low the same bulk mass will create a larger pile volume. This issue needs to be further investigated.

A more detailed time-sequence of the experiment and simulation is provided in Table 4. As seen, the simulation matches the experiment very well with some minor deviations. The congruence between simulation and experiment has been reached through a relatively low number of manual adjustments to the friction coefficients. The initial values for friction have been given by laboratory scale calibration tests. An even better match can be reached by instantiating a design-of-experiments batch simulation and applying a surrogate based optimization framework for calibration of the friction coefficients.

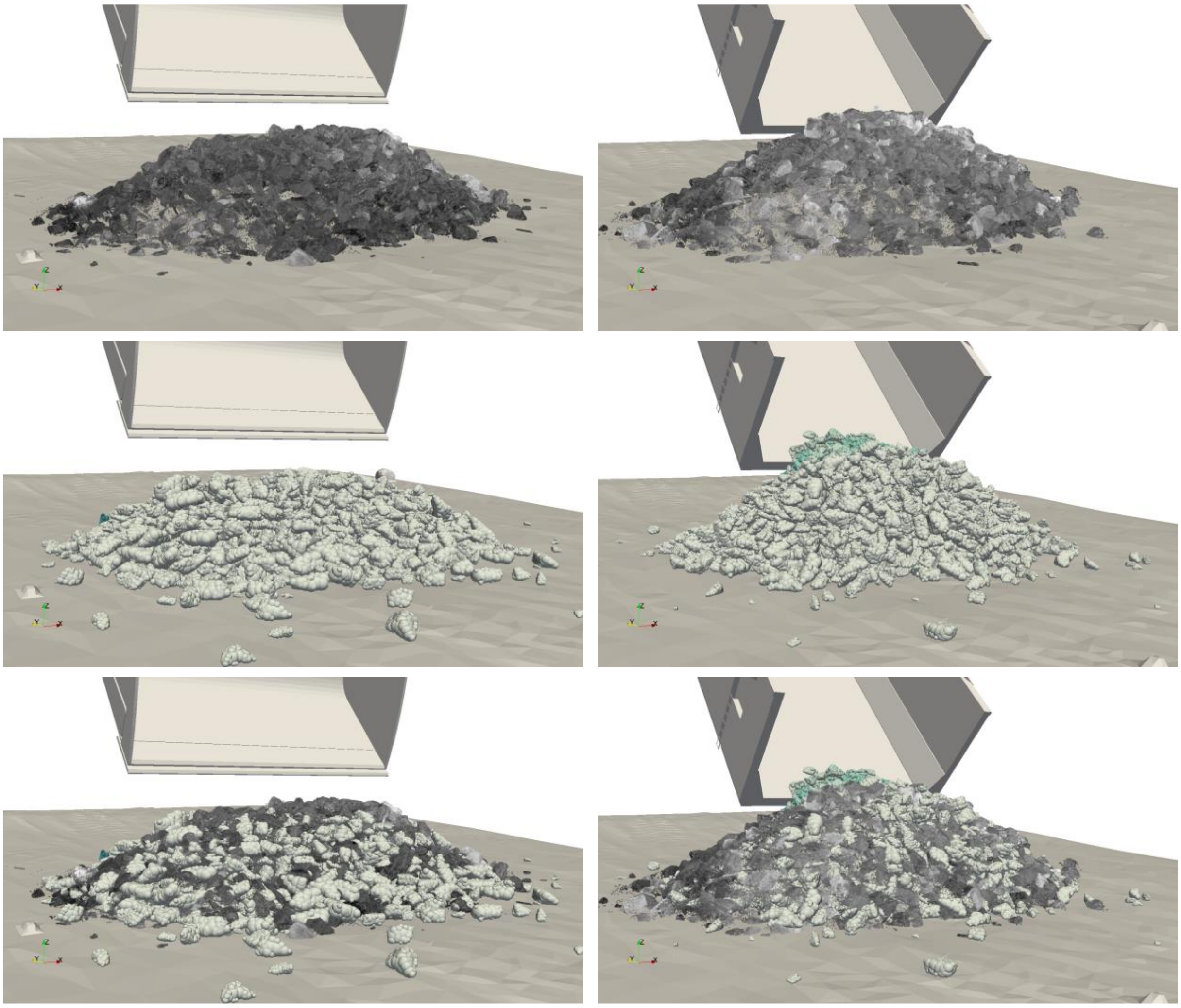
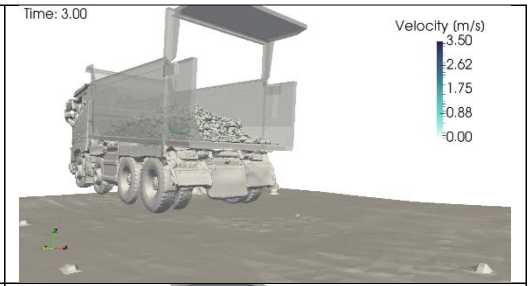
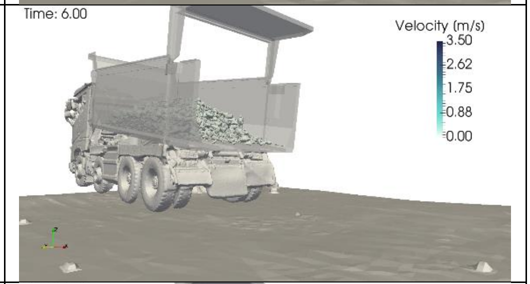


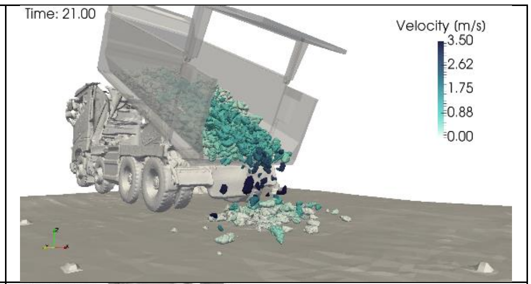
Figure 30. Overlay of simulation result and the 3D scan point cloud data. Left side: C2 Wheel loader. Right side: C1 Aggregate truck. The point cloud data has a transparency of 50% in order to assess the congruence between simulated and experimental pile formations.

Table 4. Time sequence comparison between video recording and simulation for the C1 aggregate truck.

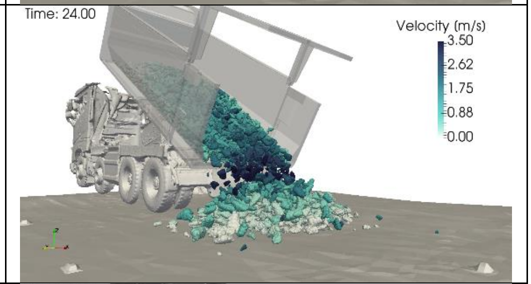
Time	Experiment	Simulation
[s]	Test C1 (Camera 3 ISO)	Simulation ID C1_T12
0		

3		Time: 3.00 Velocity (m/s) 3.50 2.62 1.75 0.88 0.00
6		Time: 6.00 Velocity (m/s) 3.50 2.62 1.75 0.88 0.00
9		Time: 9.00 Velocity (m/s) 3.50 2.62 1.75 0.88 0.00
12		Time: 12.00 Velocity (m/s) 3.50 2.62 1.75 0.88 0.00
15		Time: 15.00 Velocity (m/s) 3.50 2.62 1.75 0.88 0.00
18		Time: 18.00 Velocity (m/s) 3.50 2.62 1.75 0.88 0.00

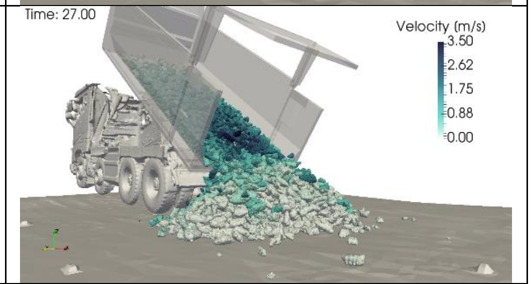
21



24



27



30

33

36

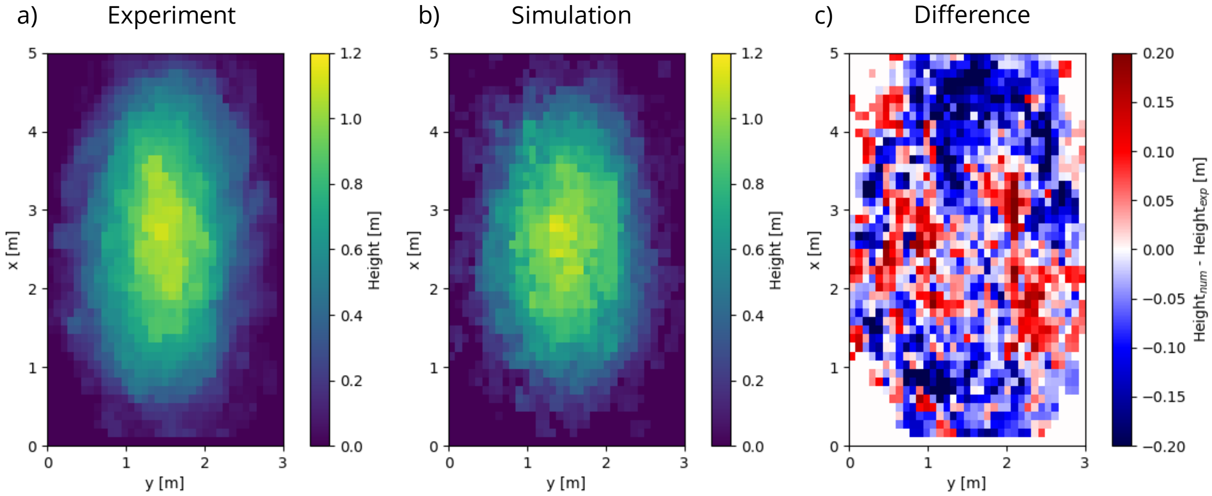


Figure 31. Comparison between the experimental (a) and simulated (b) pile height for the C1 aggregate truck test. Each bin is coloured by height in meters. The heat map plot in (c) shows the difference in height for each bin in the grid in meters. (SIM ID: T12_C1_Osprey)

I order to evaluate the pile formation topography a post-processing tool was developed that evaluates the pile based on a grid bin approach. For each bin, the code checks the highest particle position for the simulated and experimental pile. Based on this data, heat maps of the pile height may be generated as shown in Figure 31. The congruence between simulation and experiment is relatively good. An improved method for determining a congruence criterion would be to perform several pile unloading experiments with the same settings and estimate an error variance. If the experimental variance is known and the simulation result falls within the limits of variance it may serve as a criterion of validation. An alternative practical approach would be to relate the error to e.g. the P_{50} or P_{90} particle size.

5.2 Wheel loader C2 +22/-250

In Figure 32 a comparison of the simulated and experimental unloading for the C2 case is presented for the three camera views. A time sequence comparison is presented in Table 5 with a 3 second resolution. As seen the material falls over the bucket edge slightly too early compared to the experiment. This aligns with the behaviour of the C1 simulation.

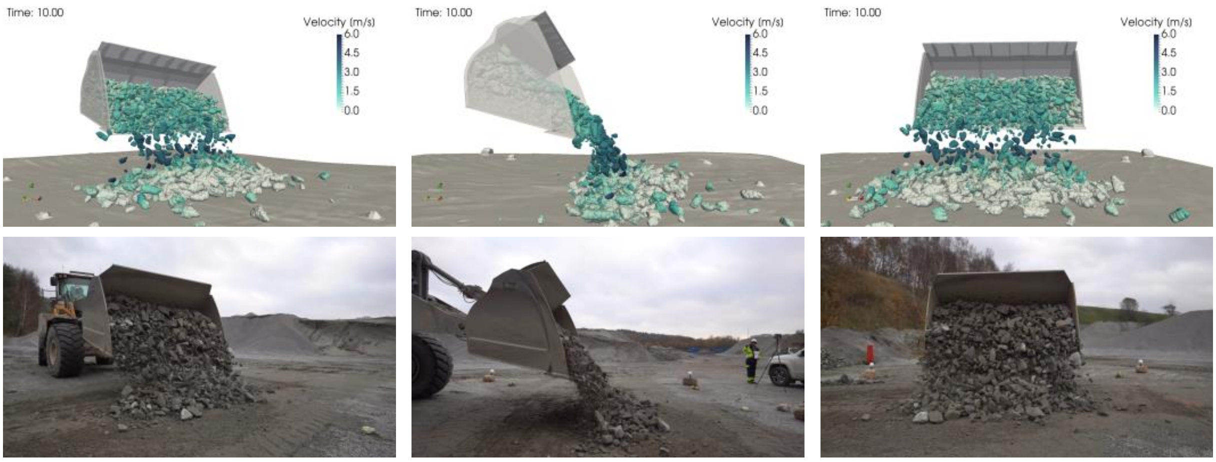
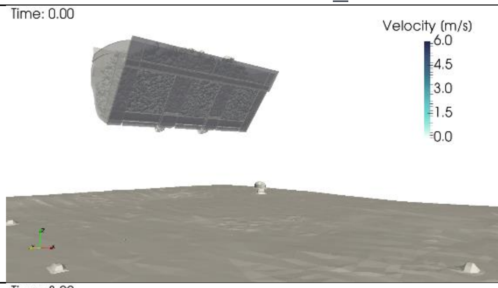
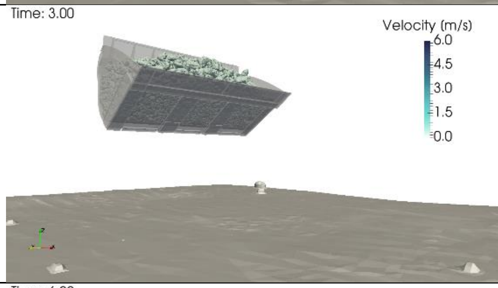
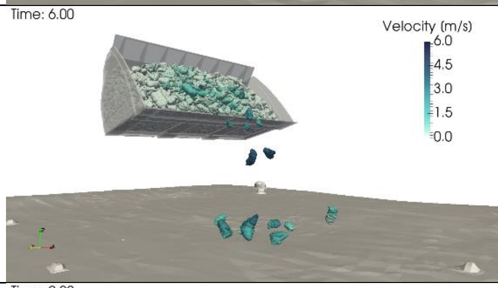
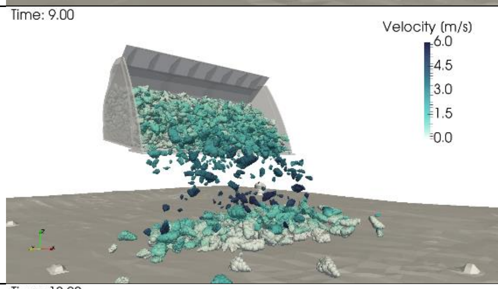
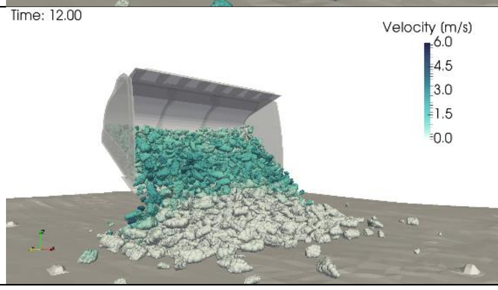
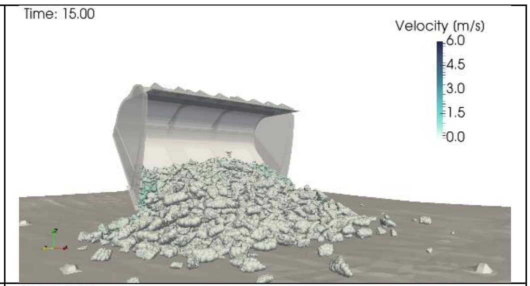


Figure 32. Comparison of C2 wheel loader experiment and simulation with three different views: ISO, Left, Front. displayed at time=10s

Table 5. Time sequence comparison between video recording and simulation for the C2 wheel loader.

Time	Experiment	Simulation
[s]	Test C1 (Camera 3 ISO)	Simulation ID C2_T5
0		
3		
6		
9		
12		

15		
18		
21		

The simulated pile shows a slightly wider and flatter profile with less sharpness on top as seen in Figure 33. In Figure 34 the size distributions for the C2 test is compared with the simulated result. Due to the sampling issue it is difficult to draw conclusions regarding the individual section sample positions. However, a major point of attention is that the total size distribution matches very well which from a modelling point of view is a success.

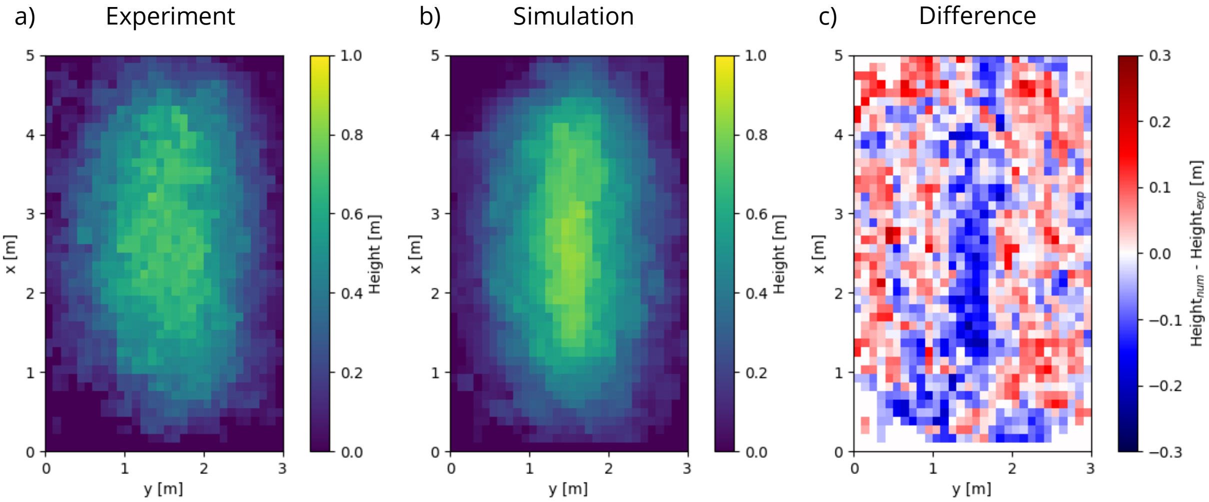


Figure 33. Comparison between the experimental (a) and simulated (b) pile height for the C2 wheel loader test. The heat map plot in (c) shows the difference in height for each bin in the grid (SIM ID: T5_C2_Osprey).

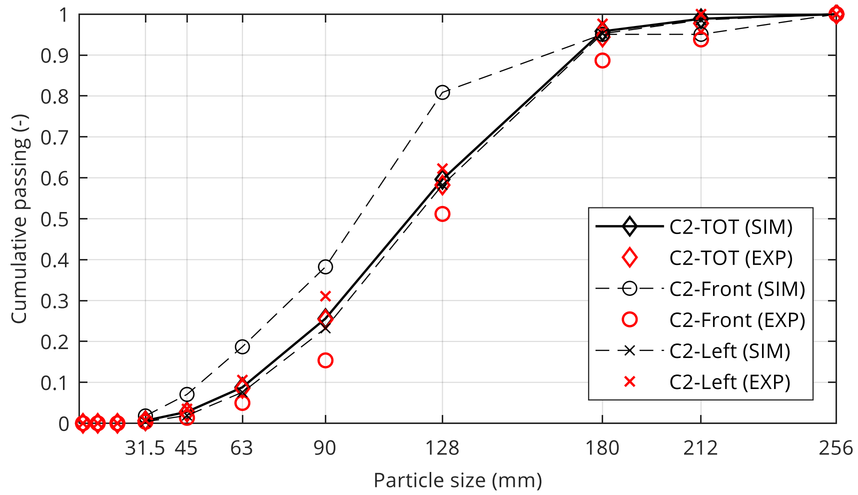


Figure 34. Particle size distribution from simulation of the C2 wheel loader unloading test compared with experimental data as red markers.

6 Discussion

The following section summarises details on what was learned during this project and what could be improved in the experimental campaign as well as for the simulation development.

6.1 Specific learning outcome details

- The method for capturing the kinematics of the machine proved to be successful. With that being said it could be improved by placing markers of known positions on the equipment. The next level for performing the test would be to program/automate the actual movement of the wheel loader and truck. This would not only allow for a 1:1 kinematic description, it would also allow for repeating the exact same materials handling sequence. This would be very beneficial for analysing the statistical repeatability of these kind of operations.
- In the case of the +22/-250 material it would have been beneficial to 3D scan from four positions instead of three to get a better coverage
- In this study there has been no analysis of the 3D scan data of the pile to estimate the size distribution utilizing image processing. There are techniques that performs this kind of estimations on conveyor belts that could potentially be used here as well. This would provide an alternative to the manual sampling and sieving analysis.
- The 3D scanning resolution could have been reduced one level based on the scan quality report. This would allow for a fourth scan in the same time span.
- The cameras could be equipped with a reference marker (e.g. cardboard checkerboard) which would allow for automatic registration of the positions in the 3D scanning analysis software.
- The spray paint used happened to have the same light reflective properties as the rocks hence it was difficult to see the sampling areas in the point cloud data. The colour should be selected so that it appears well distinguishable.
- The lightning conditions changed during the day however the camera settings were not adjusted. A light meter or similar should be used to control the camera ISO and shutter time better.
- A sign was used (e.g. C1, C2 etc) so that the camera recordings could be linked to each specific test. It was not a good solution that a person was in the initial video frames showing the sign. A sign holder or similar should be used instead since the person got in the way of the recording.
- The corner stones worked relatively well as markers for the test area. An improved solution would be to cast concrete cubes placed in each corner. This would be a more accurate reference system for all tape meter measurements performed when preparing the test site and when aligning camera positions.
- The removing of material after each test was very labour intensive. Also, the wheel loader could only access the material from one side. Hence the “side view” camera tripod had to be removed and repositioned for each test. Even though the wheel loader could remove most of the material, it took a considerable amount of time to clean the test area from rocks.
- The initial positioning of the machines before unloading was done with eye measure precision. This resulted in unnecessary tilted initial positions that made the process of matching the exact positions difficult in the simulation environment. It would be possible to spend some preparation time to carefully measure the initial reference position of the machine and mark the wheel positions on the ground.
- The machine operator performed the unloading sequence slightly differently for each test, especially the wheel loader. It would be beneficial to first exercise a sequence and then make sure to match that sequence as similar as possible for each test.
- In order to evaluate the segregation in the pile, five sampling positions were used. It could be discussed if fewer sampling positions with a higher sampling mass would provide more robust results.

- In was not possible to control the moisture content of the material during the test campaign. If the source material could be kept dry under a temporary roof before the test it would be beneficial.

6.2 Simulation learning outcomes

- There is an inherent definition problem of the actual size of an irregular particle. During the simulation configuration work this became apparent when comparing the simulated size distribution to the experimental. After several iterations of improvements to the implementation a good match was achieved. This process exemplifies the value of the experiment-simulation validation process.
- The total test times for the unloading sequence was normally 30-45 s. In a simulation perspective this a very long time to simulate with a fully resolved size distribution, well resolved particle shape and all of the bulk mass. This leads to very long computational times for running a case. In turn this means that the total number of simulation iterations performed prolonged the project to some degree before an acceptable validation level could be achieved. For upcoming validation studies, the experimental sequence should be optimized to remove any unnecessary static time and slow movement.
- Significant time was spent on CAD modelling of the machine geometry based on the point cloud data and official data-sheets. If known machines with existing CAD models can be used, it would reduce the development time.

7 CONCLUSIONS

Overall the project has been successful and the main objectives have been reached. The hands-on experience from the experimental campaign combined with the code development and simulation iterations have resulted in a distinct improvement in computational speed and accuracy.

7.1 General findings

- The segregation/separation effect from unloading material from an aggregate truck and a wheel loader have been proven and demonstrated experimentally and with simulation.
- A new experimental methodology has been developed to capture the rock particle material flow in an industrial setting
- The C1 and C2 test cases have been modelled and simulated and a reasonable validation level has been achieved.
- The simulation model responds as anticipated to changes in e.g. friction properties.
- The particle shape resolution is highly influential to match the rock pile formation properties.
- The test series suffers from the issue of variance in each of the performed test sequence steps, from extracting material from the stockpile, to the actual stochastic nature of particle flow, and the sampling in the pile.

7.2 Recommendations for future studies

- Perform repeatability experiments where the exact same test is performed N times in order to estimate the variance. Would require automated machine control.
- Utilize the DEM model to evaluate the physics of segregation and the variance relationships between size distribution and sample mass.
- The experimental data-set has not yet been fully utilized as only the C1 and C2 cases has been simulated. The simulation case suit should be expanded to all of the cases.
- In this project the unloading sequence has been the object of study. Other handling operations could be evaluated. Most valuable would probably be to perform experiments on the spreading and compaction processes as these requires the DEM model to accurately describe a slightly different kind of physics that sets other demands on the contact model.
- Perform experiments on a sequence of operations. For instance, loading – unloading - spreading and compaction.
- Perform experiments on the compaction process, evaluating the influence of potential segregation due to the pile formation and spreading operations.

8 REFERENCES

Cundall, P. A. & Strack, O. D. L., 1979, A discrete numerical model for granular assemblies, Géotechnique, 29, 47-65

Tracker [Computer software], (2019), Tracker is a free video analysis tool built on the Open Source Physics (OSP) Java framework, retrieved from https://physlets.org/tracker/

9 List of Figures & Tables

10 APPENDIX

10.1 Appendix A – Experimental work description (SWE)

Arbetsbeskrivning SBUF Projekt Försök 5-6 Nov

Projekt: Fullskaliga försök för DEM validering och undersökning av segregering

Ansvariga: Pär Johnning, NCC AB
Johannes Quist, FCC (Fraunhofer-Chalmers Centre)

Medverkande: Jonatan Berglund, 3D Scanning konsult Visinator AB
Maskinopertörer NCC Stenungsund

Datum: 5-6 November 2018

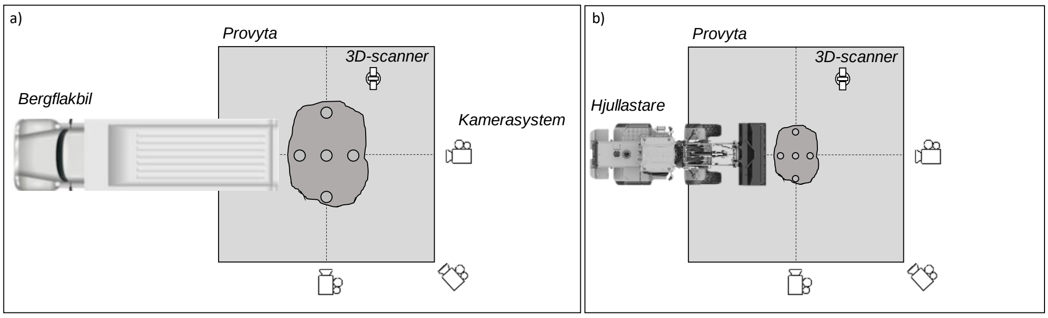
Kort beskrivning

Mätning av flöde från bergflakbil samt hjullastarskopa med 3-punkts kamerasystem samt 3D-scanning vid start- och sluttillstånd. Därefter provtagning i hög med skyffel för mätning av partikelstorleksfördelning för att studera separations-/segregeringseffekten.

Mätningarna utförs för att jämföra med simuleringsmodeller där en så exakt motsvarighet som möjligt byggs upp virtuellt. En bevisat validerad simuleringsmodell är av intresse för förbättring av maskiner och arbetsprocesser vid vägbyggnation.

Utöver mätningar vid provytan skall hjullastare och bergflakbil 3D scannas separat. Detta görs förslagsvis då maskinföraren har rast så att onödig tid ej slösas.

För dessa tester kan vi inte styra fukthalten i materialet, bara mäta den.



Figur 1. Illustration av provyta med kamerasystem och 3D scanner a) Bergflakbil b) Hjullastare. De mindre cirklarna visar provtagningspunkter ut provhög för analys av segregering.

Mätningar & Resultat

- Videoupptagning från 3 vyer
- 3D scanning punktmoln före och efter förlopp
- Storleksfördelning genom siktning – 5 positioner i hög
- Luftfuktighet
- Temperatur
- Fuktighet i material
- Total provmassa flak/skopa

Förberedelser av provyta (Johannes & Jonatan)

1. Uppmätning av 6x6 meter yta med hörnstavar (15 min)
2. Utmätning av centrum samt sido-mitt (10 min)
3. Utplacering av 2 större stenar runt provyta (15 min)
4. Epoxy-limning av 5 magnetbrickor för scan-ref (100 mm vita bollar) (20 min)
5. Utplacering av kameror 3 st RX0 och 1 st FZ200 (10 min)
6. 3D scanning av tom provyta (färg) (20 min)

Mätning händelsekedja – Exempel

Förslagsvis genomförs först test med flakbil. Därefter med hjullastaren eftersom lastaren ändå behövs för bortforslandet av tidigare hög.

1. Johannes ”beställer” material från maskinförare enligt provserie. (exempelvis 10 ton 25/90)
2. Maskinförare positionerar bergflakbil/hjullastare centrerat mot provytan. Målet är att högbildningen landar i centrum så här få vi prova oss fram hur nära centrum flak/skopa skall placeras.
3. Start-tillståndet 3D-scannas
4. Kamerasystem sätts igång
5. Skylt med provnamn visas för kamera
6. Maskinförare genomför tömning och står kvar i slutligt läge. Så jämn rörelse som möjligt.
7. Kamerasystem stängs av
8. 3D scanning av slutligt läge med både maskin och hög.
9. Maskin klar - Förare sänker/stänger flak och kan köra vidare
10. Utmärkning av provtagning med märkspray
11. 3D scanning av materialhög (3 positioner)
12. Provtagning ur hög med skyffel (Fram, Bak, Vänster, Höger, Topp)
13. Hjullastare avlägsnar högen
14. Provytan skrapas ”ren” med bräda
15. Test klart

Provserie

Provmängderna är anpassade för att möjliggöra simulering genom att inte ha allt för många partiklar. Mängden för hjullastare kan behöva anpassas. Exakt massa i varje test kommuniceras och skrivs ner av Johannes.

Test nr.	**Maskin**	**Storleksfraktion**	**Massa**	
A1	Bergflakbil	+25/-90	10 ton	Grov makadam
A2	Hjullastare	+25/-90	8 ton	Grov makadam
B1	Bergflakbil	+0/-90	10 ton	Förstärkningslager
B2	Hjullastare	+0/-90	8 ton	Förstärkningslager
C1	Bergflakbil	+50/-250	10 ton	Mellankross
C2	Hjullastare	+50/-250	8 ton	Mellankross
D1	Bergflakbil	+50/-250 & +16/-19	9 + 1 ton mix	Specialmix
D2	Hjullastare	+50/-250 & +16/-19	8 ton av mix	Specialmix

Utrustningslista

- [ ] 3D scanner Faro
- [ ] Referenssystem 3D scanning
- [ ] Hygrometer
- [ ] Kamerasystem Sony RX0 x3
- [ ] Stativ Benro x3
- [ ] Extra kamera Panasonic FZ200 + stativ Velbon
- [ ] Magnetbrickor
- [ ] Epoxy Loctite repair putty
- [ ] Epoxy Loctite extreme
- [ ] M4 skruv + mutter
- [ ] Gasbrännare + gas
- [ ] Hörnkäppar
- [ ] Slägga
- [ ] Plastskopa
- [ ] Provpåsar
- [ ] Hängvåg Kern
- [ ] Märkspray
- [ ] Måttband 25m
- [ ] Tumstock
- [ ] Magnet neodym för motion capture ref
- [ ] 12 hinkar + lock
- [ ] Märkpapper
- [ ] Neddelare
- [ ] 22.4 mm siktdäck
- [ ] Presenning
- [ ] Sopborste liten
- [ ] Handskar
- [ ] Gummihandskar
- [ ] Skyddsglasögon, skor, hjälm
- [ ] Arbetsbeskrivning papper x5 i plastficka
- [ ] Anteckningsbok
- [ ] Linjal
- [ ] Penna
- [ ] Permanent marker
- [ ] Etikettlappar kartong
- [ ] Dator
- [ ] Laddare
- [ ] SD micro adapter
- [ ] Komradio

Intentionally left blank

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