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Mine Detonation Trailers: Stresses Induced by Wheels Below the Surface of a Soil Road

This article examines the use of wheels to detonate mines buried in soil roads. Realistic pressure patterns and loading of the footprints of two types of detonation wheel were established. Solid modeling created typical tire footprints above a medium representing soil. Finite element analysis investigated stress patterns in the soil for two types of wheel at loads of both 1,800 and 5,000 kgf.

by Peter Renwick [Independent Consultant]

Detonation trailers are used to prove the safety of roads that have been cleared of anti-tank mines. There have been a variety of rollers used on roads, varying from the (rarely used) steel rollers, through the solid-tired rollers to the pneumatic tires used on the Chubby and the HALO Multidrive. These rollers were initially developed in South Africa and Rhodesia in the 1970s in response to road mining by independence movements. These developments are fully documented by Peter Stiff.1

One example of such a vehicle is the Chubby Detonation Train. This type of vehicle was originally deployed during the conflicts in southern Africa. They are now being used by humanitarian mine-clearance organizations, principally in Angola. There is some concern as to how effective these detonation trailers are when employed in such operations—they have not yet detonated any mines; but, it is not certain whether this is because there have been no mines in the road or because they have developed insufficient force to activate the fuze. It is unfortunate that the wheels of these detonation trailers are only loaded to about 36 percent of the typical wheel loads of the heavy trucks. The HALO Trust recognizes this inadequacy and, as a result, has developed a prototype detonation trailer fitted with pneumatic tires, which is able to exert a force of 5 metric tons per wheel. There is a difference in the way that rollers transmit their load into soil. A solid tire deflects very little. A steel wheel does not deflect. A pneumatic tire spreads itself over the road surface according to the load on the tire and the inflation pressure of the tire. The area covered by the tire is referred to as the “footprint.”

This article examines the ways in which soil stresses can be increased both by increasing the tire load of pneumatic tires and by substituting steel wheels of similar dimensions. This paper uses soil mechanics theory, in particular the theories applied to road engineering, to examine the way in which forces exerted by wheels may be transmitted down through the soil by both pneumatic tires and solid wheels.

Methodology

Comparison was made between an actual pneumatic tire loaded with 1,800 kgf and an actual pneumatic tire loaded with 5,000 kgf. The tire pressure in both cases was 7 bar, this being the maximum pressure for a tire. All wheels were 1,100mm in diameter, with a tread width of 300mm.

Footprints and tire pressure for the pneumatic tires were measured on the HALO medium detonation trailer and the HALO prototype heavy detonation trailer. For a low-pressure tire, the pressure exerted by the footprint is relatively constant and approximately equals the tire-inflation pressure. For a high-pressure tire, the high pressure induces
considerable tension in the carcass of the tire, which distorts the pressure of the footprint. In this case, higher pressures are found in the center of the footprint where the pressure approximately equals the tire-inflation pressure. From the center of the footprint, pressure was seen to diminish toward the outer edges of the footprint (for example, see Evaluation of the Effects of Tire Size and Inflation Pressure on Tire Contact Stresses and Pavement Response). This difference can be depicted on the footprint as contours of pressure. Evidence of the uneven nature of pressure from the footprint of a high-pressure tire is also outlined by in the Survey on Tyre Contact Area and Ground Pressure Models for Studying the Mobility of Forest Tractors.

These tires were compared with a hypothetical steel wheel loaded with 1,800 kgf and 5,000 kgf. The length of contact for the steel wheel was calculated to provide an area sufficient to support the wheel at a given soil strength.

Finite element analysis aided this investigation. To establish the validity of using FEA, a test was first conducted to determine the bulbs of pressure under a uniform circular load (Figure 1). These results compared closely with those predicted by Boussinesq’s Application of Potential to the Study of the Equilibrium and Movements in Elastic Soil (Figure 2), as illustrated in Soil Mechanics for Road Engineers.

With the viability of FEA established for this study, it was then necessary to develop a method to analyze the way forces are applied to the road by:

- A pneumatic tire 300mm wide, 1,100mm in diameter, with a smooth tread (no tread pattern) and inflated to 7 bar, loaded with 1,800 kgf
- A pneumatic tire 300mm wide, 1,100mm in diameter, with a smooth tread and inflated to 7 bar, loaded with 5,000 kgf
- A plain steel wheel 300mm wide, 1,100mm in diameter and loaded with 1,800 kgf
- A plain steel wheel 300mm wide, 1,100mm in diameter and loaded with 5,000 kgf

These scenarios are related to machines used to roll mines, the HALO/Multidrive prototype heavy detonation trailer, the HALO/Multidrive medium detonation trailer and the steel-wheeled Casspir.

For each type of tire/wheel and wheel load, a three-dimensional solid model was created in Autodesk Inventor, which would mimic both the base of the tire and the soil. These models (Figures 3, 4 and 5) were based on a block 1,000mm by 1,000mm by 300mm representing the soil. To the top surface of each block smaller shapes were added.
depending on which type of wheel was being modeled. The FEA model allows only uniform pressures to be applied. A force was applied uniformly to the top surface of each shape. Each shape transformed this force into appropriate contours of pressure at the junction of the large block and the smaller shape above it representing wheel/soil interface. These contours of pressure for the pneumatic tires were organized to decline from a peak of 7 bar in the center, which is the maximum tire pressure.

Figures 3 and 4 mimic the effects of the footprints of 1,800-kgf and 5,000-kgf pneumatic tires. Figure 5 mimics the footprint of a steel wheel as a narrow strip whose width is varied to reflect the difference between a contact area produced by a 1,800-kgf and a 5,000-kgf steel wheel.

To this solid model forces were applied using the FEA package ANSYS 10®. The model treats the soil as a homogeneous solid and calculates von Mises stresses accordingly.

The effect of elastic deflection in the most severe case—being a 5,000-kgf steel wheel above a 200-mm diameter cavity 100mm deep—was examined using a Young’s modulus of 300 MPa, which equates approximately with a laterite road whose soil strength, measured by the California bearing ratio, is CBR 30. The maximum elastic deflection shown by FEA was 0.75mm. This movement is insufficient to operate a fuze. Altering a Young’s modulus of the solid did not alter the stress patterns. The matter of elastic deflection was not examined further.

The 1,800-kgf tire had a footprint 300mm by 300mm and produced circular contours of diminishing pressure from the center. The 5,000-kgf tire had a footprint 300mm by 480mm and produced elliptical contours of diminishing pressure from the center. The steel wheels exerted their pressure from strips 30mm and 83mm wide for the 1,800-kgf and 5,000-kgf loads, respectively. The assumption is that the nature of the force applied by the steel wheel peaks at the precise base of the wheel and diminishes linearly to each side. Here the assumption is that we are dealing with a hard, dry soil that does not deform plastically. Damp clay would be otherwise.

Initially, models were created for each of the three wheel type load conditions where the block representing the soil was a uniform medium. The investigation was then carried further. The dynamics of the fuze mechanism of an anti-vehicle mine also have to be considered. To detonate a mine, the fuze has to move. The force or pressure that begins to move the fuze plate can, under the influence of soil bridging, decline before sufficient movement has occurred to cause detonation. An attempt has been made to mimic this effect in FEA by creating a cavity in the medium whose diameter represents the fuze area of a mine. The diameter of the cavity has been varied from 100mm through 150mm to 200mm, and it is set at 100- and 200-mm depths, respectively.

The FEA model then calculated the stresses (expressed as Von Mises stress) throughout each solid model. The program allowed one to take a sectional view of these stresses on chosen planes. By choosing a plane close to the interface between the big block (representing the soil) and the smaller block (representing the footprint), one is able to view the characteristics of the pressure contours at what would be the tire/road interface.
Results

FEA showed the different ways pressure is distributed through the soil by pneumatic tires and steel wheels. Comparing Figures 7 and 8, one sees how the extra load is spread more widely with the 5,000-kgf pneumatic tire, resulting in little added benefit.

Soil pressures with a shallow cavity. A big increase in tire load from 1,800 kgf to 5,000 kgf gives a disappointing 30-percent improvement in soil pressure at a 75mm depth in plain soil. The effect of bridging over the various cavities at that depth reduces that advantage to a 20-percent improvement on average.

Switching from pneumatic tires to steel wheels—both at 1,800 kgf—yields a more worthwhile improvement—31 percent in plain soil and an average of 60 percent over the three cavity sizes. It is also significant that the 1,800-kg steel wheels created the same pressure at a 75mm depth in plain soil as the 5,000-kgf pneumatic tire. Where the effect of cavities was examined, the 1,800-kgf steel wheel had advantages averaging 35 percent over the 5,000-kgf tire. Steel wheels loaded at 5,000 kgf showed significant advantage over other wheels, being three times more successful than 1,800-kgf tires at 75mm deep.

Soil pressures with a deeper cavity. Notable is the reduction in pressure at this greater depth. Comparing the tires, the increase in tire load from 1,800 kgf to 5,000 kgf gives a better (79-percent improvement) soil pressure at a 175mm depth in plain soil. The effect of bridging over the various cavities at that depth gives an improvement of 65 percent on average, which is disappointing, considering that the tire load has been increased by 177 percent.

Switching from pneumatic tires to steel wheels—both at 1,800 kgf—improves results in plain soil (31 percent) and over the three cavity sizes (52 percent). The advantage that the 1,800-kgf steel wheels had over the 5,000-kgf pneumatic tire, seen in Figure 12 at a 100-mm depth, was not evident at a cavity depth of 200 mm. Steel wheels loaded at 5,000 kgf still showed significant advantage over all other wheels.

Discussion

How applicable are these findings to using rollers on roads? There is a difference between the uniform, solid modeled material used in the FEA analysis and the road material. Soil roads are non-uniform and fissured. They vary both in material content and moisture level with depth. Most road-engineering data on road strength is gathered from newly constructed roads. Results on long-established laterite roads are difficult to find; for these reasons, it is unwise to use...
this analysis to establish actual levels of stress for different depths or fuze sizes. The value of this analysis must be restricted to comparison between the effects of different wheel types.

**How valid is it to use a cavity in the FEA model to explore the bridging effect of the soil above a fuze?** The use of a cavity is simplistic and can only generally reflect the bridging effect above a mine fuze. Fuzes generally operate by fracture (shearing of a part) or by spring movement. Pressure plates tend to move either as one, like a piston, or more in the center as a diaphragm. It would be impossible to model accurately all the different arrangements.

Steel wheels show such an improvement over pneumatic tires that they should be considered as an alternative. While the 5,000-kgf steel wheel produced excellent results, practical problems may make it difficult to field such a heavy piece of equipment. There is a case for using, for example, steel wheels loaded at between 3,000 and 4,000 kgf, which could still give rise to road stresses significantly above those from truck tires.

Plain steel wheels will slip and slide easily; studs or cleats will be necessary to prevent this action. They will also penetrate and puncture the road surface, further increasing road stresses and resulting in damage to the top skin of the road. This damage may concern road engineers but it is a fact that the more damaging the wheels are to the road, the more likely they are to set off mines. Comparison has been made for only two wheel types; the effect of solid rubber tires has not been analyzed. The relative inflexible nature of solid rubber tires compared with pneumatic tires means that they will give a significantly smaller footprint than a pneumatic tire, depending on the thickness of the tire and the hardness of the rubber. As such, they will exert a more intense pressure on the road than a pneumatic tire. The harder the rubber, the more intense the pressure will be. An extremely hard rubber may approach the properties of a steel wheel in terms of footprint size.

**How valuable is this study?** There is a debate in the mine-action world as to the value of using demining road trains. This study shows that most of the detonation trains (with the exception of the HALO prototype HDT) fail to stress the road as much as a truck.

![Figure 10](image1.png)

**Figure 10:** 3D plot of the data for the 100-mm-deep cavity, pressure measured 75mm deep.

**GRAPHIC COURTESY OF THE AUTHOR**

![Figure 11](image2.png)

**Figure 11:** 3D plot of the data for the 200-mm-deep cavity, pressure measured 175mm deep.

**GRAPHIC COURTESY OF THE AUTHOR**

However, to detonate, all fuzes need to move significantly more than the 0.75 mm achieved by the elastic movement of simulated soil; therefore, bridging must occur prior to detonation. Detonation can only occur if sufficient force is created to fracture this bridge. The cavity in the FEA model was unable to replicate the resistance to movement offered by the fuze prior to detonation. This shortcoming makes it unwise to use the pressures obtained in this analysis as predictive of detonation. Comparison between the effects, however—in terms of stress above the mine—of different wheel types, using cavities of varying size and depth, is valuable.

**Conclusions**

Several conclusions can be made from the results obtained through this study:

1. The benefit of adding extra weight to pneumatic tires is disappointing, much of the additional force being lost. There is, however, significant benefit by using a wheel that is harder than a pneumatic tire.
2. Using steel wheels at wheel loads in excess of 3,000 kgf will improve the margin of safety of detonation trains significantly above that of truck wheels.
3. The effectiveness of mine-rolling diminishes with depth. This reduction is approximately proportional to inverse of the depth raised to the power of 1.5.

**Future Studies**

Where steel wheels are not acceptable, solid rubber tires have the potential to provide a worthwhile improvement over pneumatic tires. Further work would be required to establish the degree of benefit of using solid rubber tires as opposed to steel wheels.

It might be useful to set up a chain of experiments to further investigate what it takes to set off a mine well-cemented in a hard-soil road. This scenario would be difficult to achieve, however. How does one...
replicate the cementing effect of many years of alternating wet and dry season conditions that have set the soil above and around mines so firmly? Such research might be both expensive and inconclusive.

More useful might be the collection of more data on the physical properties of roads and the variation of these properties between wet and dry seasons. A falling mass penetrometer (as used by road engineers) would establish the CBR at the surface and in the layers below. To be meaningful, one would also have to know the composition of these layers both in terms of aggregate/fines and moisture content. Such information would help greatly in accessing the difference in rolling effectiveness between the seasons and among different road material types. See Endnotes, page 114

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As chief designer for Pearson Engineering, Peter Renwick was responsible for the development of a number of machines for mine action, with funding from the U.S. Department of Defense. These machines include segmented rollers for area reduction, the Survivable Demining Tractor and the Rotary Mine Comb. He now works as an independent consultant, assisting mine-clearing organizations and machinery manufacturers. He recently participated in a study of road-clearance techniques conducted by the Geneva International Centre for Humanitarian Demining.

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News Brief

Newly Implemented Demining Program Faces Difficulty in Senegal

Although the government of Senegal finally succeeded in launching a demining program in the Casamance region in early 2008, ongoing conflict has made clearance difficult. The Casamance-based Movement for Democratic Change signed a peace accord in December 2004 with the government of Senegal; however, violence persists. Recent mine casualties have brought the continuing threat of landmines to the forefront once again.

Demining efforts in the region have been modest because of the security situation. International partners have said that current demining staff, numbering in the single digits, will need to be supplemented with as many as 250 personnel if demining is to have a serious impact. More than 90 villages in Casamance are mined, disrupting the lives of 90,000 villagers; additionally, 149 more villages are suspected to be mine-contaminated.

UNICEF and other international organizations, like the United Nations Development Programme and Handicap International, have been taking small, measured steps to increase safety and awareness despite the precarious situation. UNICEF has marked potentially dangerous areas and delivered mine-risk education to 500 schools in the area. Demining efforts by the Senegalese Army have been sporadic, helping but not healing the mine situation.