Theoretical determination of the harvester propulsion type for rice harvesting

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Abstract. Theoretical justification of the choice of harvester propulsion for rice harvesting is presented in the paper. The main features of rice harvesting were described. Moreover, soil bearing capacity is the main factor that limited the use of different harvesters in the climatic conditions of the Krasnodar krai. Thus, the numerical model was developed to determine the specific types of harvesters. The model took into account correlations of design parameters and soil rheological properties with the rut depth. The results of the calculations made it possible to justify the mass of the harvester depending on the actual bearing capacity of the soil during the harvesting period for the conditions of the Krasnodar krai.

1. Introduction

Rice harvesting takes place in difficult soil and climatic conditions and vary greatly from the process of grain harvest. Rice growing features and biological properties determine the process of harvesting. Rice plots are covered with water during the vegetation period (115 - 125 days). Soils are usually over saturated before the harvest. Desirable soil moisture level is about 20%. The harvesting period occurs in Autumn during September- November when the temperature is low and the level of precipitation is quite high so the soil could not be dry enough.

Described features are influencing the choice of rice harvest machinery. Thus, these factors have limited the use of combiners a lot. The wheel-based combiners are not suitable for the bogging areas. Moreover, the above-mentioned features are restricting the after harvesting works and soil remediation process.

The soil characteristics and bearing capacity are the main criteria for the pneumatic tires combines used in rice harvesting. The bearing capacity has not been considered as a significant factor in evaluation analysis. However, it is well known that there is a correlation between bearing load values and the speed and track length of the agricultural machinery.

If the bearing capacity, soil properties before and after harvesting, the weight of agricultural machineries are known it could be possible to predict the most efficient way of rice collection.

Thus, the soil bearing load capacity (p_r) is the main deciding factor of the harvesting machinery selection. Moreover, the type of machinery movement, energy efficiency, soil properties also should be taken into account during the decision-making process. The specific pressure on the soil applied by the movable parts of the machinery is the significant parameter that shows the possibility of the specific machinery use. The pressure (P) is the parameter that shows the load of the machinery on the square unit of the rice check. Thus, both these parameters are correlated with each other. If the bearing capacity
is known the pressure could be calculated or vice versa if the weight of rice machinery is known so the rutting depth and the possibility of the specific harvester usage could be estimated. It allows applying different technological and managerial measures into rice harvesting process. Thus, the level of impact on the soil could be minimized by the use of tracked or semi-tracked harvesters. Moreover, the dismantling of the additional devices e.g. straw choppers, stackers, etc., could reduce the weight of the machinery and as a result lower the pressure on the soil surface.

The bearing capacity depends not only on the soil’s physical properties but also on the geometry of vehicle propulsion, e.g. tracks, semi-tracks or wheels [1, 2]. One needs to consider the inclusion of propulsion movement features as a part of the bearing capacity evaluation process. Moreover, the weight of the harvester, types, and sizes of vehicle propulsion should be included in the analysis as well.

The main parameter of the bearing capacity is the depth of the ruts after the harvester movement. So, the numerical model allowing to evaluate the depth of the ruts could be proposed. Moreover, the model should take into account the soil properties and the features of vehicle propulsion.

Consider Ageikin’s [1, 2, 3] equation as a numerical baseline for the current evaluation. The equation shows the correlation between rut depth, load level, and soil physical and mechanical properties:

\[ h = \frac{p_s p_a b \arctan \left( \frac{H-h}{ab} \right)}{(p_s - p)E}, \]  

where \( p_s \) - bearing capacity; 
\( p \) - average pressure on the wheel contact spot applied by vehicle propulsion on the soil; 
\( J \) - parameter of the wheel contact spot geometry; 
\( a \) - parameter of the soil deformation depth; 
\( b \) - average width of the wheel contact spot, m; 
\( H \) - depth of the deforming soil horizon, m; 
\( E \) - soil deformation modulus.

Average value of the wheel contact spot is calculated using the following equation:

\[ b = B + \frac{10h h_x}{1-h+H_{TF}-h_x}, \]  

where \( B \) - width of the tire, m; 
\( H_{TF} \) - height of the tire (0.75B), m; 
\( h \) - depth of the rut, m; 
\( h_x \) - radial deformation of the tire while rolling on the ground, m.

Following equation describes the radial tire deformation:

\[ h_x = \frac{G_w}{\pi dp_{w}}, \]  

where \( G_w \) - load on the wheel, kg; 
\( p_{w}\) - internal pressure in the tire chamber, MPa; 
\( d\) - wheel diameter, m.

The parameter determining the geometry of the wheel contact spot is calculated by the following formula:

\[ J = \frac{0.3b+1}{0.6b+0.43l}, \]  

where \( l \) - average length of the propulsion contact spot, m.

It could be figured out by the use of this equation:

\[ l = \sqrt{dh_x - h_x^2} + \sqrt{d(h_x + h) - (h_x + h)^2}, \]

Consider using the following equation to calculate the coefficient of the soil deformation depth:

\[ a = \frac{0.64H+0.64b}{H}, \]
The average pressure is equal to:

\[ p = \frac{Gw_k_d}{bll_k_f}, \]  

(7)

where \( k_d \) - dynamic load factor,

\( k_f \) - soil stiffness coefficient that is allowing to figure out the influence of the soil deformation on the wheel contact spot.

The factor of the dynamic load \( (k_d) \) could be determined by using the harvester speed \( (V) \) and the time of the relaxation \( (t_p) \):

\[ k_d = \frac{1}{1 + Vt_p} \]  

(8)

Thus, the time of the relaxation is equal to:

\[ t_p = 0.0083\varphi^{-1}, \]  

(9)

where \( \varphi \) - angle of the internal soil friction.

The soil stiffness parameter is evaluated by using the following equation. The deformation modulus \( (E) \) is measured in MPa [4]:

\[ k_f = 0.8949E^{-0.12}, \]  

(10)

The bearing capacity depends on the different parameters such as physical soil properties and rice harvester features.

In general, the equation calculating the bearing capacity has the following form:

\[ p_s = p_{s0}a_z, \]  

(11)

where \( p_s \) - the soil bearing capacity;

\( p_{s0} \) - the soil bearing capacity with unlimited soil depth;

\( a_z \) - coefficient of the soil deformation depth.

The deformation parameter \( (a_z) \) is calculated using the following equation:

\[ a_z = 1 + \frac{H'h}{2H(H-h-0.25H')} \]  

(12)

where \( H' \) - additional parameter:

\[ H' = \frac{\sqrt{7}}{2} \exp \exp \left[ \left( \frac{\pi}{4} + \frac{3\varphi}{4} \right) \tan \frac{2\varphi}{4} \right] b \cos \frac{3\varphi}{4} \cos \varphi \]  

(13)

The soil bearing capacity with the unlimited soil depth is determined with this equation:

\[ p_{s0} = 0.5J_1K_1N_1\gamma b + N_2\gamma h + J_3K_3N_3C, \]  

(14)

where \( K_1, K_3 \) - parameters of the load deviation (from the normal to the surface of the soil);

\( J_1, J_3 \) - parameters that are taking into account the geometry of the wheel contact spot,

\( N_1, N_2, N_3 \) - parameters of the internal soil friction,

\( \gamma \) - soil density,

\( C \) - specific soil adhesion.

Parameters of the wheel contact spot geometry have the consecutive form:

\[ J_1 = \frac{1}{1+0.04b^5} \]  

(15)

\[ J_3 = \frac{1+b}{1+0.5b^5} \]  

(16)

The parameters of the soil inner friction are calculated using the following equations:
\[ N_1 = \frac{1-S^4}{S^3}, \]  
(17)
\[ N_2 = \frac{1}{S^2}, \]  
(18)
\[ N_3 = \frac{2(1+S^4)}{S^3}, \]  
(19)

where, \( S \) - the additional parameter of the soil friction.

\[ S = \tan\left(\frac{\pi}{4} - \frac{\phi}{2}\right), \]  
(20)

Deviation coefficients are evaluated using these equations:

\[ K_1 = \frac{\pi-4(f+\alpha)\tan\phi}{\pi+4(f+\alpha)\tan\phi}, \]  
(21)
\[ K_3 = \frac{3\pi-2(f+\alpha)}{3\pi+2(f+\alpha)}, \]  
(22)

where \( \alpha \) - the angle of the movement surface inclination relative to the horizon (set as the initial value), \( \beta \) - angle of the resulting load deviation from the normal caused by the tangential stress.

The equation 23 calculates the angle \( \beta \):

\[ \beta = \arctan\left(\frac{\tau}{p}\right), \]  
(23)

where \( \tau \) - tangential load.

The tangential load is calculated by the equation:

\[ \tau = \frac{jG(\delta p\phi + C_e - C_i)}{t(\delta p\phi + jG + C_i + C_j)}, \]  
(24)

where \( G \) - soil shear modulus,
\( t \) - the step of the lugs of the vehicle, m,
\( j \) - soil shear deformation.

Soil shear deformation is evaluated by this formula [4]:

\[ j = 1.331^{0.55}S^{1.46}, \]  
(25)

where \( S \) - skidding parameter.

The numerical model was developed taking into account the above-mentioned equations (1-25). The model allows the usage of both soil parameters and technical features of rice harvester.

The soil properties used in the equation were following: deformation modulus \( E \), internal adhesion \( C \), angle of internal friction \( \phi \), specific gravity of soil \( \gamma \), shear modulus \( G \), thickness of the deformable horizons \( H \), angle of inclination \( \alpha \) [5,6];

The characteristics of rice harvester described above were included in the analysis. So the load \( G_{\text{w}} \), internal tire pressure \( p_{\text{w}} \), tire width \( B \), tire height \( H_{\text{r}} \), wheel diameter \( d \), skidding parameter \( S \), machinery translational speed \( v \), lug pitch \( t \) were used in the evaluation process and design of the numerical model [7,8].

Unaccounted soil properties are expressed through the deformation modulus according to the formulas:

\[ H = 0.4714E^{-0.479}, \]  
(26)
\[ C = 10.774E^{0.7737}, \]  
(27)
\[ \phi = 13.669E^{0.1818}, \]  
(28)
\[ \gamma = 8.4008E^{0.1168}, \]  
(29)
\[ G = 0.242E^{-0.422}, \]  
(30)
The results have shown little influence of different parameters. Thus, the skidding parameter, lug pitch, and speed of the wheel movement were insignificantly influenced by the rut depth.

According to the previous evaluation, the rut depth \((h)\) could be described with the use of the following equation:

\[
h = 0.015 \frac{p_{w}^{0.23} \delta_{w}^{1.5}}{E^{1.4} B^{0.9} d^{0.6}}
\]  

(31)

In order to use the above-mentioned correlations further calculations should be done. Moreover, the results could be used in the environmental risk assessment of rice harvesting in the Krasnodar krai.

Consider the range of initial values that were used during the calculations.

- Soil deformation modulus \((E)\) varies from 2.6 to 3. MPA.
- Width of the wheel \((B)\) is 0.6 m on the wheeled combiners such as TORUM-740, TUKANO, MASSTJ-FERGUSON etc. [10];
- The tire pressure \((p_{w})\) should be no more than 0.3 MPa, because as the pressure increase and the lug pitch reduces and as a result the rut depth increase too [10];
- Load on the wheel \((G_w)\) varies from 2.5 to 5.0 t. while the weight of the combiners lays in the range 10 - 20 t. [10];

Results of the calculations could be seen in table 1.

Table 1. Rut depth \((h)\) from propulsors with different loads on rice harvesting machinery wheel and deformation module.

| Load on the wheel \((G_w)\), t. | Rut depth \((h)\) depending on the deformation modulus \((E)\), mm |
|-------------------------------|-------------------------------------------------------------|
|                               | 2.6 MPA | 2.8 MPA | 3.0 MPA |
| 2.5                           | 19      | 17      | 15      |
| 3.0                           | 26      | 22      | 20      |
| 3.5                           | 32      | 28      | 25      |
| 4.0                           | 39      | 35      | 31      |
| 4.5                           | 47      | 42      | 37      |
| 5.0                           | 55      | 48      | 43      |

The results of the rut depth and the correlation with the type of vehicle propulsion are shown in figure 1.

![Figure 1](image-url)
Taking into account agricultural requirements specifying rice harvesting procedures and analyzing the results of the model, it could be concluded that the weight of the harvester on one wheel should not be more than 3.3 - 3.8 tons and in total 13.2 - 15.2 t. In that case, the soil deformation modulus (E) varies from 2.6 to 3.0 MPa. However, the average weight of rice harvesters is 15 - 30 t. Such a heavy weight of harvesters is a result of the design features and multitasking of the combiners. It was proposed that in parallel with rice harvesting, the combine for the straw chopping and rice threshing could be used. However, the use of the additional equipment raises the engine power in 30-40%, which leads to the increase in weight in about 25-30%.

2. Conclusion

1. It is necessary to take into account the soil bearing capacity while making the probability assessment of different vehicle propulsion usage within rice irrigation systems.
2. The decision should be done bearing in mind the rut depth formed after the harvester cross.
3. In order to reduce rutting, the weight of the combine should stay low and do not exceed 15t. It could be done by removing additional equipment used for the straw chopping or reducing the volume of the grain hopper and using modern polymeric materials.

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