Effect of Grouser Movement to Sand-Grouser Interaction on Unconsolidated Soft Sand Incline Using Discrete Element Method (DEM) Simulation

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Abstract. Wheel rover is a lightweight robot that is used for driving over rough terrain such as on unconsolidated sandy dune incline. Typically, a rover is equipped with fixed grousers on its wheels (conventional grousers). A problem that usually occurs by using conventional grousers is the rover getting stuck on an unconsolidated sandy dune incline as the wheel tends to slip and sink into the sand. This happens when the conventional grousers rotate and moves the sand from below of the wheel to the back of the wheel causing sand accumulated behind the wheel. A solution to minimize sand movement and subsequent sinkage to prevent this problem has been proposed during previous research where a prototype of a wheel rover which uses “adjustable grousers” with adjustable angles. During comparison experiments by previous researcher, the result shows that the length of fixed grousers affect the performance of the wheel in soft terrain and shows high tendency to get stuck in the sand. The purpose of this study is to investigate the interaction between the rotating motion of a fixed grouser and the sand movement by means of computer simulation. By utilizing computer simulation, the parameters that affects the movement of sand particles was observed. For the simulation process, Discrete Element Method (DEM) is used. The result shows that the longer grouser has higher average of sand displacement and moves higher volume of sand under the rotating wheel. The result will be used to assist in analysing the optimal parameters for wheel design for use on soft sand.

1. Introduction
Mobile robots are widely used to perform tasks that cannot be done by human because the task is too dangerous, or the task is out of ordinary human capabilities. Wheeled rover robot is a type of robot that is commonly used for driving over irregular terrain. For example, two Soviet mobile robot vehicles, the Lunokhods, have landed on the moon in November 1970 and January 1973. The robot task was to measure the physical and chemical properties of the lunar soil [1]. One of the challenges when using wheeled rover is it has a tendency to get stuck in soft sandy inclines which causes mobility failure. It happened to NASA “Spirit” Mars rover in 2009. It was embedded into the sand and unable to move forward when trying to move over a sandy dune [2].

Efforts to improve mobility on sandy slope have been made. From previous research, a new prototype design of wheeled rover was built by attaching “assistive” grouser to the conventional wheeled rover. The performance of rover wheels with assistive grousers and rover wheels with only
conventional fixed grouser was compared. From the result of the experiment, it can be observed that the length of conventional fixed grousers affects the amount of sinkage of the wheel into the sand and the amount of current consumed by the rover. However, from the experiment it was unable to observe the direct effect of the grouser movement direction to the flow of the sand due to the difficulty of measuring subsurface sand movement. Observing the flow of the sand is important because from the previous experiment it was believed that the purposed assistive grousers was effective compared to conventional fixed grousers because of the difference in the direction of net generated force by grouser-sand interaction under the surface of the sand.

This study is to investigate the effect of single grouser movement on sand particles flow by simulation modelling using Discrete Element Method (DEM). The scope of this study is to observe how a single grouser and sand particles interact for one rotation (one pass).

Discrete Element Method (DEM) was initially proposed by Cundall. DEM solution is generally based on an explicit integration whose stability was conditional which implies that the time step should be small as possible [5]. In DEM simulation, at every numerical iteration time step, the properties of stressed assembly of rigid spherical particles such as position, velocity, and contact forces were updated. The translational and rotational displacement for each particles was obtained based on Newton’s second law of motion equation [6]. 2-dimension (2D) DEM was commonly used by researchers for the simulation model. For example, 2D DEM has been used by Khot, L.R [7] and Nakashima et al. [8] to simulate the running behaviours of a rigid wheel on sandy solid or granular lunar soil. DEM have an advantage when modelling the flow of sand, soil or rock.

Nakashima et al. analysed the performance of a lugged wheel for a lunar micro rover on slope terrain by a 2D DEM. In the study, in order to confirm the applicability of DEM for slope terrain locomotion, the relationship of slope with slip, wheel sinkage, and wheel torque obtained by DEM were compared with experimental results measured using a slope test bed consisting of a soil bin filled with lunar regolith simulant.

2. Methodology

For the simulation preparation in this study, conventional wheel rover with fixed grouser was designed. Table 1 show the conventional wheel rover parameter.

| Parameter               | Value            |
|-------------------------|------------------|
| Tire diameter           | 296 mm           |
| Tire width              | 90 mm            |
| Fixed grouser length    | 20 mm and 80 mm  |
| Fixed grouser width     | 90 mm            |
| Fixed grouser thickness | 2 mm             |
| Number of fixed grouser | 1                |
| Sand box length         | 520 mm           |
| Sand box height         | 220 mm           |
| Sand box width          | 190 mm           |
| Sand box slope angle    | 0-degree and 30-degree |

Figure 1 and 2 shows the design of conventional wheel rover (CWR) at 0-degree inclination slope and 30-degree inclination slope. The black arrow shows the rotation direction. The initial position is the point when the grouser starts to enter the sand and ends when the grouser exits the sand. To assist in the analysis of the result, each recorded data is divided into three parts of grouser angle ranges $\theta_1$, $\theta_2$ and $\theta_3$ with the values as shown in Table 2.

The simulation was done with the wheels fixed to a static position and rotated at a constant 1RPM speed. This is because the focus is on observing the effect of the grouser movement on the subsurface particle movement.
3. Results and Discussion

3.1. Particle Velocity Pattern
Table 3 below shows the results of simulation for 20 mm and 80 mm grouser length at slope of 0-degree and 30-degree. It shows the velocity magnitude of particles when the wheel rotates. The blue colour represents minimum velocity which is 1.75E-003 m/s. The green colour represents the middle velocity which is 6.57E-003 m/s and red colour represents maximum velocity which is 8.18E-003 m/s.
Table 3: Particles velocity distribution

| 0-degree slope |
|----------------|
| 20 mm grouser | 80 mm grouser |

| Degree | 20 mm grouser | 80 mm grouser |
|--------|---------------|---------------|
| 0°     | ![Image 1]    | ![Image 2]    |
| 36°    | ![Image 3]    | ![Image 4]    |
| 90°    | ![Image 5]    | ![Image 6]    |
| 135°   | ![Image 7]    | ![Image 8]    |

- 1  2  3  4
From the table, the movement of particles as the grouser moves under the sand surface can be observed. At 0-degree slope, longer grouser length which is 80 mm caused a higher number of particles to move at significant velocity compared to the shorter 20 mm grouser. It can also be seen that the longer grouser affected the movement of subsurface sand particles further away from the grouser itself, extending to the back of wheel. This can be confirmed by counting the actual number of particles that was moved during each simulation run. For grouser angle range $\theta_1$, grouser length 80 mm moved 13511 particles compared to grouser length 20 mm with 12029 particles. For grouser angle
range θ₂, grouser length 80 mm moved 12813 particles compared to grouser length 20 mm with 11557 particles. And for grouser angle range θ₃, grouser length 80 mm also moved higher number of particles which is 12810 compared to grouser length 20 mm with only 9199 particles.

At 30-degree slope, the longer grouser length 80 mm affected the movement for a large area of sand particles compared to 20 mm grouser, with the same observation that the particles affected is not restricted to the area around the grouser and extended to the sand particles that is behind the wheel. When the actual number of particles moved during each run is calculated, at grouser angle range θ₁, grouser length 80 mm moved 13692 particles compared to 20 mm grouser with 12693 particles. For grouser angle range θ₂, grouser length 80 mm moved 13032 particles compared to grouser length 20 mm with 12345 particles. And finally, for grouser angle range θ₃, grouser length 80 mm moved 11772 particles while grouser length 20 mm moved 10854 particles.

It can be concluded that a longer grouser will significantly affect a large area of particles and the effect includes all sand particles under the wheel until to the back of the wheel. This shows that if the wheel experiencing slipping on a soft sand surface, a longer grouser might cause more sand particles to be displaced from under the wheel towards the back of the wheel and cause the wheel to sink inside the sand.

![Figure 3: Average sand displacement for 0-degree inclination slope (a) X-axis (b) Y-axis](image)

3.2. Average Particle Displacement
The value of displacement distance for the particles could help in understanding the movement pattern of the sand particles. This is important because the sand movement will show the direction of applied force by the grouser when the wheel rotates. If the sand movement is largely towards the back of the wheel, it can be assume that a large traction force could be generated by the grouser from the resulting shearing forces and the internal friction of the particles. If the sand movement is largely moving upward toward the surface, it can be assumed that the grouser is wasting energy on excavating the sand from under the surface, which will contribute towards the wheel to dig inside the sand and increase sinkage.

Figure 3 shows the average particle displacement for 20 mm and 80 mm grouser length for 0-degree slope and Figure 4 for 30-degree slope, separated according to the grouser angle ranges θ₁, θ₂, and θ₃ with the values as shown in Table 2. The values recorded has a positive and negative sign that shows the direction of the particle’s movement. For X-axis, the positive value is the direction towards the back of the wheel (to the left of Figure 1/Figure 2). For Y-axis, the positive value is the upward direction towards the surface and negative value is the particle moving downward. The higher the positive value for X-axis, it means on average the particles were moved farther to the back of the wheel. The higher the positive value for Y-axis shows that the particles on average were moved upward to the surface of the particle.
The graph at Figure 3 (a) and (b) shows the average particle displacement that moved at X-axis and Y-axis for 0-degree slope. For X-axis, the highest average sand displacement at grouser angle range 02. At grouser angle range 02, grouser length 80 mm has higher average sand displacement which is 12.83 mm compared to grouser length 20 mm with 3.06 mm. Grouser angle range 03 has the lowest average sand displacement for both 20 mm and 80 mm length, with the average sand displacement value does not have significant difference of 1.30 mm for grouser length 80 mm and 1.02 mm for grouser length 20 mm. From there it can be concluded that grouser length only slightly affects the sand movement at θ3 X-axis. At grouser angle range 01, grouser length 80 mm has higher average sand displacement which is 12.38 mm compared to grouser length 20 mm with 2.06 mm.

For Y-axis, grouser length 80 mm has higher average sand displacement compared to 20 mm at all grouser angle range. At grouser angle range 03, grouser length 80 mm has the highest average sand displacement which is 6.61 mm but grouser length 20 mm has the lowest average sand displacement which is -0.40 mm. The negative sign at Y-axis 20 mm grouser length means that most of the particles moved downward opposite to the surface. One the other hand, at grouser angle range 01, grouser length 80 mm has higher average sand displacement which is 1.78 mm compared to grouser length 20 mm with 0.02 mm. And at grouser angle range 02, grouser length 80 mm has higher average sand displacement which is 5.54 mm while grouser length 20 mm with 1.02 mm.

Figure 4 shows the average sand displacement that moved at X-axis and Y-axis for 30-degree slope. For X-axis, the highest average sand displacement is at grouser angle range 02. However at grouser angle range 02, grouser length 80 mm has higher average sand displacement which is 30.83 mm while average sand displacement for 20 mm is 4.78 mm. On the other hand, the smallest average sand displacement is at grouser angle range 03, where grouser length 80 mm has higher average sand displacement which is 13.74 mm compared to grouser length 20 mm with 1.90 mm. At grouser angle range 01, grouser length 80 mm has higher average sand displacement with 17.03 mm compared to 20 mm with 3.72 mm.

For Y-axis, grouser length 80 mm has the highest average sand displacement at grouser angle range 03 with average sand displacement value for 80 mm is 43.68 mm and -0.13 mm for grouser length 20 mm. It means, by using 80 mm length, more sand particles moved upwards at greater distance towards the surface of the sand compared to 20 mm length at grouser angle 03. On the other hand, grouser angle range 01 has the smallest average sand displacement for both grouser length. For grouser length 80 mm, the average value is -5.75 mm and for grouser length 20 mm, the average value is -1.47 mm. The negative sign means the particles moved downward. The reason why at grouser angle range 01 the values are small or negative, is because the moved particles was pushed downward as the grouser enters the sand on the 30-degree incline. At grouser angle range 02, grouser length 80 mm has higher average sand displacement with 37.83 mm compared to grouser length 20 mm with -1.71 mm.

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**Figure 4: Average sand displacement for 30-degree inclination slope (a) X-axis (b) Y-axis**
From the result, it can be confirmed that a longer grouser will move a high number of sand particles at larger distances, which will generate a large force from the shearing resistance and internal friction between the particles if the wheel position is not fixed and rotated. However, from Y-axis graph (Figure 3b and 4b), the longer grouser will also cause a large displacement of particles to the upward direction towards the surface of the sand. This is the condition where the wheel excavating the sand from under the wheel to the back of the wheel and will contribute to the wheel sinking into the sand as the wheel rotates. If there is no slipping, the wheel might not sink into the sand, but if there is high slippage such as on the 30-degree inclination, the wheel will experience a large value of sinkage due to this effect.

Using a longer grouser might generate large forward traction, but in condition with slipping, it might also contribute towards the wheel getting stuck in the sand instead.

3.3. Particle Displacement Volume
If a wheel does not slip when moving on a soft sand surface, it can be expected that there is only a small volume of sand being moved due to the grouser movement and the wheel passing on the wheel. However, if the wheel experiences slipping, a large volume of sand will be moved as the grouser rotates under the sand surface. The total volume of particles moved during one pass of the wheel rotation is an important indication of the total amount of resistance the wheel will encounter in conditions off high slippage.

For this simulation study, the wheel position is fixed while the wheel rotates, which is similar to a condition of 100% slippage. By calculating the volume of displaced particle based on the number of the total number of moved particle during one simulation run, the amount of resistance that the wheel will have to overcome under high slippage can be estimated.

Figure 5 shows the graph for volume of sand displacement for grouser length 20 mm and 80 mm at 0-degree incline and Figure 6 for 30-degree incline.

Figure 5: Volume of sand displacement at 0-degree inclination slope
From Figure 5, the data shows by using grouser length 80 mm at 0-degree inclination slope, the volume of the sand that has been moved from below of the wheel to the back of the wheel is 0.007827 m$^3$ which is higher compared to grouser length 20 mm with 0.007571 m$^3$.

From Figure 6, when using grouser length 80 mm at 30-degree inclination slope, the volume of sand that has been moved from below of the wheel to the back of the wheel is 0.007791 m$^3$ compared to grouser length 20 mm with 0.007402 m$^3$.

As mentioned before, the result is for a static position of the wheel, where the wheel does not move forward or downward as it is rotated, which simulates a 100% slippage condition. If an actual wheel does not experience a large amount of slippage, the effects of the sand displacement might be smaller. But for a high slippage condition, the amount of resistance that the wheel will encounter when trying to rotate on a soft sand surface is significant and amplified if the grouser is longer. A large amount of resistance will consume a large amount of energy and combined with a large sinking due to the slippage, will contribute towards the wheel sinking inside the soft sand surface.

4. Conclusions

In this study, a simulation modelling was done to observe the interaction between sand and grouser by using DEM method. For the simulation, a single grouser that attached to a wheel was designed and simulated with sand particles. The result from the simulation of the particle-grouser interaction was recorded such as the distribution of velocity magnitude of each particles as the wheel turned, average sand displacement for each grouser angle range and total volume of sand displaced by the rotating wheel.

From the velocity magnitude distribution, it could be observed that a longer grouser length will affect significantly the movement of large area of particles under the surface. It can also be observed that for longer grouser the affected particles were not limited to just the particles near the exact position of the grouser but extends to the particles at the back of the wheel. This means that if the wheel experiences high slippage for example on a slope, then the wheel will have a very high probability of digging and sinking into the sand.

Based on the comparison of average sand displacement values for 20 mm and 80 mm grouser on slopes of 0 and 30-degree, it can be confirmed that the 80 mm grouser generated higher displacements in both X and Y direction, meaning that although the longer grouser could generate higher forward traction, it also excavated more sand from under the wheel towards the surface, causing the wheel to dig into the sand.

Comparison of the displaced particle volume shows that for a high slippage, the longer grouser moved a large number of particles which will generate a higher amount of resistance for the wheel to turn. A high rotation resistance is one of the cause of the wheeled rover to get stuck in the sand.
In conclusion, although a longer fixed grouser could generate a large amount of traction due to the higher number of particles that interacts with the grouser, the rotating motion of a conventional fixed grouser will also cause the long grouser to displace a large amount of sand from under the wheel towards the back of the wheel increasing sinkage, and also increase the wheel rotation resistance under high slippage condition such as on a steep slope.

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