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THE IMPACT OF WHEEL SPACING ON ALLOWABLE FORCE APPLIED TO THE AXIS OF THE AGRICULTURAL VEHICLE

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ABSTRACT

The objective of the study was to develop computational methods for determination of the impact of the twin-wheels (their positioning along the axis) and soil conditions, specified by the stress concentration factor, on the limit values of the forces loading the axis of the agriculture vehicle, thus reducing the risk of excessive soil compaction. The formula of Boussinesqu (1885) supplemented by Fröhlich (1934) with the stress concentration factors was used. The values of the limit force were determined by adopting assumptions that wheels loaded soil surface in points and stress caused in soil should not exceed its agro-technical bearing capacity defined by the value of the limiting stress. The developed method allows setting the limit value of twin-wheelbase, at which the effect of adjoining force onto stress in soil semi-space fades away. This means that through a relatively small change of a wheelbase, it is possible to achieve more convenient conditions of load transfer on soil, in the context of the risk reduction of excessive soil compaction. The proposed method enables to construct diagrams for calculation of allowable axis load on the base of the known value of stress within the soil profile which determine its agro-technical capacity.

Introduction and objective of the paper

In the light of present knowledge, one of the main issues of the contemporary agriculture is lack of due care for maintaining all functions of soil in satisfying the human needs, in maintaining and survival of ecosystems (Dawidowski, 2009). One of more considerable threats posed to these functions is its excessive compaction (Dawidowski andWalczykova, 2013). From the point of view of soil compaction, the most significant factor is loading the soil surface with wheels of agricultural vehicles. Pressure on the surface of soil influences basically all soil properties and its processes and affects the environmental effects of agricultural production (Nowowiejski, 2004). The results of its impact depend greatly on the structure of driving mechanisms used in tractors and other agricultural vehicles. The soil loading is the best for control in the cause-result chain of soil compaction (fig. 1) The use of twin wheels is one of the methods of limiting the soil surface load. There is a question on the allowable value of the impact force of such a driving mechanism on soil in the context of limiting the risk of its excessive compaction. It is closely related to the limitation of stresses developed in soil influenced by those forces. Recommendations and norms existing in some countries provide for allowable values of these stresses at specific depths and in specific conditions (Rusanov, 1994; Hakansson and Medvedev, 1995; Tijink, 1998; Grecenko, 2002). Taking these indications into account, the paper attempts to develop a computational method for determination of values of allowable forces in relation to the wheel spacing and soil conditions. It is obvious that above the border value of forces distribution, the impact of the adjoining force on stresses in the soil point, which is located in the line of the considered force operation, vanishes. Thus, a fundamental objective of the developed method is determination of the border value of this range.

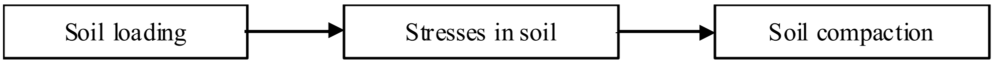

Figure 1. Cause-effect chain of soil compaction

Methodology of research

Calculation model

Taking into consideration the stress formation phenomenon triggered in the semi-space of soil by a vertical force applied to its border surface, the vertical component value σ_z of the stress state along the axis z may be determined with Boussinesqu formula completed by Fröhlich with the stress concentration factor which are to include, to some extent, the soil conditions (Boussinesq, 1885; Fröhlich, 1934). This formula for the mentioned stress component in the soil point $M(x_M, y_M, z_M)$ according to symbols on fig. 2a) is as follows:

$$\sigma_z = \frac{\nu}{2} \cdot \frac{P}{\pi \cdot R^2} \cdot (cos\alpha)^{\nu} (\mathrm{N \cdot m^{-2}}) \quad (1)$$

where:

ν – stress concentration factor(4, 5 lub 6),(-)

R – radius which combines the considered point of soil M with the point of application of force P,(N)

α – angle between R and vertical axis Oz,(rad)

In case of two concentrated forces spaced as presented in fig. 2b) in the distance $a/2$from the beginning of the system $Oxyz$, they cause stresses in point M for which the superposition principle may be applied. Thus, these components in the coordinates systems $O_1x_1y_1z_1$ and $O_2x_2y_2z_2$, related to the application point O_1 and O_2 forces P_1 andP_2 on the surface of soil, will have values determined with the following formulas:

$$(\sigma_z)_1 = \frac{\nu}{2} \cdot \frac{P_1}{\pi \cdot R_1^2} \cdot (cos\alpha_1)^{\nu}; \quad (\sigma_z)_2 = \frac{\nu}{2} \cdot \frac{P_2}{\pi \cdot R_2^2} \cdot (cos\alpha_2)^{\nu} \quad (2a, 2b)$$

Therefore, the resultant stresses:

$$\left((\sigma_z)_{1,2}\right) = (\sigma_z)_1 + (\sigma_z)_2 \tag{2c}$$

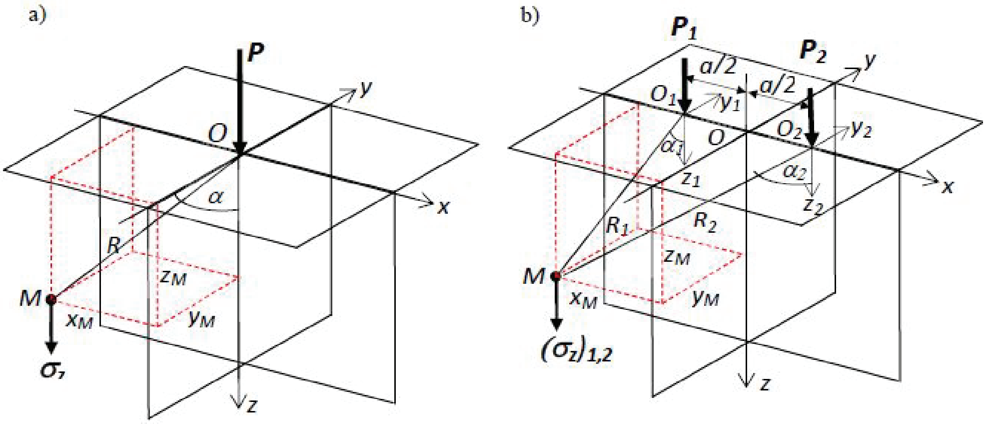

Figure 2. Diagram of soil loading: a) with single concentrated force, b) two concentrated forces

Formulas (1) and (2) prove that for a given depth z the highest values of stress occur in points on the plane which is common for forces $\boldsymbol{P}$, $\boldsymbol{P_1}$ and $\boldsymbol{P_2}$, namely on the plane x-z. Moreover, a symmetry of the value towards the plane y-z takes place.

In the analysis of the impact of spacing of the forces on the distribution of the value of stresses a non-dimensional coefficient k_σ was used, which is a relation of the stress $(\sigma_z)_{1,2}$ in point $M(x_M, 0, z_M)$, caused by forces $\boldsymbol{P_1}$ and $\boldsymbol{P_2}$, to the stress σ_z caused by force $\boldsymbol{P}$ in point with the coordinates $(0, 0, z = z_M)$, which is located on axis Oz, with the highest stress from the force $\boldsymbol{P}$.

$$k_\sigma = \frac{(\sigma_Z)_{1,2}}{\sigma_z(0,0,z_m)} = \frac{\frac{\nu}{2}\cdot\frac{P_1}{\pi\cdot R_1^2}\cdot(\cos\alpha_1)^\nu + \frac{\nu}{2}\cdot\frac{P_2}{\pi\cdot R_2^2}\cdot(\cos\alpha_2)^\nu}{\frac{\nu}{2}\cdot\frac{P}{\pi\cdot R^2}\cdot(\cos\alpha)^\nu} \tag{3}$$

Taking into consideration the mentioned assumptions and geometric relations resulting therefrom, which are as follows:

$$R_1^2 = (x_M)_1^2 + (z_M)_1^2;\quad R_2^2 = (x_M)_2^2 + (z_M)_2^2;\quad R^2 = z_M^2;\quad (z_M)_1^2 = (z_M)_2^2 = (z_M)_M^2 = z_M^2 \tag{4}$$

equation (3) may be converted into the following form:

$$k_\sigma = \frac{\frac{P_1}{(x_M)_1^2+(z_M)_1^2}\cdot(cos\alpha_1)^\nu + \frac{P_2}{(x_M)_2^2+(z_M)_2^2}\cdot(cos\alpha_2)^\nu}{\frac{P}{z_M^2}\cdot(cos\alpha)^\nu} \tag{5}$$

Assuming that $P_1 = P_2 = 0{,}5 \cdot P$,and replacing trigonometric functions with geometric relations:

$$cos\alpha_1 = \frac{z_M}{\sqrt{(x_M)_1^2 + z_M^2}}; \quad cos\alpha_2 = \frac{z_M}{\sqrt{(x_M)_2^2 + z_M^2}} \text{and} cos\alpha = 1 \quad \text{since} \alpha = 0,$$

the equation (5) has the shape as follows:

$$k_\sigma = 0{,}5 \cdot z_M^{\nu+2} \cdot \left\{ \frac{1}{[(x_M)_1^2 + z_M^2]^{\frac{\nu}{2}+1}} + \frac{1}{[(x_M)_2^2 + z_M^2]^{\frac{\nu}{2}+1}} \right\} \tag{5a}$$

On the other hand, taking the coordinate $(x_M)_1$ and $(x_M)_2$ down to the system *Oxyz,* namely $(x_M)_1 = x_M + a/2$ and $(x_M)_2 = x_M - a/2$,the formula which determines the value of the coefficient $k_\sigma$in point *M*takes the following form:

$$k_\sigma = 0{,}5 \cdot z_M^{\nu+2} \cdot \left\{ \frac{1}{[(x_M + a/2)^2 + z_M^2]^{\frac{\nu}{2}+1}} + \frac{1}{[(x_M - a/2)^2 + z_M^2]^{\frac{\nu}{2}+1}} \right\} \tag{6}$$

Relation (6) may be presented as a sum of two coefficients $(k_\sigma)_1$ and $(k_\sigma)_2$, which reflect the impact of forces spaced on the stress in point *M:*

$$k_\sigma = (k_\sigma)_1 + (k_\sigma)_2 \tag{6a}$$

where:

$$(k_\sigma)_1 = 0{,}5 \cdot z_M^{\nu+2} \cdot \left(\frac{1}{[(x_M + a/2)^2 + z_M^2]^{\frac{\nu}{2}+1}} \right); \quad (k_\sigma)_1 = 0{,}5 \cdot z_M^{\nu+2} \cdot \left(\frac{1}{[(x_M - a/2)^2 + z_M^2]^{\frac{\nu}{2}+1}} \right) \tag{6b}$$

Determination of the allowable force

In order to avoid the soil compaction, its agrotechnical capacity should not be exceeded, thus a condition$\sigma_z \leq \sigma_{dop}$ has to be met.

For the system as in figure 2, this condition may be expressed as follows

$$(\sigma_z)_{1,2} = (\sigma_z)_1 + (\sigma_z)_2 = \frac{\nu}{2} \cdot \frac{0{,}5 \cdot P}{\pi \cdot R_1^2} \cdot (cos\alpha_1)^\nu + \frac{\nu}{2} \cdot \frac{0{,}5 \cdot P}{\pi \cdot R_2^2} \cdot (cos\alpha_2)^\nu \leq \sigma_{dop} \tag{7}$$

After conversions and replacing force ***P*** with the allowable force $\boldsymbol{P_{dop}}$ the expression (7) takes place

$$\frac{\nu}{2} \cdot \frac{0{,}5 \cdot P_{dop}}{\pi} \cdot \left[\frac{(cos\alpha_1)^\nu}{R_1^2} + \frac{(cos\alpha_2)^\nu}{R_2^2} \right] \leq \sigma_{dop} \tag{7a}$$

Then, by replacing trigonometric functions with geometric relations, the following inequality (7b) is acquired:

$$\frac{\nu}{4} \cdot \frac{P_{dop}}{\pi} \cdot z_M^\nu \cdot \left[\frac{1}{R_1^{\nu+2}} + \frac{1}{R_2^{+\nu 2}} \right] \leq \sigma_{dop} \tag{7b}$$

Because the equation (6) proves that:

$$\left[\frac{1}{R_1^{\nu+2}}+\frac{1}{R_2^{+\nu 2}}\right]=\frac{k_\sigma}{0{,}5\cdot z_M^{\nu+2}} \tag{6c}$$

Then, after the connection of expression (7b) and (6c) the inequality which combines the allowable stresses and allowable forces is acquired

$$\frac{\nu}{4}\cdot\frac{P_{dop}}{\pi}\cdot z_M^{\nu}\cdot\frac{k_\sigma}{0{,}5\cdot z_M^{\nu+2}}\leq\sigma_{dop} \tag{8}$$

The conversion of this inequality towards $\boldsymbol{P_{dop}}$ shows that the allowable force must meet the following condition:

$$P_{dop}\leq\sigma_{dop}\cdot\frac{2\pi}{\nu}\cdot\frac{z_M^2}{k_\sigma} \tag{9}$$

By introduction of the multiplier $k_P=\frac{2\pi}{\nu}\cdot\frac{z_M^2}{k_\sigma}$ relation (9) may be finally expressed as:

$$P_{dop}\leq\sigma_{dop}\cdot k_P \tag{9a}$$

The value of the multiplier (at a specific value of spacing) at depth z_M, for which allowable stresses are determined, is established by assuming the highest value of the factor k_σ for this depth.

Results and discussion

According to the above-described methodology of searching for the border value of a wheel spacing placed on one axis of an agricultural vehicle, at which the impact of the adjoining force on the stresses in the semi-space of soil vanishes, the first procedure is to determine the maximum values of the factor k_σ. Its value is a function of the soil properties included in the stress concentration factor ν, depth z_M, and the value of forces spacing a. The variability of values of this factor along with its elements was presented in plots in figure 3.

They were drawn in coordinates (a, x_M, k_σ), for three depths and two values of the concentration coefficient ν. On account of the symmetry towards the plane *0yx* only positive values of the coordinate $x_M$were considered. Moreover, a plane parallel to the coordinates a andx_M with the value of $k_\sigma = 0.5$ was placed. Arches which are the maximum values of the factor k_σ for particular values of $a$forces spacing are characteristic on the surface of plots.

The analysis shows that the relation of the value of distribution of forces decreases along with depth. Contrary, its maximum value aims to reach 0.5 with the increase of the forces distribution and the coordinate x_M of the location of the point *M*, where it occurs, aims to reach $a/2$, that is moves towards the line of impact of the force $\boldsymbol{P_2}$.

In order to determine the maximum values of this factor maxk_σ, a numerical method of the so called "golden division" for determination of the function extremum was used. An iteration procedure entered into the spreadsheet of Mathcad 14 was used for calculations. Calculations were carried out within a = (0.0-2.0) m, with the iteration step of 0.005 m and with 100 iterations for each value a. Extreme values and corresponding coordinates x_M of the location of the point *M*, were determined for two depths 0.3 m and 0.5 m. The first one is an assumed border which separates topsoil and subsoil, susceptible to formation of the so-called plough pan. The depth of 0.5 is a depth for which admissible stresses values available in literature are formulated (Rusanov, 1994; Hakansson and Medvedev, 1995; Tijink, 1998). Results are presented in the form of plots in figure 4.

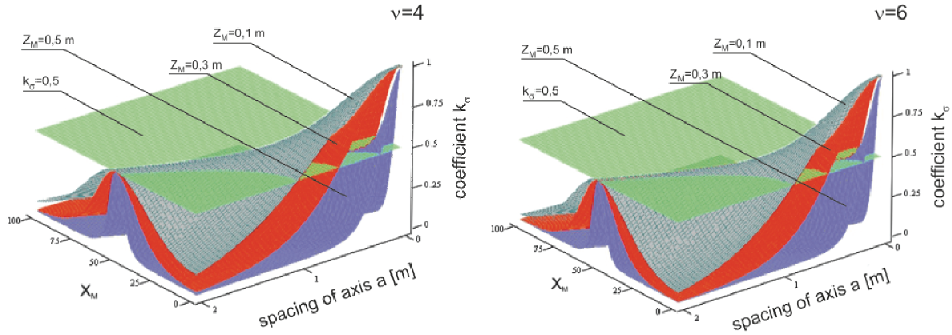

Fig. 3. Plots of relation of factor kσfor depth z_M*=(0,1; 0,3; 0,5) m and stress concentration factor a) ν=4, b) ν=6 in the function of forces a distribution and coordinate* x_M

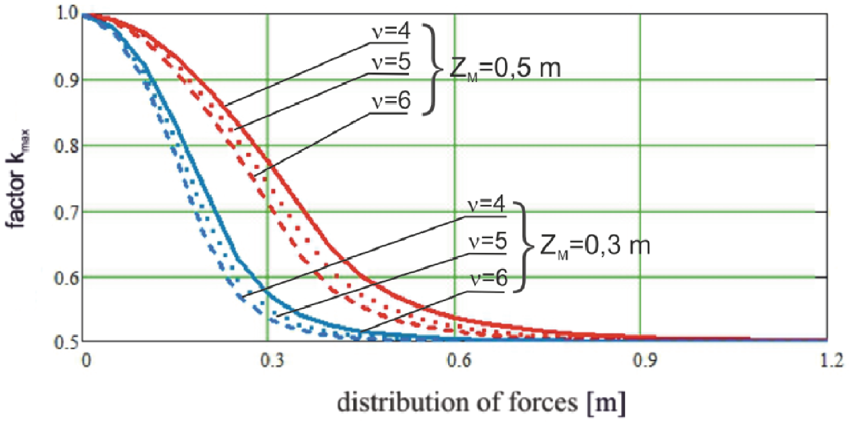

Fig. 4 Relation of maximum values of factor k_σ *to the distribution of forces a for concentration factors ν=4; 5 and 6, for* z_M*=0.3 m and* z_M*=0.5 m*

Plots presenting relations of the factor k_P to the distribution of forces *a,* for the depth of z_M equal to 0.3 m and 0.5 m and factor ν=4; 5 and 6, were presented in fig. 5.
The calculations show that the value of the factor k_P rises along with the distribution of forces $\boldsymbol{P_1}$ and $\boldsymbol{P_2}$, reaching a stable maximum value for the border distribution a_{gr} (tab.1) and the corresponding coefficient $max k_\sigma$ assumes the value equal to 0.5.

Table 1.
List of border values of distribution aof forces P_1 *and* P_2 *and corresponding maximum values of factor* k_P

	z = 0.3 m			z = 0.5 m		
ν	4	5	6	4	5	6
a_{gr}(m)	0.905	0.750	0.650	1.505	1.245	1.08
$max k_P$(m^2)	0.283	0.226	0.188	0.785	0.628	0.524

Curves of relations *kp(a)* arrange in the shape of sigmoidal curves (fig. 5) An attempt was made to adjust a logistic function thereto with the following form

$$(k_P)_{ap}(a) = \frac{\beta_0}{1+e^{\beta_1+\beta_2 \cdot a}} + \beta_3 \qquad (10)$$

Coefficients which occur in this expression were numerically determined in the Excel spreadsheet with the use of Levenberg-Marquardtalgorithm. Their values were presented in table 2 and graphs of functions, for the previously considered concentration factors and depth in fig.6. For all the considered cases, values of the coefficient of correlation between the approximated values $k_P$and the obtained ones, due to the approximated function k_{Pap} are over 0.999.

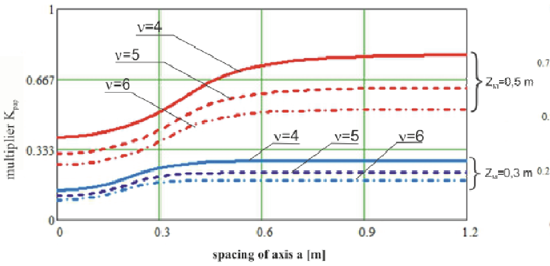

Fig. 5 Relation of the value of multiplier k_P *to distribution of forces a for coefficients of concentration* $\nu=4$; *5 and 6 for* $z_M=0.3$ *m and* $z_M=0.5$ *m*

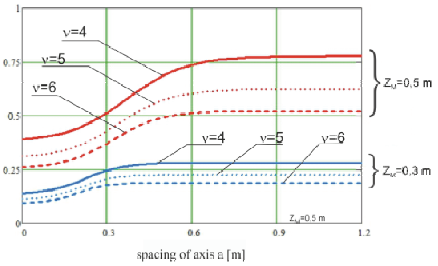

Fig. 6 Relation of the approximated value of multiplierk_{Pap} *to distribution of forces a for concentrationfactors* $\nu=4$; *5 and 6 and* $z_M=0.3$ *m and* $z_M=0.5$ *m*

It is characteristic that on the curves *kp(a)* ranges of distribution of forces occur, where a fast increase of the value of this factor and thus the value of the allowable force acting on the wheels operating on one axis takes place. It means that in the context of reducing the risk of excessive soil compaction, through a considerably slight change of the distribution, it is possible to obtain more favourable conditions of transferring the load on soil. Taking into consideration variability of soil and climatic conditions, which influence the present agri-technical soil capacity, there is a need to introduce structural solutions, which would enable adjusting the wheel spacing to the conditions of operation of wheels on a field.

Table 2.
List of values of coefficients $\beta_{0,1,2,3}$ which occur in the approximating function $(k_P)ap(a)$ for various values of concentration factor v=4; 5; 6 and depth z=0.3; 0.5 m

		z = 0.3 m			**z = 0.5 m**	
ν	**4**	**5**	**6**	**4**	**5**	**6**
β_0	-0.1462508935	-0.1164030139	-0.0966850357	-0.3980951810	-0.3192643037	-0.2662076245
β_1	-3.4220540697	-3.5988048051	-3.7241477535	-3.5663487070	-3.6914729883	-3.7994754961
β_2	15.29321710	17.4052345154	19.3368233735	9.6190748889	10.7705160166	11.87540904
β_3	0.2813636893	0.2254874825	0.1880951775	0.7761740003	0.6233966945	0.5207832571

The obtained results reflect the impact of the mutual influence of two forces on stresses in the point of soil. The assumption of the point impact of forces on soil, made herein, causes their limitation to such systems of wheels, where the surface of the contact of wheel with soil is small, which may occur e.g. in garden tractors. In other cases, discussion should be extended by including both the ended value of this surface and distribution of pressures on it (Söhne, 1953; Söhne, 1958).Taking into account that the force applied point-wise to the soil surface causes stresses of a higher value in comparison to the distributed force, one may expect that in case of distributed forces, the safety margin will be bigger (Nowowiejski et al., 2001).

Conclusions

1. In case of two forces which load soil, in order to determine their total admissible value, one may use the multiplication factor - which depends on the value of distribution of forces, stress concentration factor and the considered depth - by which the value of admissible stresses should be multiplied at the considered depth.
2. The developed method enables preparation of nomograms for determination of admissible load of axis of a vehicle based on the knowledge on the value of stresses in soil, which determines its agrotechnical capacity.
3. In case of two forces which load the soil, there is a border value of distribution of these forces - which depend on the stress concentration factor and the considered depth - above which the total value of the admissible force depends only on the value of admissible stresses at the considered depth.

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WPŁYW ROZSTAWU KÓŁ NA DOPUSZCZALNĄ SIŁĘ OBCIĄŻAJĄCĄ OŚ POJAZDU ROLNICZEGO

Streszczenie. Celem pracy było opracowanie metody obliczeniowej do określania wpływu rozstawu kół bliźniaczych (ich rozsunięcia na osi) i warunków glebowych, określonych współczynnikiem koncentracji naprężenia, na wartości dopuszczalnych sił obciążających oś pojazdu rolniczego, zmniejszających ryzyko nadmiernego zagęszczania gleb. Wykorzystano przy tym formułę Boussinesqu (1885) uzupełnioną przez Fròhlicha o współczynniki koncentracji naprężenia (1934). Wartości sił dopuszczalnych wyznaczono przyjmując założenia punktowego obciążenia powierzchni gleby przez koła a wywołane nimi w glebie naprężenia nie powinny przekraczać jej agrotechnicznej nośności, określonej wartością naprężenia granicznego. Opracowana metoda pozwala wyznaczać graniczną wartość rozsunięcia kół bliźniaczych, przy której zanika wpływ siły sąsiadującej na naprężenia w półprzestrzeni glebowej. Oznacza to, że poprzez stosunkowo niewielką zmianę rozstawu możliwe jest osiąganie dogodniejszych warunków przenoszenia obciążenia na glebę, w kontekście ograniczania ryzyka nadmiernego zagęszczania gleby. Zaproponowana metoda umożliwia wykonanie nomogramów do określania dopuszczalnego obciążenia osi pojazdu na podstawie znajomości wartości naprężenia w glebie, wyznaczającego jej agrotechniczną nośność

Słowa kluczowe: pojazd rolniczy, koła bliźniacze, dopuszczalne obciążenie osi, rozstaw kół bliźniaczych, metoda obliczeniowa