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Assessing Soil Stress Distribution from Agricultural Machinery

The tendency in technical development in agriculture is towards heavier and higher-capacity machines, where tyre size and form is decisive on depth effect and stress distribution, depending on soil type and hydraulic situation. Using nomograms, the distribution of soil stress with given soil conditions tyre contact areas - ground interface - and machine masses can be derived graphically. This procedure, which is based on well known principles of soil mechanics, can assist in decision making on the use/purchase of appropriate machines and/or tyres.

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Keywords

Machine mass, tyre size, soil stress distribution

Structural changes in agriculture have resulted in the last 50 years in tremendous changes in harvesting technology [1]. The accompanying trend to bigger and higher capacity machines does not only imply special requirements on technical developments, but also on the load of the soil, which as a natural, not renewable resource must bear increasingly higher machine loads. The maximum load a soil is able to bear is defined by the so-called pre-compression stress (DIN V 19688) [2]. To assess the risk for unfavourable soil deformation due to machine-use not only stability parameters like the pre-compression stress are needed but also induced stress increases in the soil upon loading. In this respect modelling has made much progress during the last years. However, advanced computer techniques like the finite element model (FEM) are usually not available to farmers. With the aid of nomograms it is possible to estimate with sufficient accuracy the stress distribution underneath a loaded finite area by means of a graphical procedure. This procedure is demonstrated on four different loading cases.

Determination of stress distribution under tyres

Theory

The theory on the distribution of stresses in the soil is based on the studies by BOUSSINESQ [3]. His well known equation has been extended by FROEHLICH [4] to account for various soil stabilities by introducing the so-called concentration factor vk. For most soils this concentration factor varies between 3 (=very stable hard soil) and >5 (=unstable soft soil) [5]. An increasing concentration factor leads to a pressure increase under the load centre and therefore to a deeper penetration of soil stresses. Stresses under a load applied to a finite area may be calculated by integrating the BOUSSINESQ or FROEHLICH formulas for a point load (principle of superposition). Since the expressions are sometimes rather difficult to integrate and may partly be solved only by numerical approximations, corresponding nomograms and tables have been developed to facilitate the calculations [6].

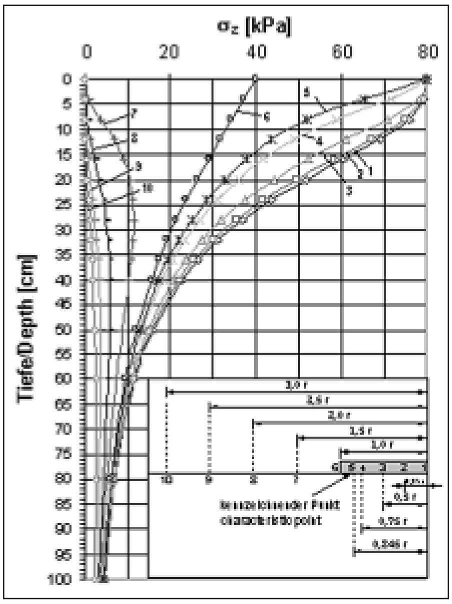

Fig. 1: Vertical soil stress function (σ_z) in different distances from the load centre of a circular load area. Point 1 = load centre, point 6 = edge of tyre, point 10 = one tyre-diameter distance from the edge of the tyre

The summation of the single solutions under discrete elements of a subdivided arbitrarily shaped contact surface as suggested by Newmark [7] and Soehne [8] are usually cumbersome. To avoid this, one may without a substantial loss of accuracy assume the tyre contact area to be of circular shape. Grasshoff [9] supplies for a non-rigid, equally distributed circular load a table of so-called influence factors which serves for the calculation of vertical soil stresses for various points under as well as outside the contact area (*table 1*). Non-rigid loads (= no flexural rigidity) result in comparison to rigid loads (= infinite flexural rigidity) principally in a different stress distribution. However, the settlement of the load is for the so-called characteristic point (circular load = 0,845 • Radius) for both cases considered to be the same. Thus for settlement analysis it is possible to revert to the stress distribution at the characteristic point of a non-rigid load [10].

Method

First, the vertical stresses for different distances from the load centre are determined as a function of depth. To do this the vertical stress is computed from the product of the influence factor in table 1 and the ground contact pressure $\sigma_z = i \cdot p$ for various depth to radius of contact area ratios (z/r). From the tyre radius r the corresponding depth in which the computed vertical stress prevails can be calculated form $z = (z/r) \cdot r$. Thus a set of curves is derived each representing the stress distribution at a distinct distance from the load centre (*Fig. 1*). The nomogram in figure 1 then allows for a graphical determination of soil stresses in the form of the well known pressure bulbs by choosing appropriate isobars (e. g. 10, 20, 30, ... kPa) and reading the depth in which the isobar intersects each curve. The distance from the load centre represented by the curves and the depth of the intersection with the isobar give the co-ordinates of the isobar in the r,z-plane. Connecting all points of equal stress finally delivers one half of the pressure bulb, which due to rotational symmetry may be mirrored at the axes of the load centre (*Fig. 2a*). In an analogous manner further nomograms may be derived for various contact pressures and tyre diameters thus enabling the determination of the pressure bulb for arbitrary machine dimensions (*Fig. 2b, c, d*).

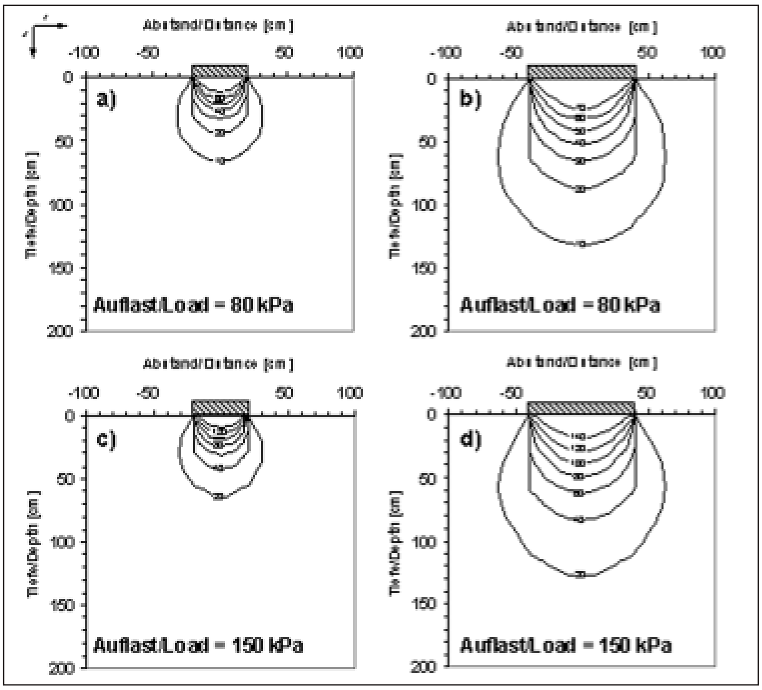

Fig. 2: Pressure bulbs (isobars in kPa) of vertical soil stresses for different wheel loads and tyre diameters. a) wheel load = 1 t, Ø = 40 cm; b) wheel load = 4 t, Ø = 80 cm; c) wheel load = 1,9 t, Ø = 40 cm; d) wheel load = 7,5 t, Ø = 80 cm

Influence of the load and tyre dimensions on stress distribution

Figure 2 clearly shows that at the same ground contact pressure but with increasing tyre diameter the pressure bulb penetrates deeper into the soil. Underneath the plough pan (> 30 cm) soil stresses at a wheel load of 4 t and a tyre diameter of 80 cm (Fig. 2b) reach approximately 60 kPa while with the same tyre dimension but a wheel load of 7,5 t (Fig. 2d) soils stresses even exceed ~110 kPa. According to DIN V 19688 [2] this means that in the case shown in figure 2b merely as instable classified soils are supposed to react with plastic soil deformation. However, in the case shown in figure 2d also as medium to highly stable soils may react plastic causing irreversible soil deformation underneath the plough pan.

Conclusions

A simple method has been introduced to graphically estimate with the aid of nomograms the stress distribution under agricultural vehicles. The derived pressure distributions point out the limits of a proportionally increase in tyre diameter with increasing wheel load in order to keep ground contact pressures at the same level. Although ground contact pressure may stay the same, higher wheel loads by heavier machines are distributed over a larger soil volume and thus into greater soil depth. This bears the risk that, if soil stability is exceeded, a zone which is not directly accessible by the usually applied tillage tools will be irreversibly compacted. Thus important soil functions like hydraulic conductivity may adversely be affected for long consequently decreasing the period in which the soil is in a favourable condition for machine applications.

Table 1: Influence values for determining the vertical soil stress at different distances to the load axis for different depth to radius ratios of an non-rigid equally distributed circular load (after Grasshoff [9]). Elastic-isotropic soil, $v_k = 3$

z/r	i = σ_z/p									
	0 r	0,25 r	0,5 r	0,75 r	0,845 r	1,0 r	1,5 r	2,0 r	2,5 r	3,0 r
0,2	0,992	0,990	0,977	0,898	0,817	0,465	0,011	0,001	0,0002	0,0001
0,4	0,949	0,963	0,885	0,735	0,650	0,430	0,047	0,006	0,0016	0,0006
0,6	0,864	0,840	0,766	0,615	0,546	0,397	0,087	0,016	0,0048	0,0017
0,8	0,756	0,727	0,652	0,523	0,470	0,363	0,115	0,028	0,0097	0,0037
1,0	0,646	0,619	0,553	0,449	0,409	0,330	0,132	0,041	0,0157	0,0064
1,2	0,547	0,523	0,469	0,388	0,358	0,298	0,140	0,052	0,0222	0,0097
1,4	0,460	0,442	0,400	0,337	0,314	0,269	0,142	0,061	0,0283	0,0132
1,6	0,390	0,374	0,342	0,294	0,276	0,241	0,140	0,067	0,0337	0,0167
1,8	0,332	0,319	0,295	0,258	0,244	0,217	0,135	0,071	0,0383	0,0200
2,0	0,284	0,274	0,256	0,227	0,216	0,195	0,129	0,073	0,0418	0,0230
2,5	0,200	0,193	0,184	0,168	0,162	0,150	0,111	0,072	0,0466	0,0286
3,0	0,146	0,142	0,137	0,128	0,124	0,118	0,093	0,067	0,0471	0,0315
4,0	0,087	0,085	0,084	0,080	0,078	0,076	0,066	0,052	0,0419	0,0316
5,0	0,057	0,056	0,056	0,054	0,053	0,052	0,047	0,041	0,0346	0,0282

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