AD#:	TITLE:
P004 283	The reasearch of the driving wheel with movable lugs of the paddy field floating tractor
P004 284	An investigation of the driving wheel thrust of paddy field tractors
P004 285	Mobility of the small combine (track type) on soft ground - Relationship between the position of the center of gravity and the mobility
P004 286	The stress-strain- ime graph of reheological soils and its application
P005 287	Behaviour of soil under a lugged wheel
P004 288	Prediction accuracy of the torques for rotary tillage by an analog tool
P004 289	The analysis on the dynamic performance of a single lug
P004 290	Study of the motion of agricultural vehicles on steep grass-covered slopes
Pool 291	Some stability and control problems with trailed farm tankers on slopes
P004 292	Control of tractors on sloping ground
P004 293	Stability indicators for front end loaders
P004 294	Pressure tests in soil below tires of agricultural vehicles
P004 295	Quality control in soil compaction by behaviour of exciter
P004 296	Smoother terrain machine
P004 297	Compaction of sand using ordinary off-road vehicles
P004 298	A simple perdiction model for soil compaction under various wheel loads and geometries as an aid to vehicle design
P004 299	Flotation tires and subsurface compaction
P004 300	Tractor power selection with compaction constraints
P004 301	The guidelines to design the lever turning gears in asticulated vehicles
P004 302	Study on controllability and stability of high speed tracked vehicles
P004 303	Forces on undriven, angled wheels
P004 304	Turning behaviour of articulated frame steering tractor

COMPONENT PART NOTICE (CON'T)

AD#:	TITLE:
P004 305	A tracked vehicle test plant for the simulation of dynamic operation
P004 306	Proffleinfluss auf Widerstands-und lenkkraft frei rollender reifen (The influence of the tyre tread on the rolling resistance and steering forces on undriven wheels) (including English translation)
P004 307	Basic study on the turning resistance of track
P004 308	Study on steerability of articulated tracked vehicles

Pressure Tests in Soil below Tires of Agricultural Vehicles

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SUMMARY Design and measuring method of a cheap and efficient soil pressure gauge are described. Soil tank tests carried out in the laboratory demonstrate some properties of the gauge like indifference towards orientation in soil. In the soil bin the gauge measures pressures below tires rolling over and outside in the field the influence of wheel load, number of passes and vehicle speed are investigated. The results are interpreted with modified formulas of Soehne [1], which can be managed by a pocket calculator.

Introduction

Since Soehne [1], [2] and Chancellor [3] had done fundamental work on this subject in the beginning fifties, the amount of fertilization and the weight of agricultural machinery increased as well as the yield rates. Today chemical soil optimization had reached its bounderies and one lookes after possibilities to improve soil structure. Von Boguslawski and Lenz [6] gave valuable advice to this problem. What did the farmer get from science to find out whether compaction is severe or not? He knows, that he has to avoid work under wet field conditions with heavy machinery and he uses the spade to estimate pore volume reduction. Perhaps it will be useful to provide him with reference values of pore volume reduction for several kinds of soils with several degrees of water content.

In view of this aim one has to get information about the range of soil stresses brought up by the actual agricultural machinery. To rise the number of data one has to select an efficient measuring procedure and the significant variables. Most common methods are bulk density and cone penetrometer measurement. Applying them, one has to concern the amount of work, the influencing parameters and the mission. The interdependence of bulk density, cone penetrometer resistance and water content together with varying kinds of soil imply a high number of experiments to get sufficient information in the field.

Measuring Method

This arguments led to the consideration to measure the pressure in soil under the tires of agricultural vehicles, which is causal responsible for soil compaction. To find out the right procedure one has to observe several criteria. The most important are:

1. The gauge should be of a bulk density close to that of the soil, in order to avoid stress concentrations, if the gauge density is higher, or to avoid stress drop at the gauge, if the gauge density is lower.

2. The gauge application should cause a minimum of disturbances in soil and it should be possible in a justifiable range of time.

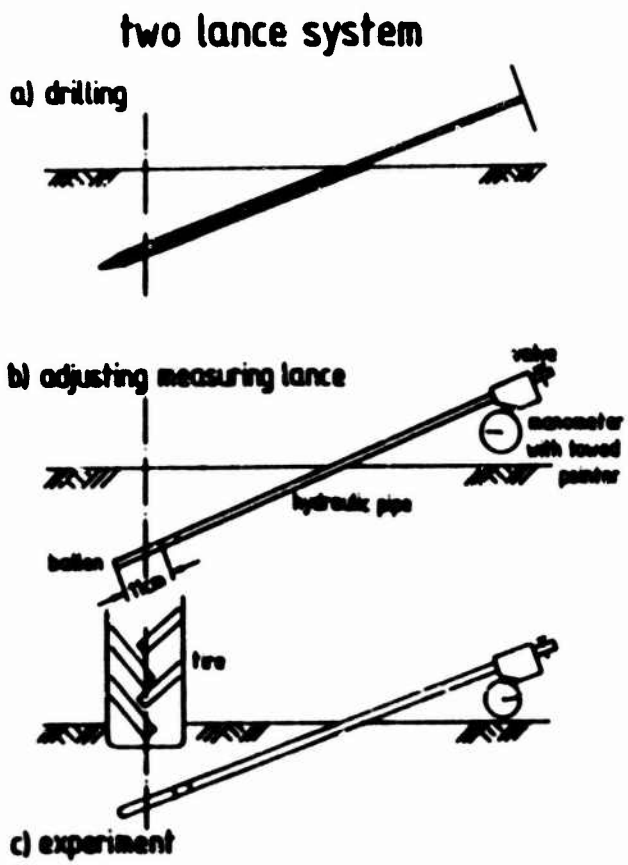

Fig. 1.: Principle and application of the pressure gauge

3. The gauge should measure defined stress components.

4. The gauge should be able to record the pressure during tire operation, to get information about dynamic effects.

5. Inexact gauge orientation in soil should cause minimum errors.

6. To use many gauges at the same time the costs must not be high.

Viewing the literature to this subject many valuable advices have been found for example in the works of Berdan [4], Cooper [5], Hovanesian [7], Barnes [8] and Blackwell [12]. The compromise made to observe most of the shown main criteria represents fig. 1:

A hole inclined about 15^0 - 20^0 to the surface is drilled into the soil, in which a pipe is pushed. A ballon with walls being 0,5 mm thick, a length of 11 cm and a diameter of 2 cm is turned out of the pipe by an air pump. Now the system is filled with water. This causes a gauge density of 1 g/cm³.

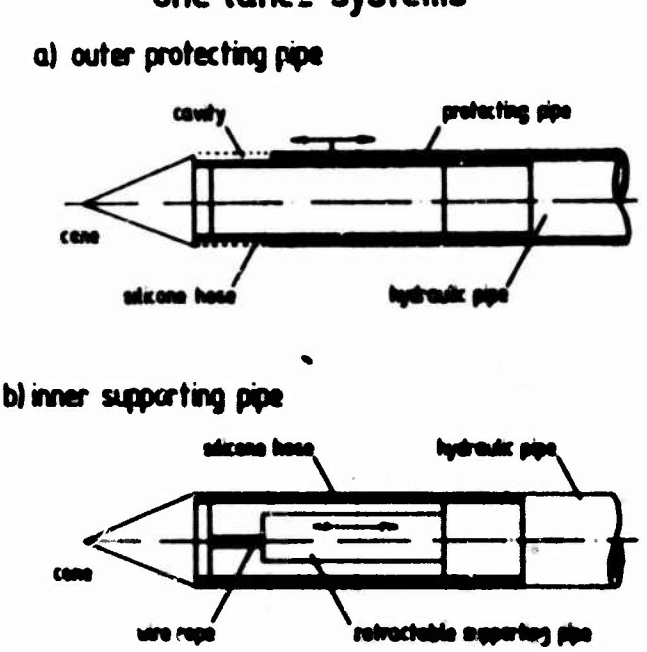

Fig. 2: Designs of one lance systems for simplified soil pressure gauge application

If a mixture of water and magnesium dichloride is used, higher densities are possible. With other fluids gauge densities between 1 and 2 g/cm³ are conceivable, to accommodate gauge and soil density. When the air bubbles are pushed out of the system, the valve is closed and the experiment starts. When the tire rolls over the gauge, the pressure in the system rises. The maximum value can be recorded by a manometer with towed pointer or one can apply a usual pressure gauge with recording system to measure dynamic processes. To improve the handling abilities of this measuring principle, it was tried to design one lance systems shown in fig. 2. Here the three steps in fig. 1 are combined: The cone forms the hole in soil and when the protecting or supporting pipes are retracted, the fluid filled silicone hose with a wall thickness of 1 mm gets flexible similar to the ballon. The most significant advantage of the one lance system is, that turning out the proper gauge and filling the system with fluid is not necessary. Later more details will be described.

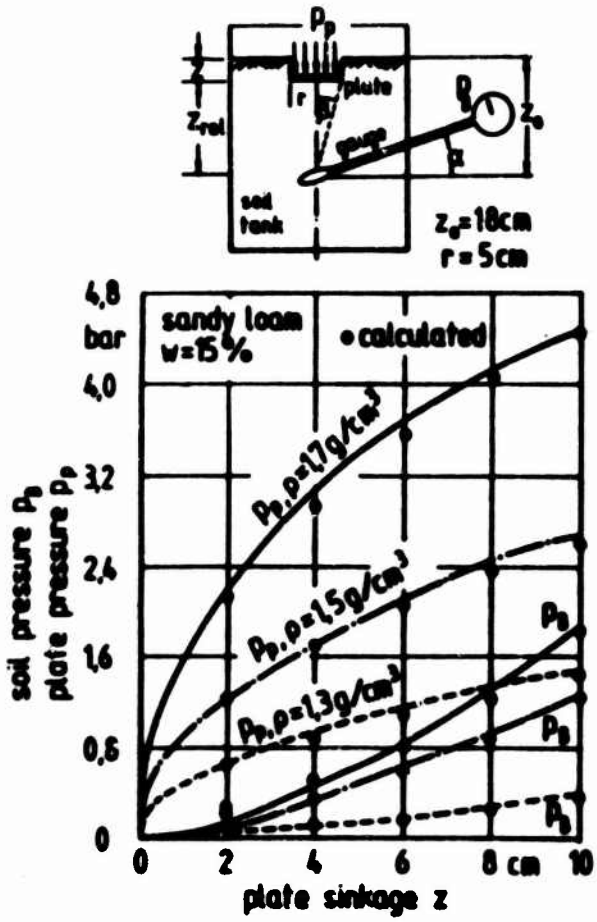

Fig. 3: Testing the pressure gauge in a soil tank with sandy loam of different dry densities

First the properties of the two lance system should be shown. In fig. 3 the curves of the soil pressure p_B in the gauge are plotted against the sinkage z of a circular plate moving into a tank with sandy loam of different densities. Increasing plate pressures p_p cause increasing gauge pressures p_B. With the bulk density the final values at z = 10 cm of p_p and of p_B rise, whereas the caracteristics of the curves don't change. (The water content was 15 %.)

Fig. 4 gives evidence of the tests varying the inclination α of gauge and pipe. The influence is of the order of the variations caused by soil preparation. The reason may be, that the gauge is exposed to the varying

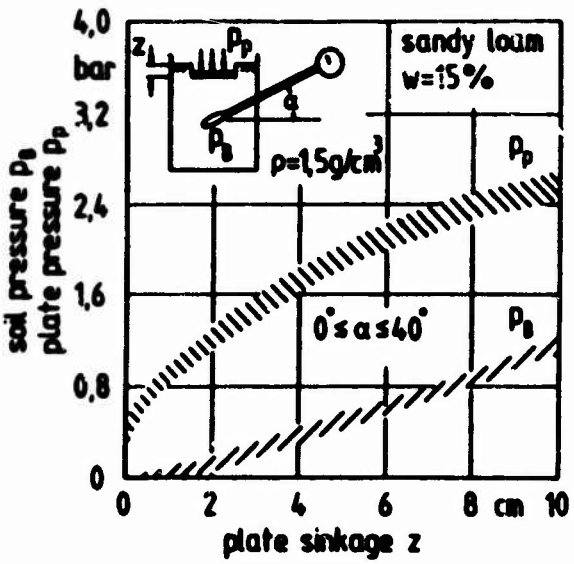

Fig. 4: Influence of gauge inclination α on the measured pressure p_B in a soil tank with sandy loam

stresses on its surface and the manometer shows the mean value of all of them. So turning the cylindric gauge body round its center of gravity is of almost no effect in the range $0^\circ \leq \alpha \leq 40^\circ$. This fact is of advantage during work in field, because the rough terrain causes considerable errors of the measurement of the angle of inclination α. Therefore one always has to excavate the gauge in field after the test to determine its real depth below the surface.

The record of the gauge pressure p_B during the roll over of a tire is plotted in fig. 5 against the position x of the tire relative to the gauge. p_B starts with zero, when the tire is half a meter away from the gauge. It reaches the maximum, when the center of the tire is over the gauge but does not decrease in the same manner. The remaining pressure of 0,25 bar at x = 60 cm reduces to values of about 0,1 bar after some minutes and then does not change for longer time.

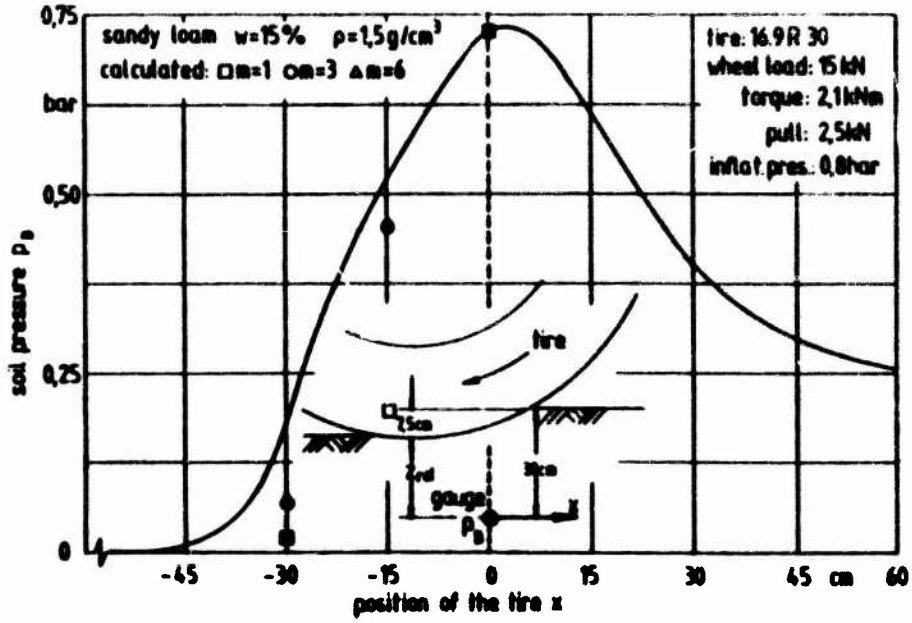

Fig. 5: Record of soil pressure p_B below a tire rolling over in the soil bin of the Institute for Agricultural Engineering of the Techn. Univ. of Munich

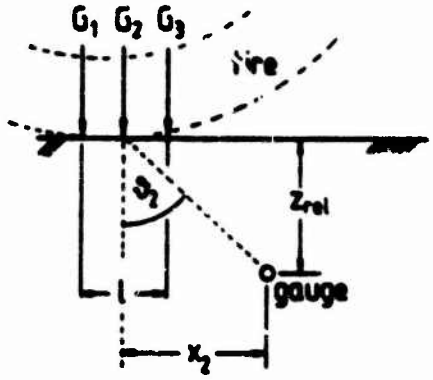

Fig. 6: Approximating the distribution of the wheel load G in the contact area of the tire by three single loads G_1, G_2, G_3

Before field tests were made, it was investigated whether the one lance system (fig. 2a) could be used. Fig. 7 shows the insufficient result: The cavity caused by retracting the protecting pipe has to be filled up with compacting soil and therefore up to a sinkage z = 2 cm no signal p_B is measured. Afterwards p_B is much higher than that measured with the two lance system, surely because the steel cone and the silicon tube are stiffer than the ballon and concentrate stresses on the gauge. The one lance system with supporting pipe (fig. 2b) has not yet been tested, but obviously this system avoids the problems arising with the cavity around the gauge.

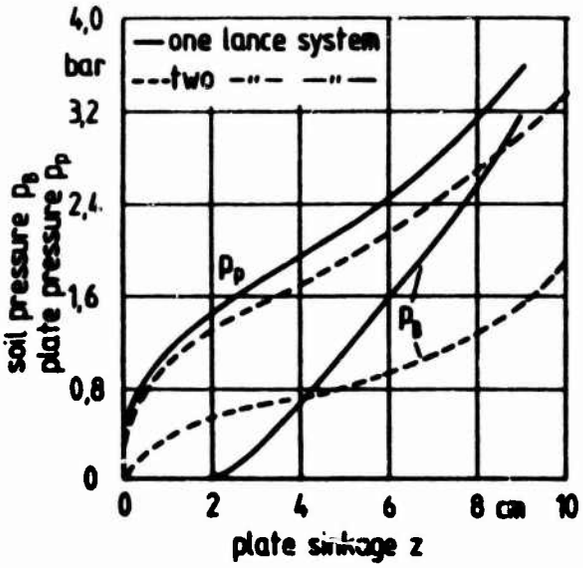

Fig. 7: Pressure p_B in sandy loam in a soil tank, measured with the one lance system (fig. 2a) and the two lance system (fig.1)

Summarizing the important properties of the two lance system in fig. 1 one can say:

1. The bulk density of the gauge can be fitted to that of the surrounding soil by using the right fluid. (For this first tests only water was used).

2. Gauge application causes disturbances in soil as far as the drilling of the hole is concerned. The amount of time for one application is less than 15 minutes.

3. The gauge does not measure defined stress components in the soil, but on the other hand

4. the gauge orientation causes minimal errors. So only the comparison of results is possible at present.

5. Using pressure gauges in spite of manometers one is able to record dynamic processes like the roll over of a tire.

6. The costs of the gauge are of an amount of about 200 - 300 DM, if a manometer is used. (The valve was built with acryl glass, to be able to observe air bubbles rising in the pipe, when the fluid is filled in.)

Field Tests

After introducing the measuring procedure now the results of field tests are described. First it was investigated whether the influence of wheel load is visible in field too. Three vehicles with a wide range of maximum rear wheel loads were tested. The maximum gauge pressure p_B occuring during one roll over correlated to the distance between the contact area of the tire and the gauge z_{rel} is plotted in fig. 8 for a smaller tractor D 4006 with 8.5 kN wheel load on the rear tire. The curve of the DX 140 tractor shows higher values of p_B. Its rear wheel load was twice as high than that of the D 4006. The front wheel of the Fahr 1300 combine harvester was loaded with 34,5 kN. One recognizes that redoubling the wheel load does not lead to redoubled values of the pressure p_B in a certain depth z_{rel}. Supposed z_{rel} = 10 cm, and the p_B-values are related to that of the small tractor, the heavy tractor's p_B is 143 %, that of the combine 257 %.

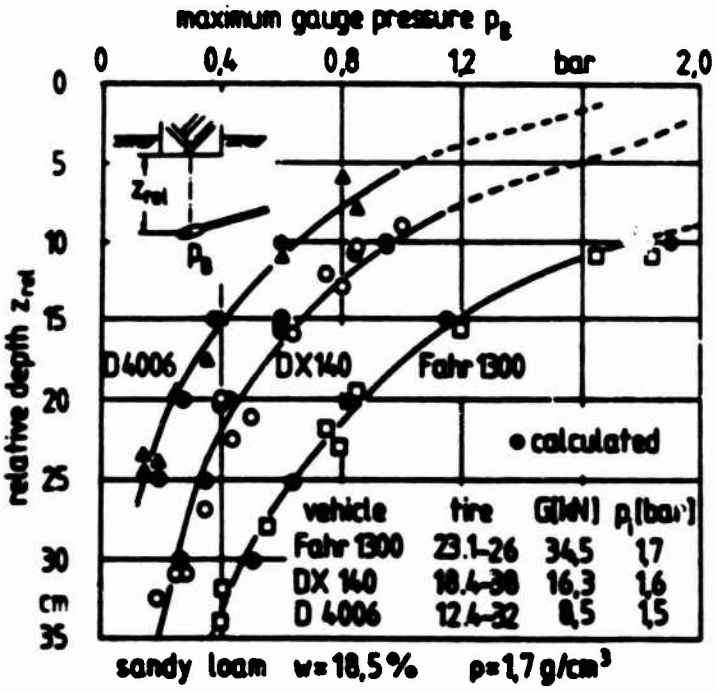

Fig. 8: Gauge pressures p_B in a sandy loam field below vehicles with fast increasing maximum rear wheel loads

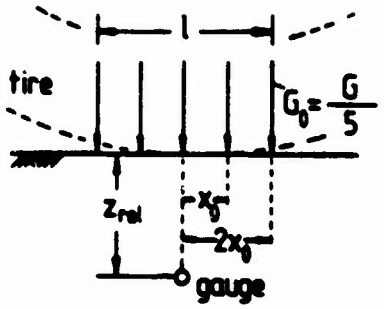

Fig. 9: Approximating the distribution of the wheel load G in the contact area of the tire length l by five uniform single loads G_0

As Raghavan [9, 10, 11, 14, 15] pointed out, besides wheel load the number of passes is of essential influence on compaction. Fig. 10 shows the sinkages z_1, z_5, z_{10} of a tractor after the 1st, 5th and 10th roll over in the same rut. The amount of the maximum gauge pressure p_B increases from the 1st to the 5th roll over more intensive than from the 5th to the 10th. This multi-pass effect on p_B is dependent on the initial pore volume P.V. of the field. Fig. 11 shows the influence of vehicle

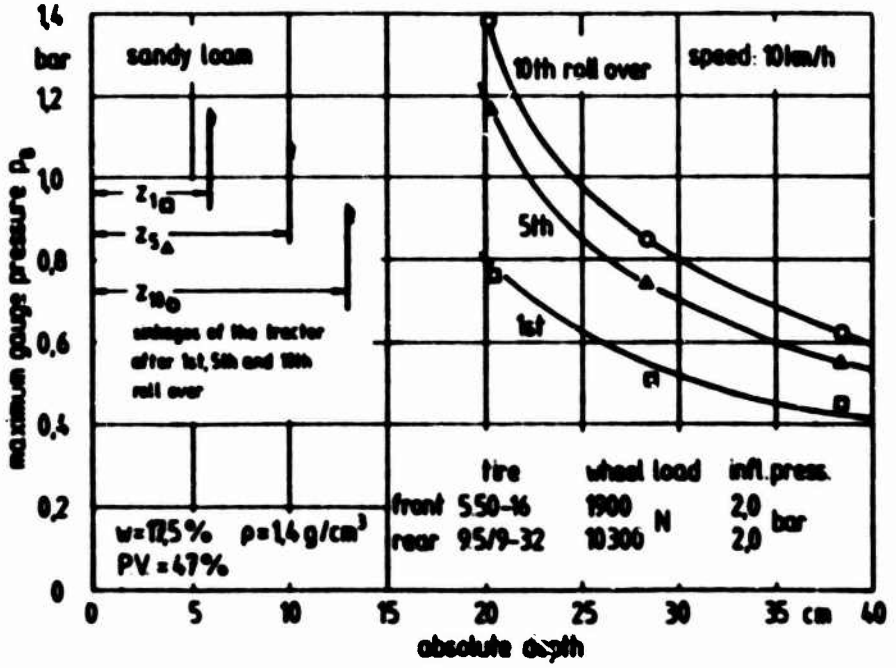

Fig. 10: Gauge pressures p_B in a field with sandy loam after one, five and ten passes

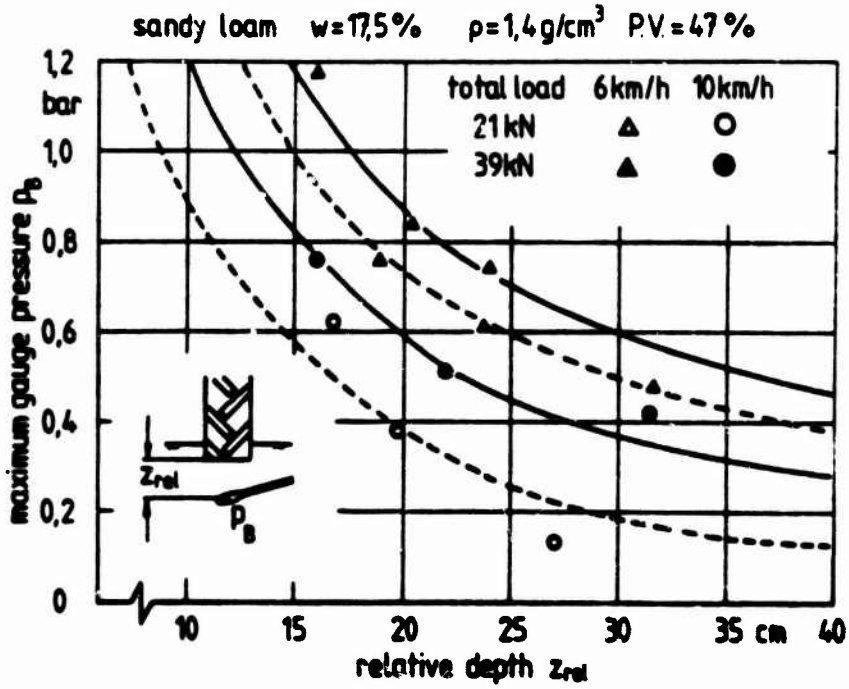

Fig. 11: Gauge pressures p_B in a soft sandy loam of high pore volume P.V. are considerably influenced by vehicle speed

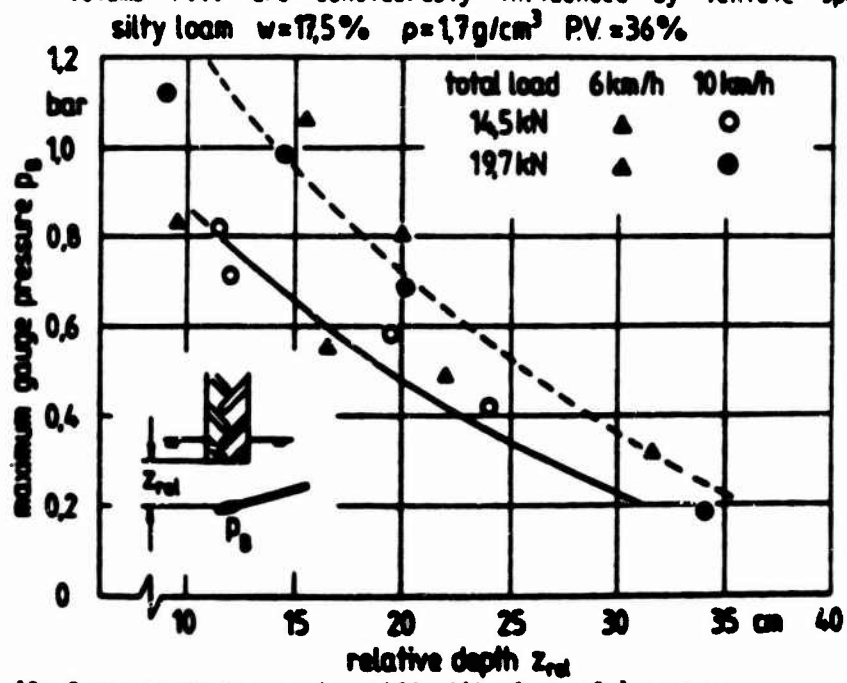

Fig. 12: Gauge pressures p_B in stiff silty loam of low pore volume P.V. are unessentialy influenced by vehicle speed

speed in a soft sandy loam with high pore volume P.V. = 47 % and a dry density of $\rho = 1.4$ g/cm³. Increasing speed reduces the values of p_B. If one compares this results with those of a silty loam with higher initial dry density $\rho = 1{,}7$ g/cm³ and a smaller amount of initial pore volume P.V. = 36 % in fig. 12, one realizes, that only wheel load makes an effect, if the pores filled with air are of considerable smaller amount. So in the silty loam field the influence of vehicle speed is not visible. Both soils had a water content of about 17,5 %.

Soltynski [13] and Stafford [16] have found similar tendencies by investigating the increase of bulk density in soil below tires rolling over.

This view on some field tests should have demonstrated, that the introduced gauge is useful to compare the influence of different vehicle weights, speeds and numbers of passes on soil compaction.

First Simple Analytical Analysis

Now it is tried to apply the formulas stated by Soehne [1]. The vertical stress σ_z in a depth z_{rel} below the load axis of a circular plate of radius r with uniform load distribution p_p in a soil with the stress concentration factor ν is (cf. fig. 3):

$$\sigma_z = p_p \cdot \left(1 - \cos^{\nu}\beta\right) \qquad (1)$$

$$\cos\beta = \frac{z_{rel}}{\sqrt{r^2 + z_{rel}^2}} \qquad (2)$$

σ_z is not identical with the pressure measured by the gauge. But we know, that σ_z is the highest stress component appearing at the gauge. The stresses σ_z together with all other, smaller stress components acting on the fluid filled cylindrical ballon, produce a mean stress p_B in it. Therefore on can state:

$$p_B = c \cdot \sigma_z \quad 0 < c < 1 \qquad (3)$$

If the plate pressure p_p is expressed by the formula describing plate sinkage tests:

$$p_p = k \cdot \left(\frac{z}{z_0}\right)^n \qquad (4)$$

we can combine formulas (1) to (4):

$$\rho_\vartheta = c \cdot k \cdot \left(\frac{z}{z_B}\right)^n \cdot \left[1 - \left(\frac{z_{rel}}{\sqrt{r^2 + z_{rel}^2}}\right)^\nu\right] \qquad (5)$$

The curves in fig. 3 are well approximated by (5), if the constants of table 1 are used:

table 1:

ρ(g/cm³)	k (N/cm³)	n (-)	c(-)	ν(-)	z_B (cm)
1,3	4,8	0,46	0,43	6	1
1,5	9,0	0,46	0,85	5	1
1,7	15,5	0,46	0,85	4	1

(z_B: reference depth)

The stress concentration factors ν had been chosen analogous to those Soehne [1] used in his paper. The assumption that $0 < c < 1$ came true.

To calculate the vertical stress σ_z in the distance x from the load axle of the tire in a depth of z_{rel} below its contact area, formula (6) is useful (cf. Soehne [1]):

$$\sigma_z = \frac{\nu \cdot G}{2\pi \cdot r_\vartheta^2} \cdot \cos^\nu \vartheta \qquad (6)$$

$$r_\vartheta = \sqrt{x^2 + z_{rel}^2} \qquad (7)$$

$$\cos \vartheta = \frac{z_{rel}}{r_\vartheta} \qquad (8)$$

(ν: stress concentration factor)

To take into account, that the wheel load G is distributed over the contact area of the length l of the tire with radius R one can use the formulas (9) and (10):

$$l = \sqrt{R^2 - (R-z)^2} \qquad (9)$$

$$\sigma_z = \frac{\nu}{2\pi} \cdot \sum_{i=1}^{m} \left[\frac{G_i}{(x_i^2 + z_{rel}^2)} \cdot \left(\frac{z_{rel}}{\sqrt{x_i^2 + z_{rel}^2}}\right)^\nu\right] \qquad (10)$$

(z: tire sinkage)

Here i is the index of a proper single load G_i shown in fig. 6. m is the number of single loads.

Regarding (3) we get the term for the gauge pressure p_B:

$$p_B = c \cdot \frac{V}{2\pi} \cdot \sum_{i=1}^{m} \left[\frac{G_i}{(x_i^2 + z_{rel}^2)} \cdot \left(\frac{z_{rel}}{\sqrt{x_i^2 + z_{rel}^2}} \right)^V \right] \quad (11)$$

$$G = \sum_{i=1}^{m} G_i \quad (12)$$

In fig. 5 the results for m=1, m=3 and m=6 are shown for the distances x = -30 cm, -15 cm and x = 0 cm. The wheel load G was divided up into uniform single loads G_i. The constants c resulting from the calculations with a different number m of single loads shows table 2:

table 2:

m (-)	G_i (N)	c (-)	V(-)
1	15 000	0,31	5
3	5 000	0,48	5
6	2 500	0,48	5

V was set to 5, because the soil bin was filled with the same sandy loam used for the soil tank tests (fig. 3). The mean density in the bin was ρ = 1,5 g/cm³ and the water content (dry base) w = 15 %. Fig. 5 shows, that the step from m=1 (1 single load) to m=3 (3 single loads) improves the result of the calculation significantly, but not the step from m=3 to m=6. In the latter case also c does not change. Perhaps a better fit would be reached, if the wheel load G is divided up along the contact length l and along the tire width B into single loads. The lower constants c compared with those of the soil tank tests (table 1) are imaginable, if one takes into account, that in the tank with a diameter of 0,4 m soil flow in horizontal direction is more hindered by the side walls of the tank than in the soil bin where the walls have a distance of 2.5 m. So the small main stresses in the tank will be greater than in the soil bin.

At last the field tests of fig. 8 are discussed. Because tires are concerned, the formulas (6) to (12) are used for the analysis. The sandy loam had a dry density of 1,7 g/cm³ and a water content of 18,5 %. Therefore a stress concentration factor V = 4 was assumed. The wheel loads acting on the rear tire were divided up into five uniform single loads G_0 applying the experiences made with the evaluation of the soil bin tests. For different depths z_{rel} the pressures p_B in the load axle were calculated.

Formula (11) for this purpose becomes:

$$p_B = c \cdot \frac{\nu}{2\pi} \cdot \sum_{i=1}^{5} \left[\frac{G_i}{(x_i^2 + z_{rel}^2)} \cdot \left(\frac{z_{rel}}{\sqrt{x_i^2 + z_{rel}^2}} \right)^{\nu} \right] \tag{13}$$

If symmetry is taken into account (cf. fig. 9), we get:

$$p_B = c \cdot \frac{\nu}{10\pi} \cdot G_0 \cdot \left[\frac{1}{z_{rel}^2} + \frac{2}{(x_0^2 + z_{rel}^2)} \left(\frac{z_{rel}}{\sqrt{x_0^2 + z_{rel}^2}} \right)^{\nu} + \frac{2}{(4x_0^2 + z_{rel}^2)} \left(\frac{z_{rel}}{\sqrt{4x_0^2 + z_{rel}^2}} \right)^{\nu} \right] \tag{14}$$

$$G_0 = G_i = \frac{G}{5} \tag{15}$$

Table 3 shows the constants used for the calculations and in fig. 8 the results are plotted.

table 3:

tire	rear wheel load G (kN)	sinkage z (cm)	tire radius R (cm)	length of contact area l (cm)	single load distance x (cm)
12.4-32	8,5	7,25	69,75	31,0	7,75
18.4-38	16,3	8,83	89,75	39,0	9,75
21.3-26	34,5	12,25	83,00	43,4	10,85

Best fit was achieved by putting $c = c_F = 0{,}36$ in formula (14). Compared with the value of c calculated for the soil bin test (fig. 5) $c_S = 0{,}48$ in the field c was lower.

This short view on mathematical description shows, that the formulas stated by Soehne [1] need only the modification with the factor c, to regard the gauge properties. Surely this few results are not adequate to give evidence about all aspects of the constant c, but it is encouraging to see, that just simple assumptions for the calculations yield good fit. Further tests, easy to do with the described gauge, will show more about the parameters influencing c. Especially the correlation between c, stress concentration factor ν, dry density ρ and the water content w should be investigated.

Conclusions

A cheap and handy gauge to measure pressures in soil below tires and pressure plates was introduced. The influence of soil density and gauge inclination on the measured pressures was shown. Tests in the soil bin proved, that the gauge can be applied in dynamic

tests. The problems arising by simplifying the test mode with one lance systems were demonstrated. In spite of the wall thickness of 0,5 mm making the inherent stiffness of the ballon negligible, several missions in field showed, that the gauge is sturdy enough for scientific purposes. Variation of wheel load, number of passes and vehicle speed yielded well distinguishable results. Some of them could be described by the well known formulas of Soehne [1]. Modifying them by a factor c and making simple assumptions about load distribution in the contact area of the tires, led to results encouraging to further tests, yielding more details about this type of pressure gauge.

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