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A model for prediction of vertical stress distribution near the soil surface below rubber-tracked undercarriage systems fitted on agricultural vehicles

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ABSTRACT

Rubber-tracked vehicles are becoming increasingly popular in agriculture. Rubber-tracked undercarriage systems are typically fitted instead of tyres on heavy agricultural vehicles, with the aim of e.g. decreasing soil stress and soil compaction risks. Therefore, accurate prediction of soil stresses below rubber-tracked systems is important. Here, we present a model for prediction of vertical stress distribution at the rubber track–soil interface. In the model, the rubber-tracked undercarriage system consists of a front and rear wheel (idler and drive wheel) and a number of support rollers. The stress distribution in the longitudinal direction under a wheel or roller is described by harmonic oscillation, with the dynamic contact length being a function of wheel or roller diameter. In the lateral direction, the stress distribution is modelled by a linear function, with the maximum stress under the centre line of the track. Model input parameters include the load on the track, track width, track length (distance between front and rear axles), number of support rollers and wheel and roller diameter. The model, which is written in Visual Basic and implemented as a macro in an Excel spreadsheet, then computes the vertical stress at the rubber track–soil interface based on these inputs and the stress distribution generated in the contact area can be used to simulate soil stresses. The model provides realistic estimates of the vertical stress at the contact between rubber track and soil, thereby improving predictions of soil stress and the compaction risks of rubber-tracked agricultural vehicles.

1. Introduction

Soil compaction caused by agricultural machinery traffic negatively influences a range of soil functions and ecosystem services, such as soil productivity, water storage and soil filtering function. In principle, compaction occurs when soil mechanical stress exceeds soil mechanical resistance (soil strength). Consequently, the risk of soil compaction could be reduced by either reducing soil stress or by increasing soil strength. In practice, it is much easier to regulate the soil stress induced by the vehicle running over the soil than to control soil strength, which is largely influenced by soil structure, soil–root interactions and soil matric potential. The soil stress can be reduced by either reducing the load or by increasing the contact area of agricultural machinery. Furthermore, soil stress can be reduced by achieving a close to uniform stress distribution at the tyre–soil or track–soil interface.

Rubber-tracked undercarriages that replace the tyres on agricultural machinery have become increasingly popular in recent years. Such rubber-tracked systems are fitted mainly on tractors and harvesters. Free-rolling rubber tracks are sometimes used on trailers, but these are rare. Different systems exist for tractors: quad-tracks (i.e. four tracks replacing wheels) or two long tracks (one on each side). Harvesters (combine harvesters, self-propelled sugar beet harvesters) typically only have rubber tracks on the front axles and tyres on the rear axles. One of the main reasons for using rubber tracks instead of tyres on agricultural machinery is to mitigate soil compaction, due to the larger contact area of tracks compared with tyres. Another important reason is to improve trafficability, i.e. allow traffic at high loads on wet soil.

Our previous work (Keller et al., 2002; Arvidsson et al., 2011) has shown that the vertical stress at the rubber track–soil interface is unevenly distributed. As a consequence, the maximum stress in the contact area is much larger than the average ground stress calculated from the load and the track contact area. This may

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jeopardise the track's potential for reducing the risks of soil compaction. We have demonstrated that the stress distribution at the tyre–soil interface has a significant impact on the stress pattern in the soil profile (Keller and Arvidsson, 2004; Keller and Lamandé, 2010; Keller et al., 2014). One could expect the stress distribution at the track–soil interface to affect the stresses in the soil in a similar way.

Various models for predicting the performance of rubber-tracked vehicles have been developed (Garber and Wong, 1981; Wong et al., 1984; Dwyer et al., 1993; Okello et al., 1998; Ma and Perkins, 2002). They use an approach that combines geometrical considerations and force equilibrium of the track–soil interaction with empirical pressure–sinkage relationships (e.g. by applying the equation proposed by Bekker (1969)). The normal stress at the track–soil interface is calculated from sinkage, which in turn is calculated from the load, track unit geometry and soil strength parameters, using empirical equations (e.g. Bekker, 1956). The focus of this suite of models is on the tractive performance of track units. While these models are very valuable and allow detailed quantitative description of track–soil interaction, they typically include many parameters and rely on data on soil strength parameters derived from plate sinkage and shear tests that are not easily available. Therefore, such models cannot be readily combined with soil compaction models that predict the stress propagation and soil deformation in the soil profile.

This paper presents a simple model for prediction of the vertical stress beneath rubber-tracked undercarriage systems fitted on agricultural vehicles. The objective in development work was to produce a model that predicts the vertical stress in the contact between rubber track and soil from easily obtainable track properties. A static approach, similar to that used by Keller (2005) and Schjønning et al. (2008) for their model that predicts the vertical stress in the contact between tyre and soil from readily-available tyre properties, was also adopted in the present work. The simulated stress at the track–soil interface was then used as the upper stress boundary condition to simulate soil stresses.

2. Measurements of vertical stress below rubber-tracked undercarriages

A typical rubber-tracked undercarriage system used on agricultural vehicles has a front and rear wheel and two to four rollers, where the diameter of the wheels is typically larger than that of the rollers (Fig. 1). The arrangement of the wheels and rollers is often symmetrical with respect to the middle of the track length, and the front and rear wheel are often of the same diameter. However, other systems exist, for example, the rear wheel may have a larger diameter than the front wheel (e.g. some rubber-tracked systems on tractors with one long track per side).

We used the data reported by Keller et al. (2002) and Arvidsson et al. (2011) to find suitable equations for describing the distribution of vertical stress below rubber-tracked undercarriage systems, to derive empirical relationships between model parameters and properties of the rubber-tracked undercarriage system, and to compare simulated with measured stress distributions, as described below.

Keller et al. (2002) measured the vertical stress distribution below a tractor equipped with two long rubber tracks (total weight: 185 kN; track dimensions: 3.1 m × 0.7 m; four support rollers; average ground stress: 43 kPa). Arvidsson et al. (2011) made stress measurements using a medium-sized tractor fitted with four tracks (weight on rear axle: 47 kN; track dimensions: 1.9 m × 0.6 m; three support rollers; average ground stress: 21 kPa). For further details, see the respective publication. The vertical stress distribution near the track–soil interface was measured at 0.1 m depth using compression load cells that were placed on a line perpendicular to the driving direction at the centre line of the track, at the edge of the track and at an intermediate position between centre and edge. We assumed that the stress at the contact would not be significantly different from that measured at 0.1 m depth, although we acknowledge that stress peaks are slightly dampened at 0.1 m. The method is described in detail in Keller et al. (2002) and Keller (2005).

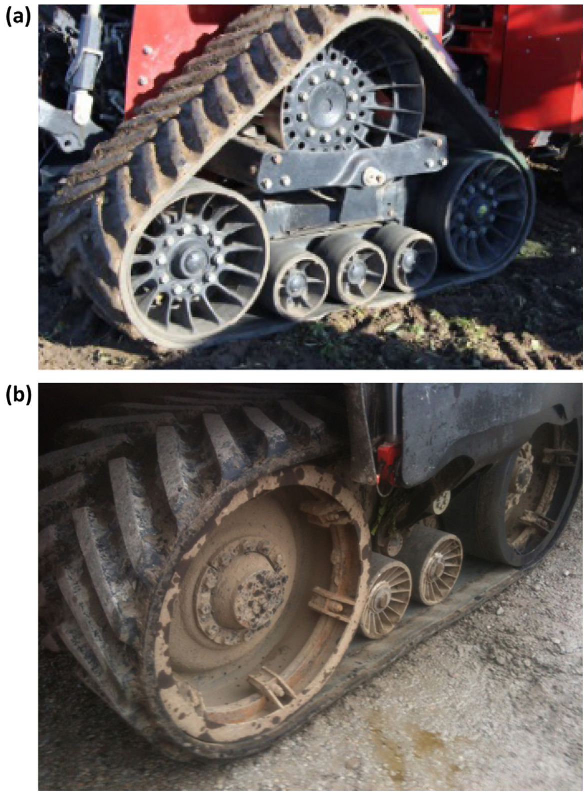

Fig. 1. Example of rubber-tracked undercarriage systems fitted on (a) a tractor and (b) a combine harvester.

3. Model development

3.1. Basic model equations

The contact area at the track–soil interface, A, was described by a rectangular form:

$$A = W_c L_c \quad (1)$$

where W_c is the contact width and L_c the contact length.

The distribution of vertical stress, σ, in the longitudinal direction (i.e. the driving direction) under a moving wheel (idler or drive wheel) or roller of the undercarriage system was described by harmonic oscillation:

$$\sigma(x) = \left(\frac{\sigma_{\max}}{2}\right)\left[\cos\left(\left(\frac{2x}{L_r}\right)\left(\frac{\pi}{2}\right)\right)+1\right] \quad (2)$$

where $\sigma_{\max}$ is the maximum vertical stress under the axle, L_r is the dynamic contact length of one wheel or roller, and x is the x-coordinate taking values between $-L_r/2$ and $+L_r/2$ (Fig. 2a). The amplitude in Eq. (2) is half the maximum stress, i.e. $\sigma_{\max}/2$. The description of the longitudinal stress distribution used here (Eq. (2), Fig. 2a) is similar to the formula for stress distribution under a moving tyre proposed by VandenBerg and Gill (1962) and used by Or and Ghezzehei (2002). Here, we used the cosine rather than the sine