Simulation of contact forces and wear in rock conveyor systems

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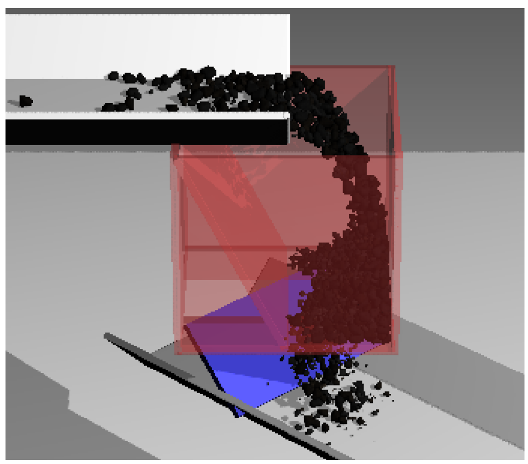


Abstract

The feasibility of using rigid multibody dynamics simulation with nonsmooth frictional contacts for analysis of contact forces and wear in conveyor systems is demonstrated. An example application with a transition between two conveyor belts of different height and angle are considered based on a real system at Boliden in Aitik. Statistics of contact forces for a flow of 2500 rocks is computed and a simple model for calculating the mechanical wear on the surfaces is applied. 1 second of simulation takes roughly 60 seconds of computational time - involving 25.000 contacts - with the current version of AgX Multiphysics Toolkit and parameter and solver settings.

1 Background

1.1 Purpose

Demonstrate the feasibility of using rigid multobody dynamics simulation with nonsmooth frictional contacts for analysis of contact forces and wear in conveyor systems. With efficient and validated simulation it is possible to design conveying systems with more optimal throughflow and less wear. The study includes creating a simple 3D model of a conveyor system used in Aitik (Boliden) for transporting rocks from one conveyor belt to another.

1.2 Problem

The system consists of many discrete parts which interact through contacts that vary dynamically. Large scale experiments of this conveyor system is impractical, difficult and expensive compared to a simulation.

1.3 System

The conveyor transition makes out a small part in a larger process from ore to processed product. In the illustration in Fig. 1 it is located between the ore storage and the primary grinding highlighted with a circle.

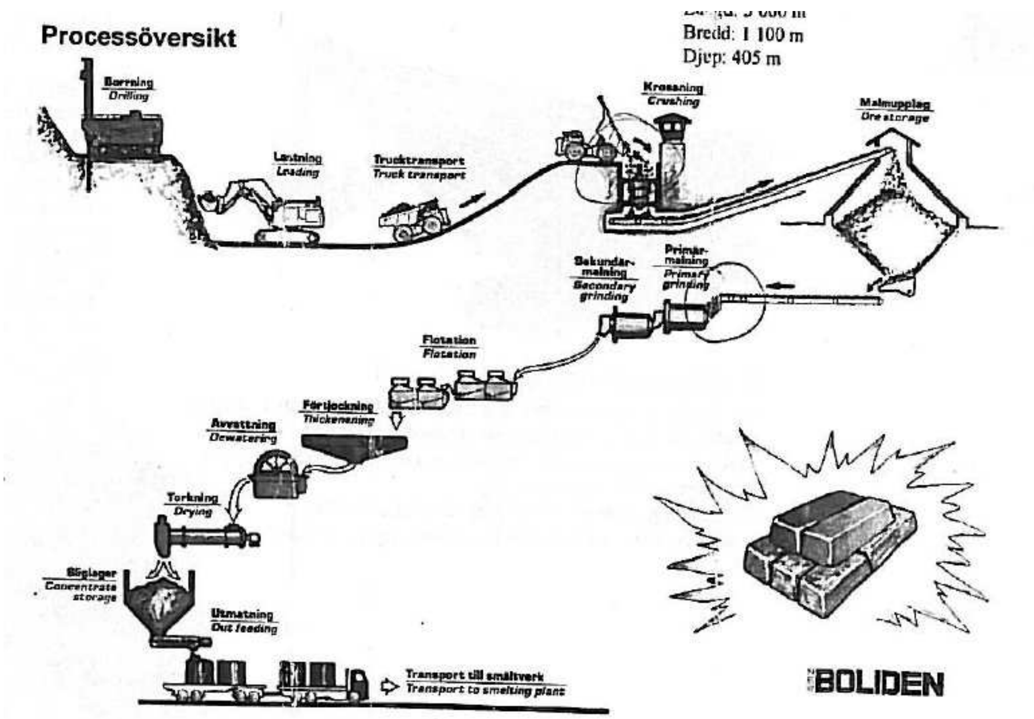


Figure 1: An overview of the mining process.

2 Setup

The system consists of two conveyor belts leading to and from the *mullhylla* and *akselerator*. Simple geometries are used to create the system described in figure 2 below

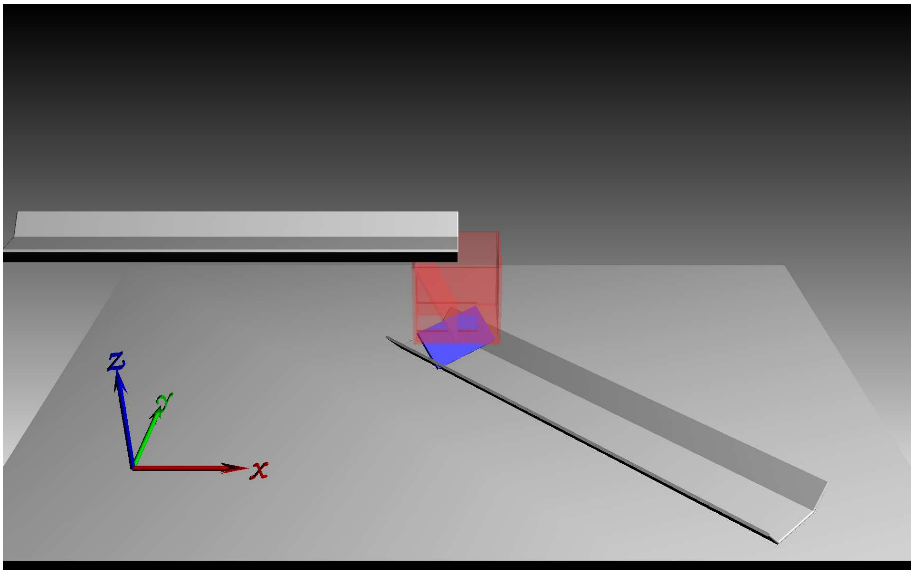


Figure 2: Fixed system with the mulhylla in red and akselerator in blue.

Rocks are created from composite spheres, i.e., groups of 1-3 rigid spheres create one rigid rock. The points of interest in the analysis is the wall and floor of the *mullhylla*, the *akselerator* and the lower conveyor belt. When examining the *mullhylla* floor only the rectangular part to the right of the hole is considered.

3 Simulation tools

The simulation is based on the AgX Multiphysics Toolkit version 1.10.X and is run with the specified setup and models using the Lua interface. Puerly iterative Gauss-Seidel solver is used. Contact data is exported in ascii format and then post-processed and visualized using Octave.

AgX Multiphysics Toolkit handles rigid multibody and particle systems with nonsmooth frictional contacts and an extensive constraint library for modeling complex mechanical systems, e.g., vehicles, robots, cranes, ships, transporter systems and complex materials such as rocks, gravel, pellets, fluids, trees and branches, terrains. The software is used in realtime physics based simulators for operator training, research and marketing and for off-line simulations for engineering and rendered special effects. AgX is developed and maintained by Algoryx Simulation (`http://www.algoryx.se`) and is an off-spring from Umeå University.

The different approaches to simulating rock are finite element methods (FEM), smooth discrete element method (smooth DEM, e.g., [1]) or nonsmooth discrete element method (nonsmooth DEM, e.g., [?], [?], [?]) - the latter also known as nonsmooth contact mechanics. FEM is suitable for resolving the stress and strain inside the material (individual rocks or large bulks). The computational cost prevents time-efficient simulation of large system of contacting bodies. For simulations of large-scale contacting systems smooth or nonsmooth DEM are used. Smooth DEM is most suitable for large-scale simulations of fine-grained material. Nonsmooth DEM is most suitable for coarse-grained materials.

3.1 Material hardness & wear

In the material provided to us from Boliden it is stated that the *mullhylla* is made out of *Hardox 500* and the *akselerator* from *Dolomite*, which is 6-8 times more durable than *Hardox 500*. The hardness of *Hardox 500* used for any calculated data is 500 Brinell[1]. Translating from Brinell to Vickers which is the usual unit to measure wear from impact is done from a conversion table[2] leading to the material properties

FiXme Warning: *Vickers standard? Translation?*

Material	Vickers HV
Hardox 500	565
Dolomite	3390

Table 1: Material hardness

where the *Dolomite* is assumed to be 6 times more durable than *Hardox 500*.

The wear of the two surfaces due to material impacts can be cal-

[1] http://www.ssab.com/Products-and-solutions/Hardox/
[2] http://en.wikipedia.org/wiki/Hardness_comparison

culated from the Archard equation[3]

$$\dot{Q}_i = \frac{KW_iV_i}{H} \tag{1}$$

where $\dot{Q}_i$ is the volume of the wear debris produced per unit time by the contact i, K is a dimensionless constant, W the total normal load, V the sliding velocity and H the material hardness. We use $K = 10^{-6}$ and W and V are calculated in the simulation. We compute the total wear by integrating over time for all contacts

$$Q_{tot} = \sum_i \int_{t_1}^{t_2} \frac{KW_iV_i}{H} dt \tag{2}$$

between any two given timesteps, t_1 and t_2

In *DEM modelling of linear evolution and its influence on grinding rate in ball mills*[4] this equation is extended to account for the wear track width d $Q = \frac{KdWL}{H}$.
In this report, the original Archard equation (1) together with the material parameters above is used in the simulation to calculate wear. In the simulations the rock composites are made out of 1-3 spheres as mentioned earlier, these spheres have a diameter in the interval 0.01-0.1 meters. The mean weight of the rocks is approximately 4kg and the max weight 26kg.

The rocks are probably much smaller and lighter than what is typical in this process. Other than that there are uncertainties in the parametrisation of the Archard equation, K for instance, but the purpose of the simulation is to illustrate the many possibilities for data extraction and analysis. Input from someone that is well-read on the process would be interesting to get parameters and results that can be compared to the real world.

[3]This assumes that the surface is softer than the impacting material but we use it anyway.

[4]http://www.sciencedirect.com/science/article/pii/S0892687510003535

4 Results

The duration of the simulation is 16 seconds with the timestep 0.01. The runtime of 1600 timesteps with 2500 rocks made out of 1-3 rigid spheres is approximately 40 minutes. During these 40 minutes 3.8 GB of data is written to a file in hdf5 format. If the data writing is turned off it results in a run time closer to 20 minutes. That means a ratio of 1:60 seconds, i.e., 1 simulated second takes 60 seconds, for the system with roughly 25000 contacts at any given time.

The magnitude of the normal forces at each time step is illustrated in figure 3 The data displayed above can be better understood from

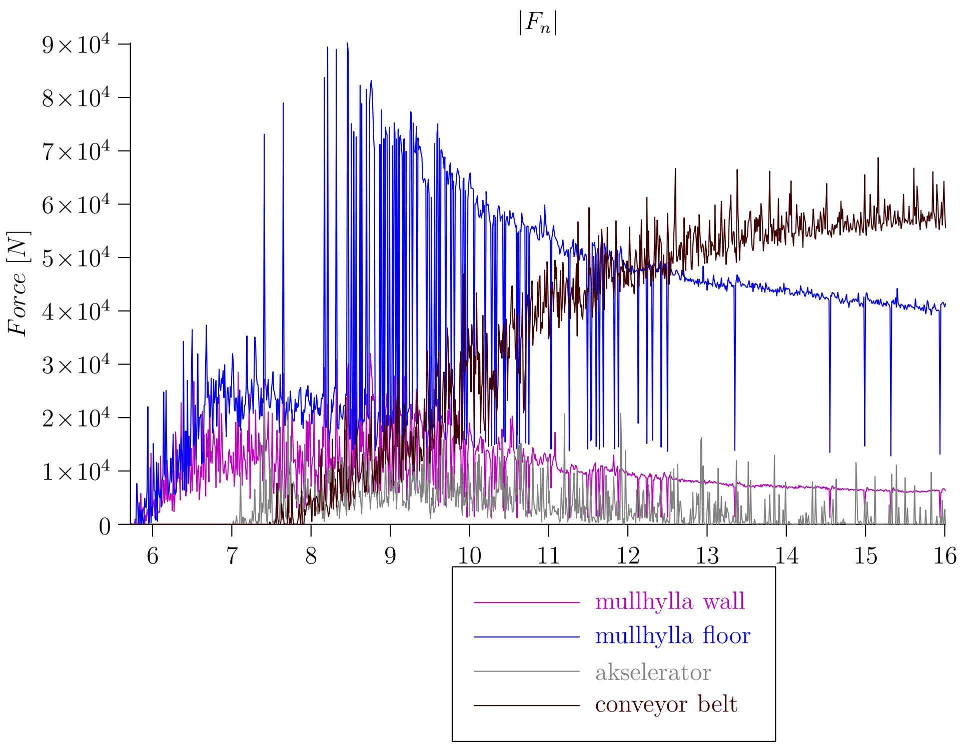


Figure 3: Magnitude of normal forces over time.

figure 5. The first 5 seconds of the simulation are cut off since there is no interaction with the *mullhylla* until 6 seconds in.

The magnitude of the normal forces on the *mullhylla* floor increases as rocks pile up. The effect on the wall is similar but the magnitude is significantly smaller which can be expected since it does not bear the full weight of the rock pile.

The *akselerator* will not have a pile of rocks at rest on it since they will either slide or bounce of it. This makes the magnitude of the normal forces smaller than for the *mullhylla*.

The force on the lower conveyor belt increases steadily as long as the flow of rocks is continous, the decaying increase at the end can be understood from the last frame in figure 5 where there is almost no flow of rocks through *mullhylla*.

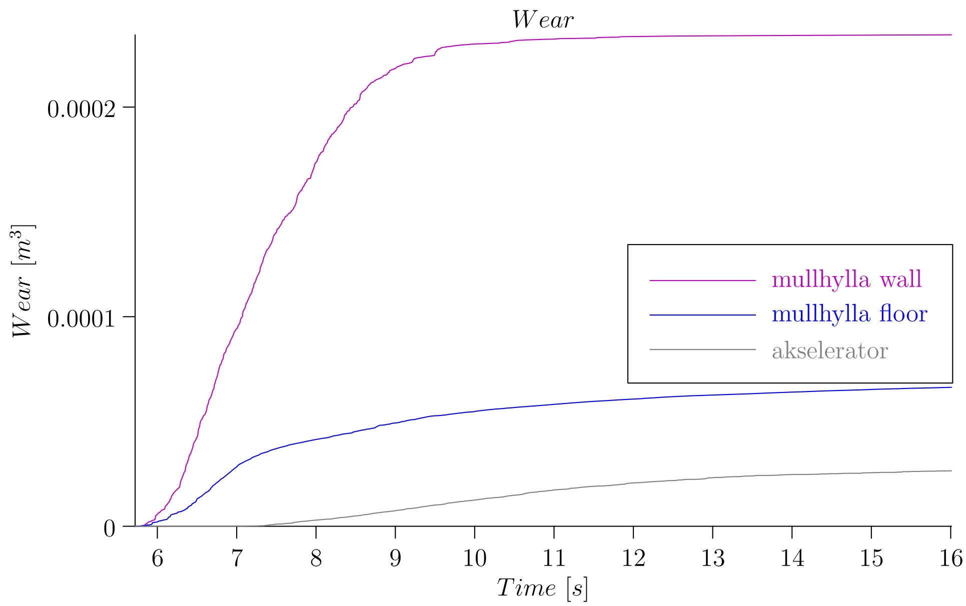
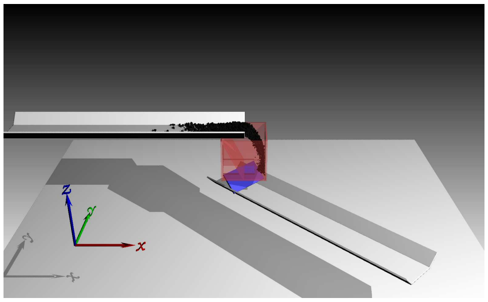
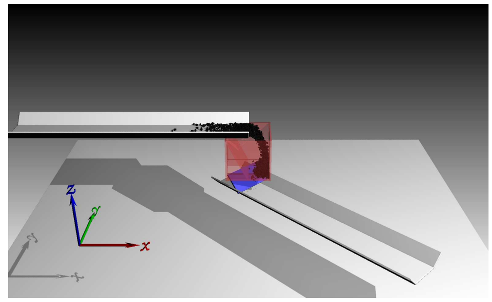


Figure 4: Wear over time.

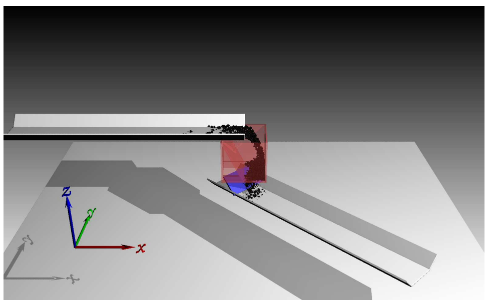
Figure 4 shows that the wear is largest at the *mullhylla* wall. This could be expected from equation (1) since the variable L depends on the tangential velocities relative to the surface normal and the timestep. With the current setup described in figure 2 the first group of rocks in contact with the *mullhylla* wall are in free fall from the upper conveyor belt. Almost all of the velocity at the impact is tangential in this case. For the other surfaces, the rocks have notably lower tangential speed at the contact, leading to lower calculated wear values.



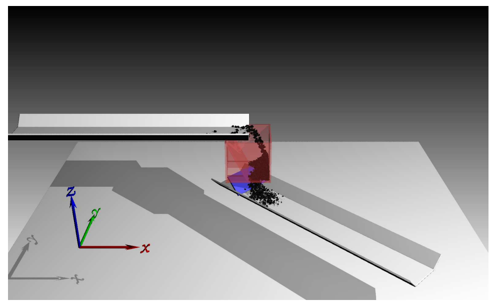
(a) 6 seconds



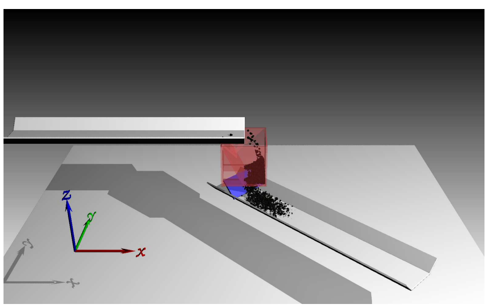
(b) 7 seconds



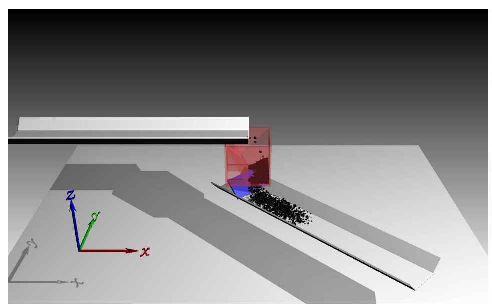
(c) 8 seconds



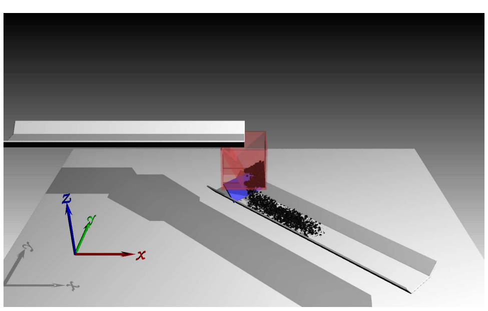
(d) 9 seconds



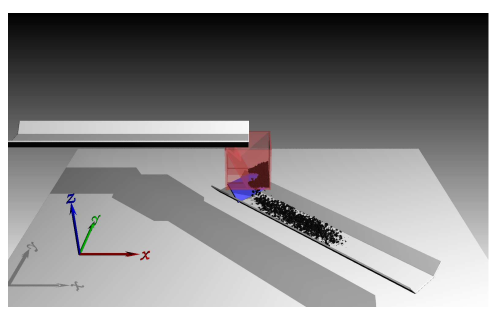
(e) 10 seconds



(f) 11 seconds



(g) 12 seconds



(h) 13 seconds

Figure 5: Simulation displayed in 1 second intervals beginning at 6 seconds.

The *mullhylla* wall and floor, the *akselerator* and the lower conveyor belt is examined closer and the following data is extracted and calculated from the simulation.

1. Normal force histogram.
2. Surface plot of normal force distribution.
3. Wear rate histogram.
4. Surface plot of wear distribution.
5. Small duplicate of surface plots for force and wear side by side.

The wear data is not calculated for the conveyor belt. Each item mentioned above is presented in one page displaying the data after 1, 5 and approximately 10 seconds after the first impact of a rock with the surface. Approximately 10 seconds corresponds to the full length of the simulation since the first impact occurs close to 6 seconds and the total simulation time is 16 seconds.

The histograms show the frequency of the normal force per time step, i.e., the wear rate, and the total wear on the different sections are displayed in figure 4. When the word rate is used in the figures below it indicates the force or wear per time step during the simulation.

In the surface plots, the surfaces are aligned in the direction of the flow, the width of the surface is roughly perpendicular to the flow direction and the height is in the direction of the flow.[5] The surface plots illustrates the intensity and concentration of force and wear on a given surface.

The purpose of the duplicates in item 5 is to provide a visual comparison of the high intensity areas of the force and wear in one page.

[5]Except for the *mullhylla* wall where the height is along the z-axis.

4.1 Mullhylla wall

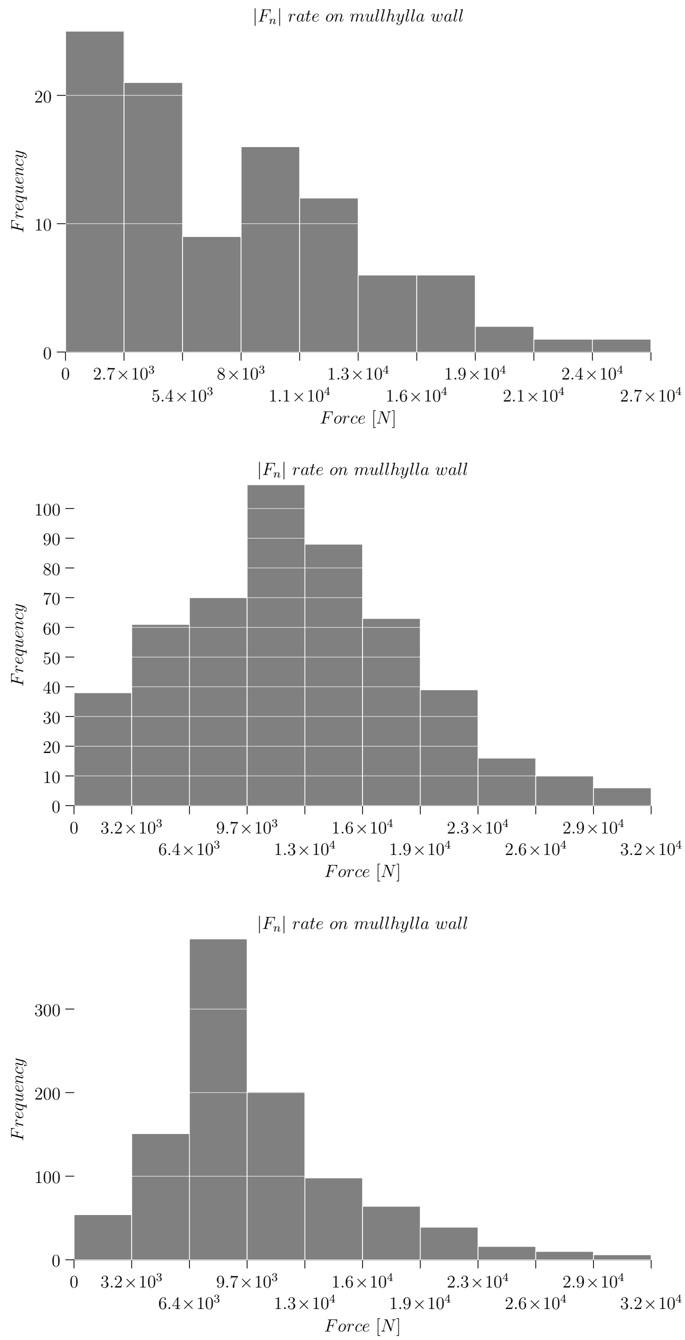


Figure 6: Mullhylla wall normal forces at 1, 5 and 10 seconds.

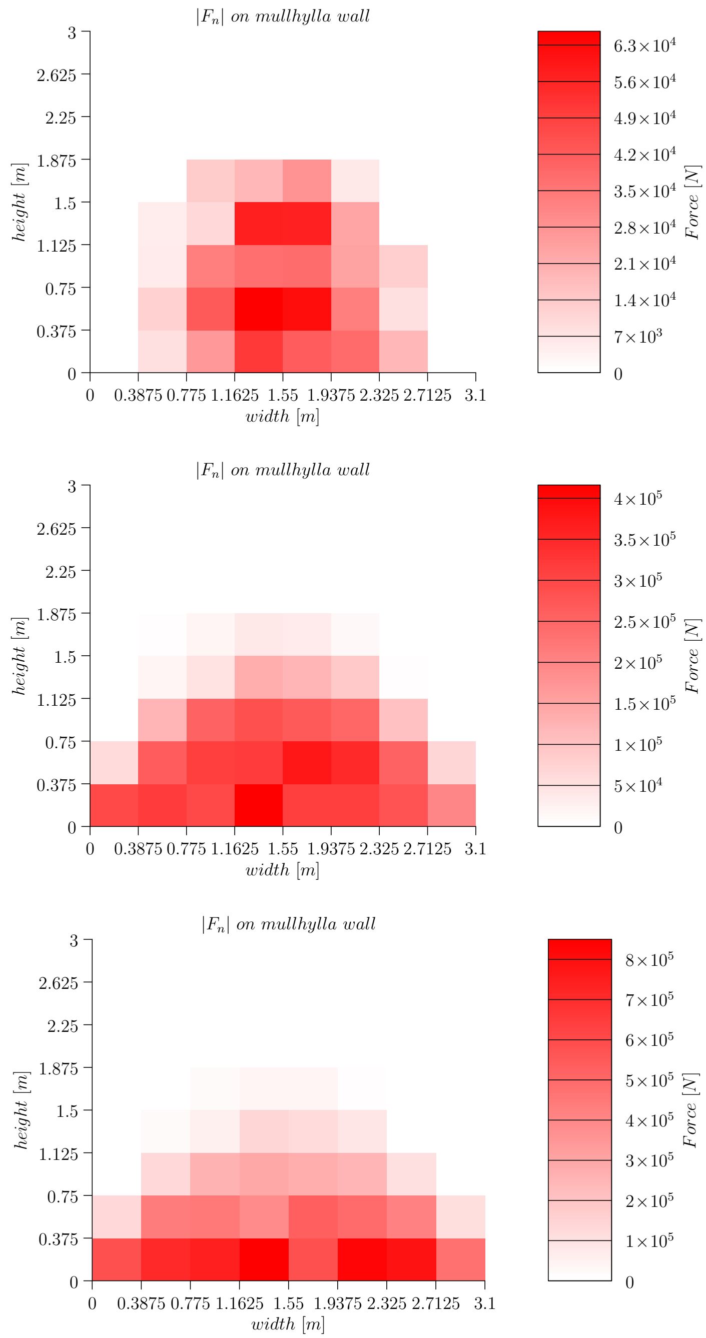


Figure 7: Mullhylla wall normal force distribution at 1, 5 and 10 seconds.

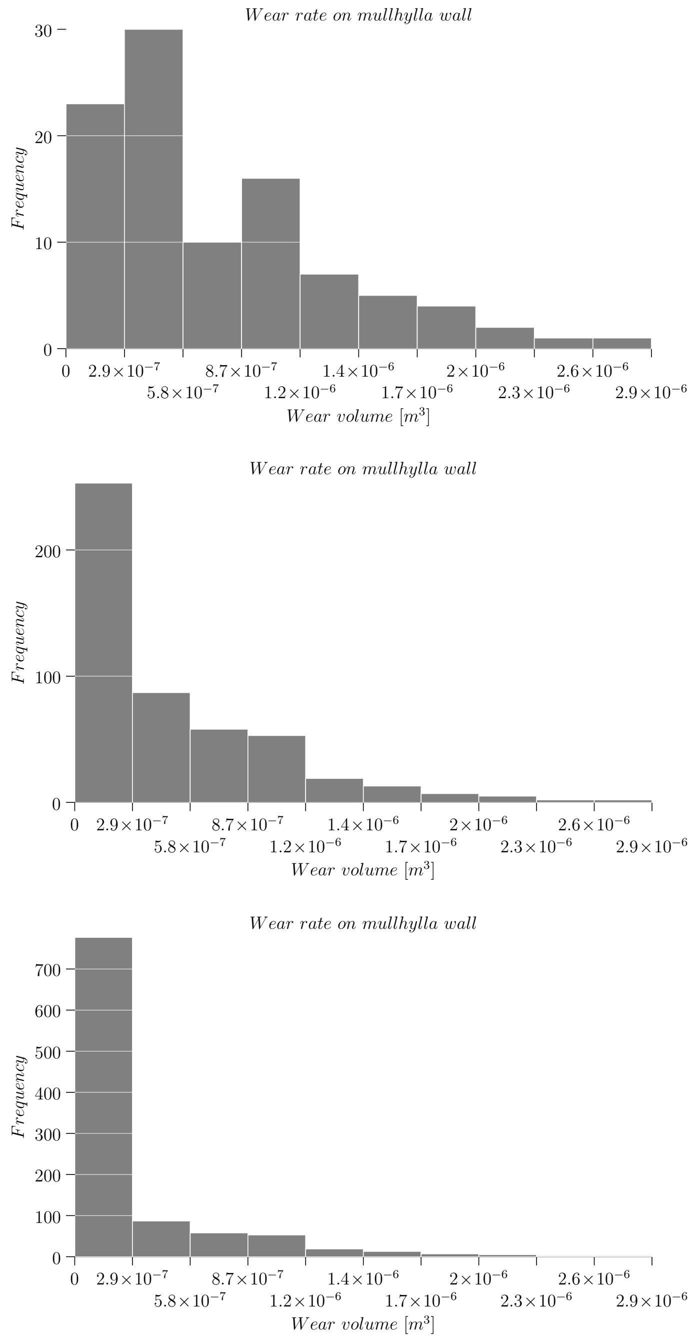


Figure 8: Mullhylla wall wear rate at 1, 5 and 10 seconds.

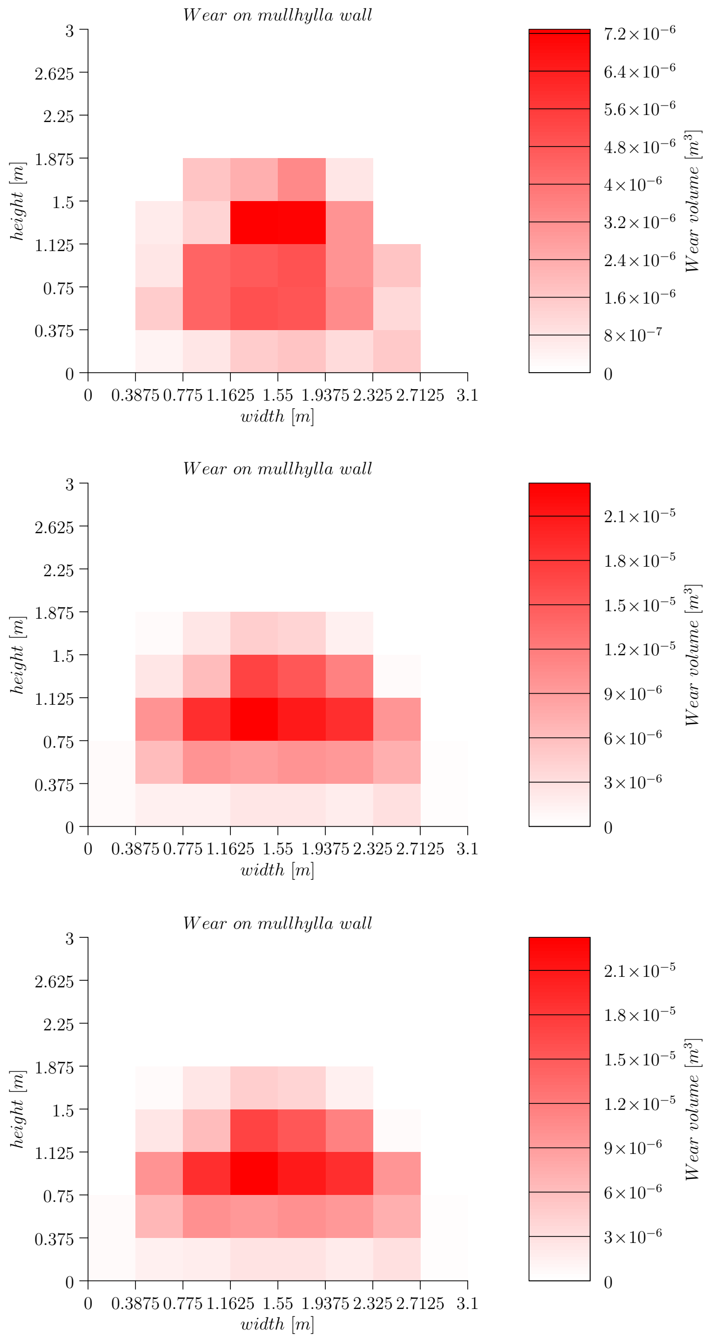


Figure 9: Mullhylla wall accumulated wear distribution after 1, 5 and 10 seconds.

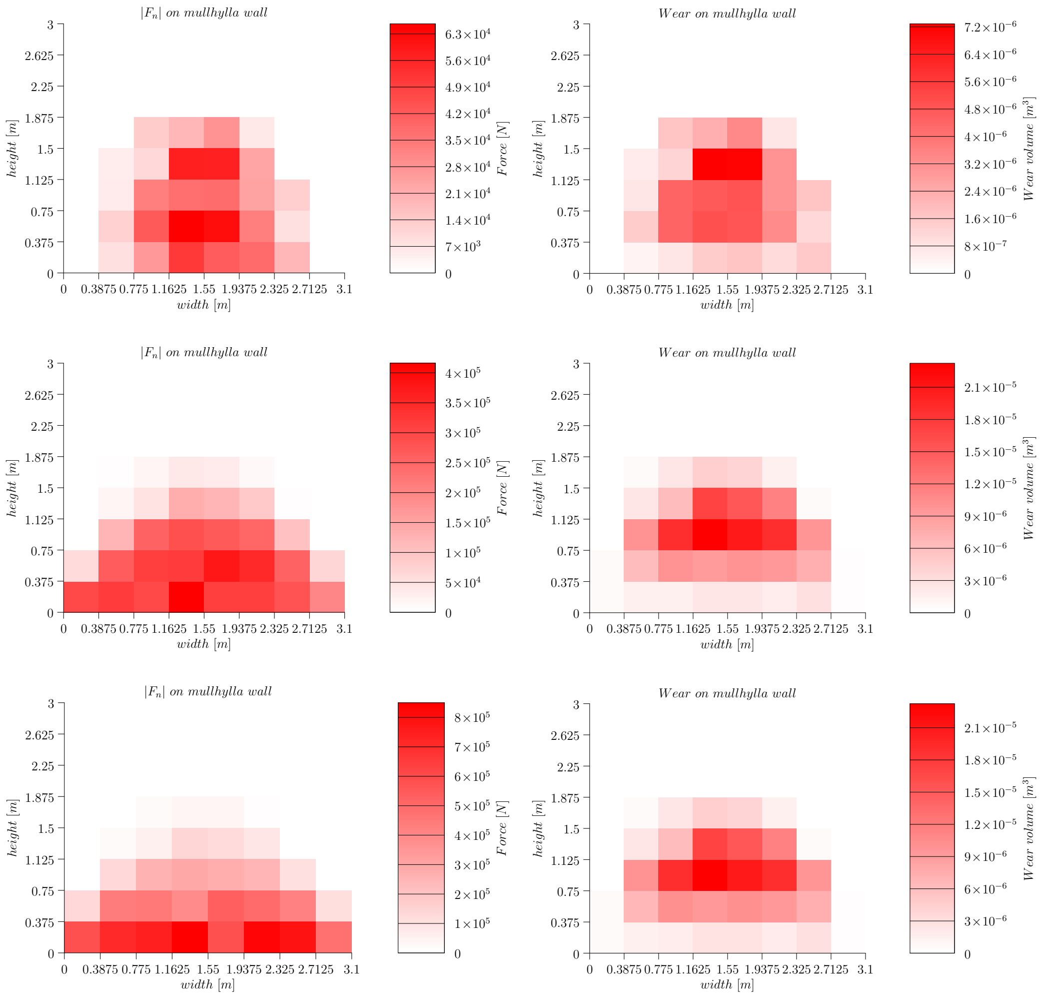


Figure 10: Mullhylla wall surface plot comparison of force and wear rate at 1, 5 and 10 seconds.

4.2 Mullhylla floor

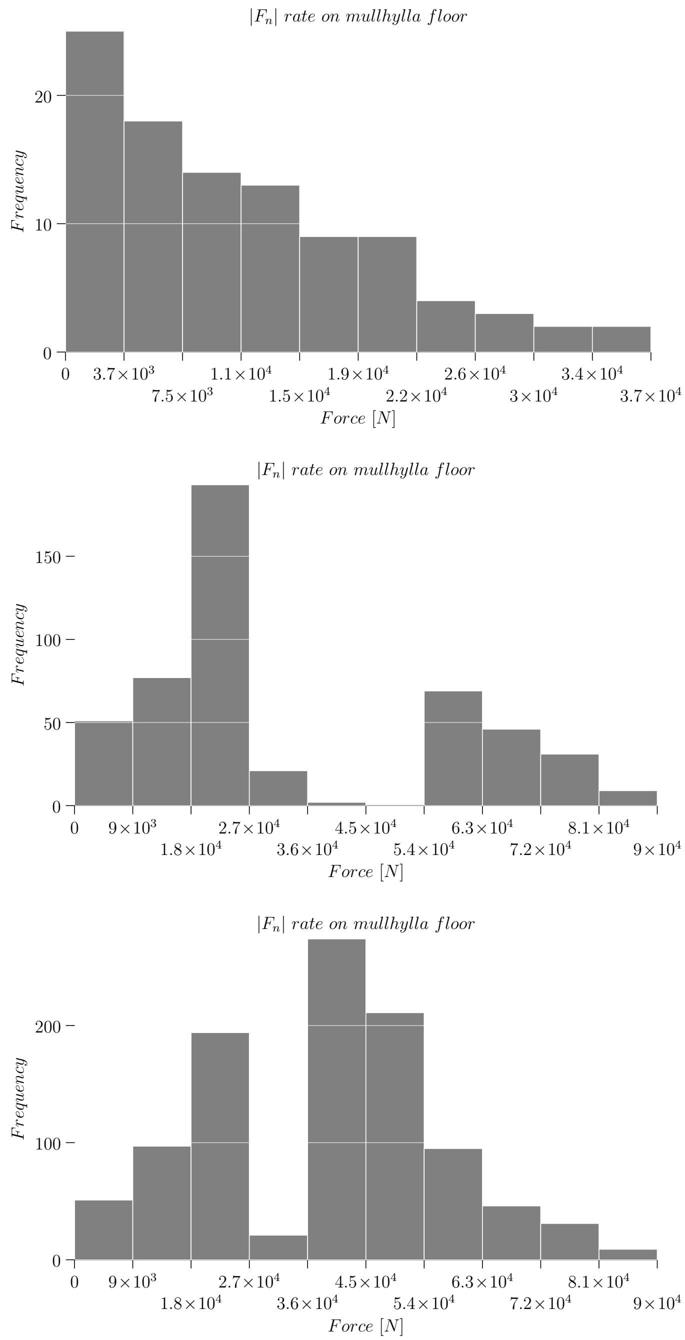


Figure 11: Mullhylla floor normal forces at 1, 5 and 10 seconds.

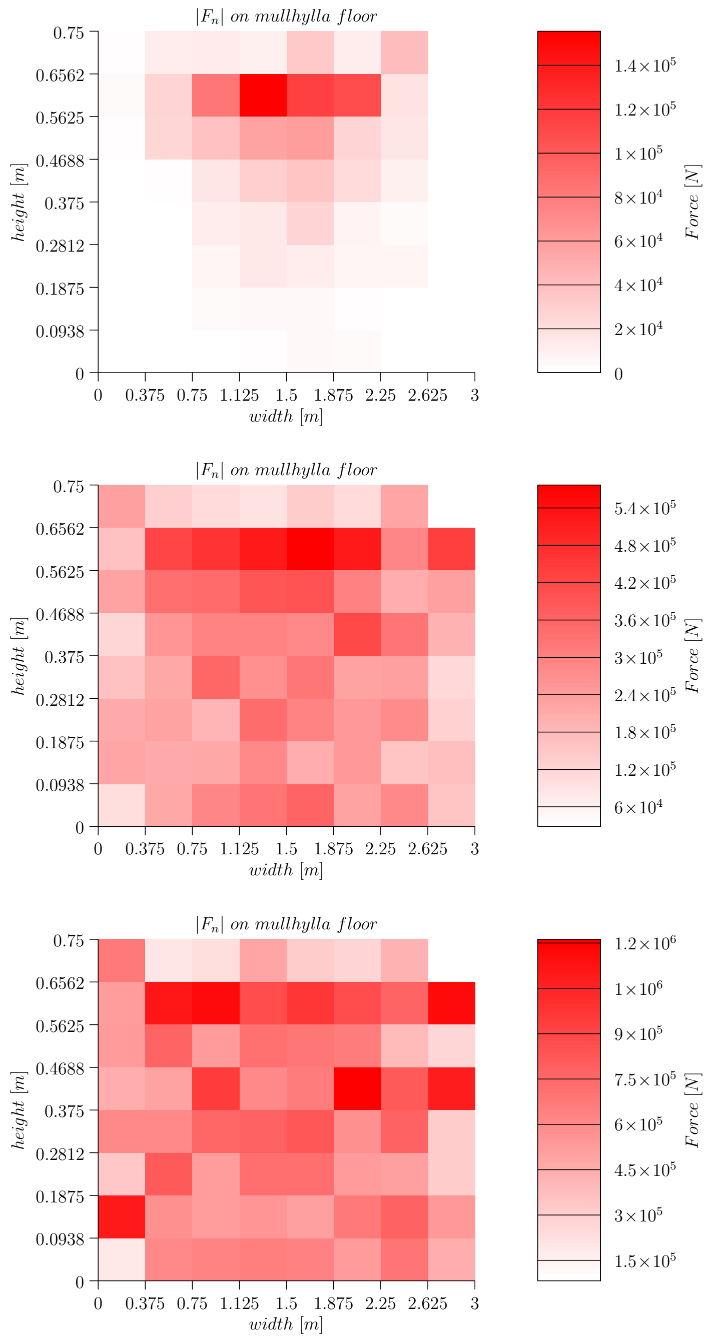


Figure 12: Mullhylla floor normal force distribution at 1, 5 and 10 seconds.

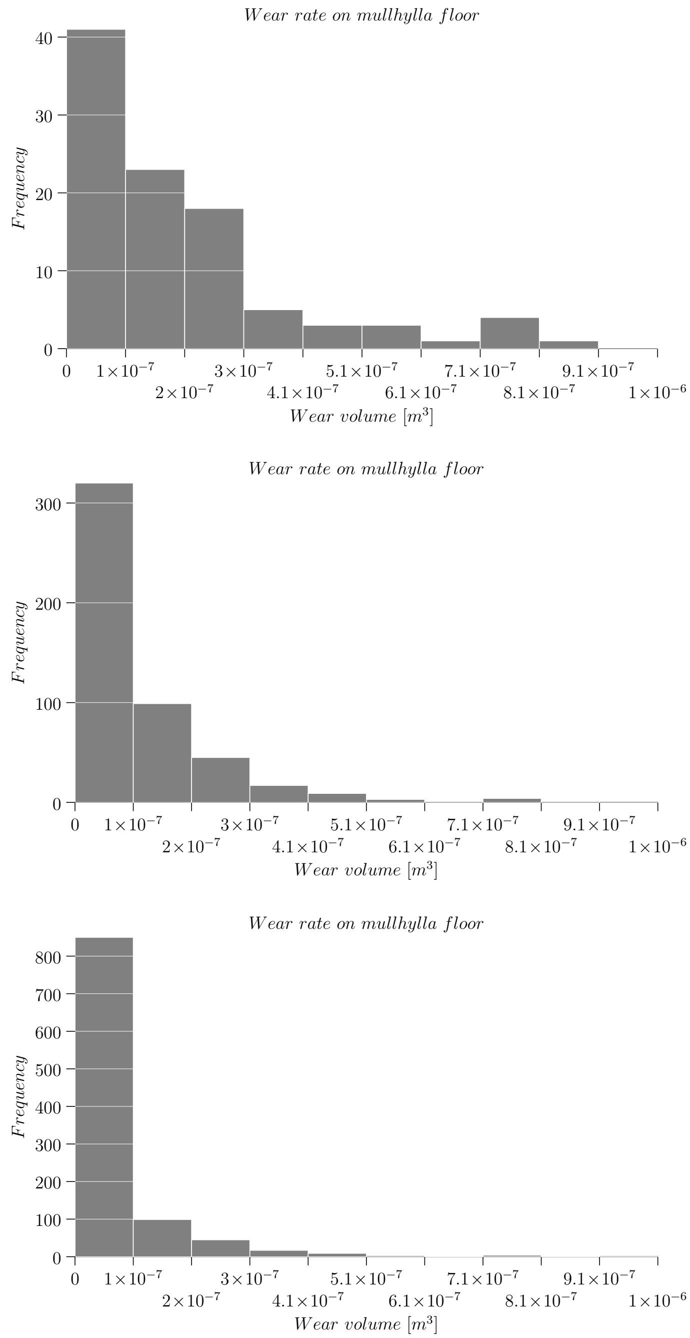


Figure 13: Mullhylla floor wear rate at 1, 5 and 10 seconds.

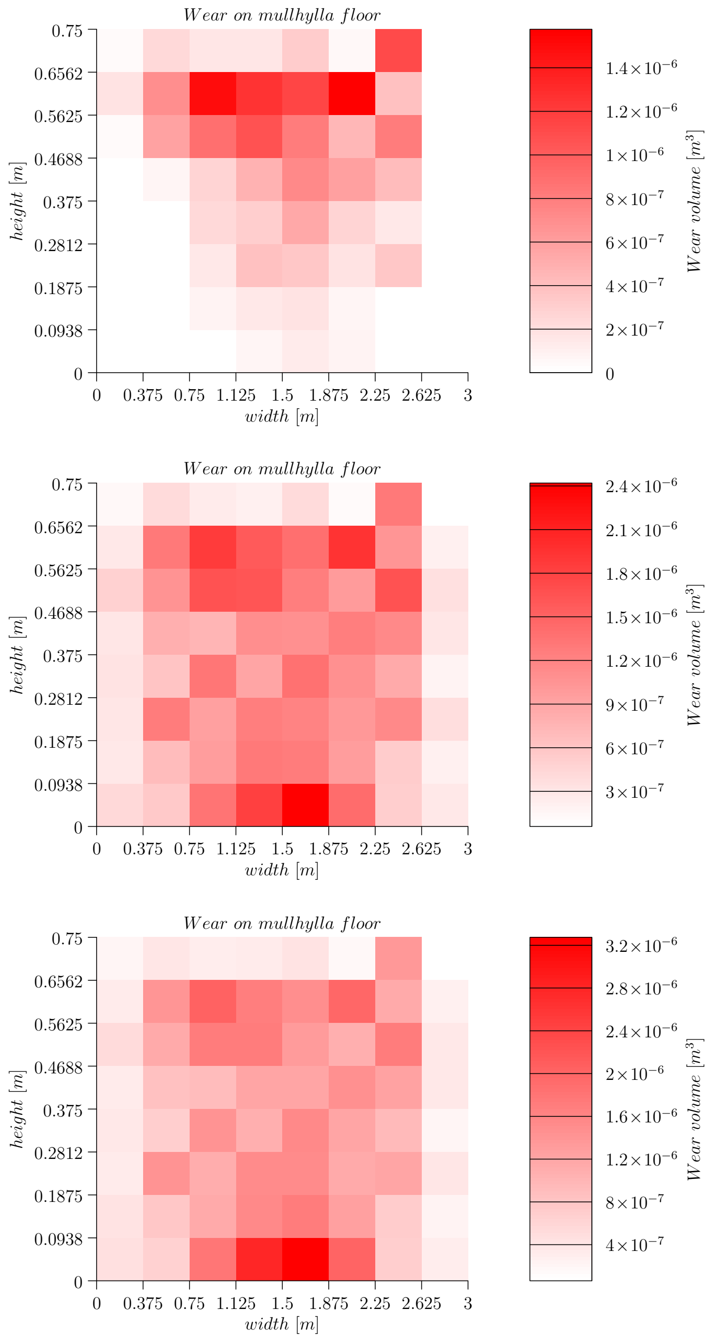


Figure 14: Mullhylla floor accumulated wear distribution at 1, 5 and 10 seconds.

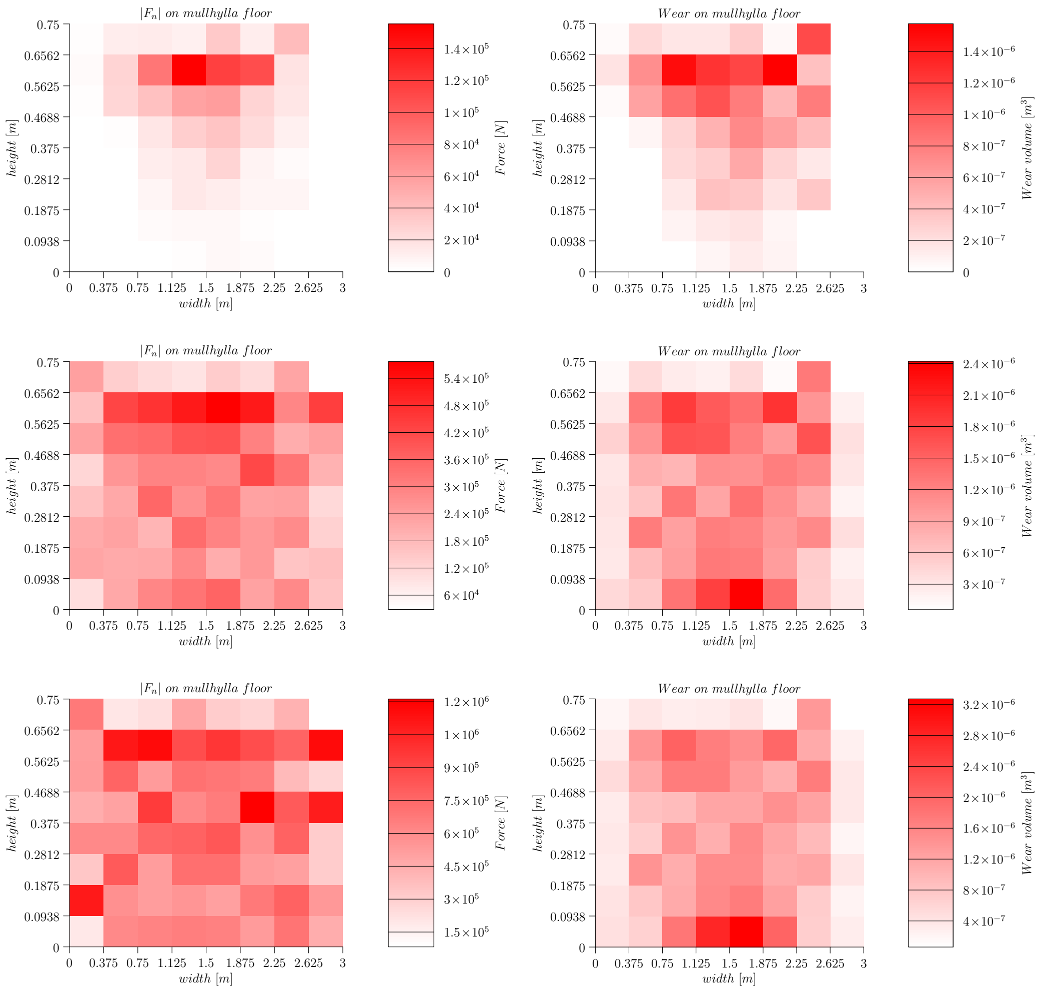


Figure 15: Mullhylla floor surface plot comparison of force and wear rate at 1, 5 and 10 seconds.

4.3 Akselerator

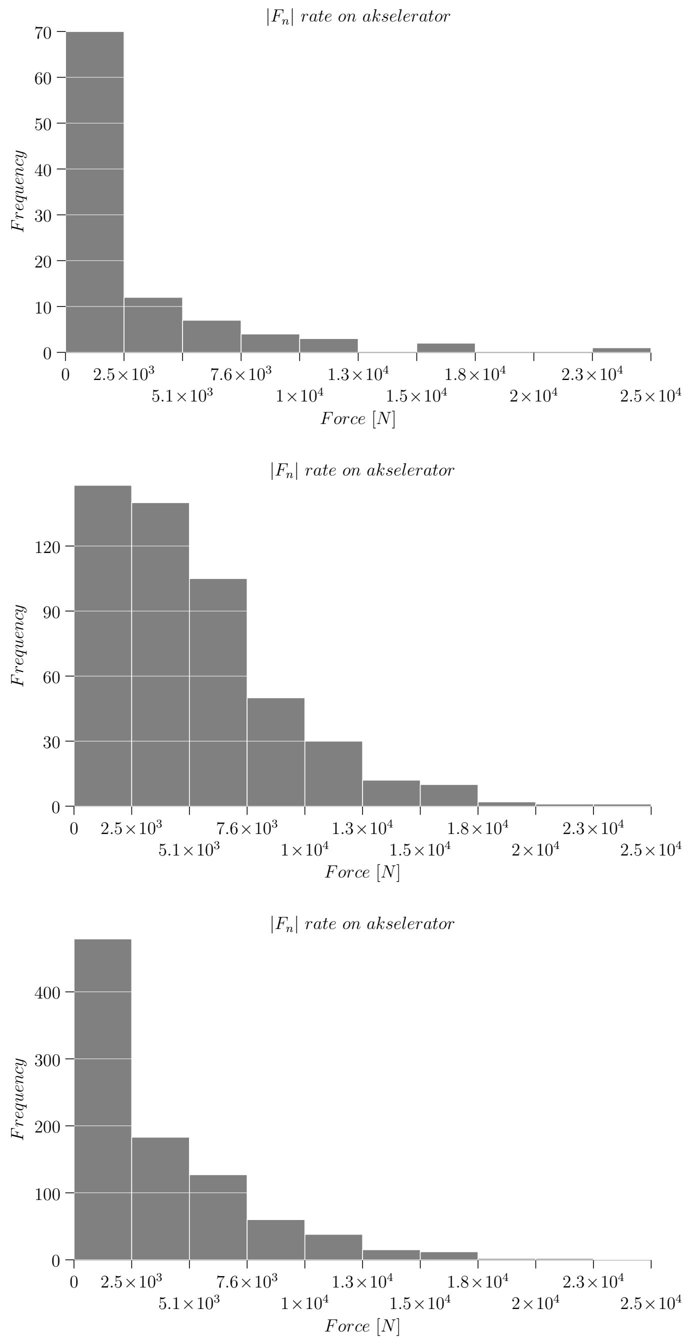


Figure 16: Akselerator normal forces at 1, 5 and 10 seconds.

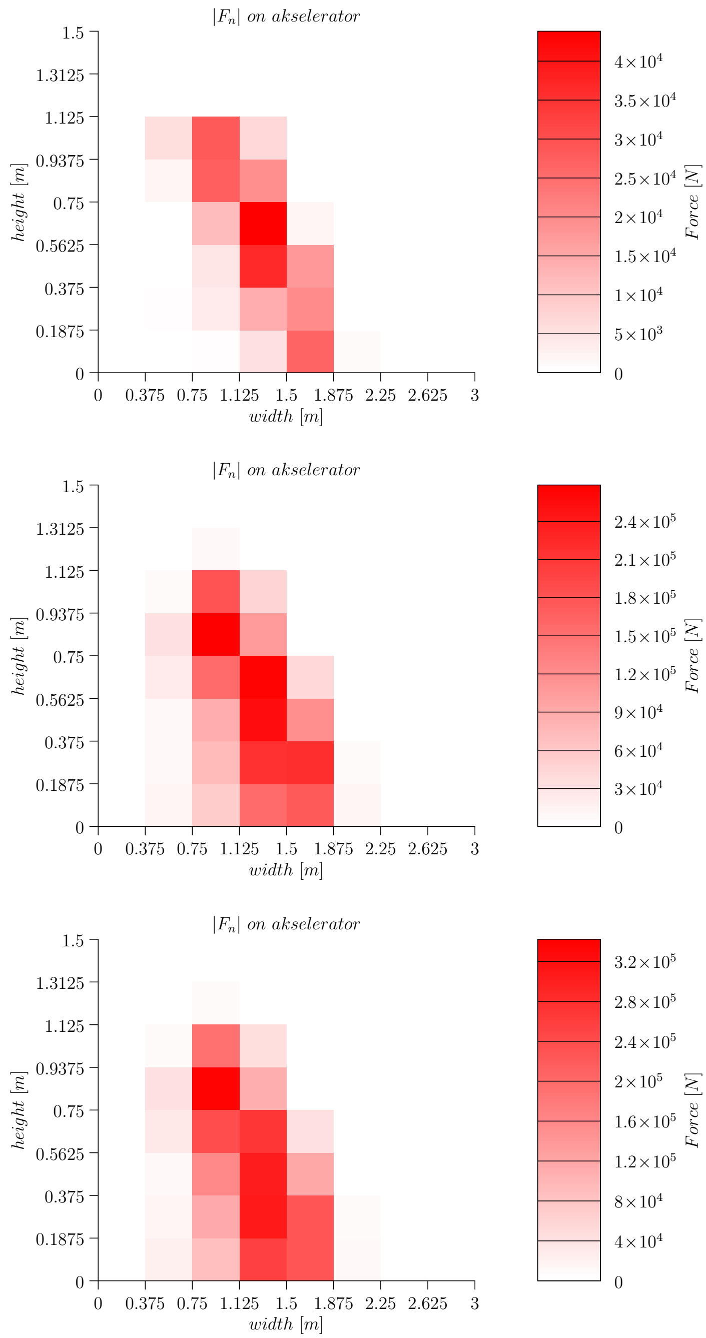


Figure 17: Akselerator normal force distribution at 1, 5 and 10 seconds.

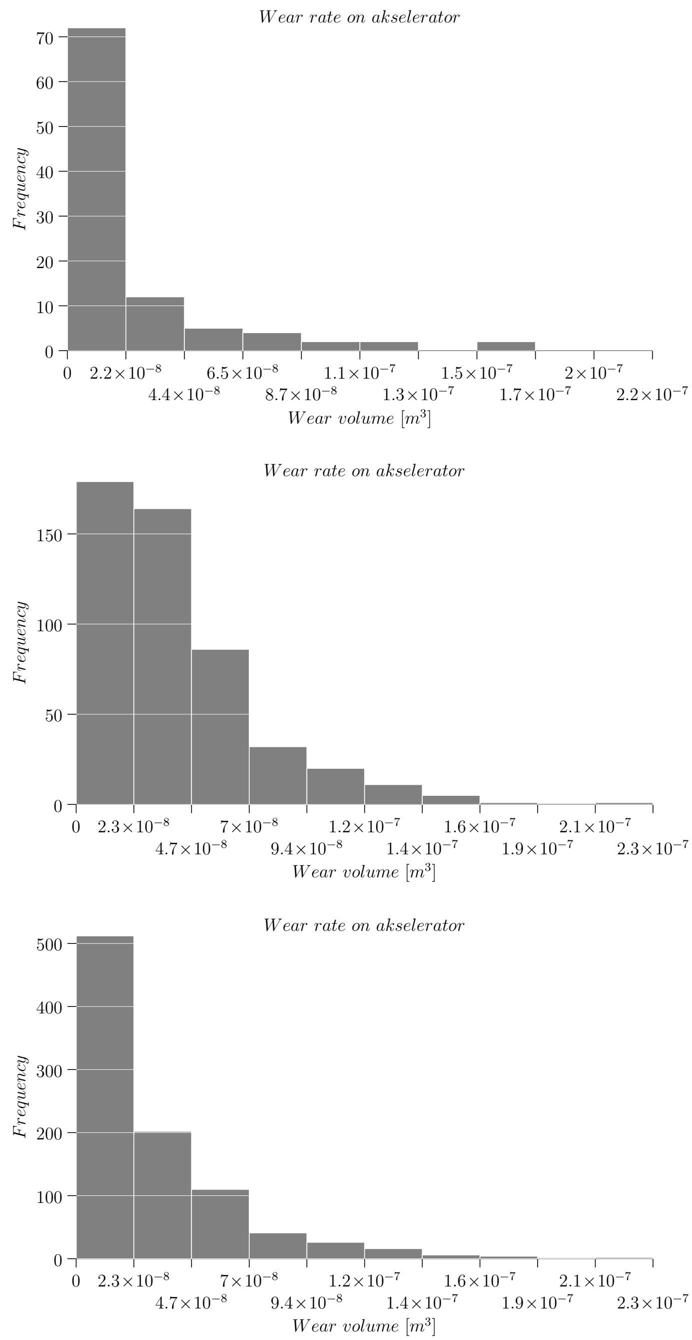


Figure 18: Akselerator wear rate after 1, 5 and 10 seconds.

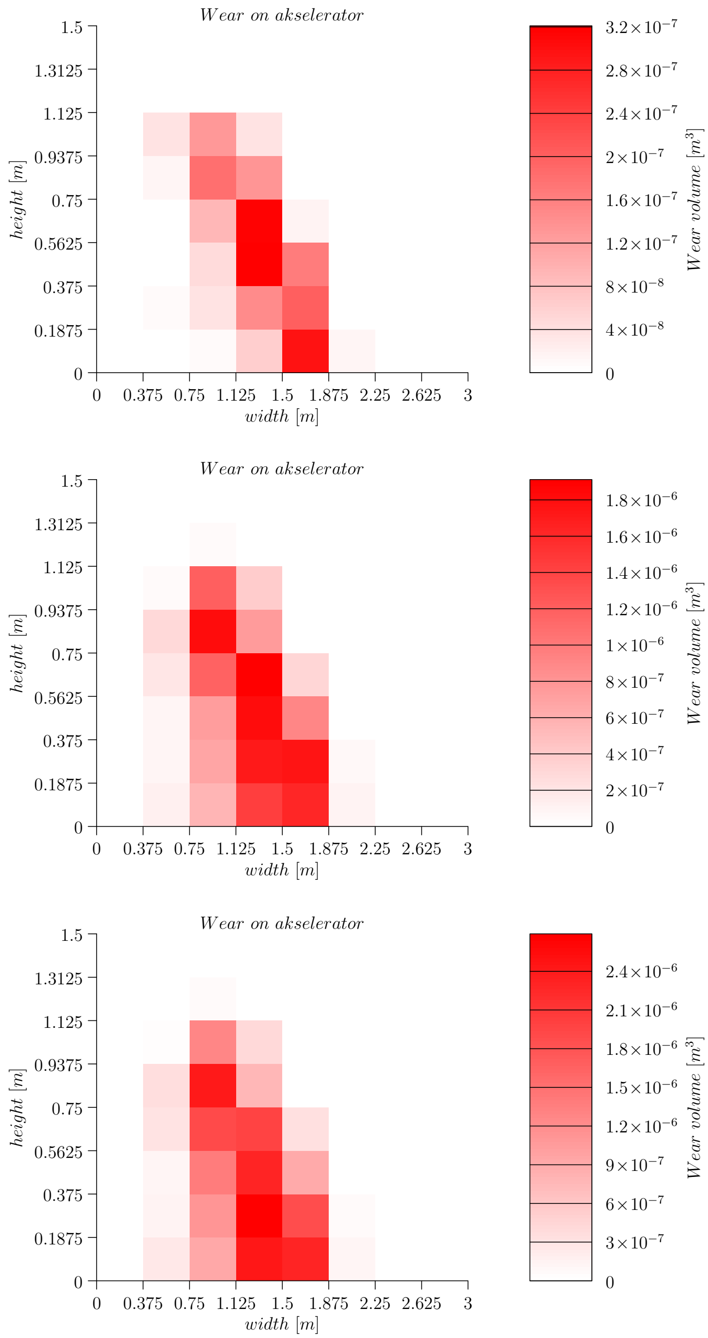


Figure 19: Akselerator accumulated wear distribution after 1, 5 and 10 seconds.

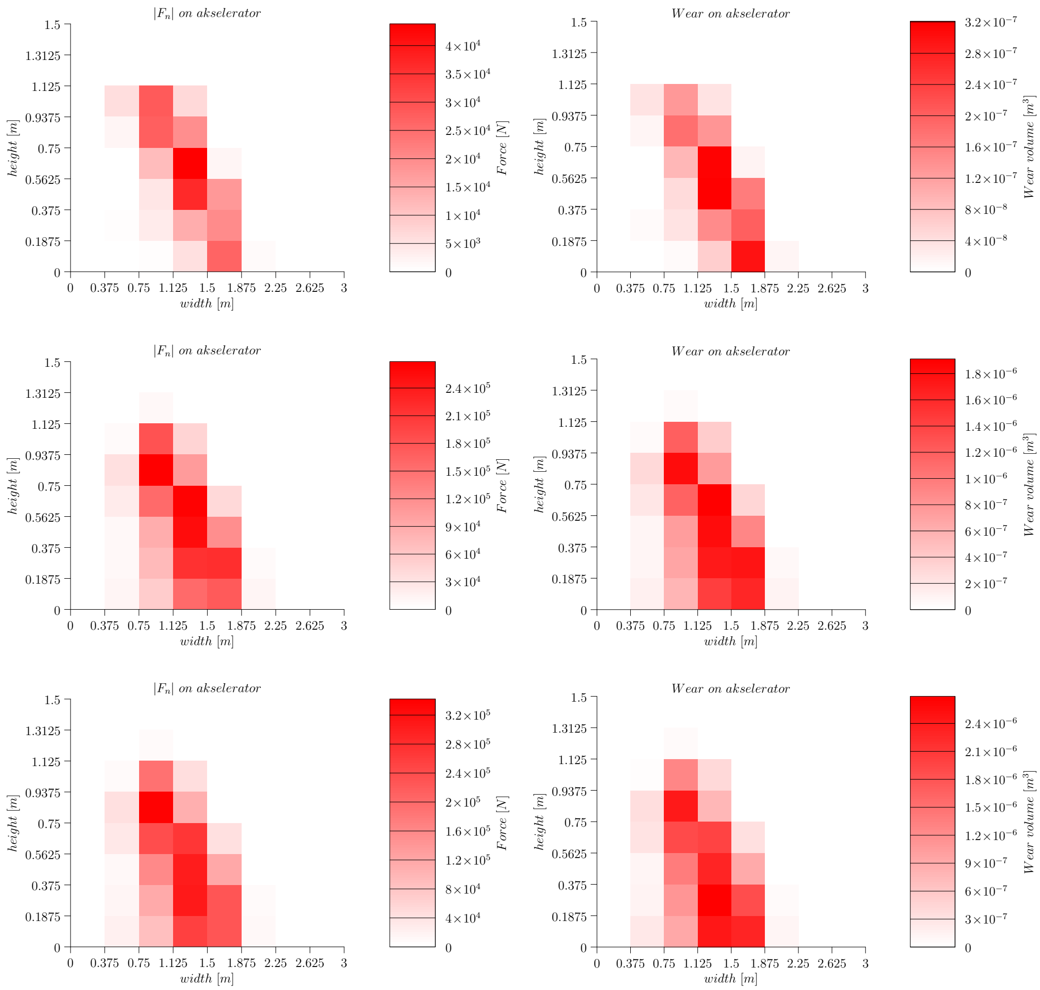


Figure 20: Akselerator surface plot comparison of force and wear rate at 1, 5 and 10 seconds.

4.4 Lower conveyor belt

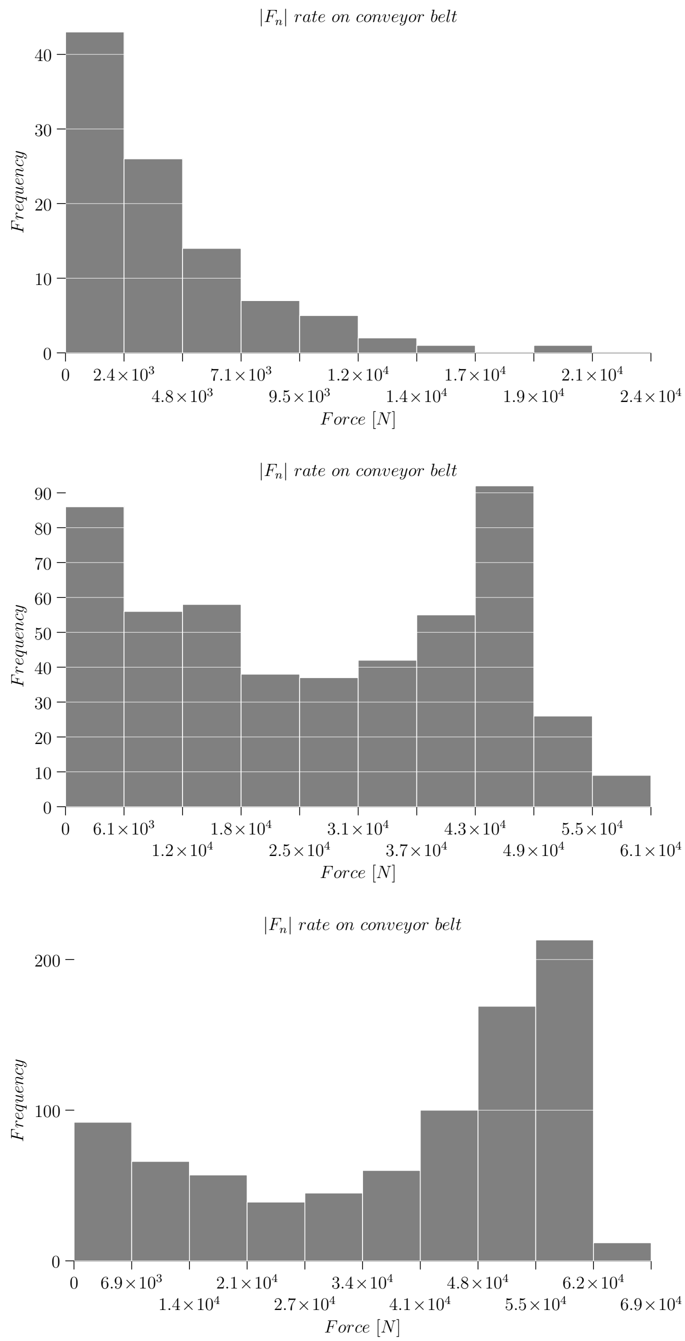


Figure 21: Lower conveyor belt normal forces at 1, 5 and 10 seconds.

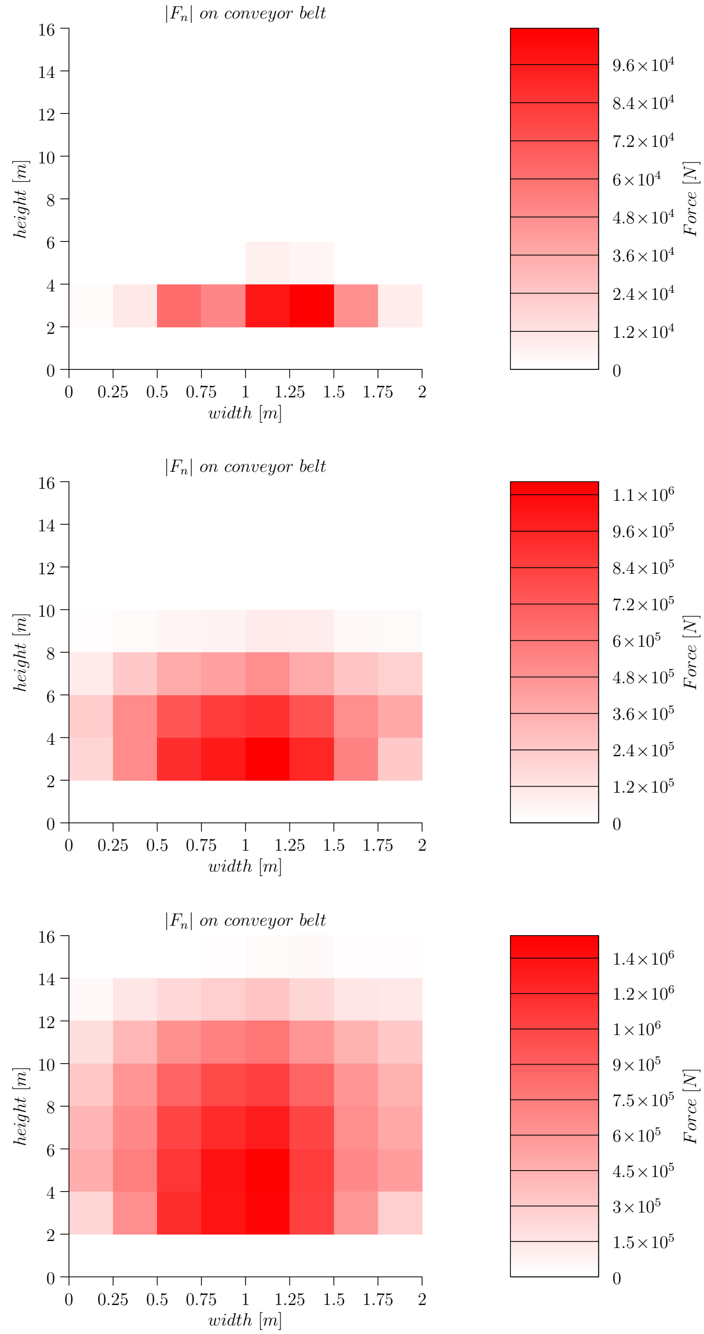


Figure 22: Lower conveyor belt normal force distribution at 1, 5 and 10 seconds.

5 Discussion

5.1 Mullhylla wall

The histograms in figure 6 show that as the rocks build up and create a pile, forces around $9.7 \times 10^3 N$ are dominant. As the pile grows, rocks will not hit the wall directly and the normal forces in the dominant interval are resting contacts from rocks in the pile.

The normal force distribution is described in figure 7. After 1 second from the first impact of a rock on the wall the pile has not grown much and the maximum normal force is scattered over half the height of the wall. As the pile grows, the maximum normal force is more clearly defined at the bottom of the wall.

The wear rate histograms in figure 8 show that the wear rate is located in the interval between 0 and 0.019.

The maximum wear area of the wall does not correspond exactly to the maximum normal force area as shown by figure 10. The maximum wear area is slightly above the maximum normal force area which can be understood from the parameter L in equation (1). The parameter L is the sliding distance, which is connected to the tangential velocity which is usually close to zero in the corner where the wall and floor meet.

The wall area has the cell with the highest accumulated wear in the system, it is in the interval 1.1625-1.55 m along the width and 0.75-1.125 along the height. The wear over time for this element is described in figure 23. Throughout the simulation, this cell has 190 nonzero

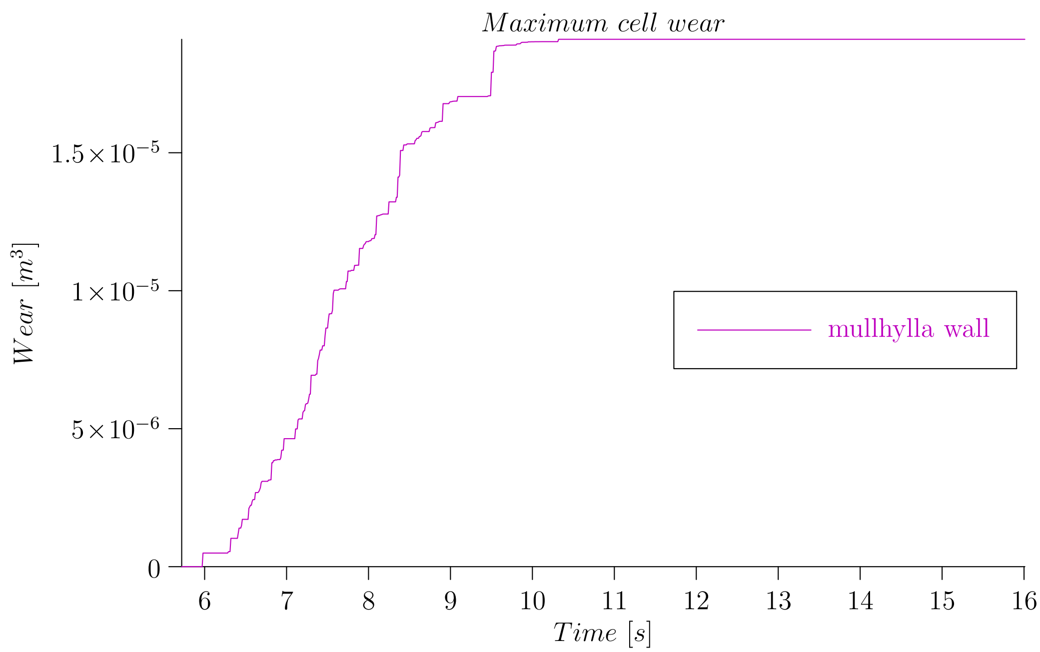


Figure 23: Accumulated wear over time on the cell on mullhylla which has the maximum wear.

values. Comparing this cell to the total wear of the *mullhylla* wall in figure 4 it is clear that the wear on this cell in some timesteps represent approximately half of the total wear on the wall area.

5.2 Mullhylla floor

There is a sudden increase of normal forces in the interval 4.5-5.4$\times 10^4$ in figure 11 between the 5 and 10 second histogram. This can be explained from the force plot in figure 3 where the *mullhylla* floor force graph is less *spiky* after 5 seconds. That part of the graph coincides with the cease of the rock flow from the upper conveyor belt.

The distribution of normal forces across the surface area has a slight focus on the upper middle part in the 1 and 5 second plots, however the maximum intensity areas are scattered in the 10 second plot.

The wear of the *mullhylla* floor described in figure 13 is slightly less than the wear of the *mullhylla* wall. This is because the tangential velocity is low at the floor of the *mullhylla*.

In the comparison of the normal force and wear distribution in figure 15, the wear distribution is scattered during the first 1 and 5 second intervals. In the 10 second interval the maximum wear can be detected at the bottom of the floor which is closest to the hole where the rocks fall through on to the *akselerator*.

5.3 Akselerator

The histogram of the normal force on the *akselerator* described in figure 16 shows that the forces are focused below 2.5$\times 10^3$. This is less than most of the normal forces on the *mullhylla* as figure 3 illustrates. This is expected since the height difference between the *mullhylla* and *akselerator* is much lower than between the upper conveyor belt and the *mullhylla*.

The distribution of normal forces are clearly defined slightly off center and at an angle due to the rotation of the *akselerator* relative to the hole in the *mullhylla*. There is not a large difference between the 5 and 10 second value which is explained by the simulation snapshots in figure 5. The 5 second simulation stops at 11 seconds, and at 12 seconds the flow of rocks on the *akselerator* has almost ceased.

The wear on the *akselerator* is lower than on the *mullhylla*. This is once again related to a low tangential velocity, making the *akselerator* longer could give more sliding contacts which is probably more realistic. With the current simulation setup the rocks can bounce of the *akselerator*.

The concentration of the wear on the *akselerator* follows the concentration of the normal forces as described in figure 20.

5.4 Conveyor belt

The histogram of the normal forces on the histogram described in figure 21 follows the conveyor belt graph in figure 3 well. As the time interval increases, the frequency of the larger normal force values in the histogram increases due to an increase of rocks on the conveyor belt.

The surface plot of the normal distribution in figure 22 shows that the area with highest intensity is the area below the *akselerator*. This is expected since falling rocks hit that area while the rest of the conveyor belt will have resting contacts with the rocks.

FiXme: *Wear on the conveyor belt is missing.*

References

[1] Thorsten Pöschel and Thomas Schwager. *Computational Granular Dynamics, Models and Algorithms.* Springer-Verlag, 2005.