The Effect of Tyres and a Rubber Track at High Axle Loads on Soil Compaction:

Part 2: Multi-Axle Machine Studies

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This paper reports on a study of the effect of the passage of multi-axle harvesting machines on the soil physical properties. In particular, to determine the effect of the rear tyre of a combine harvester on the amount of soil compaction subsequent to the passage of the front tyre/track. The work was conducted in controlled laboratory conditions to determine the effect of a simulated self propelled combine harvester with a total machine weight of 30 – 33 t. This was assessed by embedding talcum powder lines as a tracer in the soil to measure soil displacement and soil density changes. Additionally, dry bulk density and penetrometer resistance were measured. The results showed that the benefit of the rubber track found by Ansorge and Godwin (2007, a) was maintained after the additional passage of the rear tyre. After the passage of a track the effect of rear tyre size was insignificant, but the rear tyre size had a significant influence on soil density when following a leading tyre. This was due to a higher strength layer at the soil surface created by the track which was able to withstand the load of the subsequent passes and protect the soil below from further compaction. Results similar to those found for a tracked machine were also achieved by three passes of a 900 mm section width tyre at 5 t load and 0.5 bar inflation pressure. The track results for the 33 t machine were very similar to those of a smaller combine harvester with a total load of 11 t and similar rut width. The study corroborated the benefit of tracks with regard to soil compaction and emphasised the fact that total axle loads and machine weights are less important than how the loads are distributed on the soil.

1. Introduction

This paper is the second in a series of three; it describes an investigation into the effect of multi-axle machine systems on soil compaction in a controlled laboratory environment. It explains the beneficial behaviour of tracks found by Ansorge and Godwin (2007a) – the first paper of the series - which compared the effect of single passes of both tyres and a track on soil compaction. The final paper will extend and develop prediction models to estimate the increase in soil density from both tyres and rubber tracks relating these to the experimental results in the earlier two papers.

The demand for higher productivity in agriculture leads to growing size and weight of harvest machinery which in turn increases the danger of soil compaction (Raper, 2005). To oppose this trend, emphasis has to be put on the design of undercarriage systems aiming to minimize the resulting soil compaction originating from field-traffic. Soil compaction could be minimized by using low ground pressure tyres (Hakansson, 2005) or equipping axles with tracks (Ansorge and Godwin, 2007 a). However, little detail is known about the individual soil compaction behaviour of single tyres within whole machine configurations. Thus for example the question cannot be answered whether the benefit found for a rubber track is maintained after the passage of the rear axle in half track configurations or which rear tyre size would be appropriate in order not to exceed the soil density increase already caused by the front axle.

Single axle configurations have been investigated in detail by Ansorge and Godwin (2007a) and showed a benefit of a rubber track with respect to soil density change and penetrometer resistance compared to tyres. Therefore the subsequent step was to investigate the implications of the effect of the passage of a tyre on the second (rear) axle. Thus, the aim of the study was to investigate the effect of the passage of whole machine configurations on soil compaction and quantify the total soil density increase caused by different combine harvester undercarriage systems, i.e. half-tracks, common wheeled configurations and a lighter older machine configuration.

The second part of this paper describes the effect of a track on soil strength immediately below the surface, which was found in penetrometer resistance measurements, by investigating longitudinal soil displacement.

2. Literature Review

The importance of soil compaction and its economical consequences were shown by Hakansson and Reeder (1994) who report that soil compaction caused by tyres at an axle load of 10 t penetrated the soil to a depth of 500 mm measurably and that it possibly permanently reduces crop yields. The demand for lighter machinery rises due to such results. The importance in reducing vehicle weight as a mean of reducing soil compaction was shown in a study by Smith and Dickson (1990). Weight reduction by using light alloys and composite materials rather than steel products has its limits due to increased machinery cost. Smaller machinery on the contrary cannot be operated at the same economical efficiency as larger machines. These two arguments strengthen the need for a better undercarriage design.

Ansorge and Godwin (2007a) discussed the literature with respect to tyres and tracks in detail and therefore only a short summary is given here. The findings from literature could not be generalized as some studies reported advantages (Bashford *et al.*, 1988; Rusanov, 1991) or disadvantages (Blunden *et al.*, 1994) for tracks which are summarized by Alakukku *et al.* (2003). Watts *et al.* (2005) found that maximum rut depths were caused by heavy trailers rather than by tractors and, moreover, showed that crawler tractors created the least soil damage supporting tracked undercarriage systems. A similar benefit was found in an infield investigation for sugar beet harvesters by Brandhuber *et al.* (2006). The tracked type undercarriage system caused less reduction in hydraulic conductivity than its wheeled counterpart. Ansorge and Godwin (2007,a) report a clear benefit of a rubber track at a load of 10.5 – 12 t in comparison to tyres laden to 10.5 t with respect to soil displacement and resulting soil density increase for both a uniform soil profile and a layered field situation replicated in a soil bin laboratory.

According to Hadas (1994) some field studies indicate that soil compaction blamed to the passage of high axle loads can be attributed to other processes and even natural variabilities, too. Thus it can be concluded that it is very important to minimize the environmental variability and their impact on the results which raises the demand for controlled repeatable laboratory studies.

Only few studies distinguished soil compaction caused by single axles in literature. One of these studies is Pytka (2005) who showed that the largest increase in soil deformation is caused after the first and second pass of a tractor tyre. The additional soil deformation from subsequent passages decreases. The studies reviewed by Ansorge and Godwin (2007, a) did not distinguish soil density increase caused by single passes compared to multiple passes with different tyre configurations in detail. None of them investigated the influence of tyres following a track on soil density increase. Therefore the focus of this second part will be on the additional soil compaction caused by the subsequent pass of the rear axle.

3. Methods

The effect of simulated self propelled combine harvesters with total machine weights ranging from 11 – 33 t and equipped with tyres, or a track followed by a tyre, on soil compaction was investigated in a full size study in a controlled laboratory environment.

The individual rubber track, large harvester tyres and implement (rear-combine) tyres and loads used in the study are specified in *Table 1*. The front axle of modern combine harvester configurations was simulated using either a track laden to 12 t or the 900/65 R32 tyre laden to 10.5 t at a recommended inflation pressure of 1.9 bar. These two units were combined with the largest (700mm/4.5t/1.0bar) and the smallest (500-70mm/4.5t/2.3bar) of the four implement tyres (Ansorge and Godwin, 2007a) to simulate the rear axle of the combine. The whole-machine abbreviations are listed in *Table 2*. Additionally, a narrow tyre combination of the 680mm/10.5t/2.2bar followed by the 500-85mm/4.5t/1.4 was investigated. In addition, the 900/65 R32 tyre was laden to 5 t at 0.5 bar inflation pressure and passed three times over the soil to represent an alternative hypothetical three axle machine concept. These machine configurations with total weights of 30 – 33 t were compared to a configuration representing the design of the Claas Dominator, manufactured in Europe from 1970, with a weight of 11 t and equipped with 23.1-26 tyres on the front axle at 4 t and 1.2 bar inflation pressure and 11.5/80-15.3 tyres at 1.5 t and 2 bar inflation pressure on the rear axle; constituting the medium tyre size configuration available for this particular machine.

Soil compaction was assessed by embedding talcum powder lines as a tracer in the soil during preparation to measure soil displacement and soil density changes. Additionally dry bulk density and cone penetrometer resistance were recorded. Full details on measured parameters are given in Ansorge and Godwin (2007, a).

The soil used was a sandy loam (Cotternham series; King, 1969) with 17% clay, 17% silt and 66% sand; the water content was maintained at 10% dry base during the studies. A uniform soil condition was prepared to a dry bulk density of 1.4 g/cm^3 which was chosen to represent soil conditions with a relatively low bearing capacity where tracks and large size tyres would have value in agricultural practice. The initial penetrometer resistance profile for a uniform soil condition is shown in *Fig. 10* with a resistance of 0.9 – 1 MPa from 0.2 to 0.7 m depth. This uniform profile was achieved by rolling each 50 mm deep layer once after it had been placed onto the underlying soil and levelled with a blade. Obviously the soil underneath was further compacted when the subsequent layer received its virgin compression with a roller of 3.5 kN and 0.6 m diameter at a speed of 1 m/s. However, as the penetrometer resistance profile in *Fig. 10* indicated, the resulting overall profile was uniform.

4. Results

4.1. *Whole machine studies*

4.1.1. *Soil displacement*

Figure 1 shows that the tyre undercarriage systems created a significantly larger soil displacement i.e. increase in soil density than the rubber track type under carriage systems. A clear differentiation is visible between the tracked types compared to the wheeled types with the exception of the three passes of the 900 tyre each with a reduced load of 5 t. All treatments were significantly different from each other except the two tracks and the three passes of the 900mm/5t/0.5bar. Thus the influence of the rear tyre size had a greater effect following a tyre on the front axle than following a track.

To investigate the effect of the rear tyre in more detail, *Fig. 2* shows the soil displacement caused by both the front tyre/track alone and after the passage of the rear tyre. The additional soil displacement caused by the 700mm/4.5t/1.0bar rear tyre was insignificant for both tyre and track. However, the additional soil displacement caused by the 500-70mm/4.5t/2.3bar tyre was significant for the tyre in front. An insignificant increase in soil displacement for the track followed by the 500-70mm/4.5t/2.3bar was visible at the surface, yet, below a depth of 300 mm this data converged with the other curves for tracks. However, if the 500-70mm/4.5t/2.3bar tyre followed the 900mm/10.5t/1.9bar tyre the additional soil displacement was significantly greater over the profile to a depth of 450 mm where the data converged with the 900mm/10.5t/1.9bar tyre followed by 700mm/4.5t/1.0bar. Thus, rear tyre size has greater significance in relation to soil displacement after the passage of a leading tyre, than when following a track. This is shown in detail in *Fig. 3*, which shows that the magnitude of the increase from the additional passage of the 500-70mm/4.5t/2.3bar compared to the 700mm/4.5t/1.0bar was smaller for the track and the differences merge at shallower depth than the differences for the tyres.

The track not only maintained its smaller rut depth, but also had a smaller increase in rut depth from subsequent passages. For the track the rear tyre only affected the soil to the depth to which conventional cultivation treatments were carried out as long as the rear tyre load could be carried and distributed by the compact zone created just below the surface by the track. We attempt to explain the reasons for the benefit of the tracks in Section 4.2.

Additional studies were conducted to compare the track systems with a smaller combine harvester having a total weight of 11 t on the following tyre sizes (Front: 23.1-26; Rear: 11.5/80-15.3) with an inflation pressure of 1.2 bar and a load of 4 t on the front wheel and 1.5 t load at 2 bar on the rear wheel. This tyre combination is in the middle of the available range.

The data is shown in *Fig. 4* and compared to a tracked machine which shows that the soil displacement below a tracked machine was not significantly different from that of a wheeled machine of one third of the weight.

The least significant difference bars (LSD) have all the same length because they compare the overall treatments whereby variability with depth has been taken into consideration.

4.1.2. *Penetrometer resistance*

The penetrometer resistance profiles resulting from different undercarriage systems are shown in *Fig. 5* which reveals two distinctive groups: (a) track and (b) tyre, in comparison with the undisturbed control. The track data exhibits a higher penetrometer resistance near the surface at approximately 150 mm which then reduces almost exponentially with depth. This indicated that the soil had its greatest strength at the soil surface; however, the penetrometer first needed to fully engage with the soil to show the peak penetrometer resistance. Consequently, the highest reading of penetrometer resistance was about 40 mm below the surface of the rut. Both track treatments were not significantly different from each other, but from the group of tyres. The tyre data in *Fig. 5 b* was overall more uniform and showed a slightly smaller magnitude at the surface, but larger values below 250 – 300 mm than the track. All two axle configurations had similar penetrometer resistance and hence there were no significant differences in penetrometer resistance for the 900mm/10.5t/1.9bar treatments and the 680mm/10.5t/2.2bar treatment. In comparison, the three axle configuration was significantly different from the other wheeled undercarriage treatments due to its lower penetrometer resistance over the entire depth.

The increase in penetrometer resistance caused by the rear tyre (500-70mm/4.5t/2.3bar) can be seen in *Fig. 6* for both the track and the 900mm/10.5t/1.9bar tyre. In both cases the rear tyre caused a small but significant increase in penetrometer resistance over the full depth range.

Similar to the data from the soil displacement, the penetrometer resistance caused by an 11t machine was compared to that of a tracked machine in *Fig 7*. Statistically there were no differences overall. The tracked machine showed its pronounced peak at the surface, however, at a depth of 300 mm the penetrometer resistance merged with that of the lighter wheeled machine, supporting the soil displacement results from *Fig. 4* and leading to the overall similarity between the two treatments.

4.1.3. *Dry bulk density*

There were no significant differences in DBD among individual under carriage systems due to the inherent large variations caused by the measurement of DBD shown in *Fig. 8*. The initial DBD was 1.43 g/cm^3. Grouping the undercarriage systems into the average wheel and average track type system, final DBD values were 1.59 g/cm^3 and 1.56 g/cm^3, respectively. This order corresponded to the measurement of soil displacement shown in *Fig. 1*, whereby tracks caused a smaller increase in DBD than tyres. The difference of 0.03 g/cm^3 between the two groups was not statistically significant. The tendency of the DBD agreed for gravimetric DBD compared to the estimated increase in DBD utilizing the slope of the soil displacement graphs; i.e. both times the DBD was greater after the wheeled than after the tracked machines. The resolution of the soil displacement measurement was greater than that of the DBD.

4.1.4. *Discussion of whole machine Studies*

The small variability within the results satisfies the requirement imposed by Hadas (1994) for a study with small variability when comparing the soil density increase of different treatments.

For wheeled machinery the findings from Pytka (2005) can be corroborated that the largest part of soil displacement is caused in the first pass. However, Pytka (2005) also reported soil displacement for the 2nd pass. In contrast, this study showed that the additional soil compaction originating from the subsequent pass could reach zero if the second tyre did not exceed the bearing capacity of the soil created with the first pass as for example with the 900mm/10.5t/1.9bar+700mm/4.5t/1.0bar configuration. For the tracked undercarriage systems the strong layer at the surface supported the load without further compaction of the underlying soil.

The advantage for a rubber track with respect to soil displacement, penetrometer resistance and soil density increase reported by Ansorge and Godwin (2007, a) were maintained after the passage of the rear axle. Therefore the advantages for rubber tracks reported by Bashford *et al.* (1994) and Rusanov (1991) can be supported even after the passage of an additional rubber tyre following the track. The same holds true for the results from Watts *et al.* (2005) who showed that crawler tractors created the least soil damage. Brandhuber et al. (2006) found the same beneficial results for tracks in comparison to tyres for sugar beet harvesters in an in-field study whereby the tracked undercarriage system caused less reduction in hydraulic conductivity than its wheeled counterpart.

A three axle tyre configuration with 5 t load per tyre caused similar vertical soil displacement compared to a track with a load of 12 t followed by a rear tyre with a load of 4.5 t. An undercarriage unit with a track unit on the front axle and a gross weight of 33 t resulted in a similar vertical soil displacement to that of an 11 t combine harvester on commercially fitted normal front and rear tyre sizes.Therefore machines with either large section width tyres and low payloads or tracked or half tracked vehicles could be the answer to satisfy the demand for increasing agricultural machinery while minimizing soil compaction. The comparison of the soil displacement caused by a half-track combine at 33 t to a wheeled combine harvester at 11 t showed, that modern heavy weight machinery must not necessarily exceed the soil displacement that would have been (or has already been) caused by older lighter machines on medium available tyre sizes. By using smart undercarriage design the demand from Smith and Dickson (1990) for reducing weight in order to reduce soil compaction can therefore be contradicted. Hakansson and Reeder (1994) reported that soil compaction caused by 10 t axle loads penetrated the soil to a depth of 500 mm measurably. Assuming a very weak field situation this is in agreement with the results of this study for wheeled undercarriage systems showing a residual soil displacement between 500 – 600 mm depth. In contrast to this soil displacement for half – track undercarriage systems has decreased to zero at about 500 – 600 mm depth. The residual soil displacement for wheeled common combine harvester tyre combinations demonstrates their possible impact on the subsoil.

4.2. *Track behaviour*

4.2.1. *Discussion of track behaviour*

The explanation for the high surface penetration resistance caused by the tracks at a load of 10.5 – 12 t at the surface shown in Section 4.1.2 and by Ansorge and Godwin (2007a) will be considered in this section. Whilst initially of some concern, it is much more easily removed than the deeper compaction caused by the tyres (Ansorge and Godwin, 2007a). For reduced or no-tillage systems this layer might cause some problems, although Ansorge (2005) found a larger effect of un-tilled wheel ruts than track ruts for broadcast sown oil seed rape. This layer is also of value by reducing the subsequent amount of soil displacement caused by the rear tyres, compared to that following a wheel as shown in *Fig. 3*.

The high penetrometer resistance was thought to originate from either vertical soil compaction close to the surface (possibly by vibrations, pressure peaks from rollers, or long contact time) or the application of shear forces during the passage of the track.

In a first instance the possibility of a larger vertical soil density increase at the surface will be investigated. If the high penetrometer resistance was caused by vertical soil compaction this would be visible from the soil displacement curves with depth at the surface. Hence, the average slope of the soil displacement lines should indicate a larger increase in soil density for the tracks than for tyres in the top 300 mm. *Figure 9* shows the relevant data from Ansorge and Godwin (2007a) including the best fit linear regression lines. Independent of the depths considered, the average slope for the tracks was always larger than the slope for the tyres (with the exception of the 800mm/10.5t/1.25bar) indicating less vertical soil displacement and compaction at the surface. If vibrations transmitted through the track onto the soil caused the peak in penetrometer resistance, this should also have been visible in soil displacement curves.

Another experimental result shedding light on the hard layer was the similar vertical soil displacement caused by the rear/implement tyres to that of the rubber track (Ansorge and Godwin, 2007a). However, the penetrometer resistance results for the smaller implement tyres did not show a peak close to the surface and as shown in *Fig. 10*, merging of the data for the track and rear tyres occurred at a depth of less than 300 mm.

Average contact pressure for the track was virtually identical to that of the 500-85mm/4.5t/1.4bar tyre at 83 kPa and 85 kPa, respectively (Ansorge and Godwin, 2007 b). For the 600mm/4.5t/1.4bar tyre a larger contact pressure of 110 kPa was measured. Nevertheless all three treatments caused similar soil displacement. Thus their increases in soil density agree well with their average contact pressures. As the true pressure distribution underneath a track was not uniform, one could argue that the dense layer was caused by the pressure peaks underneath the track; this was not visible from the study of the vertical soil displacement. Hence, neither both the absolute contact pressure or its distribution could be the cause of the higher penetrometer resistance. The same reasoning applies to vibrations transmitted to the soil and causing compaction.

Since the peak in penetrometer resistance had no counterpart in the vertical soil displacement curves or in the original soil profiles in the soil bin laboratory, no lateral displacements were found, and we did not measure displacements in the direction of travel our only conclusion can be that these displacements are the source of the hard layer. In turn such motions can only be caused by shear forces in the direction of travel.

The different slip behaviour of a tyre and a track could be responsible for this increase in soil strength indicated by the peak in penetrometer resistance. Calculating shear displacement resulted in twice the displacement underneath a track compared to that for a tyre according to Wong (2001). This seems rather strange as the track operated generally at a lower slip (5 %) compared to tyres (10 %) in this investigation (Ansorge, 2005) to develop the same thrust necessary to propel itself. The shear displacement, however, is gained by the integration of slip velocity underneath the implement over the distance traveled. Hence the long contact area of the track (2.4 m) coupled with constant slip velocity led to a greater total shear displacement. The resulting constant shear strain application over the entire contact length additionally increased plastic shear displacement. Total length of the contact area for the tyre was about half (1.2 m) of that of the track, whereby the slip velocity depended on the position of the soil with respect to the tyre. The highest slip velocity occurs at the beginning of the contact patch when the tyre surface velocity is greater than that of the deformed section of the tyre under its centre line due to differences between the actual and the rolling radius (Wong, 2001). Thus shear strain decreases in traveling direction from the edge of the tyre to the centre.

This decrease in shear strain can be compared to an impact load allowing for some elastic recovery. The track on the contrary applies the shear force for a greater length and thus an extended period of time thereby compacting the soil horizontally and allowing less elastic recovery due to the spring-damper behavior of the soil. The spring-damper behavior of soil during compaction was exemplarily shown by Aboaba (1969) who changed the contact time of a roller by altering forward velocities.

The actual longitudinal soil displacement measured in the soil bin laboratory and caused by a self propelled track and tyre will be discussed in the next Section.

4.2.2. *Longitudinal soil displacement caused by tyre and track*

To shed light onto the question how much the soil is displaced longitudinally by tyres and tracks the total longitudinal soil movement was determined by embedding a series of vertical sand columns into the soil. These columns are 5 mm in diameter at a spacing of 50 mm and reach to a depth of 250 mm in the centreline of the path of the tyre or track. After the passage of the 900mm/10.5t/1.9bar tyre and T12 track, respectively, these were carefully excavated along their centre line thereby showing the direction of the movement of the soil throughout the surface 250 mm. The position of each sand column was digitized using the same method as for the determination of soil displacement.

Figure 11 shows a uniform forward soil movement of the sand columns numbered 1 – 10 close to the surface after the passage of the 900mm/10.5t/1.9bar. The arrow indicates the direction of travel. To aid the interpretation of soil movement within the column, *Fig. 11* includes vertical lines representing the average longitudinal position of the lower 100 mm for each sand column. At the surface the forward movement of the soil varied depending on the position relative to the lug. The columns on the back of a lug exhibited only a forward movement close to the surface, but not at depth (Column 1, 6, and 10 from left); all other columns tilted forward. The soil movement caused by a rubber track at 12 t is shown in *Fig. 12*; these show an alternating backward and forward soil movement close to the surface, whereby the backward movement was more pronounced than the forward movement. The front face of a lug appears to push the soil slightly forwards (Columns 2, 5, and 8 from left), but the remaining section of the lug and the rear area push the soil backwards. The void-lug ratios in these particular cross sections were 0.43 for the track and 1 for the tyre, representing a larger proportion of lugs for the track within the contact area.

In order to conduct a statistical analysis of the longitudinal soil movement below the tyre each column within *Fig. 11* was assigned either B or F to account for the tilt direction of the soil; B - indifferently to backward; F – forward. The assigned order was from left to right: BFFFFBFFFB. Within *Fig. 12* the sand columns of the track treatment were assigned either B, F, or I depending on whether the column was tilted backward, forward or indifferent with a shear failure below the lug and the following order was assigned: BFIBFIB. The statistical analysis conducted for the entire length of each column and accounting for the treatment (track or a tyre), for the tilt direction and allowing an interaction of tilt direction with depth, revealed all parameters to significantly describe the observed sand column movement.

To investigate the soil movement with depth the columns were divided into a lower and an upper part. The lower 100 mm were taken as a reference basis and hence excluded from the comparison because of the assumption that this depth was not affected by the treatment. The assumption was confirmed by an analysis for the values from the lower 100 mm (track position -0.0008 mm, tyre position +0.0133 mm, LSD 0.51 mm). All parameters used to describe the data did not significantly influence the remaining variation and thus indicated a random distribution of the data around zero (p-values >0.9). For the upper 150 mm tilt, drive unit, and the interaction of tilt with depth were significant parameters describing the variation within the data. The mean position for the rubber track unit of the top 150 mm was -4.45 mm which was significantly different from zero. This compared to a mean position of 2.05 mm for the wheel which was not significantly different from zero with an LSD equal to 2.18 mm. Looking at the assigned tilt variables B, F, and I for both treatments, tilts B and I were negative and tilt F was significantly different from both indicating a positive, i.e. a forward soil movement.

In further support of the previous argument for shear displacement causing the peak in penetrometer resistance it is interesting to note that the longitudinal movement which ceases at approximately 150 mm is equivalent to the point where the magnitude of penetrometer resistance drops back to that of the rear tyres (*Fig. 10*) and even below front tyres (*Fig. 6*).

Hence it was shown that in this very situation overall the track caused a significant backward soil movement at the surface whereas the wheel tended to cause a forward soil movement which was not significantly different from zero. As available slip data could not be accurately assigned over the distance the units travelled across the sand columns, it could be argued that the track had positive slip and the tyre negative slip thus causing these differences. However, the sand columns enclose three replications of lug-void cycles over a distance of 0.5 m and the data in *Fig. 11* and *Fig. 12* did not indicate a change in behaviour. Therefore the slip conditions could be regarded as constant with respect to longitudinal soil movement over the distance traveled and as both units are driven, it must be positive slip. Moreover penetrometer resistance randomly taken over the length of the soil bin always showed a higher surface strength for the track. These findings may change under the application of greater thrusts/slips.

4.2.3. *Discussion of measured longitudinal soil displacement in contrast with literature*

According to Wong (2001) soil movement below a tyre is accompanied by a flow pattern including two opposing flow directions. There are two exceptional extreme conditions. At 100 % slip, soil will only flow backward. For a locked wheel, only a soil wedge will be formed pushing the soil forward whereby the size of the wedge depends on sinkage and the corresponding rake angle of the tyre. Any slip condition between these two extremes will include both forward and backward flow of soil. The higher the slip, the larger the backward movement will become. Following the soil trajectories given by Wong (2001) for three wheels (towed wheel, 37 % slip, and 63 % slip) on a clay soil, at a slip range of about 10 – 15 % the integrated longitudinal soil movement below a tyre could be zero due to the equilibrium of backward and forward soil flow. This was observed in this condition for the tyre. For the track on the contrary, the bow wave and therefore forward soil movement was smaller due to the smaller rake angle and reduced sinkage. However, the backward flow pattern was more pronounced due to the constant slip conditions leading to an overall backward soil movement. Therefore the measured longitudinal displacement agrees with the theory suggested by earlier literature.

Figure 13 shows backward soil movement at the very beginning of a passage of a track/tyre and agreed with the results above. When a track started, soil was moved backwards as shown by the left hand figure which shows a clear shear failure boundary compared to the edge of the footprint from the track. In contrast, after the start of the tyre, no shear displacement could be seen, see right hand figure, although the soil lug disturbance pattern indicate high slipage at the start.

5. Conclusions

(1) The smaller increase in soil density for a self propelled track with loads of 10.5 and 12 t compared to self propelled tyres at recommended and at half recommended inflation pressure with a load of 10.5 t found by Ansorge and Godwin (2007a) on weak uniform soil conditions in a soil bin laboratory were maintained after the additional passage of the rear axle tyre. A typical wheeled combine increased the soil density by 19 % compared to a tracked machine with an increase of 14 %.

(2) The effect of the rear axle tyre size had less effect on soil conditions following a front axle track unit than a tyre. Soil displacement increased by 6 mm compared to 12 mm for the tyre over the same depth range and extended to a shallower depth (300 mm) only after the track. This was due to the bearing capacity of the stronger layer in the top 150 mm observed from the penetrometer studies.

(3) A hypothetical three axle tyre configuration with 5 t load caused similar vertical soil displacement compared to track loaded to 12 t followed by a smaller rear tyre loaded to 4.5 t.

(4) An undercarriage unit with a front axle unit loaded to 33 t resulted in a similar vertical soil displacement to that of an 11 t combine harvester on the commercially fitted normal front and rear tyre sizes.

(5) The overall configuration of the undercarriage system of the combine harvester was more important than individual weight on a single axle.

(6) The high penetrometer resistance for the track at the surface is caused by the application of shear for a longer period of time than for the tyre leading to a larger shear displacement. This longitudinal movement was limited to the uppermost 150 mm of the soil for both, tyre and track under these conditions.

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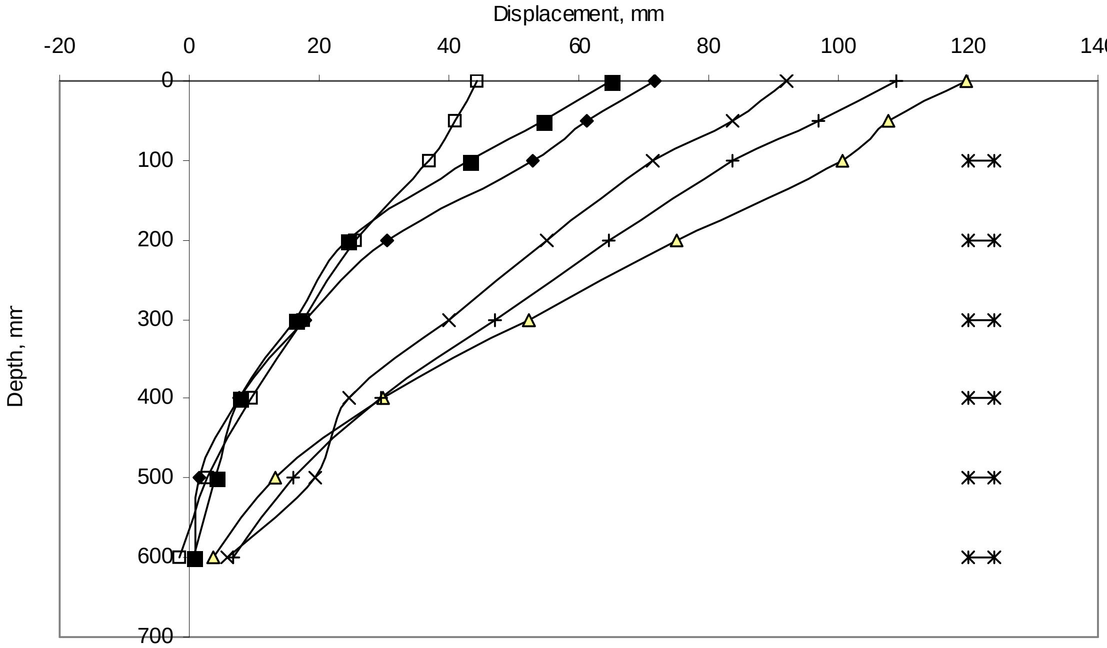

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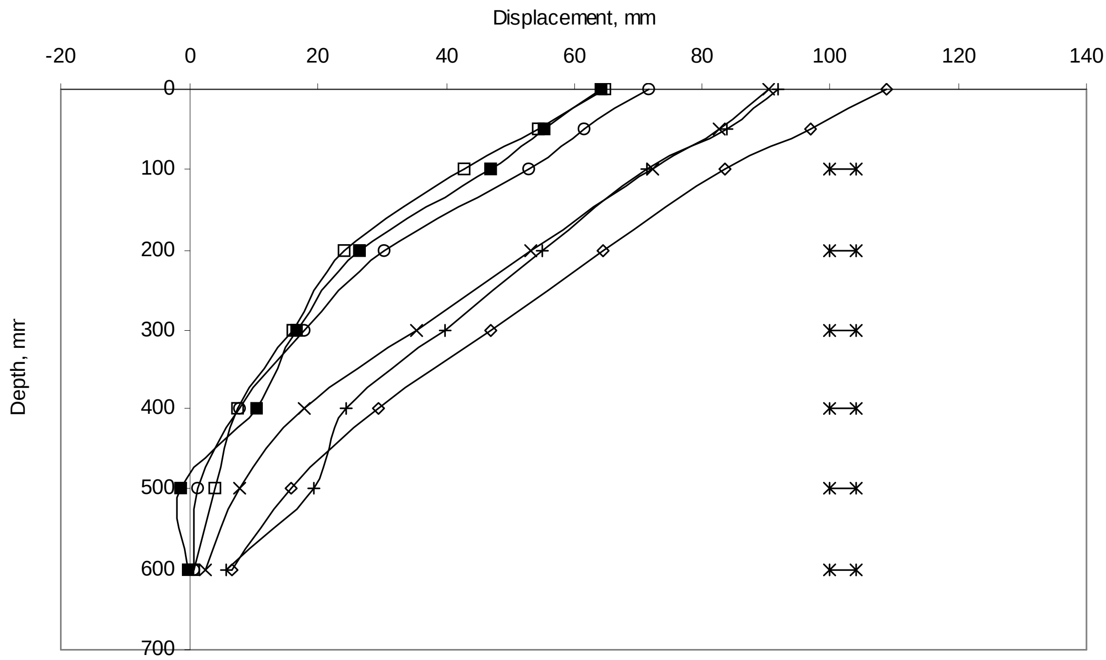

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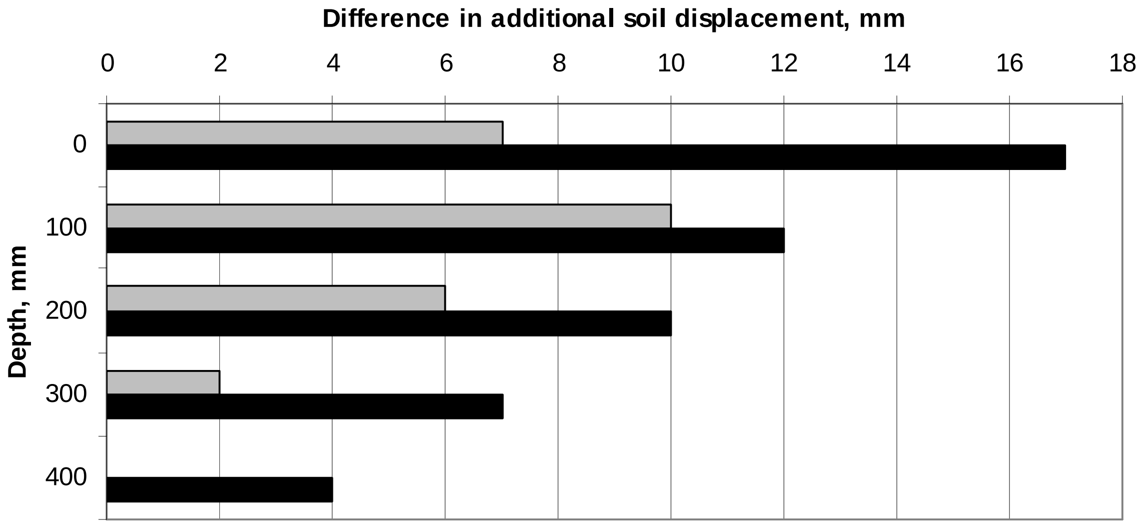

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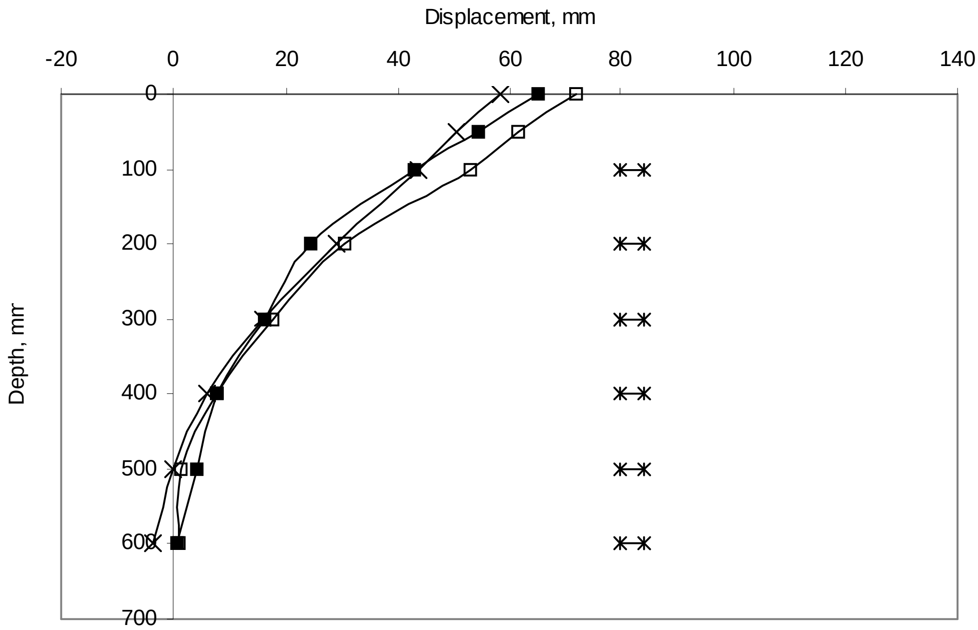

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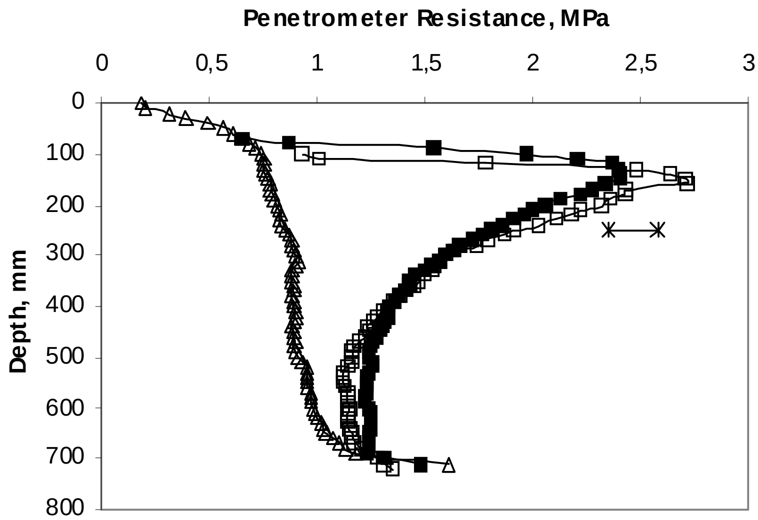
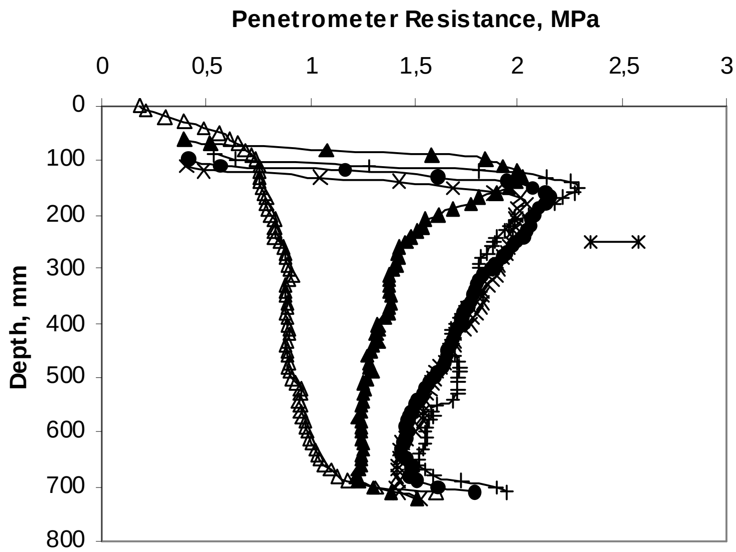


a)



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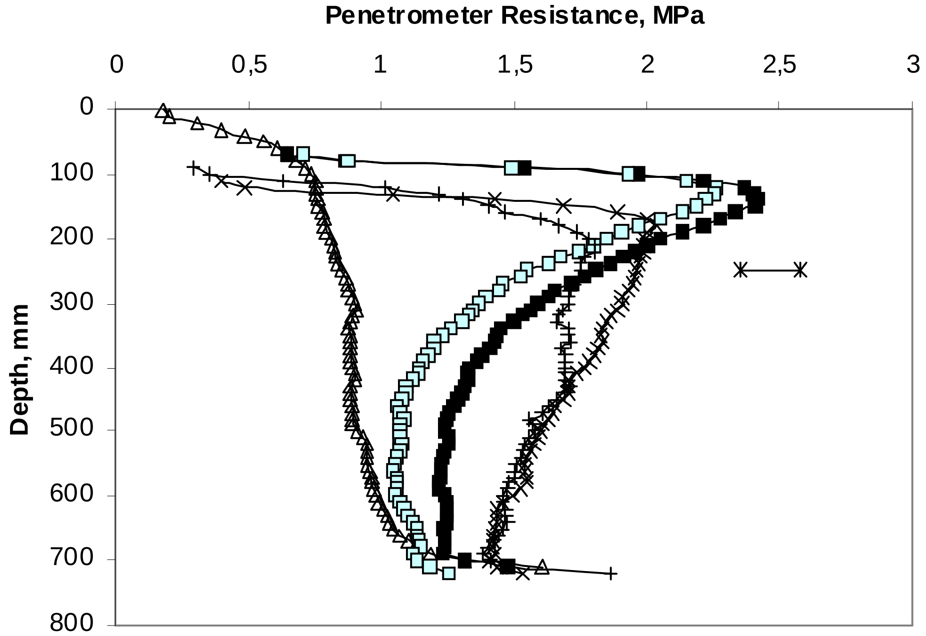

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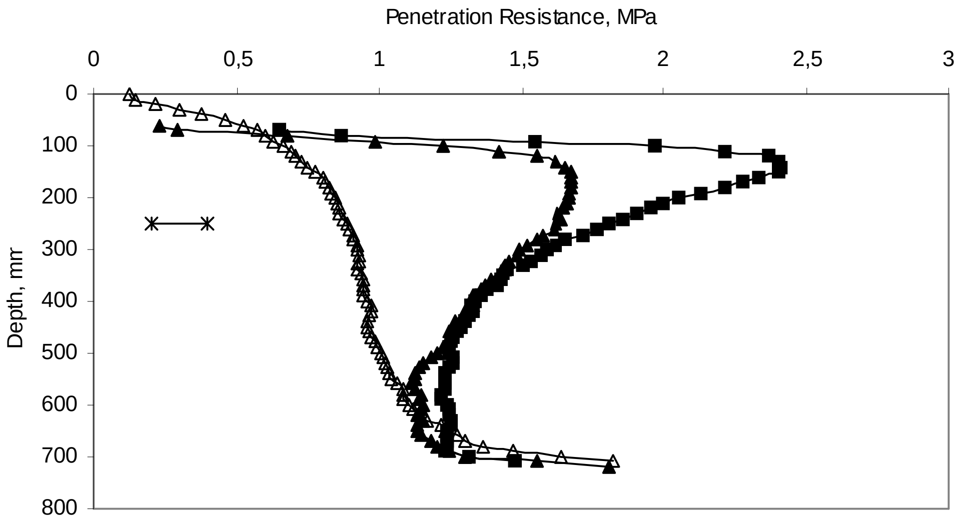

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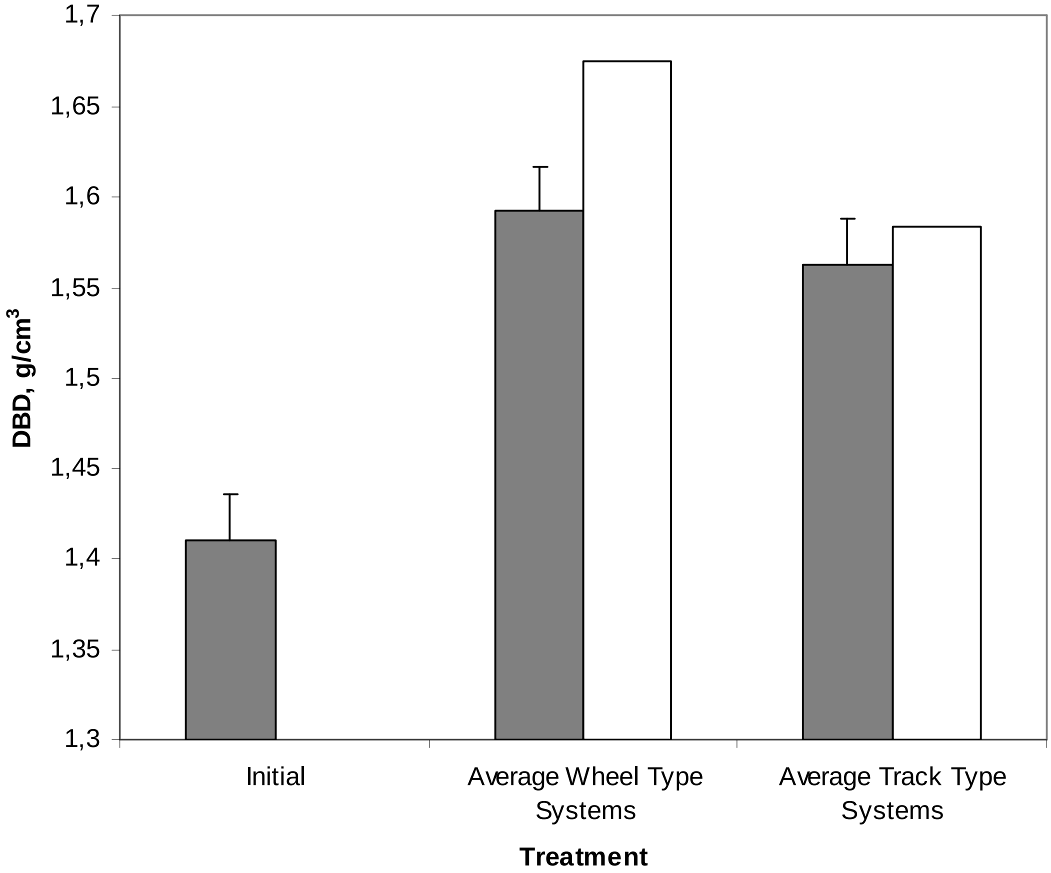

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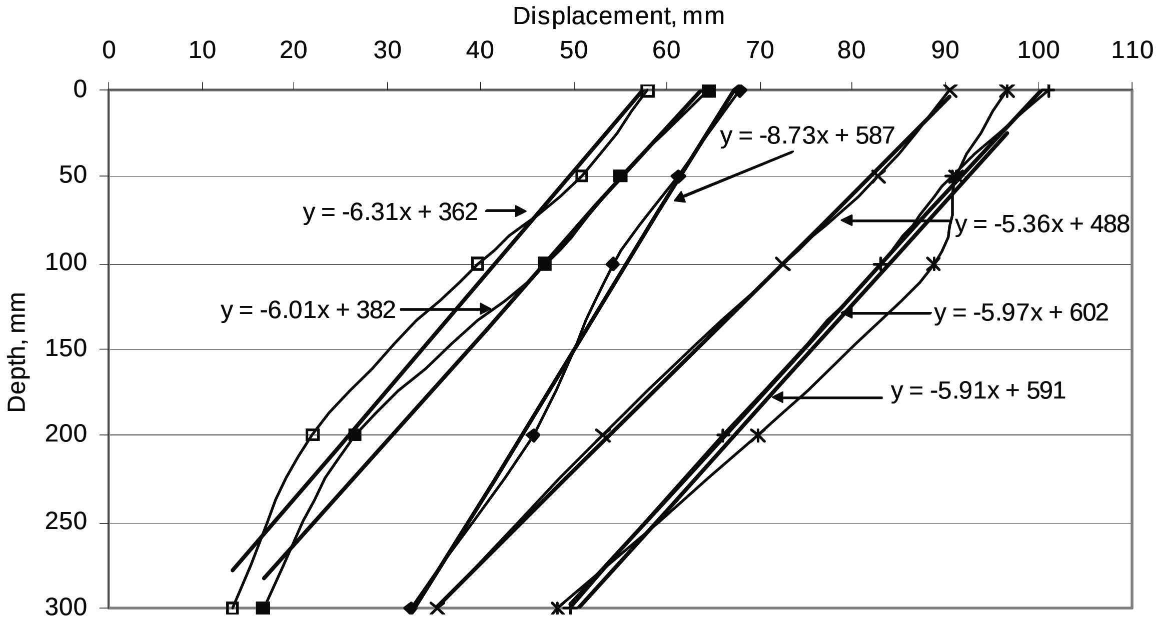

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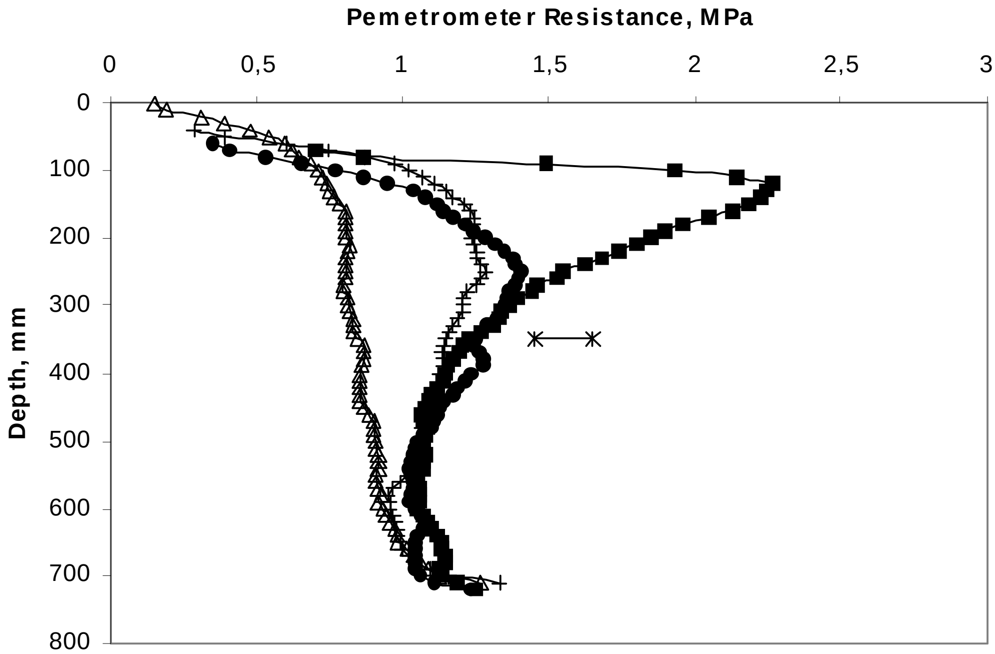

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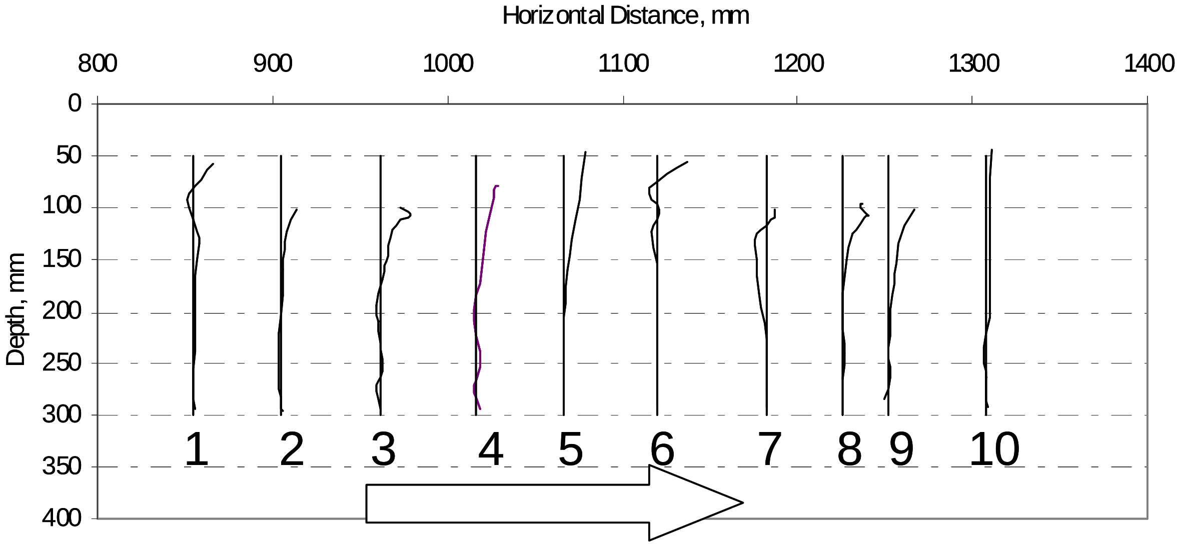

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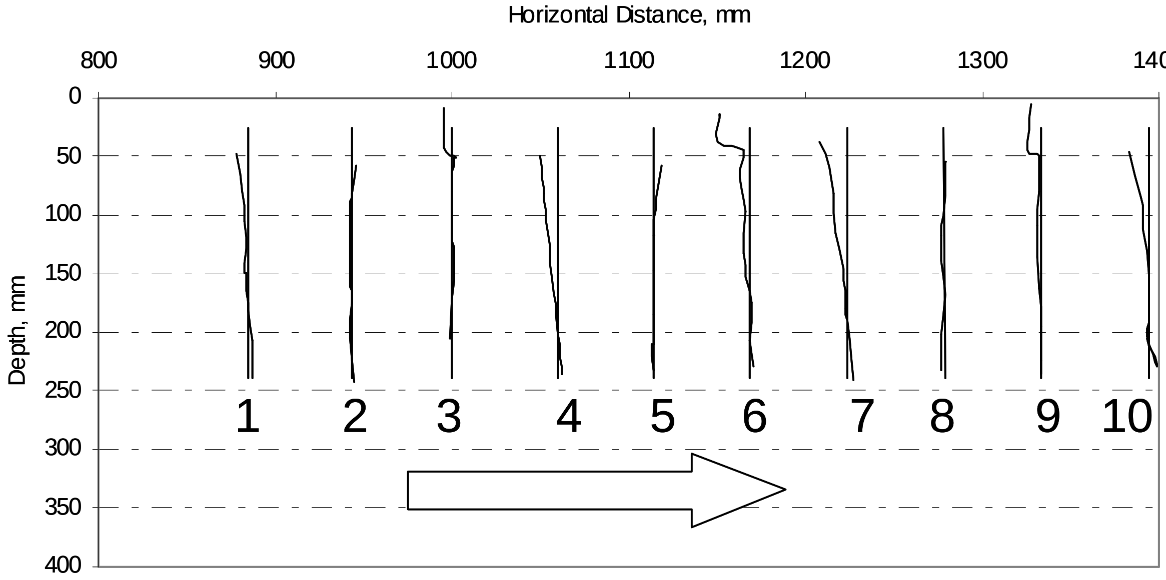

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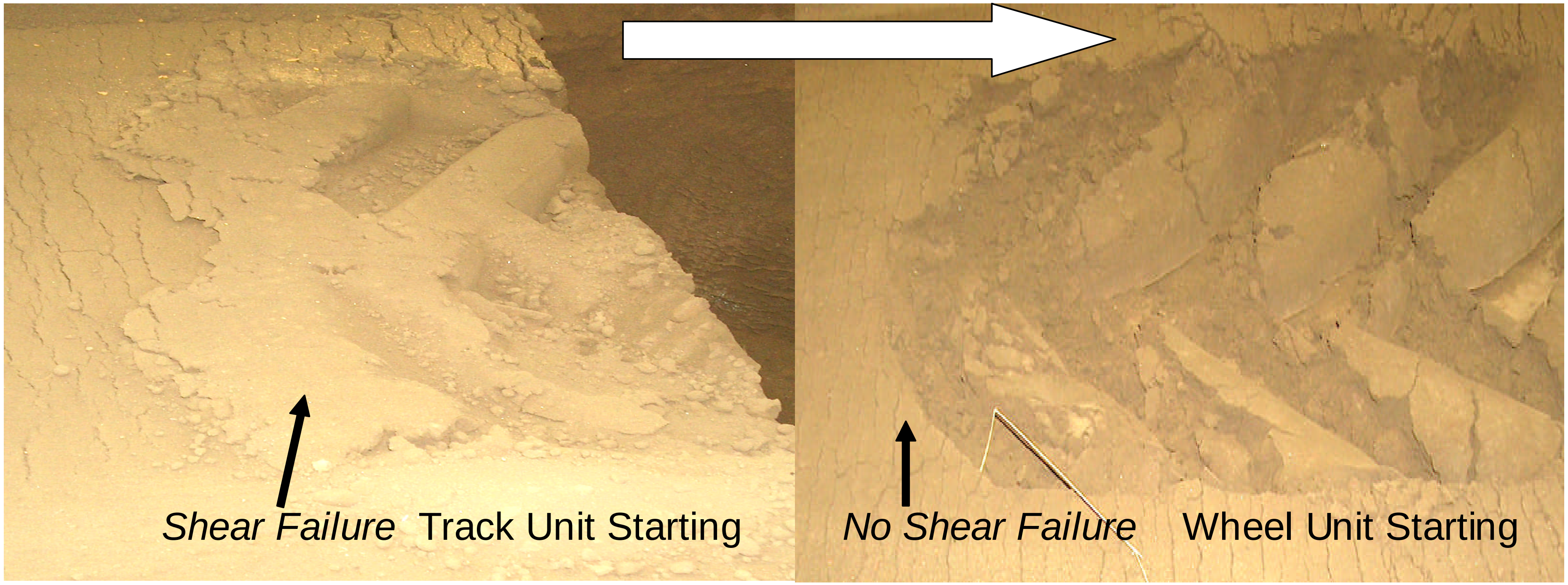

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Table 1

Tyre and Track Specifications

Undercarriage System	*Load (t)*	*Inflation Pressure (bar)*	*Abbreviation Section Width/Load/Inflation Pressure*
680/85 R32	10.5	2.2	680mm/10.5t/2.2bar
800/65 R32	10.5	2.5	800mm/10.5t/2.5bar
900/65 R32	10.5	1.9	900mm/10.5t/1.9bar
800/65 R32	10.5	1.25	800mm/10.5t/1.25bar
Claas Terra Trac	10.5	-	T10.5t
Claas Terra Trac	12	-	T12t
500/70 R24	4.5	2.3	500-70mm/4.5t/2.3bar
500/85 R24	4.5	1.4	500-85mm/4.5t/1.4bar
600/55 – 26.5	4.5	1.4	600mm/4.5t/1.4bar
710/45 – 26.5	4.5	1.0	700mm/4.5t/1.0bar
23.1-26	4.0	1.2	23in/4t/1.2bar
11.5/80-15.3	1.5	2.0	11in/1.5t/2.0bar

Table 2

Whole Machine Specifications

Front Axle Specification	*Rear Axle Specification*
T12t	700mm/4.5t/1.0bar
T12t	500-70mm/4.5t/2.3bar
900mm/10.5t/1.9bar	700mm/4.5t/1.0bar
900mm/10.5t/1.9bar	500-70mm/4.5t/2.3bar
680mm/10.5t/2.2bar	500-85mm/4.5t/1.4bar
900mm/5t/0.5bar	Three subsequent passes
23in/4t/1.2bar	11in/1.5t/2.0bar