PROJEKTNR. 13948

Differential compaction from heavy machinery traffic in road construction

Differentiell packning från tung maskintrafik vid vägproduktion

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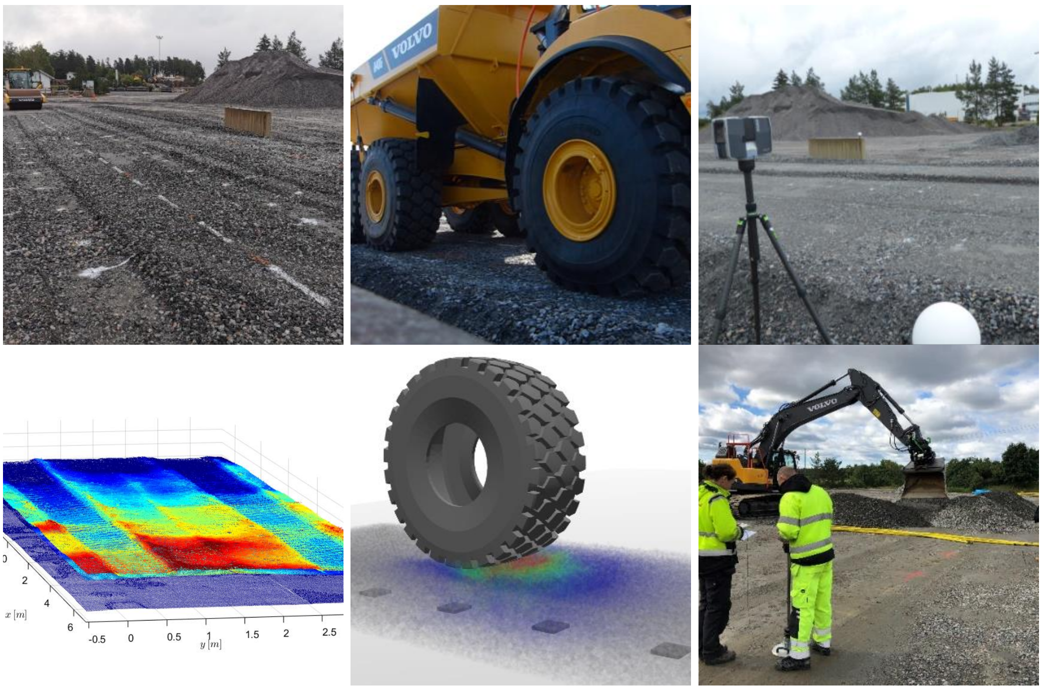

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Martyn Luby, Elianne Lindmark	Volvo Construction Equipment
Andreas Persson, Rebecka Herbertsson	Dynapac Compaction Equipment
Kristoffer Hofling	NCC Industry

Förord

Projektet har genomförts inom och med parter från konsortiet för Vinnova InfraSweden2030 projektet DigiRoad. Projektledare var Kristoffer Hofling (NCC Industry) och huvudsaklig forskningsutförare och författare av denna slutrapport är Johannes Quist (Fraunhofer Chalmers Centre). Experimenten planerades och genomfördes vid Volvo CE i Eskilstuna under ledning av Martyn Luby och Elianne Lindmark. Vid testerna deltog även Andreas Persson och Rebecka Herbertsson från Dynapac. DEM simuleringar genomfördes av Gustav Kettil, Christoffer Cromvik samt Johannes Quist.

Projektgruppen vill rikta ett stort tack till alla som bidragit till resultaten. Ett särskilt tack till operatörsteamet vid Volvo CE. Vidare vill vi tacka för finansiering från SBUF samt InfraSweden2030.

Göteborg, Augusti 2023

Sammanfattning

Anläggningsmaskiner och tunga fordon såsom ramstyrda dumprar och lastbilar spelar en avgörande roll vid infrastruktur- och vägbyggen under byggfasen. Dessa fordon används för att transportera granulära material som jord och bergmaterial till, från eller inom platsen. Det är dock vanligt att fordon på grund av nödvändighet eller andra praktiska omständigheter upprepade gånger färdas på samma spår, vilket resulterar i packning av obundna lager i dessa spår.
Eftersom dessa fordon har en betydande belastning har deras däck en packningseffekt på marken, vilket kan orsaka ökade packningsnivåer. Volvo CE har observerat att detta kan skapa problem. En hög markstyvhet är vanligtvis eftertraktad i de flesta fall, men skillnaden i styvhet vid nominell mark och i spåren efter att en normal rullkompaktering har genomförts är fortfarande problematisk. Detta fenomen kallas här differentiell kompaktering och är föremål för utredning i detta projekt.

Trots att detta fenomen sannolikt är vanligt förekommande i Sverige och resten av världen saknas djupgående beskrivningar inom akademin. Det finns närliggande områden där problemet med kompaktering på grund av interaktion mellan däck och mark inom jord- och skogsbruk, dock nämns sällan problemet inom byggd infrastruktur.

Detta SBUF projekt har därför genomförts för att skapa en första utredning av fenomenet differentiell kompaktering. Ett stort antal olika typer av berg- eller jordmaterial hade kunnat vara föremål för utredning. Valet föll på att fokusera på ett +0/-32 bärlager som trafikeras av en ledad dumper. En experimentserie genomfördes 2021 vid Volvo CEs demonstrationsanläggning i Eskilstuna med material från NCC Gröndal. En provyta skapades med en trafikerad yta samt en referensyta. Test-ytan trafikerades med 64 passager med dumper följt av 8 passager med rullkompaktering. Därefter jämfördes markstyvheten i spåren med referensytan som endast kompakterats med vält. Resultaten visar en ökning av styvheten med ca 10-15% vid trafikering jämfört med ingen trafikering.

Förutom experiment har även partikelsimuleringar genomförts med flerkroppsdynamikmodellering av dumpern. Modelleringen av systemet har visat sig vara mycket komplext och tog mer tid än planerat. Resultaten är lovande, i rätt riktning, och ger insikt i de fysikaliska fenomen och krafter som verkar. För en ännu bättre överenstämmelse mellan experiment och simulering krävs dock ytterligare arbete.

Det bör även nämnas att projektet kantats av en rad utmaningar, dels under experimenten med problematiskt väder och sensor-haveri, men även med svårigheter att rädda data genom filtrering samt med ett mycket stort antal iterationer av DEM simuleringar.

Baserat på projektresultaten rekommenderas att ytterligare arbete genomförs för att ytterligare undersöka problemet och eventuellt även hitta mildrande lösningar i fält. Det packningsarbete som lastbilar och dumprar utför skulle kanske kunna utnyttjas på ett konstruktivt sätt genom att på ett intelligent sätt fördela trafiken.

Summary

Construction equipment and heavy machinery such as articulated haulers and aggregate trucks play a crucial role in building and road construction sites during the construction phase. These vehicles are responsible for transporting granular materials such as soil and aggregates to, from, or within the site. However, it is a common occurrence that vehicles, due to necessity or other circumstances, repeatedly travel the same track, resulting in compaction of unbound layers.

As these vehicles have a significant load, their tires have a compaction effect on the ground, which can cause increased compaction levels. Volvo CE has observed that this can create a problem. A high ground stiffness is usually sought after in most cases, but the difference in stiffness after the standard roller compaction procedure has been completed is still problematic. This phenomenon is here called differential compaction and is the subject of investigation in this project.

Despite the fact that this phenomenon is likely to be common in Sweden and the rest of the world, there is a lack of in-depth descriptions within academia. There are adjacent research fields where the problem of compaction due to tire-soil interaction in agriculture and forestry is described; however, it is rarely mentioned as a problem in built infrastructure.

This SBUF project has therefore been carried out to create a first investigation of the phenomenon of differential compaction. Many different types of rock or soil material could have been the subject of investigation. The choice fell on focusing on a +0/-32 unbound base course trafficked by an articulated hauler. An experimental series was carried out in 2021 at Volvo CE's demonstration facility in Eskilstuna with material from NCC Gröndal. A test surface was created with a traffic surface and a reference surface. The test surface was trafficked with 64 passages with the dump truck followed by 8 passages with roller compaction. The ground stiffness in the tracks was then compared with the reference surface, which was only compacted by the roller. The results show an increase in stiffness of approx. 10-15% with hauler traffic compared to no traffic.

In addition to experiments, particle simulations have also been carried out with multi-body dynamics modeling of the dump truck. The modeling of the system turned out to be very complex and took more time than planned. The results are promising, in the right direction, and provide insight into the physical phenomena and forces at work. For an even better agreement between experiment and simulation, however, further work is required.

It should also be mentioned that the project was beset by a series of challenges, partly during the experiments with problematic weather and sensor failure, but also with difficulties in saving data through filtering and with a very large number of iterations of DEM simulations.

Based on the project results it is recommended that additional work is conducted to further investigate the problem and possibly also find mitigating solutions. The compaction work done by trucks and haulers could perhaps be utilized in a constructive manner by intelligently distributing the traffic.

Content

Introduction

Construction equipment and heavy machinery such as articulated haulers and aggregate trucks play a crucial role in building and road construction sites during the construction phase. These vehicles are responsible for transporting granular materials such as soil and aggregates to, from, or within the site. However, it is a common occurrence that vehicles, due to necessity or other circumstances, repeatedly travel the same track, resulting in compaction of unbound layers.

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In this technical report, we present the findings of a collaborative effort between FCC, VCE, NCC, and Dynapac. The project has been funded by SBUF and Vinnova InfraSweden2030 and is the third project in a series of SBUF project conducted within the InfraSweden2030 DigiRoad project. The first project investigated the segregation effects when unloading material from wheel loaders and aggregate trucks [1]. The second project investigated the roller compaction performance when compacting three different aggregate products when the fines had been removed to mimic the effect of size segregation [2].

In this third project we continue by performing experiments at the Volvo Construction Equipment Customer Centre in Eskilstuna with aggregate material from NCC Gröndal. The test series was designed to enable an analysis of the effects of differential compaction for a scenario of an articulated hauler moving over a 0.5m layer of +0/-32 base course material. The problem of differential compaction is further described below.

Problem description

A problem at larger construction sites with heavy construction traffic can be "Differential compaction". Large heavily loaded vehicles that are repetitively driven on unbound granular materials can achieve much higher levels of compaction than with a conventional vibrating roller. When heavy vehicles travel over more plastic materials other problems can arise, but we will not discuss these here as the focus is more on the top unbonded layers.

Although high levels of compaction are not normally negative, it can be negative when the surrounding areas are compacted with conventional rolling. While vibratory rollers compact to the prescribed minimum levels of compaction or higher, they will not achieve the levels achieved by heavy vehicle tires after multiple passes. There is thus a difference between the very high stiffness that occurs in local tracks from tires and the nominal stiffness. This difference in stiffness can further lead to variance in strain and deformation characteristics. Heavily loaded dump trucks can give rise to ground pressure in the order of 100-400 kPa which is on par with static line load for roller compactors. However, a dump truck will not give rise to only a purely static load because it is in motion. Therefore, the dynamic loads are likely to be even higher. Coarsely patterned tires can also mean varying contact areas between the tire and the surface, which means that locally, higher pressure levels can occur. During the life of the road, this variance and difference in packing can therefore have consequences. Areas compacted by the roller will likely see more settlement than areas trafficked and compacted by heavy vehicles. This causes an uneven surface for asphalt, concrete and concrete blocks. In the worst case, this can lead to local fractures in the asphalt pavement. Concrete blocks can detach from the surface, which increases maintenance costs. Asphalt surfaces can demonstrate rutting and cracking.

The tires on heavily loaded vehicles and the tread pattern also affect how the material is compressed. Roller compactors also have rubber tires that affect the compaction in the upper layers. The rubber tires on the roller help to close the surface of the material (especially if used on RCC) and increase the surface density. It is also important to consider which material is being compacted. Recently crushed material will behave differently than material that has been stored for a longer period. Although segregation and its effects on the road structure have been studied previously within DigiRoad, differential compaction can thus also be another source of variation with serious consequences for the road body.

Several contractors have flagged the problem when using a compaction system on the roller as they see extreme CMV values when trying to compact in areas where there has been intense heavy traffic. For Volvo CE, these trials also have the purpose of providing answers to how the compaction behavior and performance are affected by construction traffic with, for example, Volvo dumper machines. Volvo CE already today uses DEM and rigid body dynamic simulations to study loads and behavior of dump trucks and other machines. They are therefore suitable recipients of both software demonstrators and experimental results.

Project Scope

The primary objective of this project is to gain a better understanding of the phenomenon of differential compaction of +0/32 unbound aggregates. This will be achieved by performing physical experiments to investigate the hypothesis and using the experimental data in combination with discrete element method simulations to provide a comprehensive analysis of the phenomena.

Relevance

A brief literature study has been performed as part of the project. While the research area targeting compaction of soils and unbound granular materials is relatively well studied, no specific academic paper or report has been found that specifically mentions the problem of differential compaction due to construction vehicle traffic. The compaction of agricultural soils is described in the literature by e.g. [3, 4], and for forestry by e.g. [5]. However, the problem is not articulated to include the context of transport infrastructure. This study could therefore be the first structured attempt to investigate differential compaction in road construction.

Methodology

This section focuses on documenting the experimental and modelling methodology used in the project. Due to brevity, not all post-processing analysis methods are thoroughly described. For more information regarding such details, the reader is referred to contacting the authors.

Experiments

The tests were performed at the Volvo Construction Equipment Customer Centre site in Eskilstuna in August 2021. The test surface was constructed as a 0.5 m thick layer of base course +0/-32 mm unbound aggregate material from the NCC quarry Gröndal. The surface was prepared with a combination of laser positioning and the excavator reference levelling system to maintain 0.5m thickness along the track. Since the ground had a slight slope, the height had to be locally compensated to maintain the correct thickness. A more level initial surface would have made the preparation easier. The surface was created with two main tracks, one for the traffic of the articulated hauler, and one a reference to compare against only compacting with the roller compactor. Ground pressure sensors were positioned on the initial surface and the cables were protected with polymer tubes. The test sequence and corresponding measurement intervals are shown in Table 1. The articulated hauler used for the tests was a Volvo A40G with MICHELIN XTRA DEFEND - 23.5R25 tires and the roller compactor was a Volvo SD160B. The vehicle and load mass were 37 tons and 30.7 tons respectively. The vehicle speed was 15 km/h and the operator kept the same wheel tracks with very low deviation over the 64 passages.

Table 1. Test sequence and measurements performed.

Sequence	Passage	LWD	Nuclear Gauge	Laser scanning	Compactor CMV	Geokon 3515
Initial bed	-		x	x		
Static compaction	1-2	x	x	x		All[1]
Hauler	1	x	x	x		All[1]
Hauler	2	x	x	x		All[1]
Hauler	3-4	x	x	x		All[1]
Hauler	5-8	x	x	x		All[1]
Hauler	9-16	x	x	x		All[1]
Hauler	17-32	x	x	x		All[1]
Hauler	33-64	x	x	x		All[1]
Dynamic compaction	1-4	x	x	x	x	All[2]
Dynamic compaction	5-8	x	x	x	x	All[2]

The test area before the material bed was created can be seen in Figure 1 including the initial stiffness measurements. After initial stiffness and density measurements, the pressure sensors were positioned and secured. The unbound +0/-32 mm material was

[1] Signal noise disturbance due to sensor factory production error, partial recovery of data

[2] Complete signal disturbance, data not possible to recover by filtering.

spread out forming the 0.5m layer using the excavator levelling system and a separate laser level system as reference; see Figure 2 and Figure 3.

Figure 1. Left: Site after ground compaction and placement of concrete blocks used for laser scanning reference sphere positioning. right: Light deflectometer measurements and material spreading.

Figure 2. Left: Positioning of ground pressure sensors. Right: Dewesoft Krypton data acquisition system for ground pressure system.

Figure 3. Left: Final adjustment of bed height using excavator and laser height measurement. Right: Tracks after completion of 64 passes before final compaction.

Critical issues with ground sensors!

During the initial phase of experiments, it was found that the Geokon sensors started to experience significant signal noise. When the initial static compaction was initiated high noise levels were recorded. It was later found through inspection by the manufacturer that the sensor internal wiring had been done in the wrong order, connecting the external shield to the sensor output. This made the sensor extremely sensitive to moisture and any external electromagnetic fields in the surrounding area. The sensors have since been repaired but as will be demonstrated in the results section, the pressure signals were almost beyond saving, even though attempts were made with notch and lowpass filters. The recorded signals from the final dynamic compaction were not possible to distinguish from the noise at all.

On site during experiments, this problem also led to the team having to dig up the sensors in order to provide additional plastic coverage in order to keep the sensors from contacting any material or moisture. This damaged the initial state of the bed and probably caused some size separation around the sensors. The potential size segregation and disturbance of the virgin bed potentially reduces the quality of the study. The rearrangement of the sensors also took considerable time from the test plan, making it a considerable challenge to complete the experiments within time constraints.

In Figure 5 the test surface is shown after conditioning static roller compactor passages during the measurement of stiffness for the reference surface. A central dashed line was painted to mark the center line and crosses painted to mark the positions for the ground sensors as well as measurement positions for stiffness and nuclear density. In Figure 6, a snapshot from a video recording of the first articulated hauler passage can be seen. The sequence of passages from the 1^{st} to the 64^{th} can be seen in Figure 4. During testing, the experience was that the relatively long ramp up to the measurement zone was necessary in order to avoid any dynamic effects from a too steep ramp. The final dynamic compaction of the reference surface can be seen in Figure 7. As shown in Table 1 3D laser scanning was performed after each sequence. The setup with point cloud reference spheres and the FARO is seen in Figure 8. The method of using reference spheres enables accurate comparison between point clouds even though a significant time passes between measurements. At least as long as the reference metal washers used for the magnetic holders are not moved.

P1

P8

P16

P32

P64

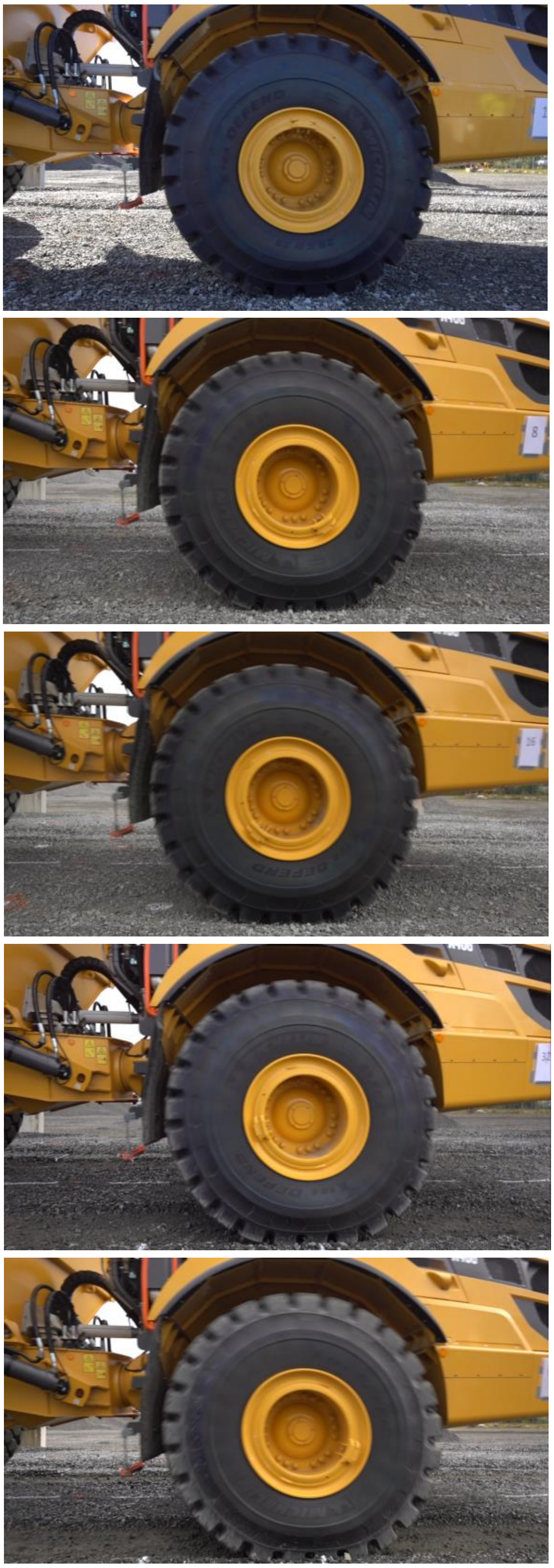

Figure 4. Side view of passage 1, 8, 16, 32 and 64.

Figure 5. Photo of the test track after the first two static roller compaction passages.

Figure 6. Photo of the first passage of the articulated hauler as it passes the pressure sensors.

Figure 7. Photo of the last dynamic compaction of the reference surface.

Figure 8. Picture of the test surface after the final 3D laser scanning has been performed.

DEM modelling of articulated hauler tire bed compaction

The discrete element method (DEM) is a numerical technique for modeling systems of particles to predict the motion and forces [6, 7]. The method has historically been applied to a variety of industrial problems, and thanks to the ever-increasing computing power, has been able to be applied to larger and larger problems. In early applications of the method, primarily spherical shapes were used to model the particles, and later also composite spherical shapes, so-called multispheres. The spherical particle has advantages in terms of being easy to count on; the force between spherical particles can be easily evaluated as a function of small overlaps between the spheres. However, spherical particles are also severely limiting as much of both the static and dynamic behavior of irregularly shaped particles is controlled by the shape of the particles. To some extent, the lack of shape can be compensated with added friction, rolling friction and/or cohesion between the particles, but this has both mathematical and simulation disadvantages.

In recent years, DEM has developed rapidly towards not only starting from spherical model particles but also with polyhedral particles [7, 8]. Since 2016, FCC has developed its own DEM software, Demify®, which was initially based on spherical particles but since 2020 can also be used to simulate polyhedra and since 2021 dilated polyhedra, see Figure 9. During the spring of 2020, a degree project was conducted at FCC where the student Adam Bilock, together with Klas Jareteg as supervisor, developed a DEM solver for simulating polyhedra through the use of GPUs (Graphical Processing Units). For a full description of this solver, its features and performance, the reader is referred to the project's final report [8].

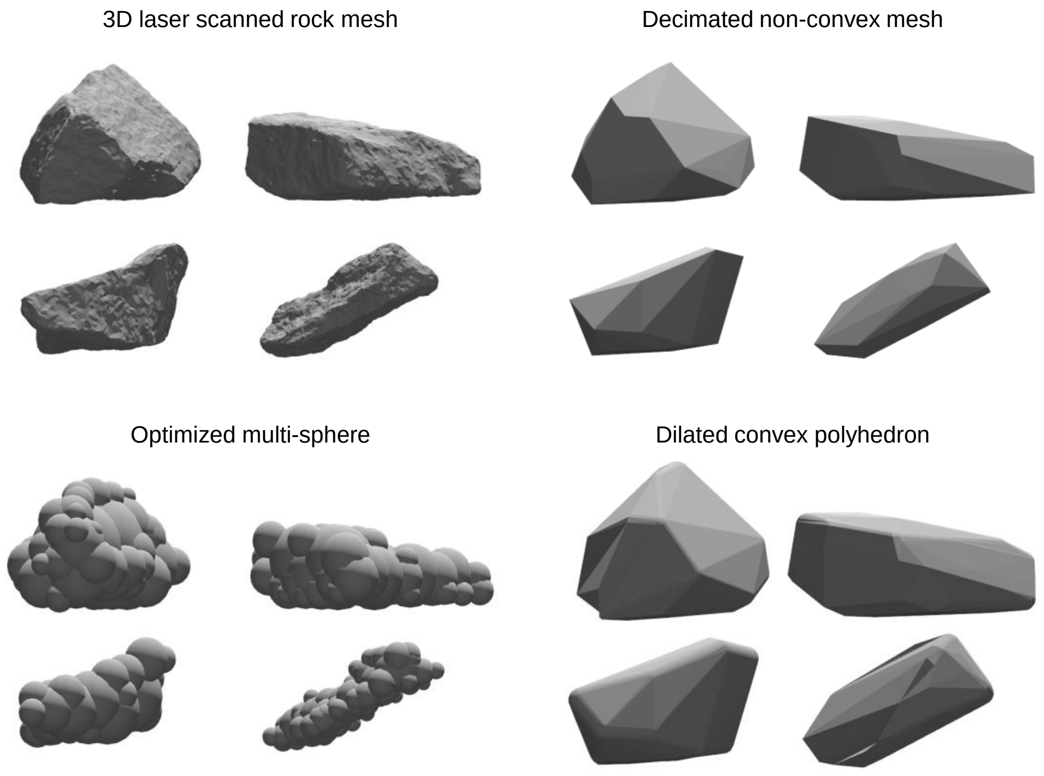

Figure 9. Four particle shape representations relevant to DEM modelling of rock materials

In this work, the so-called dilated polyhedron (DP) method has been used [8]. In the DP method a sphere is swept on the triangulation of a convex mesh, hence the name "dilation". The operation allows for faster contact detection and calculation of interaction forces than the volumetric overlap non-convex polyhedron method. The downside with the DP method is that some of the irregularity of the rock body is lost when using the convex hull of a non-convex rock shape. Additionally, the dilation operation creates a more rounded particle, hence the shear resistance of the particle population will be lower. Consequently, while the simulations are much faster, some of the accuracy and predictive performance of the model are reduced.

To achieve industrially relevant simulations, all parts of Demify are coded for calculations on graphics cards (so-called GPUs). A modern GPU has the advantage of being able to perform massively parallel calculations in an energy- and cost-efficient way, and given well-formulated algorithms, a manifold higher performance can be achieved on a GPU compared to a CPU on a normal computer. In addition to the unique implementation of contacts and overlaps between the polyhedra, a fast search tree is also used which allows non-colliding objects to be quickly filtered out and not considered when the forces between the objects are calculated. The formulation used scales linearly with the number of particles simulated and with the number of triangles in each model particle and overall a world-leading performance is achieved.

Demify's user interface consists of two parts, an API interface based on Python and a graphical user interface implemented on the IPS platform. The Python interface has the advantage that it gives the engineer a great opportunity to flexibly interact with the solver, which in the work on this report was a cornerstone for the connection between the particles and the machine model that was controlled using multibody dynamics. The graphical user interface has been used here to visualize the interaction between particles and machine, and thanks to a uniquely efficient visualization engine, a large number of particles can be quickly and efficiently visualized and studied in the software.

The Demify® DEM solver developed by FCC has been used in the project to model the tire of the articulated hauler interacting with a bed of base coarse material. The system is simplified only to include a single tire and consequently, a vehicle pass is modelled as three unique tire passages with the corresponding load balance. The vehicle has been modelled using the multi-body dynamics solver proposed by Axås and also applied for roller compactors in SBUG project 13820. In more advanced tire ground interaction simulation the tire may be modelled using the finite element method or other similar techniques that account for the deformation of the tire [11]. However, in this work the tire has been modelled as a non-deformable geometry object. The tire shape was modelled and meshed to closely resemble the correct dimensions and tire pattern.

Experimental Results

In this section the key findings from the experiments are presented. The particle size distribution of the aggregate material is shown in Figure 10. The analysis was performed for 12 kg of sampled material from the test track. No sampling was done after the surface was trafficked however it is not believed that any particle degradation or fracture was present to any measurable degree.

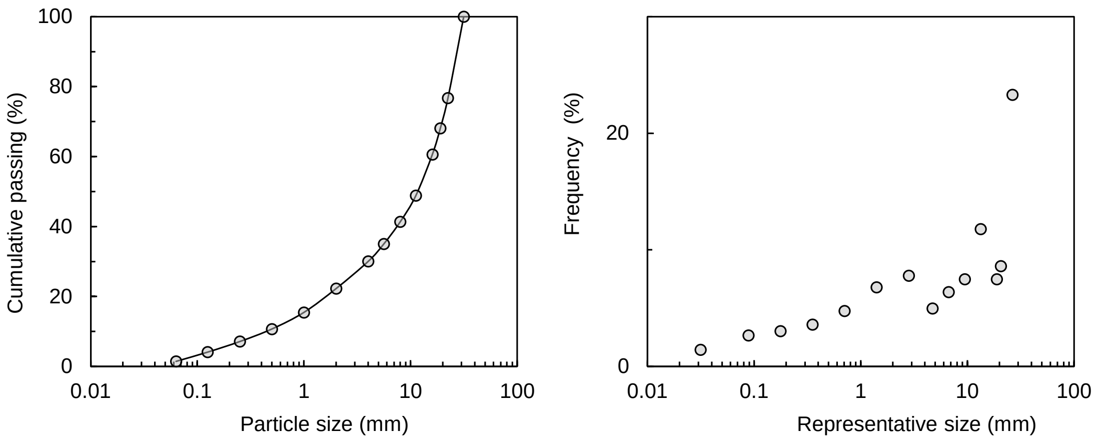

Figure 10. Particle size distribution of the +0/-32 mm aggregate material.

Light deflectometer stiffness measurement

Stiffness measurements has been carried out using the "German Light Weight Deflectometer", hereinafter referred to simply as "LWD". The plot in Figure 11 describes the mean value of the LWD measurements in the respective tire/reference path as a function of the number of passages. The first point (point 1 on the x-axis) applies after the two static passes with the roller compactor. It can be seen that, with the LWD method, the surface is "uniformly stiff" at the start of the tests, because all measuring lines show the same stiffness, around 20 MN/m^2. The stiffness then increases gradually with the number of dumper passages, but no "massive" growth is obtained. Expressed as a percentage, the increase is 100% between static passage and 64 dumper passages, but the absolute stiffness is still not very high. After 64 (point 8) passes, the surface reaches its maximum stiffness around 40 MN/m^2 in the left wheel track. In the right wheel track, the same stiffness is not achieved, and this may be because the centre of the bank has better support than the edge of the bank. If you drive the wheel close to the edge, you run the risk of the material moving sideways rather than being compacted.

After 64 articulated hauler passages (item 8), 4 roller passages were carried out with the vibrations switched on and high amplitude activated. The drop weight method recorded a reduction in the stiffness of the tire tracks and this may be due to the unpacked material between the dumper tracks being "squeezed out" and contributing to a lower overall stiffness. After the 4 vibrating rollovers, it was noted that the stiffness in the two articulated hauler lanes had "evened out" and reduced to about 35 MN/m^2. At the same time, an approximate 10% lower stiffness was noted in the reference track, which has not been trafficked by any articulated hauler passages. The difference in stiffness between articulated hauler lanes and reference roller compactor lanes persists through all compactor passages and it is, therefore, reasonable to assume that the difference in stiffness between articulated hauler and reference lanes is precisely the effect of dump truck traffic. In that case, this would mean that, according to the LWD method, the dump truck traffic (64 passages) has increased the stiffness of the substrate by approx. 10-15% compared to the section where only the roller was driven.

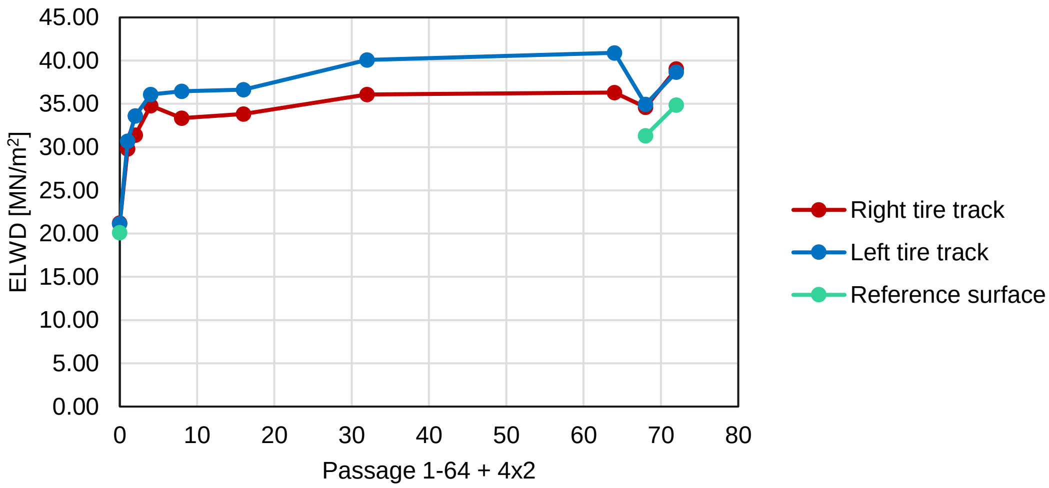

Figure 11. Stiffness response in the left and right tire track, and the reference surface.

Nuclear gauge density

Nuclear gauge density tests were conducted using a CPN MC-3 Portaprobe. Average results for the dry and wet estimates of density are plotted in Figure 12. Due to issues with rain on and off during the test campaign weeks, the recorded values display noticeable variance until approximately pass 16. The data still suggest a convergence trend with the number of passes. Unfortunately, due to issues with the device, measurements were not retrieved for the dynamic compaction. It is hence not possible to determine if there was a significant density difference in the reference surface compared to the tire tracks.

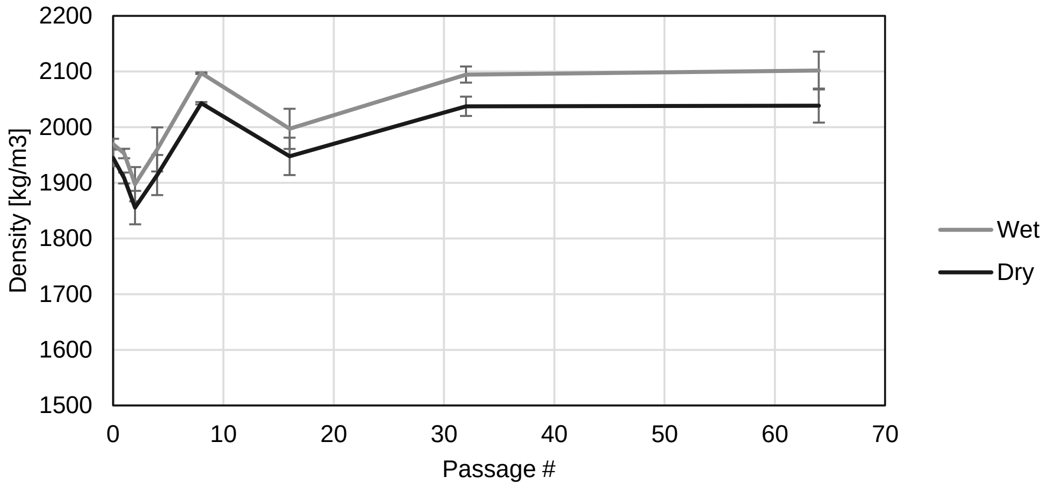

Figure 12. Nuclear gauge density measurement results for the tire tracks

Laser 3D scanning deformation measurement

Tire track surface

The laser scanning data includes the compete surroundings of the test area. Hence the point cloud has to be processed in order to conduct analysis of the progression of deformation. A section was cut out from the point cloud for each measurement point to perform a comparison. A section corresponding to the reference surface was also sampled to compare the trafficked area with the reference surface. The point cloud results from the experiments are shown in Figure 14 and Figure 13. While the 3D view of the tracks demonstrates the tracks well, it is easier to interpret the data when sampling and averaging the data in the top view and x- and y-directions. As seen in Figure 14, the hauler tire tracks are clearly seen from the first passage to the last passage. After the dynamic roller compaction, tire tracks are no longer distinguishable.

The deformation profiles in the y-direction, across the tracks, can be seen in Figure 15 and Figure 16. The results suggest that the initial static compaction on the loosely packed bed gives ~50mm of compression. The tire tracks build depth for each consecutive passage with a higher degree of compaction for the earlier passages than the later passages. The first four dynamic compaction passes compresses the surface to reach approximately the level of the tire tracks. The last four passes further compacts the bed to

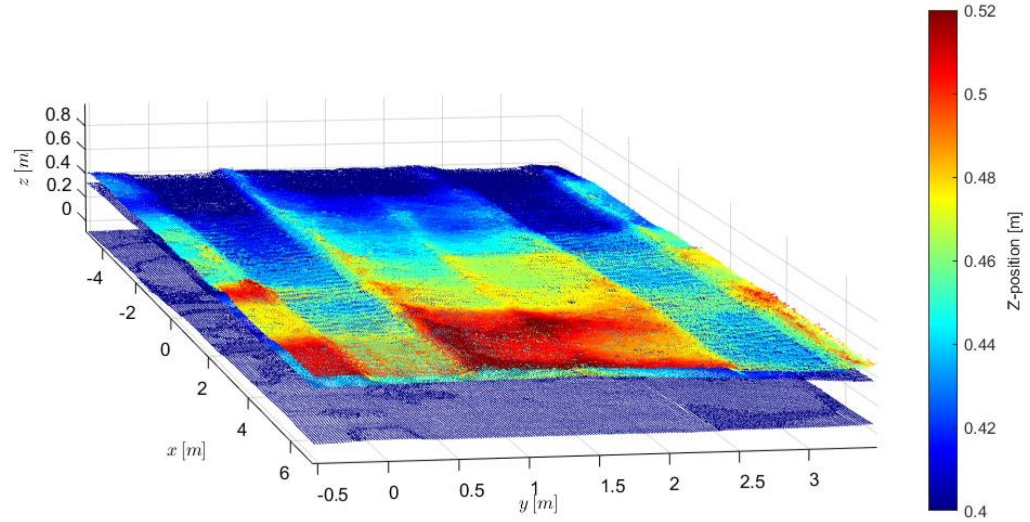

Figure 13. Illustration of point cloud of the resulting tire tracks after articular hauler passages.

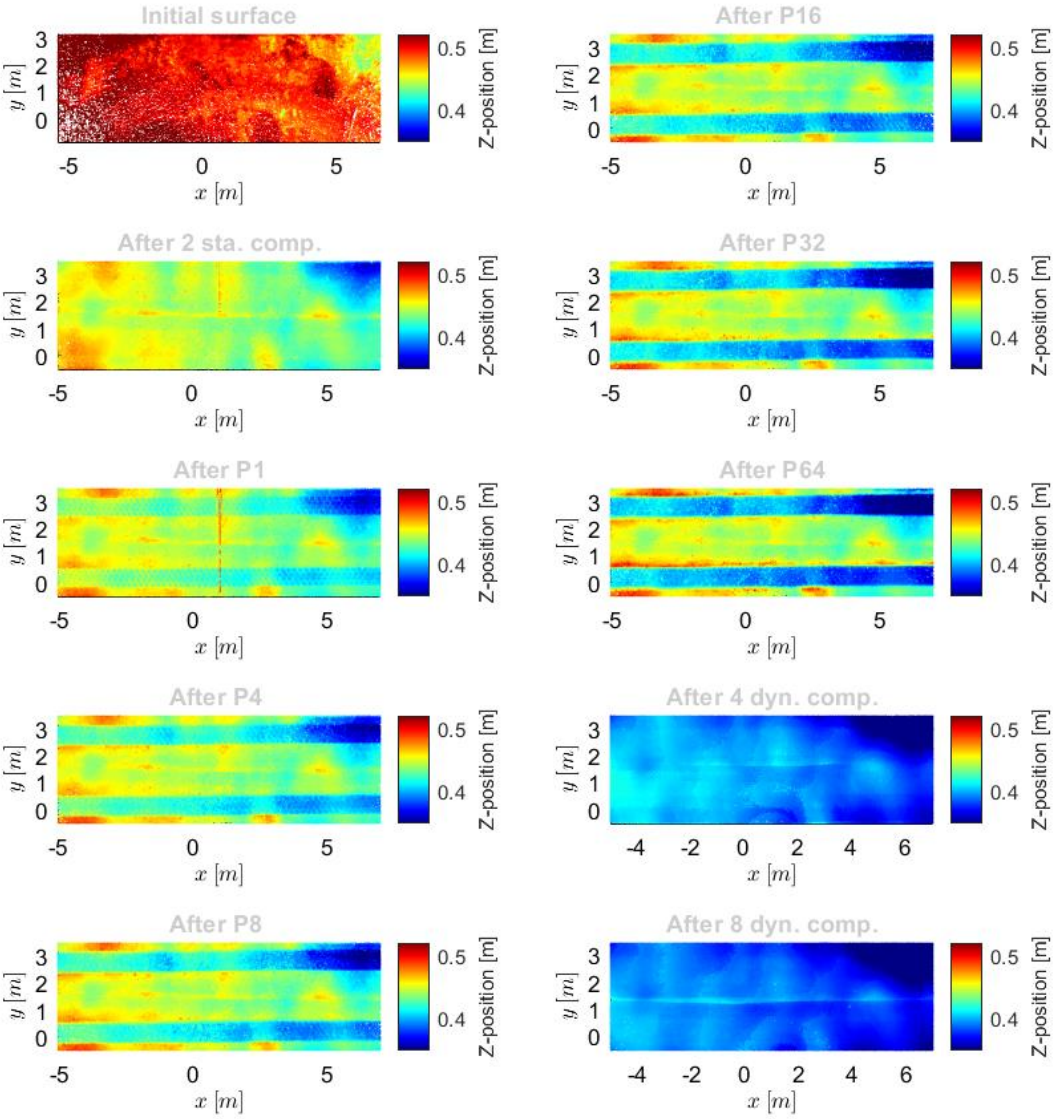

Figure 14. Point cloud top view of the test surface for the measurement sequence.

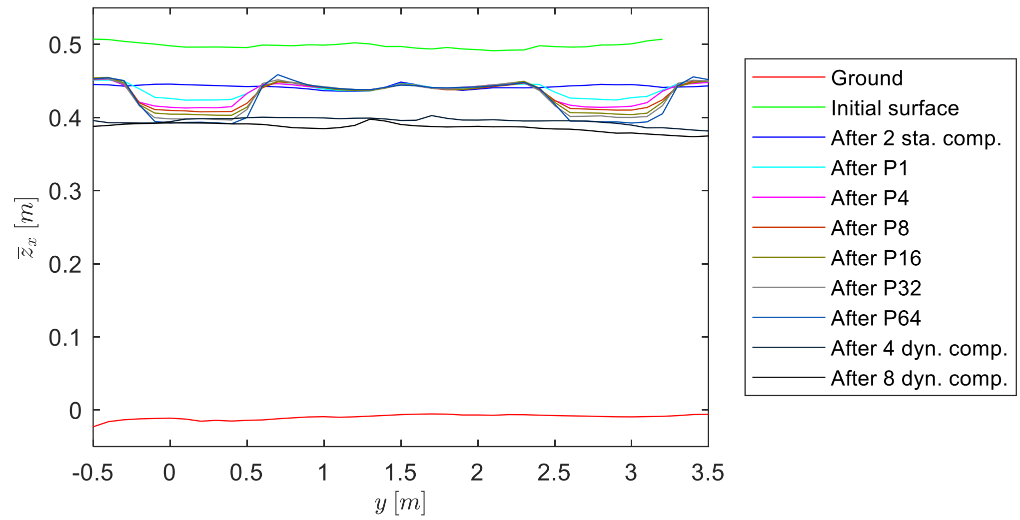

Figure 15. Measurement of surface topography from laser scanning sampled across the tire tracks including the ground level.

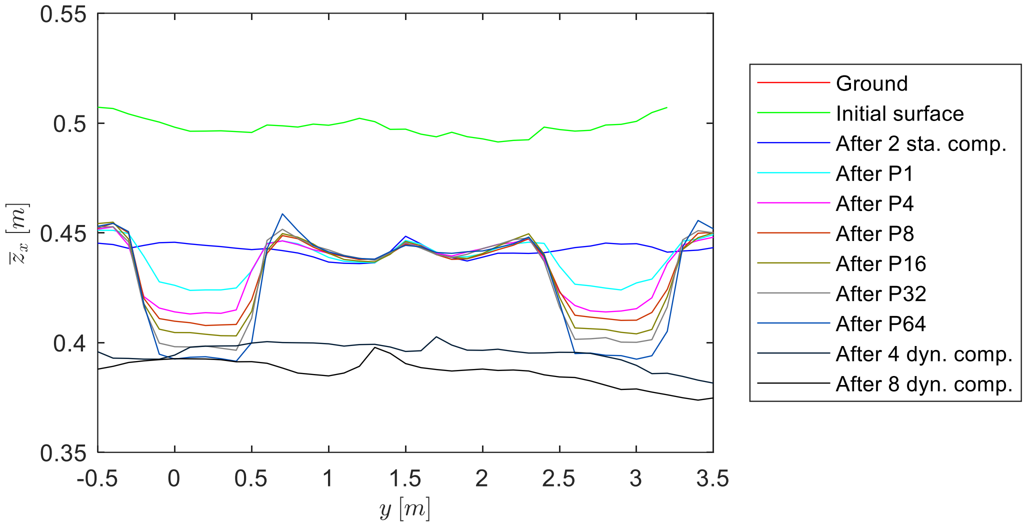

Figure 16. Measurement of surface topography from laser scanning sampled across the tire tracks with emphasis of the change in surface pattern.

The aggregated data in the x-direction sampled from the tire track is displayed in Figure 17. As seen, the test surface has a distinct slope across the sampled 8 meters of tire track. However, the slope follows the ground profile in parallel. The slope is also reflected in the error bars displayed in Figure 18, displaying the average height of the measured tire tracks for each measured passage and compaction. If compensating for the consistent slope via e.g. the angle calculated from a linear fit, the appearance of the error would be reduced and better represent the surface roughness.

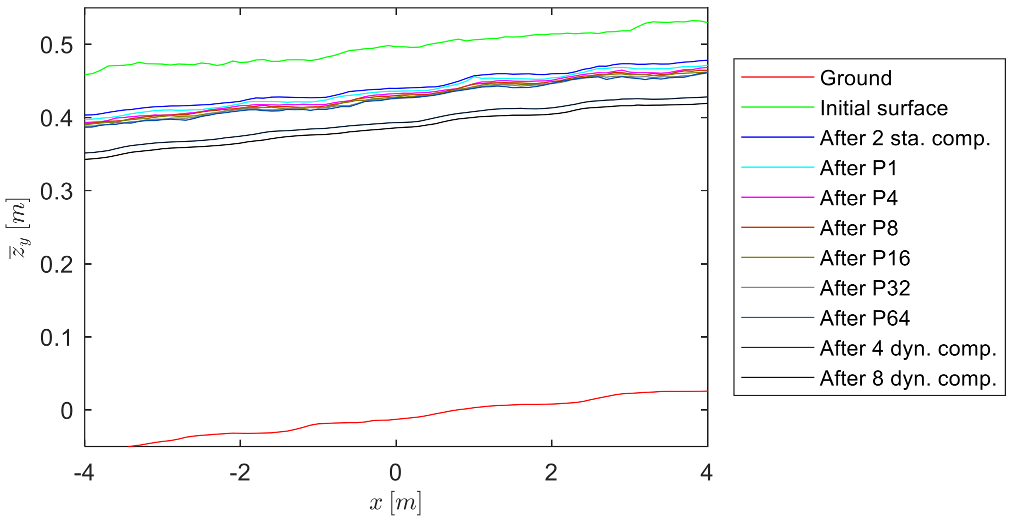

Figure 17. Measurement of surface topography in the x-direction in the right tire track from laser scanning.

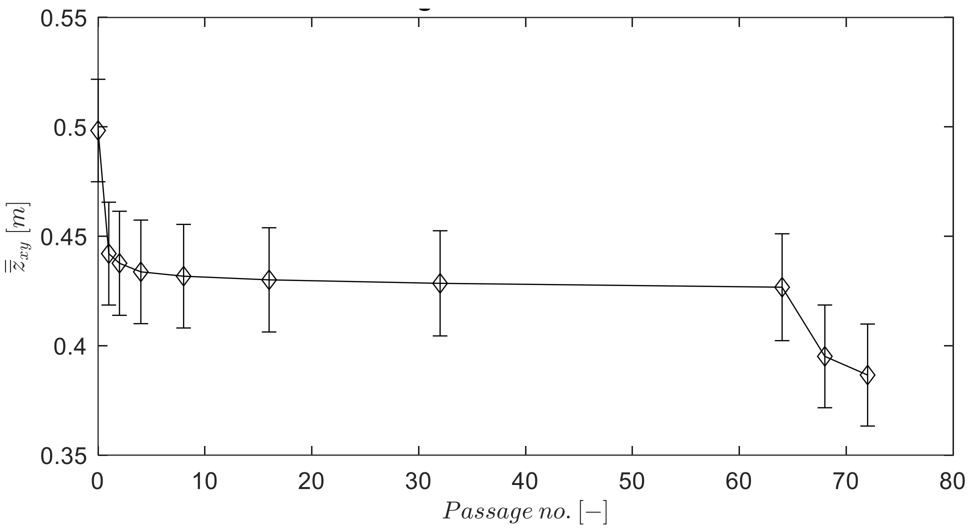

Figure 18. Height of the selected measurement surface for each measured passage and compaction.

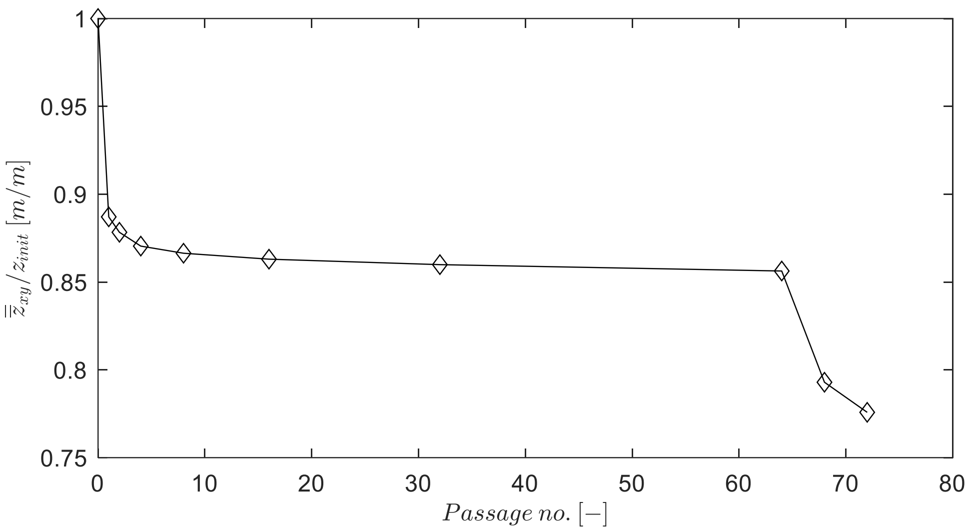

Figure 19. Compaction deformation strain subtracted from unity for each measured passage and compaction for the test surface.

Reference surface

The deformation response for the reference surface after two static compaction passages and 8 dynamic compaction passages can be seen in Figure 20. The plots clearly shows the slope of the test track. If a leveling operation would have been performed before the test surface was prepared it would have made the analysis easier and more accurate. Such leveling is a strong recommendation for future similar experiments. In Figure 21 and Figure 22 it can be seen that the deformation converges at about 25% of the initial height.

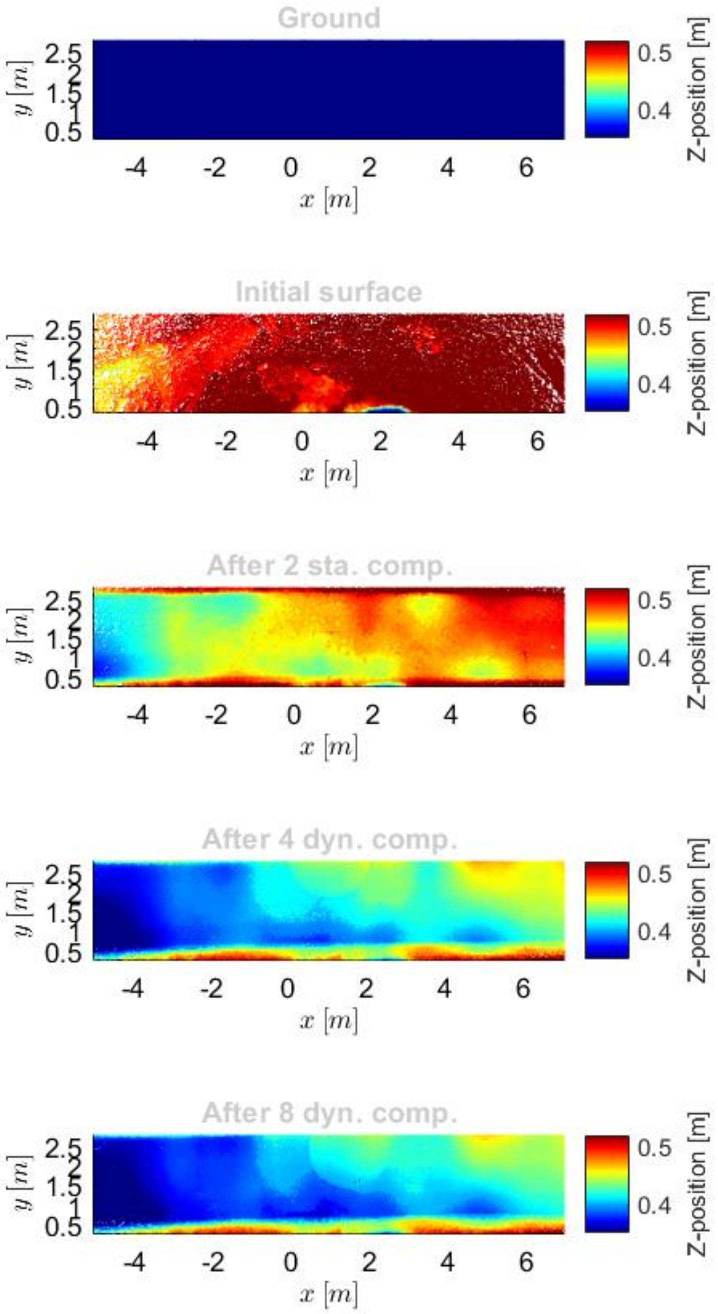

Figure 20. Point cloud top views for reference surface section

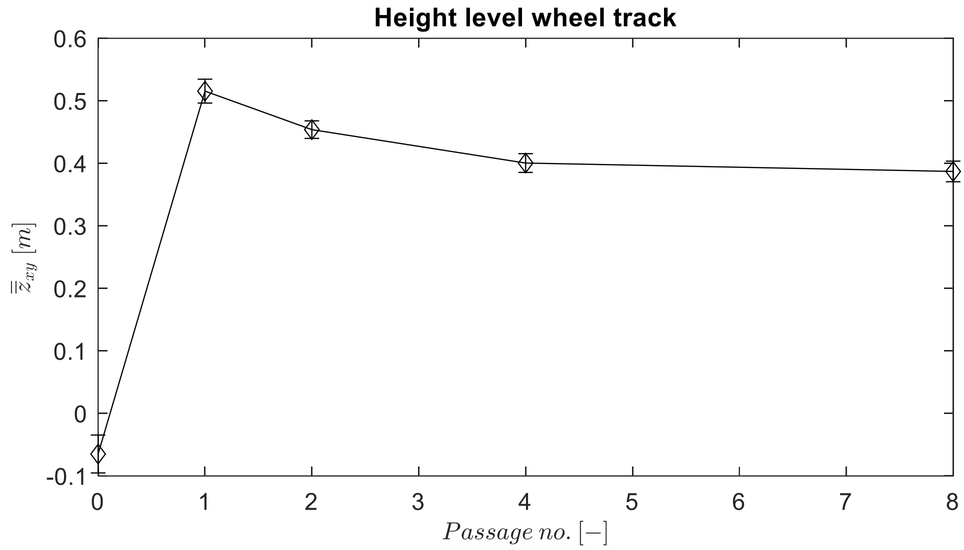

Figure 21. Height of the reference surface in the initial state and after the compaction sequence

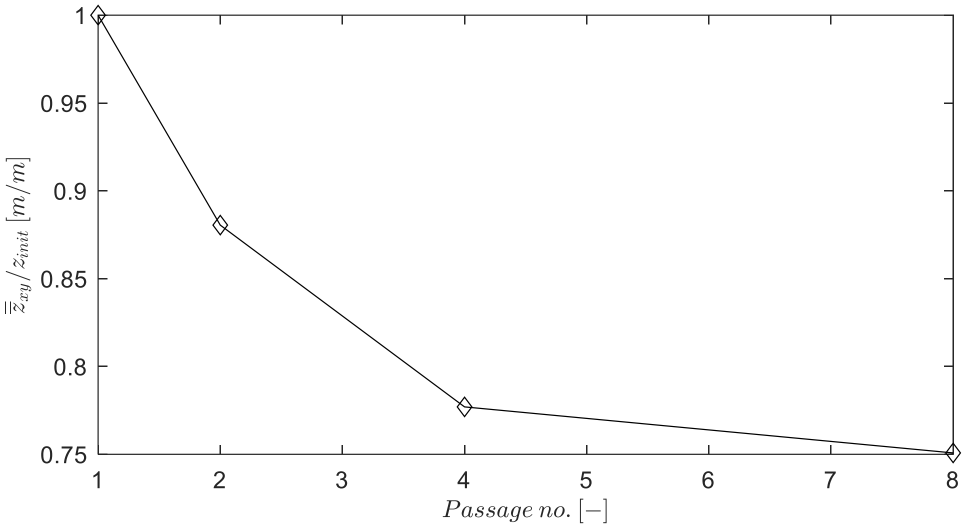

Figure 22. Compaction deformation strain subtracted from unity for each measured compaction sequence for the reference surface.

Ground pressure sensors

A series of pressure signal result from the experiments are plotted in Figure 24 to Figure 30. The 1st, 4th, 17th-32nd, and 64th passes are shown with the unfiltered and filtered signals. The sensors named P1 and P3 are located in the right tire track and P2 and P4 in the left tire track. Sensor P7 was positioned at half the depth at 250mm in the left tire track. The distance between sensor P1 and P3 was the same as the wheel base for the articulated haulers front wheel to the first back wheel. Sensors P6, P8 and P5 were positioned in the reference surface in order to measure the pressure response for the dynamic roller compaction (As explained in the methodology section these signals were not possible to recover).

Pressures are recorded at around 0.5 MPa for the front wheel and ~0.6MPa for the two back wheels. The P7 sensor at half the depth displays a higher pressure at ~0.7MPa.

As seen, already after the first passage the noise is introduced to the otherwise clean signal. The noise is well illustrated by an FFT analysis as seen in Figure 23. The reason has been further elaborated on in the methods section. With signal filtering techniques it was possible to suppress the noise to some degree, however not fully as an offset seems to be introduced for some passages, see e.g. Figure 29. It is difficult to say how and if this offset should be calculated in order to compensate for the error, the authors chose not to as the legitimacy of the data is then questionable.

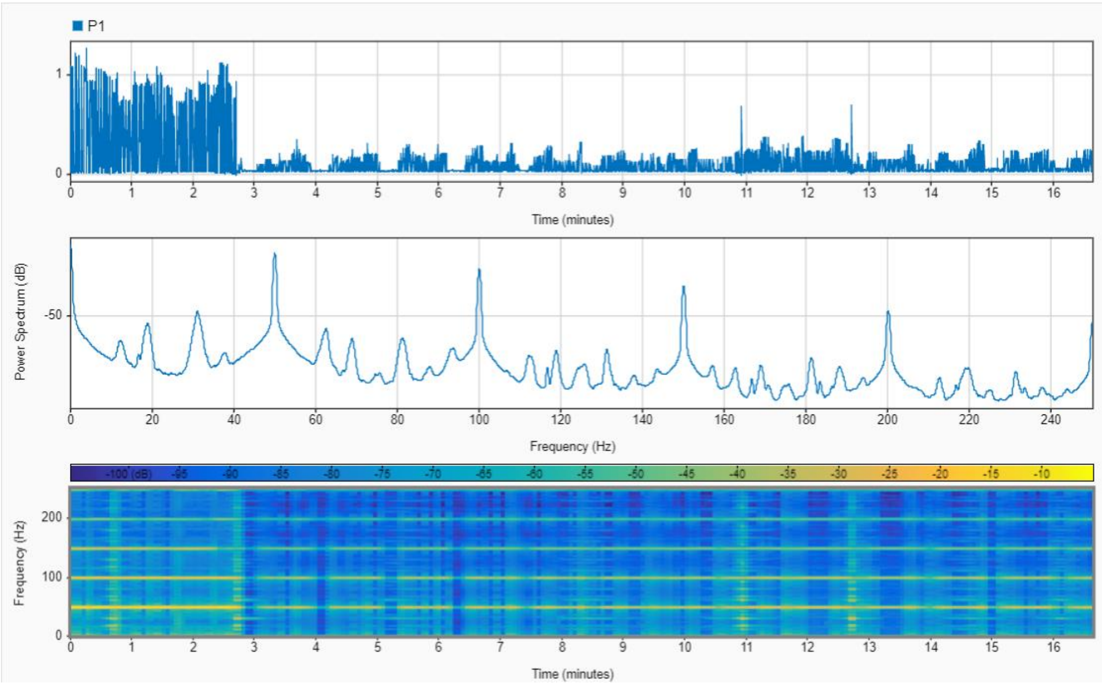

Figure 23. FFT analysis of the signal demonstrating the noise with multiples of 50Hz. (later confirmed by the sensor manufacturer as a manufacturing error.)

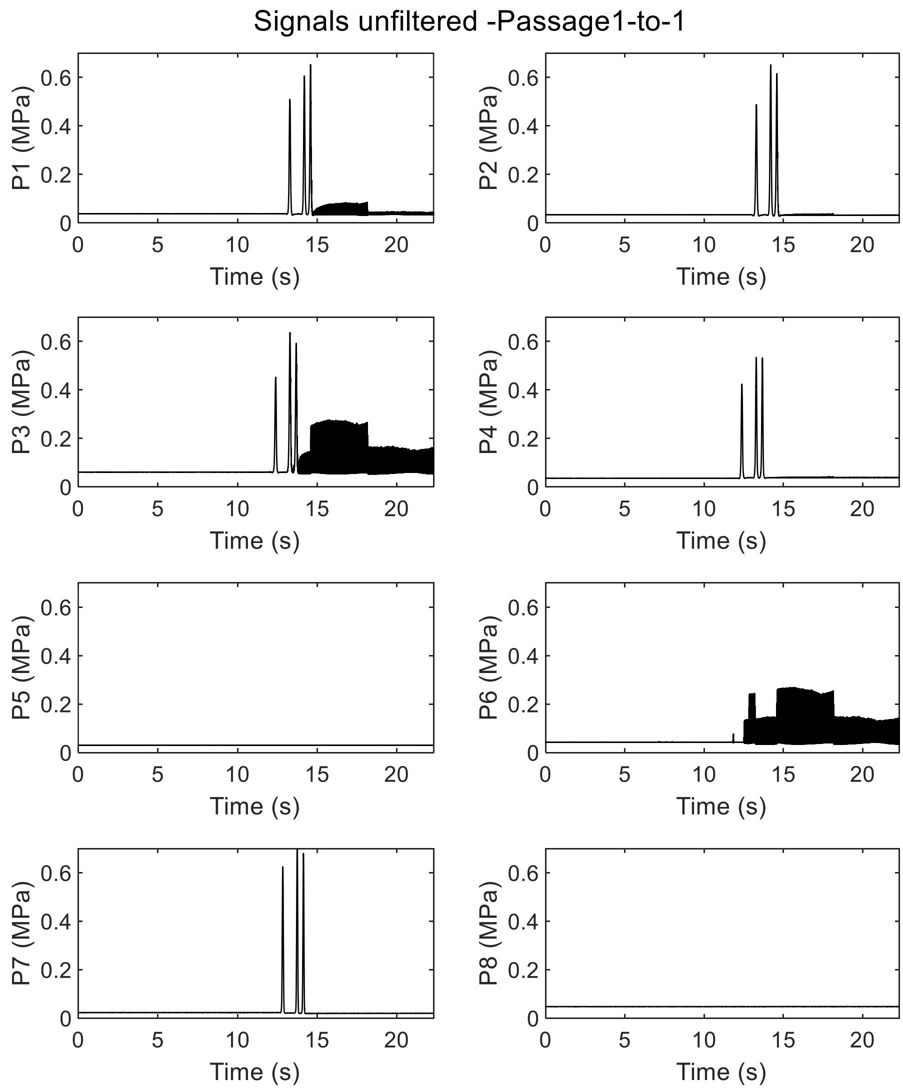

Figure 24. Pressure signals for the first articulated hauler pass (unfiltered)

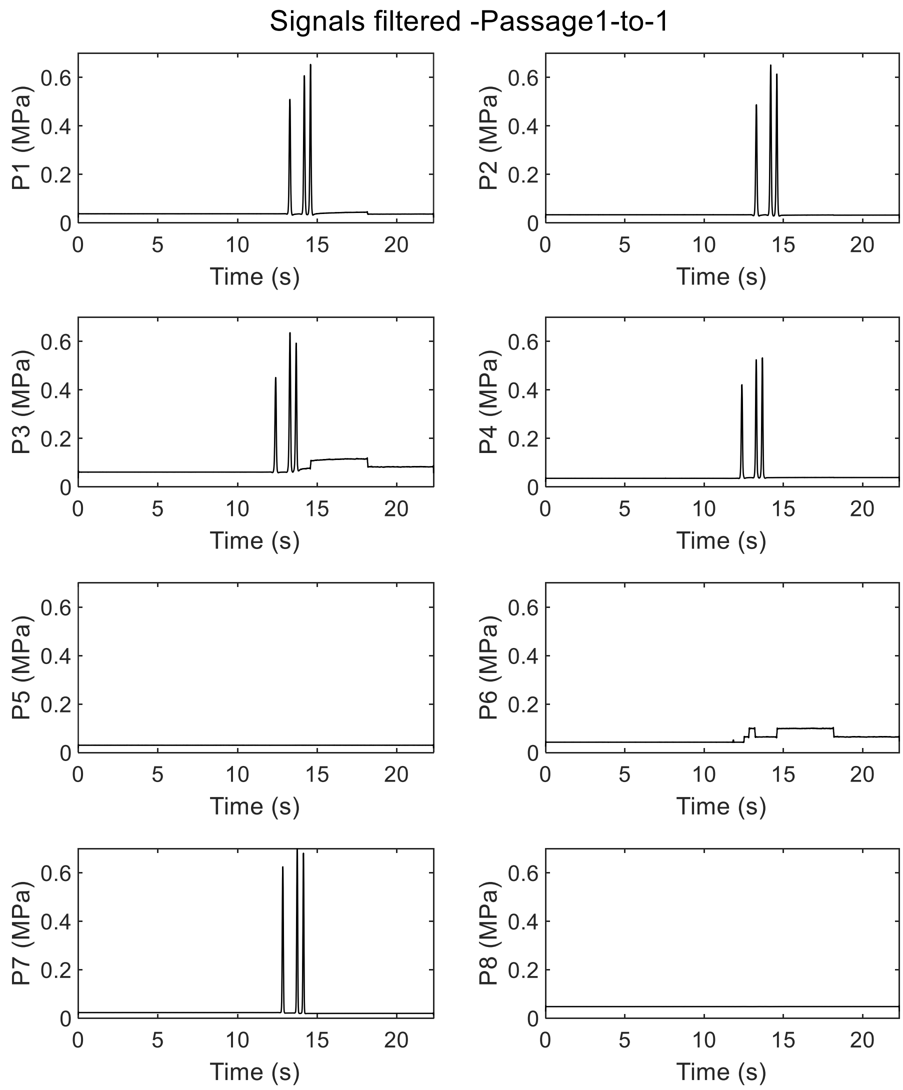

Figure 25. Pressure signals for the first articulated hauler pass (filtered)

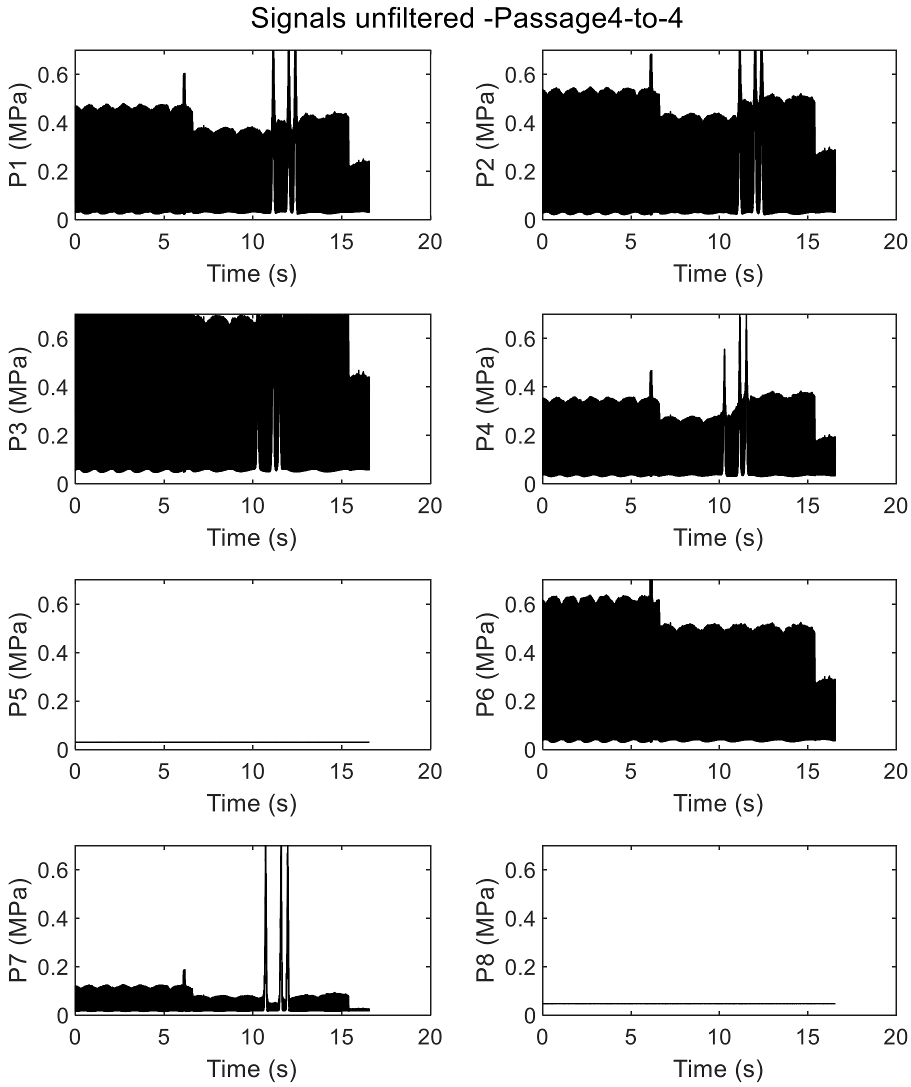

Figure 26. Pressure signals for the fourth articulated hauler pass (unfiltered)

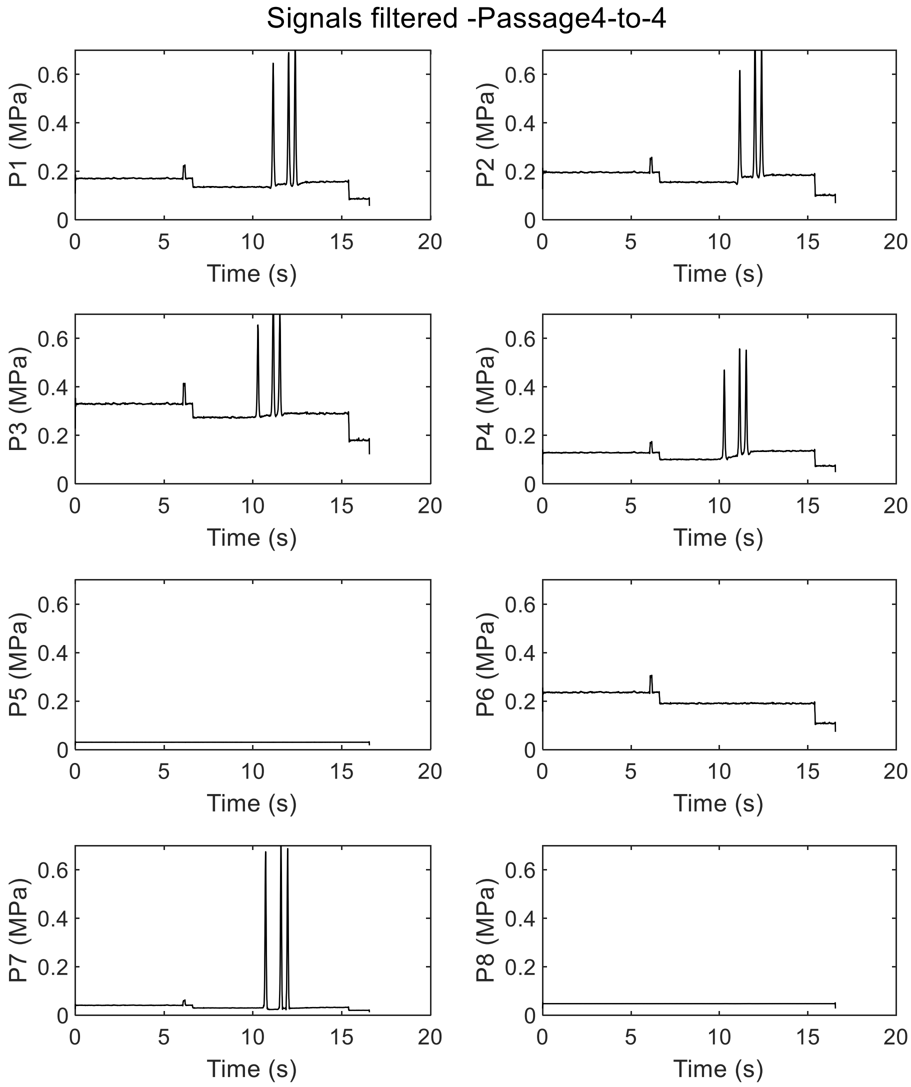

Figure 27. Pressure signals for the fourth articulated hauler pass (filtered)

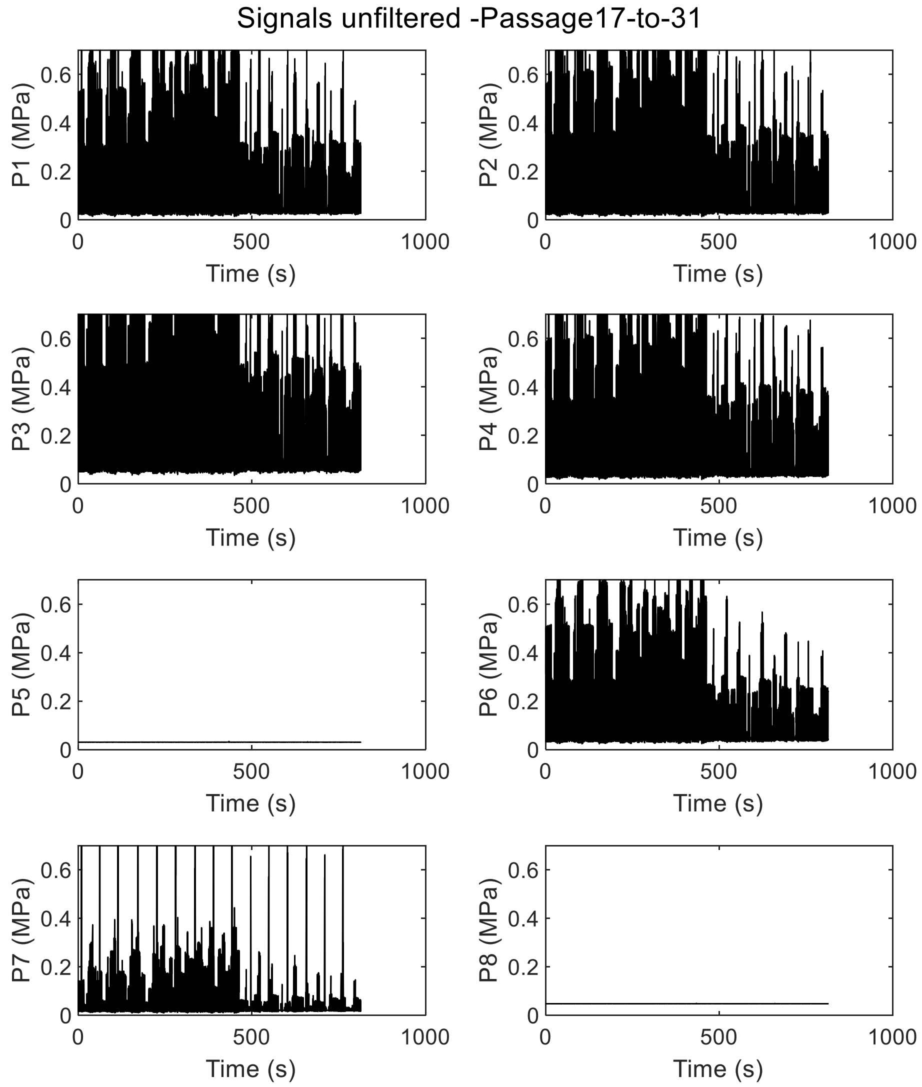

Figure 28. Pressure signals for the 17th to 31st articulated hauler passes (unfiltered)

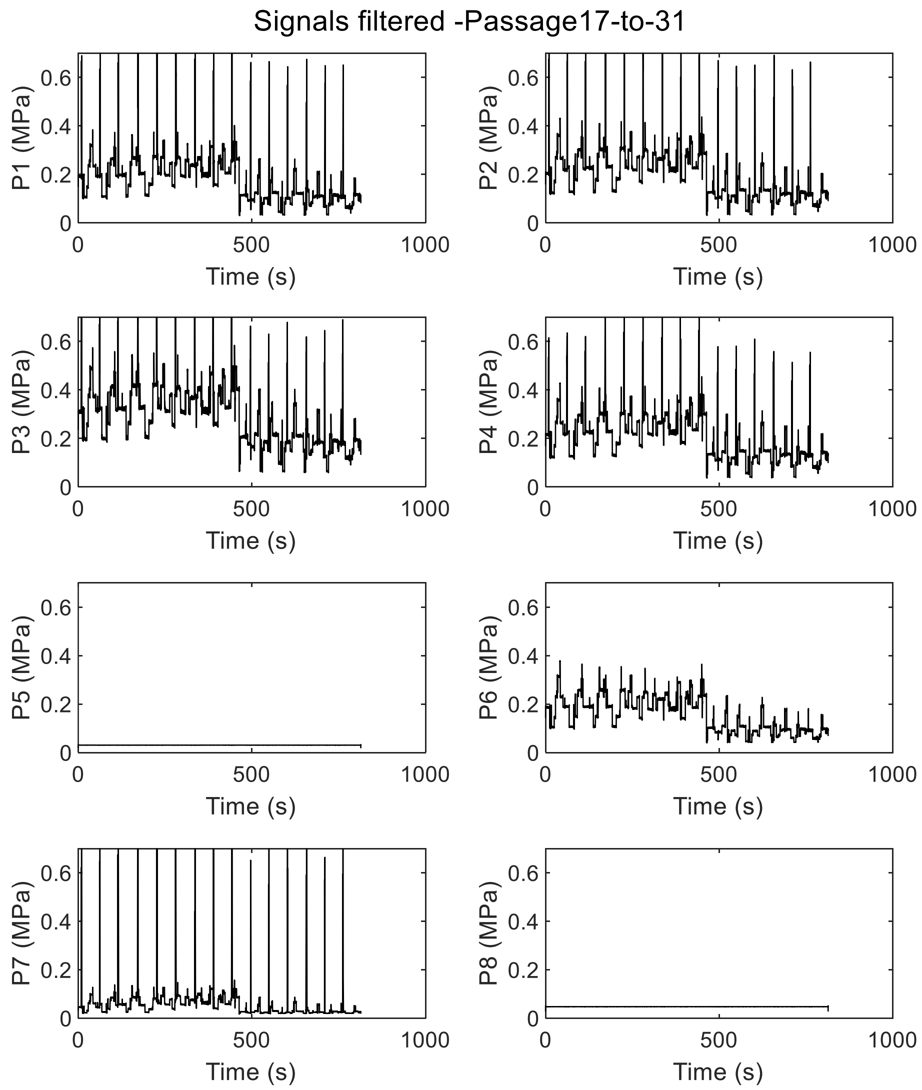

Figure 29. Pressure signals for the 17th to 31st articulated hauler passes (filtered)

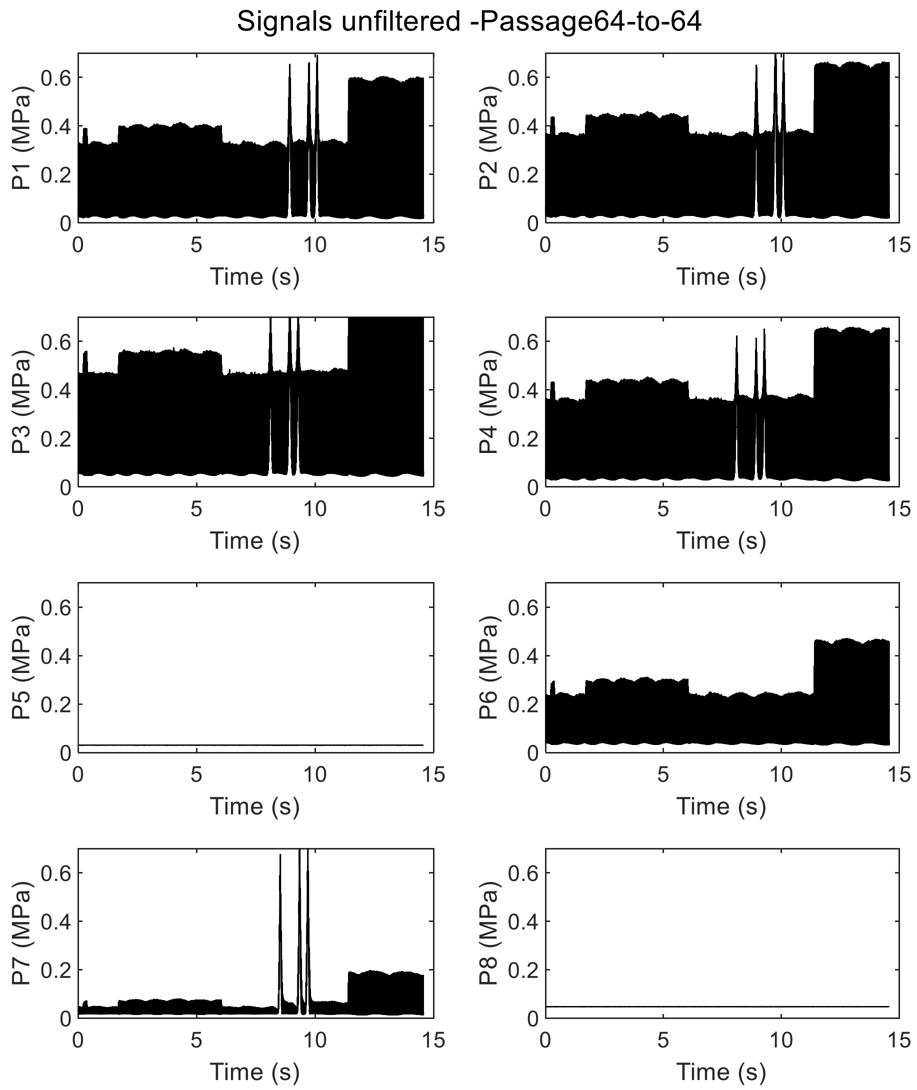

Figure 30. Pressure signals for the 64th articulated hauler pass (unfiltered)

In Figure 31 the peak pressures from the filtered signals are plotted for the first, second and third wheel. As seen the variance is significant and with close to certainty not a reflection of the true level of variance in the experiment. Rather it is a consequence of the signal noise. The data generally suggest that the pressure in sensor P7 is higher than the other sensors which is an indicator of some validity.

Further data analysis has not been performed as the authors believe that e.g. averaging across all passages would not be worthwhile.

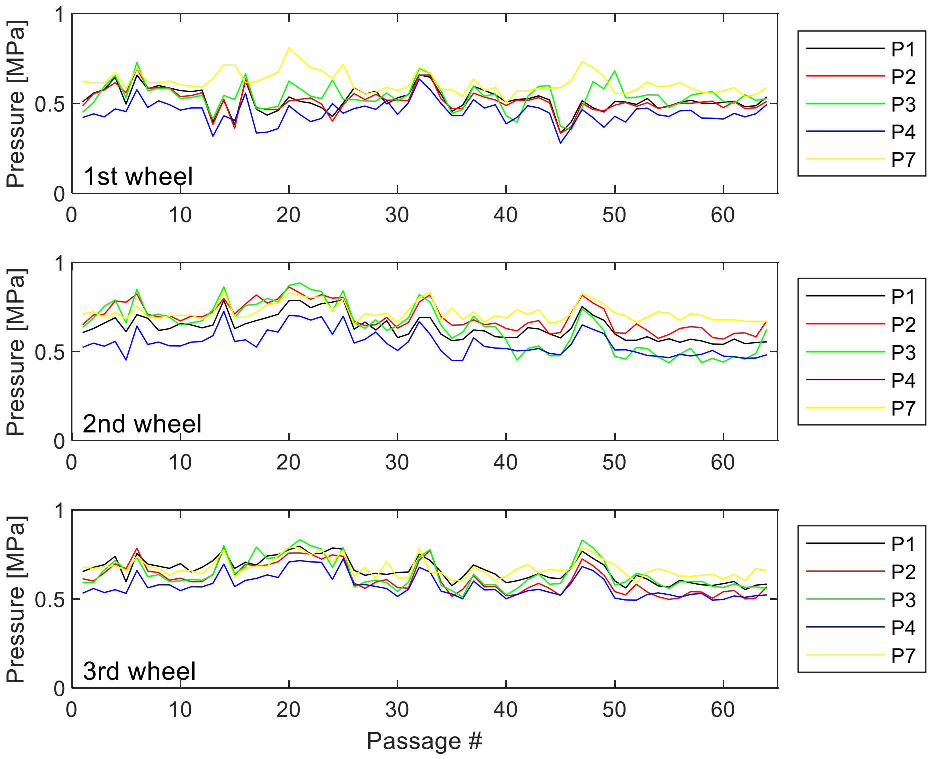

Figure 31. Peak pressure for the first, second and third wheel as function of passage number.

DEM Simulations

The modelling layout of the simulated system is illustrated in Figure 32. The particles are visualized as semitransparent and colored by velocity (hot colors are high velocity, blue are low velocity and white are stationary particles. The velocity pattern illustrates how the tire interacts with the material bed causing a rearrangement of particles the full bed depth of 0.5m.

Particle bed kinematics

The velocity profile of particles subjected to compression and shear underneath the tire is presented in Figure 35 for the first and third wheel for the four simulated vehicle passages. In the simulated tire-ground interaction the movement of the particles is overpredicted. We believe this is due to two main reasons:

- The difficulty of introducing the tire to the sample bed for each passage in the correct speed. In the experiments the articulated hauler has a long ramp of material to reach the measurement area in order to avoid dynamic effects. This was not possible to realize in the modelling hence the tire enters the bed in a too dynamic manner. This also causes problems for the multi-body dynamics model to cope with, and further tuning and evaluation would be needed to reduce of mitigate the effect.
- The structural interlocking of the granular particle packing is too low, even though it is modelled by polyhedral shapes. The experimental bed had s moisture content that probably had a significant effect on the compaction performance and cohesive nature of the bed. For these simulation cohesive force models where not included. For future studies, the level of cohesion should be calibrated using the developed triaxial load test setup against experiments performed at different moisture levels. Without such calibration it is very difficult to set the surface energy levels correctly corresponding to a certain moisture level.

It should also be noted that the modelled size distribution is not representative to the full distribution of the experiments. In DEM there must be a limiting minimum size of particles included. However, the effect of lacking the fines probably makes itself distinct in this case. An interesting comparison in this regard is the compaction experiments performed in SBUF project 13820 where both a +0/-32 and a +8/-32 aggregate material were compacted [2]. The material lacking -8 mm material behaved very differently from the standard base course material and was not possible to compact very well. It did however display a lower shear resistance, in accordance with the simulated results shown here.

Hence, future efforts should target how to model the lack of fines in compaction applications. The best option at the moment is to utilize a cohesive and rolling friction contact model. Another option is to use the computational performance boundaries to facilitate the modelling of even finer particles.

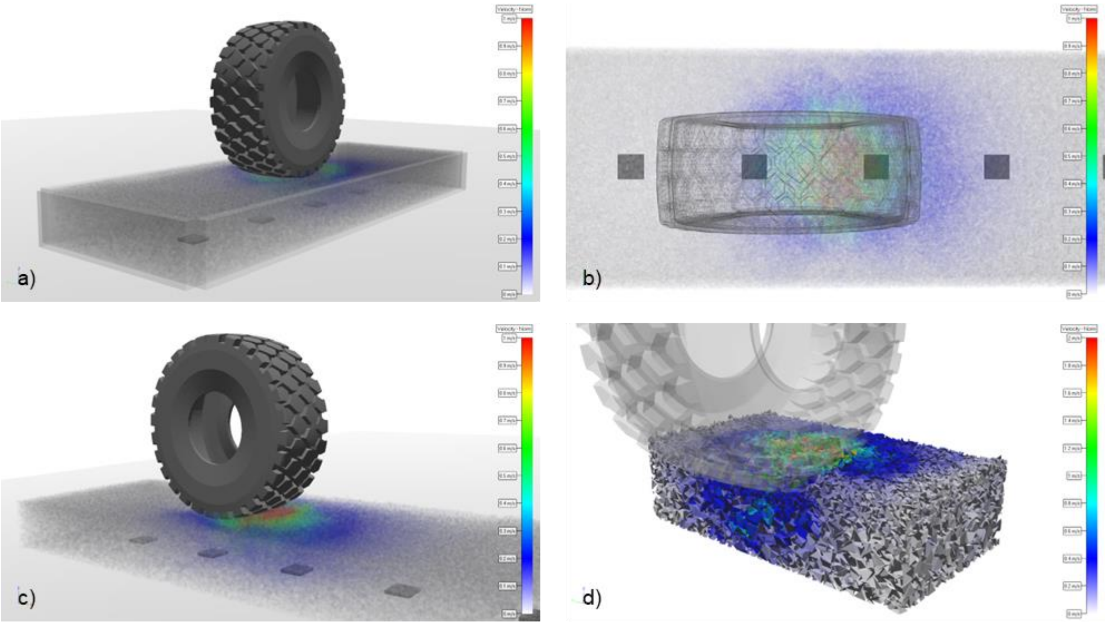

Figure 32. a), b), c) DEM simulation visualization in three views of the first wheel passage with particles semi-transparent. d) Illustration of the cross-section of the particle bed underneath the tire showing the velocity profile of particles as the tire moves over the bed.

Deformation

The simulated bed from a side view can be seen in Figure 36 for the four simulated passages. The particles are colored by their vertical position height. The tire interacting with the particle bed causes two main mechanisms: compaction of the particle bed via small rearrangements, and the flow or ploughing of particles to the sides. The simulation results indicate that the second mechanism is too strong meaning that the shear resistance/strength is not high enough. The resulting average bed deformation is plotted in Figure 33 and Figure 34. It can be observed that the deformation degree is higher than in the experimental data. Still, it is interesting that the deformation begins to converge after the third passage. It could be so that the key difference in deformation behavior is due to a difference in initial bed compaction state compared to the experiments.

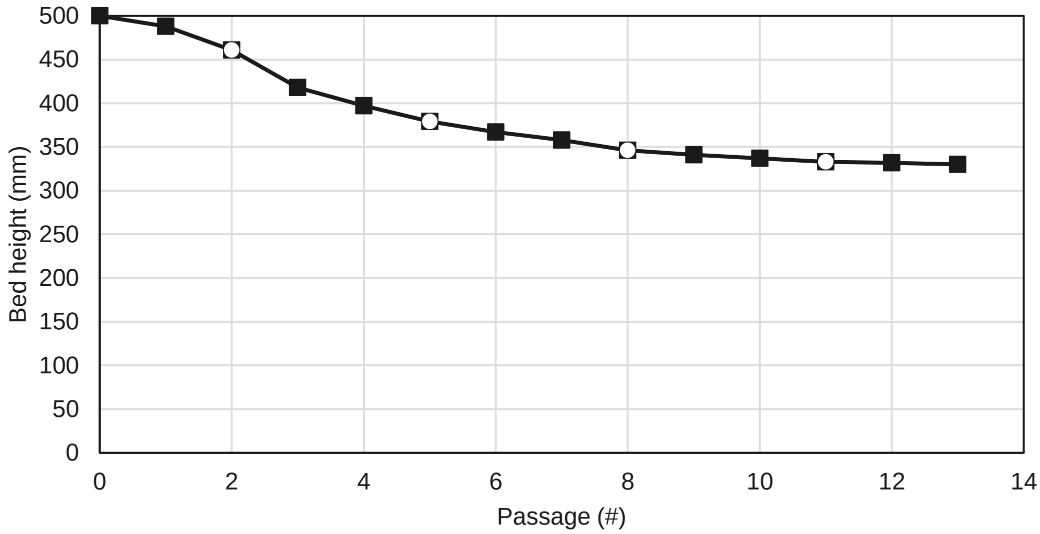

Figure 33. Bed height as function of number of passes. The white circle marker indicates a first wheel pass. The first two passes are the conditioning static roller compaction passages.

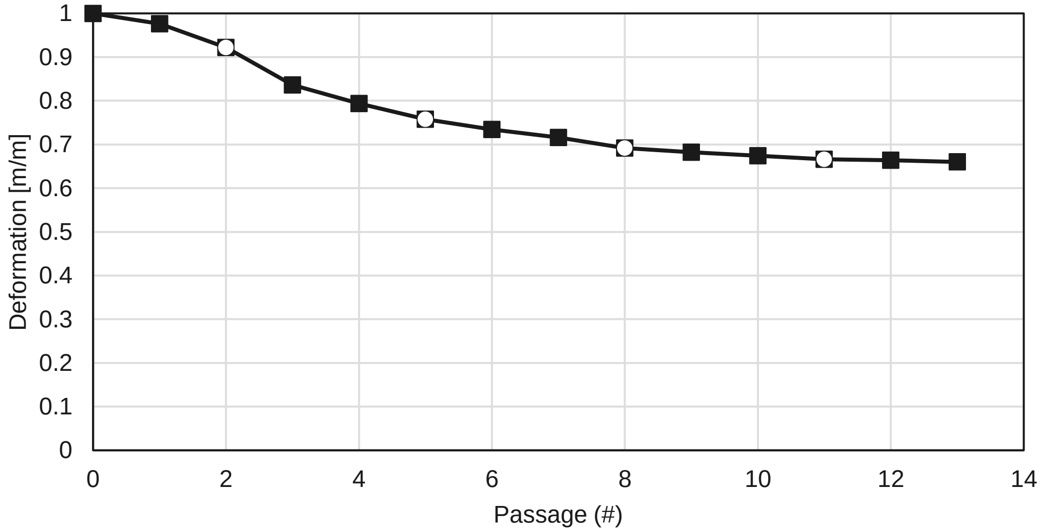

Figure 34. Compaction deformation strain subtracted from unity for each measured compaction sequence for the simulated passages.

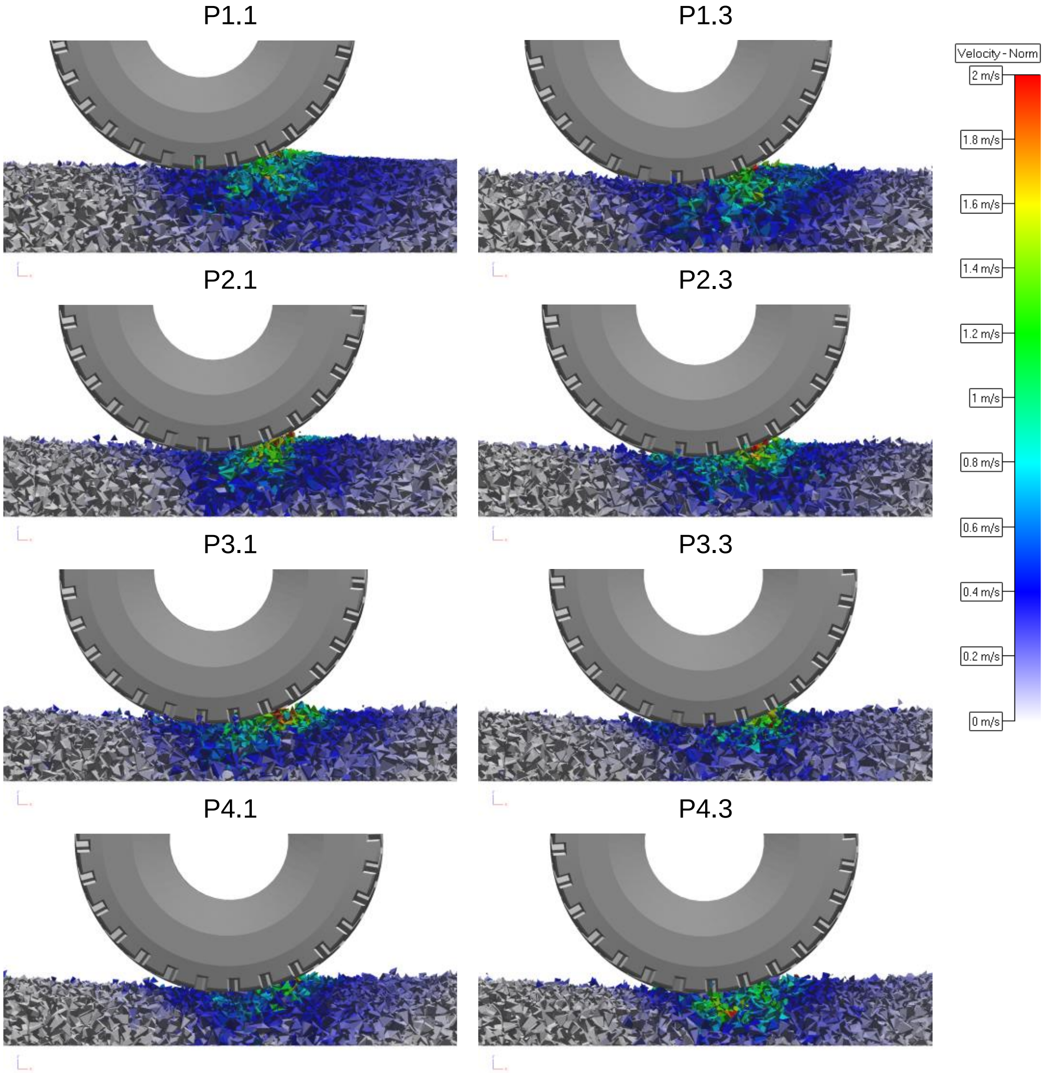

Figure 35. Visualization of the particle velocity profile in the centre cross-sectino of the tire track.

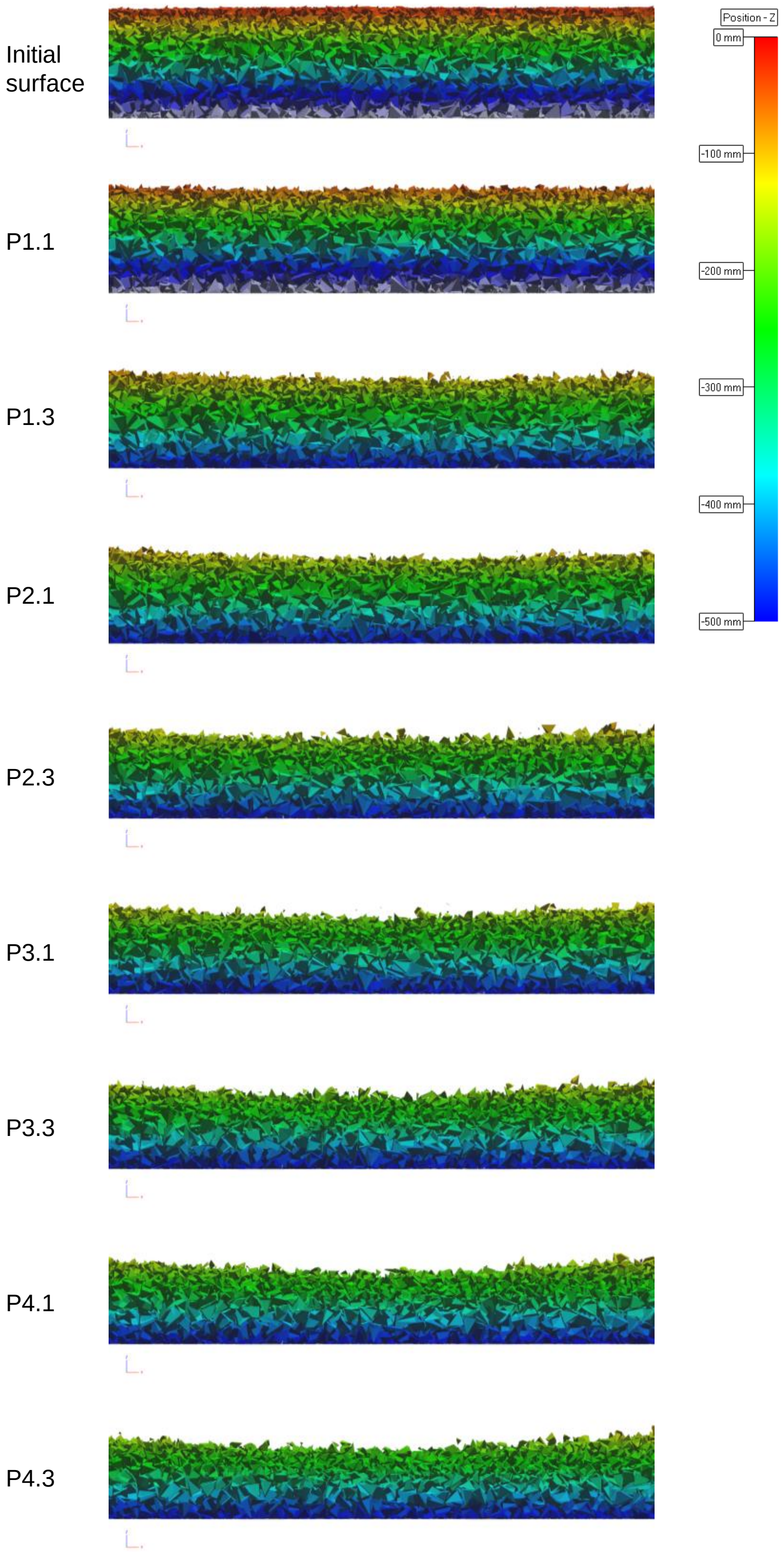

Figure 36. Cross-section of the middle part of compacted bed displayed for four vehicle passages (three wheel passes per vehicle pass)

Simulated ground pressure

The simulated force and pressure responses are plotted in Figure 38 and Figure 39. Due to the coarser size distribution the variance of the sampled force signal is higher than what would be ideal. For the first passes the pressure level is in par with the experimental results at ~0.5 MPa. The simulated bed was not modelled in such a way that the shear resistance and cohesion was high enough. Hence the particles' ability to shear and reposition is too high causing the tire to cause too deep tracks. This further on changes the distance between the tire and sensor resulting in higher pressures at the fourth pass.

Even though the simulated force and pressure signals perfectly match the recovered experimental signals, it should be noted that the force can be extracted in the horizontal direction in addition to the vertical. The real ground sensor only captures the vertical pressure/force acting on the sensor surface. The virtual sensor hence adds information regarding the shear force/stress which is difficult to measure in practice in the field.

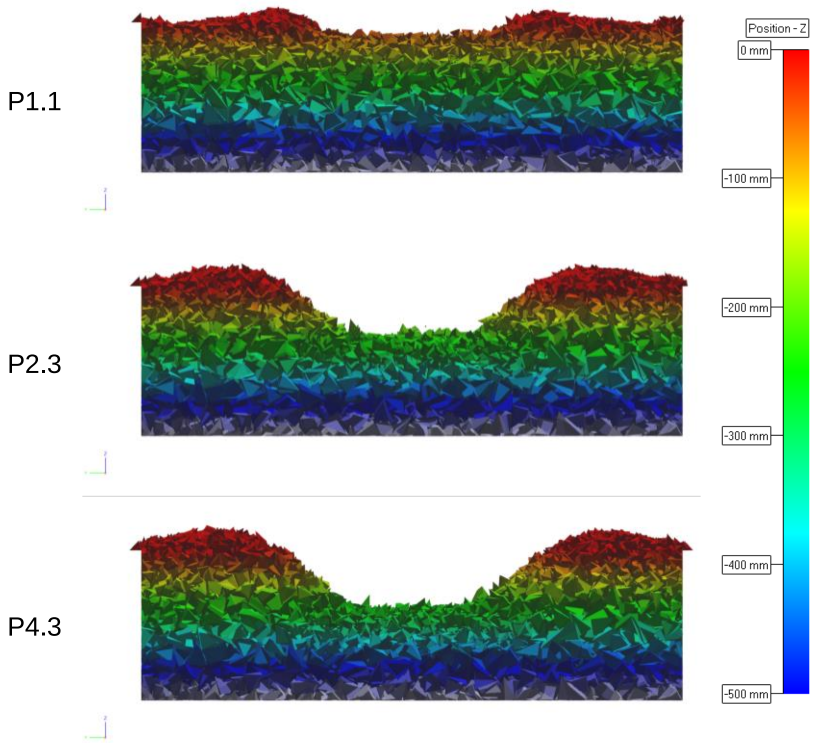

Figure 37. Cross-section of the bed for the P1.1, P2.3 and P4.3 passages displaying the progressive growth of the groove from the tire compression

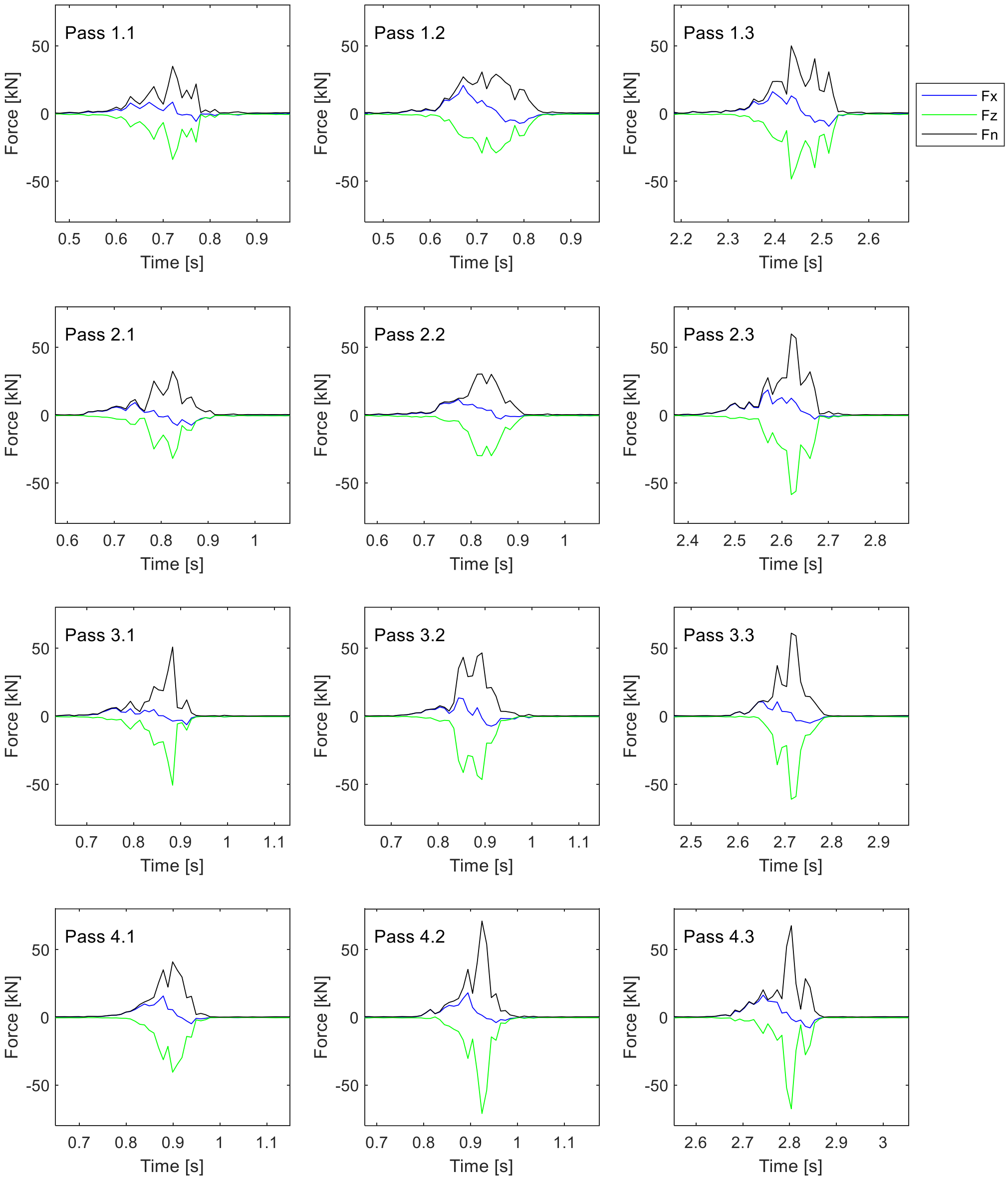

Figure 38. Simulated force response on pressure sensors.

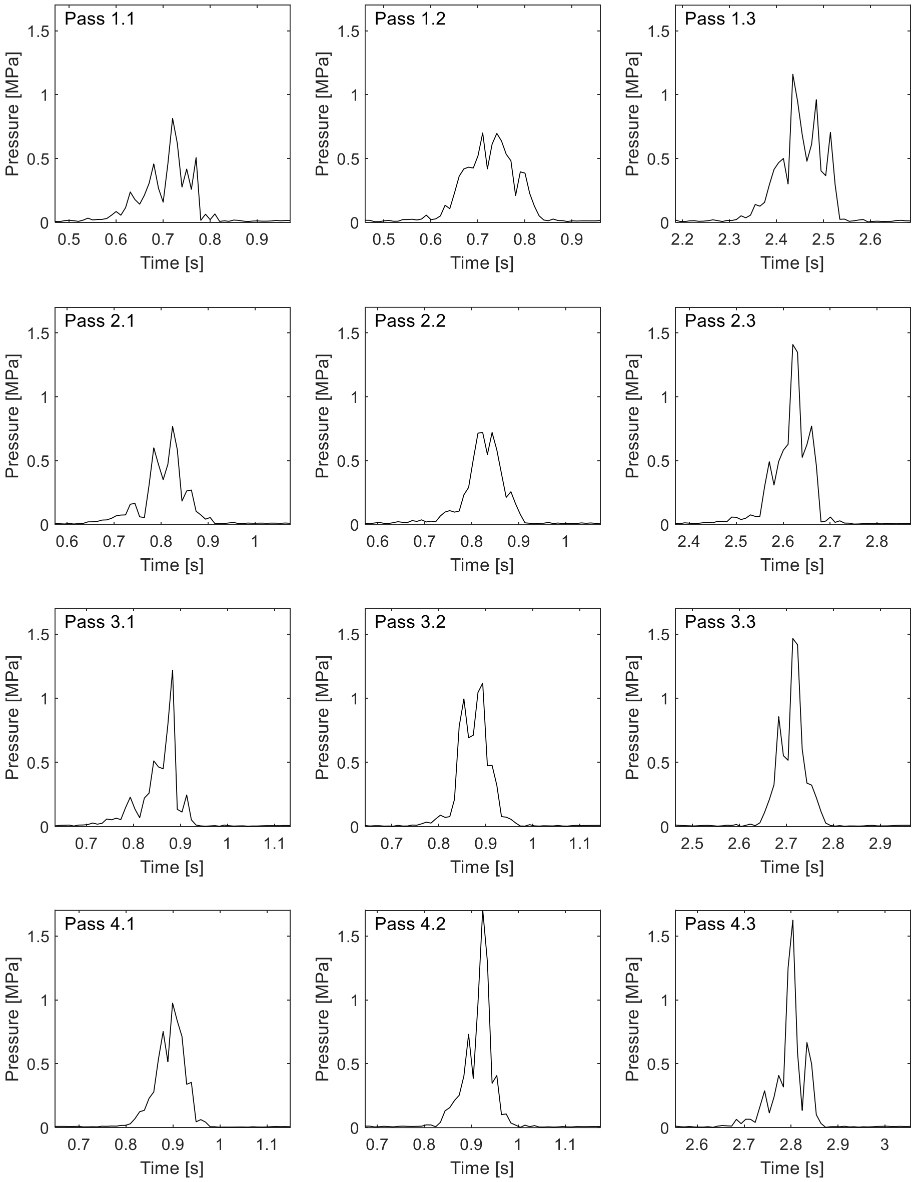

Figure 39. Simulated pressure response

Conclusions

Experiments and simulations have been conducted to evaluate differential compaction from articulated hauler traffic. While the test campaign was completed in time, several critical issues occurred during and after testing. The most crucial of these issues was the malfunction of the ground pressure sensors causing the data to be almost non-usable. With the aid of signal filtering some of the signals could be recovered however, not any of the data from the dynamic compaction. As the signal noise and filtering seemed to influence the amplitude and offset the signal it was also difficult to evaluate the progression of pressure build up over the test sequence.

While the DEM simulations are relatively advanced, at least in relation to the project budget and time available, further work is needed to reach a predictive capability that fully reflects the experimental results. One of the difficult aspects of simulating several passes is how to introduce the tire to the particle bed without causing a dynamic impact that disturbs the particle contact network. The model could be further improved by the following:

- Modelling the particles by compound dilated polyhedra with sub-particles generated from convex decomposition.
- Introducing JKR cohesion to include the cohesive effect of the moisture in the bed.
- Include more particles and a finer size distribution to increase the coordination number and interlocking.
- Model the articulated hauler as a multi-body system in e.g. Simulink and run the system in co-simulation mode with a Functional Mock-up Unit (FMU)
- Model the tire with the finite-element method in LaStfem using the Demify® DEM-FEM coupling allowing for tire deformation.

All of the improvement suggestions above are available in Demify® at this point, however unfortunately not at the time of completion of the simulation campaign. Hence the project has served a great purpose in the sense of providing insights into how additional features are necessary to model these kind of particle systems.

With these remarks made, it is still possible to draw the conservative conclusion that articulated hauler truck traffic increases bed stiffness. In this case the stiffness increased 10-15% in the tracks compared to the reference surface. This conclusion is mainly drawn from Figure 11, however also from the simple fact that permanent deformation of a granular bed will lead to an increased packing density and an increased bed stiffness. It should further on be noted that while 64 passes are a considerable number of passes to perform in a test campaign, it is very few in relation to a real construction site. Other aggregate products and soil material may also react differently with an increased or decreased sensitivity to differential compaction.

Based on these findings it is recommended that additional work is conducted to further investigate the problem and possibly also find mitigating solutions. The compaction work done by trucks and haulers could perhaps be utilized in a constructive manner by intelligently distributing the traffic.

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