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Mathematical model to calculate the critical value of the angle of gradient for a tractor-mounted tilther

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Abstract. The article is devoted to the search for a mathematical model convenient for practical calculations to determine the critical value of the angle of gradient for the tractor-mounted heavy tilther. It shows the existing mathematical model, which is then refined based on the stiffness of the elastic tractor wheels and their vertical reactions offset. Three methods of solving the resulting equations are analyzed, upon which the optimal one is chosen. As a result, a simple and convenient in practice mathematical model to determine the critical value of the angle of gradient for the tractor-mounted implement is obtained. The analysis of the calculation results showed that depending on the operating conditions and the weight of the tractor counterweight, the differences between the results calculated using the traditional and refined models can reach more than 4 degrees, which is very important to ensure the hill climbing safety.

1 Introduction

Despite the great success in the development of agricultural machines, the safety problem of their operation in difficult terrain is very acute. In 53 countries, mountain areas cover more than 50% of the country's territory [1]. Injuries when using tractors in agriculture are very high, especially when cultivating fields located in the mountain area, it is not infrequent for machines overturn, which often result in fatalities [2-3]. A number of scientists consider the need to equip agricultural machines with various safety devices as one of the ways to reduce injuries in agriculture [4]. In relation to tilthers, they are described in [5-9]. However, many scientists prefer to improve the design of the tractor itself, designed to operate in difficult conditions [10-12].

Various mathematical models to analyze the agricultural tractors stability, which ultimately allows obtaining more integrated picture of various factors impact on the machine stability are of great interest [13-15]. However, to perform practical calculations, it

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is very important to have a simple mathematical model that provides a sufficient accuracy level.

Hence, we have attempted to refine the existing mathematical models to analyze the longitudinal stability of the tractor unit operating under various conditions.

2 Materials and methods

To conduct research, we applied a theoretical method by deriving balance equations for the tractor-mounted tilther travelling up a slope. Due to the low speeds of the tractor unit, it has been decided not to consider its inertia and air flow resistance forces.

The research program is quite simple. First, give the formula to calculate the critical value of the unit angle of gradient, which is usually used for practical calculations. At the second stage, refine the balance equations by considering the horizontal offset of vertical reactions from the vertical axis of symmetry of wheels. Solve the resulting equations in various ways. At the third stage, it was necessary to compare the calculation results obtained from the traditional and refined models, evaluate the results significance for practice. It was also necessary to evaluate the acceptability for practical calculations of various simplifications made when solving refined equations.

The real parameters of a reversible plough have been adopted as a tractor-mounted machine since the travel of this machine, which has a large mass and size cause great difficulties in mountain areas.

3 Mathematical models to calculate the critical value of the unit angle of gradient

1 Traditional model

The figure shows the design diagram to determine the critical value of the angle of gradient α for the tractor unit:

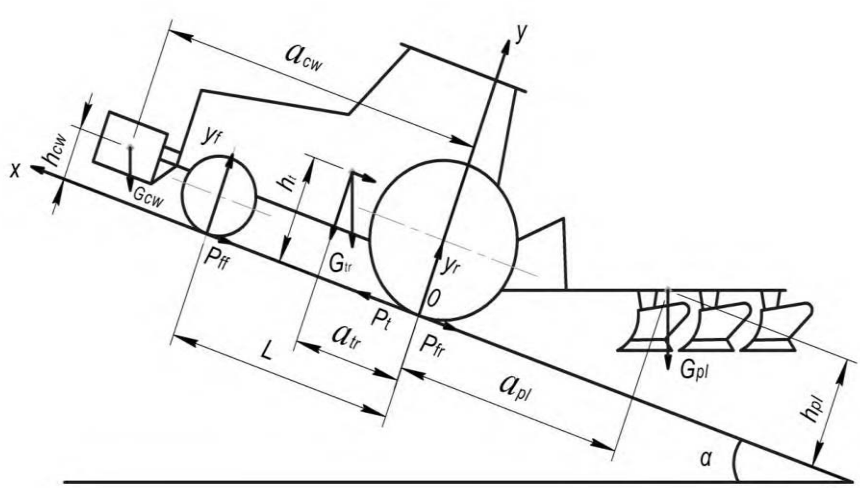

Fig. 1. Diagram of forces acting on the tractor with a plough travelling up a slope

Let us derive balance equations for the tractor unit:

$$\sum X = 0;\ -G_{pl}sin\alpha - P_{fr} - G_{tr}sin\alpha - P_{ff} - G_{cw}sin\alpha + P_t = 0, \quad (1)$$

$$\sum Y = 0;\ -G_{pl}cos\alpha + У_r - G_{tr}cos\alpha + У_f - G_{cw}cos\alpha = 0, \quad (2)$$

$$\sum M_o = 0;\ G_{pl}cos\alpha \cdot a_{pl} + G_{pl}sin\alpha h_{pl} - G_{tr}cos\alpha \cdot a_{tr} + G_{tr}sin\alpha \cdot h_{tr} + Y_f \cdot L - G_{cw}cos\alpha \cdot a_{cw} + G_{cw}sin\alpha \cdot h_{cw} = 0, \quad (3)$$

where G_{tr}, G_{pl}, G_{cw} are the weight of the tractor, plough, counterweight, (N);
P_t is a tangential tractive force, (N);
$У_f$, $У_r$ are the front and rear wheels reaction, (N);
α is an angle of gradient, (rad);
L is a tractor base, (m)
α_t, α_{pl}, α_{cw} are horizontal coordinates of the center of gravity of the tractor, plough, counterweight, (m).
h_t, h_{pl}, h_{cw} are vertical coordinates of the center of gravity of the tractor, plough, counterweight, (m);
P_{ff}, P_{fr} are the rolling resistance force of the front and rear wheels, (N).
From equation (2) we can deduce that

$$У_r = G_{pl}cos\alpha + G_{tr}cos\alpha + G_{cw}cos\alpha - У_f,$$

or having symbolized by G_s the weighted sum of the tractor, plough and counterweight:

$$G_s = G_{pl} + G_{tr} + G_{cw},$$

derive:

$$У_r = G_s \cdot cos\alpha - У_f \quad (4)$$

The value of the vertical reaction $У_f$ can be determined from equation (3):

$$У_f = \frac{1}{L} \cdot \{(G_{tr} \cdot a_{tr} + G_{cw} \cdot a_{cw} - G_{pl}a_{pl}) \cdot cos\alpha - -(G_{pl} \cdot h_{pl} + G_{tr} \cdot h_{tr} + +G_{cw}h_{cw}) \cdot sin\alpha\}. \quad (5)$$

In order to determine the critical value of the angle of gradient α_{cv} it is necessary to put value $У_f = 0$ in equation (5), then

$$\alpha_{cv} = arctg\left[\frac{G_{tr} \cdot a_{tr} + G_{cw} \cdot a_{cw} - G_{pl} \cdot a_{pl}}{G_{pl} \cdot h_{pl} + G_{tr} \cdot h_{tr} + G_{cw} \cdot h_{cw}}\right].. \quad (6)$$

Formula (6) allows calculating the critical value of the angle of gradient that the plowing unit in the transit condition can overcome. These formulas are acceptable to calculate at high values of tires pressure and driving on paved roads. Now let us derive these formulas considering the real wheels reaction points (the case of travelling the elastic wheeled tractor on soft ground).

1.2 Refined model

The design diagram is shown in figure 2. Accordingly, the balance equations for this case will be:

$$\sum x = 0.\quad G_{pl} \cdot sin\alpha - P_{fr} - P_j - P_{ff} - G_{cw}sin\alpha + P_t = 0; \quad (7)$$

$$\sum У = 0.\ - G_{pl}cos\alpha + У_r - G_{tr}cos\alpha + У_f - G_{cw}cos\alpha = 0; \quad (8)$$

$$\sum M_0 = 0. \quad G_{pl}cos\alpha \cdot a_{pl} + G_{pl}sin\alpha \cdot h_{pl} - G_{tr}cos\alpha \cdot a_{tr} + G_{tr}sin\alpha \cdot h_{tr} + \\ + \text{У}_f\left(L_1 + a_f\right) - G_{cw}cos\alpha \cdot a_{cw} + G_{cw}sin\alpha \cdot h_{cw} + \text{У}_r \cdot a_r + P_j \cdot h_{tr} = 0.$$

(9)

The value for У_f can be determined from equation (9):

$$\text{У}_f = \frac{1}{L+a_f} \cdot \left(G_{cw} \cdot cos\alpha \cdot a_{cw} + G_{tr} \cdot cos\alpha \cdot a_{tr} - G_{pl} \cdot cos\alpha \cdot a_{pl} - G_{pl} \cdot sin\alpha \cdot \\ h_{pl} - G_{tr} \cdot sin\alpha \cdot h_{tr} - G_{cw} \cdot sin\alpha \cdot h_{tr} - P_j h_{tr}\right) - \frac{\text{У}_r \cdot a_r}{L+a_f}.$$

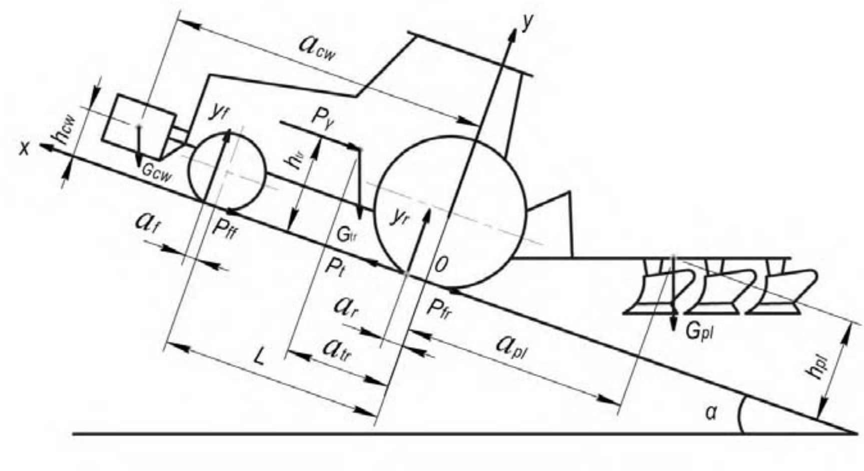

Fig. 2. Design diagram of the tractor with a plough travelling up a slope, based on the real application of front and rear wheels reaction

Let us substitute the formula for У_r from equality (4) to the last equation, then

$$\text{У}_f = \frac{1}{L+a_f} \cdot \left(G_{cw} \cdot cos\alpha \cdot a_{cw} + G_{tr} \cdot cos\alpha \cdot a_{tr} - G_{pl} \cdot cos\alpha \cdot a_{pl} - G_{pl} \cdot sin\alpha \cdot \\ h_{pl} - G_{tr} \cdot sin\alpha \cdot h_{tr} - G_{cw} \cdot sin\alpha \cdot h_{cw} - P_j h_{tr} - G_s \cdot cos\alpha \cdot a_r\right) + \text{У}_f \cdot \frac{a_r}{L+a_f},$$

wherefrom the formula to determine У_f will be:

$$\text{У}_f = \frac{1}{(L+a_f)\cdot\left(1-\frac{a_r}{L+a_f}\right)} \cdot \left[G_{cw} \cdot (a_{cw} \cdot cos\alpha - h_{cw} sin\alpha) + G_{cw}(a_{tr} \cdot cos\alpha - -h_{tr} sin\alpha) - \\ G_{pl} \cdot \left(a_{pl} \cdot cos\alpha - h_{pl} sin\alpha\right) - P_j h_{tr} - G_s a_r \cdot cos\alpha\right]. \quad (10)$$

Hence, from this equation, we can derive the formula to calculate the maximum value of the angle of gradient for the tractor unit by putting $\text{У}_f = 0$ in equation (10). That is, the angle α_{cv} will be:

$$\alpha_{cv} = arctg\left[\frac{G_{cw} \cdot a_{cw} + G_{tr} \cdot a_{tr} - G_{pl} \cdot a_{pl} - G_s \cdot a_r}{G_{pl} \cdot h_{pl} + G_{tr} \cdot h_{tr} + G_{cw} \cdot h_{cw}}\right] \quad (11)$$

Equation (11) is more exact than equation (6). Unlike equation (6), the numerator contains the product $G_s \cdot \alpha_r$, which makes a relevant correction for estimating the critical value of the angle of gradient.

However, to use equation (11), it is necessary to know the value for α_r. To do this, let us use the known dependencies that describe the relationship between the rolling resistance coefficient and the dynamic rolling radius rd:

$$f = \frac{a}{r_d} \quad (12)$$

where, α is the vertical reaction offset У from the vertical axis of symmetry of the wheel; r_d is a dynamic rolling radius of the wheel.

Accordingly, the dependence (12) for the front and rear wheels will be:

$$f_f = \frac{a_f}{r_{df}}, \quad (13)$$

$$f_r = \frac{a_r}{r_{dr}}, \quad (14)$$

where, r_{df}, r_{dr} are dynamic radii for the front and rear wheels.

Then, the formulas for α_f and α_r, based on the tires stiffness will be:

$$a_f = f_f \cdot r_{df} = f_f \left(r_{sf} - \frac{У_f}{C_{tf}} \right), \quad (15)$$

$$a_r = f_r \cdot r_{dr} = f_r \left(r_{sr} - \frac{У_r}{C_{tr}} \right), \quad (16)$$

where, r_{sf}, r_{sr} are static radii for the front and rear wheels (m);

C_{tf}, C_{tr} are the of radial stiffness coefficients for front and rear wheels, (N/m).

Having substituted the value for $У_r$ reaction from formula (4) to formula (16), we obtain:

$$a_r = f_r r_{sr} - \frac{f_r}{C_{tr}} G_s \cos\alpha - \frac{f_r \cdot У_f}{C_{tr}} \quad (17)$$

To determine the critical value of the angle α_{cv}, let us equate the formula (10) to zero and substitute the formula for α_r from (17) to it. Then, by putting $У_f = 0$, $P_j = 0$ the formula can be written as follows:

$$\left(G_{cw} \cdot a_{cw} + G_{tr} \cdot a_{tr} - G_{pl} \cdot a_{pl}\right) \cdot cos\alpha - G_s f_r r_{sr} - cos\alpha + \frac{f_r}{C_{tr}} G_c^2 \cdot cos^2\alpha = \\ = \left(G_{cw} \cdot h_{cw} + G_{tr} \cdot h_{tr} + G_{pl} \cdot h_{pl}\right) \cdot sin\alpha. \quad (18)$$

The most rational solution of equation (18) is numerical, which can be easily implemented with the given accuracy.

In practice, it is not always convenient to use the numerical solution method, so let us try to deduce the acceptable formulas. To do this, pay attention to formula (16). Since the C_{tr} value is very large, then

$$(Y_r/C_{tr}) \approx (G_s/C_{tr}). \quad (19)$$

Considering (19) and (16), formula (11) can be written as follows:

$$\alpha_{cv} = arctg\left[\frac{G_{cw}\cdot a_{cw}+G_{tr}\cdot a_{tr}-G_{pl}\cdot a_{pl}-G_{s}\cdot\left(f_{r}\cdot\left(r_{sr}-\frac{G_{s}}{C_{tr}}\right)\right)}{G_{pl}\cdot h_{pl}+G_{tr}\cdot h_{tr}+G_{cw}\cdot h_{cw}}\right]. \quad (20)$$

Thus, we have three models to analyze: formula (6) (method 1), equation (18) which is solved numerically (method 2), and formula (20) (method 3).

4 Results

To perform calculations, let us use the parameters of MTZ-80 tractor with reversible plough PON-3M. Let us also assume that the wheel tire stiffness varies from 18kN/m to 30 kN/m, the weight of counterweight – from 0 kN to 5 kN, and the rolling resistance coefficient – from 0.025 to 0.1.

The calculation results are shown in the table.

Table 1. The calculation results of the critical values of the angle of gradient for the tractor with the reversible plough weighing 1070 kg performed by various calculation methods when travelling the tractor unit on roads with surfaces of different type, the weight of counterweight and tire stiffness.

№	rolling resistance coefficient f	tires stiffness Ct, N/m	weight of counterweight Gcw, N	Calculation methods			Error	
				method1, Traditional	method 2, Refined	method 3 Approximate	method 1 p1,%	method 3 p2, %
0	1	2	3	4	5	6	7	8
1	0,025	180000	0	5,2998	4,3717	4,368	17,5	0,08
2	0,025	180000	1000	8,5528	7,6318	7,634	10,8	-0,03
3	0,025	180000	2000	11,667	10,766	10,77	7,73	-0,01
4	0,025	180000	3000	14,635	13,751	13,76	6,04	-0,04
5	0,025	180000	4000	17,451	16,587	16,6	4,95	-0,07
6	0,025	180000	5000	20,114	19,274	19,29	4,17	-0,08
7	0,025	220000	0	5,2998	4,3029	4,303	18,8	0
8	0,025	220000	1000	8,5528	7,5688	7,568	11,5	0,01
9	0,025	220000	2000	11,667	10,697	10,7	8,32	-0,03
10	0,025	220000	3000	14,635	13,682	13,69	6,51	-0,05
11	0,025	220000	4000	17,451	16,524	16,53	5,31	-0,04
12	0,025	220000	5000	20,114	19,211	19,22	4,49	-0,06
13	0,025	260000	0	5,2998	4,2571	4,258	19,7	-0,01
14	0,025	260000	1000	8,5528	7,5229	7,522	12	0,02
15	0,025	260000	2000	11,667	10,651	10,65	8,71	-0,02
16	0,025	260000	3000	14,635	13,636	13,64	6,82	-0,05
17	0,025	260000	4000	17,451	16,478	16,48	5,57	-0,04
18	0,025	260000	5000	20,114	19,165	19,18	4,72	-0,06
19	0,025	300000	0	5,2998	4,2284	4,224	20,2	0,1
20	0,025	300000	1000	8,5528	7,4886	7,488	12,4	0,01
21	0,025	300000	2000	11,667	10,617	10,62	9	-0,02
22	0,025	300000	3000	14,635	13,608	13,61	7,02	-0,01
23	0,025	300000	4000	17,451	16,444	16,45	5,77	-0,04
24	0,025	300000	5000	20,114	19,131	19,14	4,89	-0,06
25	0,06	180000	0	5,2998	3,0596	3,061	42,3	-0,03
26	0,06	180000	1000	8,5528	6,3369	6,342	25,9	-0,08
27	0,06	180000	2000	11,667	9,4882	9,497	18,7	-0,1
28	0,06	180000	3000	14,635	12,496	12,52	14,6	-0,16
29	0,06	180000	4000	17,451	15,361	15,39	12	-0,2
30	0,06	180000	5000	20,114	18,077	18,12	10,1	-0,24
31	0,06	220000	0	5,2998	2,9049	2,903	45,2	0,07
32	0,06	220000	1000	8,5528	6,1822	6,181	27,7	0,02
33	0,06	220000	2000	11,667	9,3278	9,335	20,1	-0,08
34	0,06	220000	3000	14,635	12,342	12,35	15,7	-0,09
35	0,06	220000	4000	17,451	15,206	15,23	12,9	-0,15
36	0,06	220000	5000	20,114	17,928	17,96	10,9	-0,17
37	0,06	260000	0	5,2998	2,796	2,794	47,2	0,08
38	0,06	260000	1000	8,5528	6,0676	6,07	29,1	-0,04
39	0,06	260000	2000	11,667	9,2189	9,222	21	-0,04
40	0,06	260000	3000	14,635	12,227	12,24	16,5	-0,11

41	0,06	260000	4000	**17,451**	**15,097**	**15,12**	*13,5*	*-0,12*
42	0,06	260000	5000	**20,114**	**17,819**	**17,84**	*11,4*	*-0,15*
43	0,06	300000	0	**5,2998**	**2,7158**	**2,714**	*48,8*	*0,08*
44	0,06	300000	1000	**8,5528**	**5,9874**	**5,988**	*30*	*-0,02*
45	0,06	300000	2000	**11,667**	**9,1387**	**9,14**	*21,7*	*-0,01*
46	0,06	300000	3000	**14,635**	**12,147**	**12,16**	*17*	*-0,08*
47	0,06	300000	4000	**17,451**	**15,017**	**15,03**	*13,9*	*-0,1*
48	0,06	300000	5000	**20,114**	**17,739**	**17,76**	*11,8*	*-0,13*
49	0,1	180000	0	**5,2998**	**1,5642**	**1,562**	*70,5*	*0,13*
50	0,1	180000	1000	**8,5528**	**4,853**	**4,857**	*43,3*	*-0,08*
51	0,1	180000	2000	**11,667**	**8,0214**	**8,035**	*31,2*	*-0,17*
52	0,1	180000	3000	**14,635**	**11,058**	**11,08**	*24,4*	*-0,24*
53	0,1	180000	4000	**17,451**	**13,957**	**14**	*20*	*-0,28*
54	0,1	180000	5000	**20,114**	**16,707**	**16,77**	*16,9*	*-0,35*
55	0,1	220000	0	**5,2998**	**1,3006**	**1,299**	*75,5*	*0,14*
56	0,1	220000	1000	**8,5528**	**4,5894**	**4,588**	*46,3*	*0,03*
57	0,1	220000	2000	**11,667**	**7,7521**	**7,762**	*33,6*	*-0,13*
58	0,1	220000	3000	**14,635**	**10,789**	**10,81**	*26,3*	*-0,19*
59	0,1	220000	4000	**17,451**	**13,688**	**13,72**	*21,6*	*-0,24*
60	0,1	220000	5000	**20,114**	**16,444**	**16,49**	*18,2*	*-0,28*
61	0,1	260000	0	**5,2998**	**1,1173**	**1,116**	*78,9*	*0,07*
62	0,1	260000	1000	**8,5528**	**4,4003**	**4,402**	*48,6*	*-0,03*
63	0,1	260000	2000	**11,667**	**7,5688**	**7,573**	*35,1*	*-0,05*
64	0,1	260000	3000	**14,635**	**10,605**	**10,62**	*27,5*	*-0,12*
65	0,1	260000	4000	**17,451**	**13,505**	**13,53**	*22,6*	*-0,18*
66	0,1	260000	5000	**20,114**	**16,261**	**16,3**	*19,2*	*-0,24*
67	0,1	300000	0	**5,2998**	**0,9855**	**0,983**	*81,4*	*0,28*
68	0,1	300000	1000	**8,5528**	**4,2628**	**4,265**	*50,2*	*-0,05*
69	0,1	300000	2000	**11,667**	**7,4313**	**7,434**	*36,3*	*-0,04*
70	0,1	300000	3000	**14,635**	**10,468**	**10,48**	*28,5*	*-0,1*
71	0,1	300000	4000	**17,451**	**13,367**	**13,39**	*23,4*	*-0,16*
72	0,1	300000	5000	**20,114**	**16,123**	**16,16**	*19,8*	*-0,22*

The table shows that when the weight of the counterweight increases and the tractor travel along the same surface, the tire stiffness has an insignificant effect on the calculation result. The most significant factors are the rolling resistance coefficient and the weight of the counterweight.

The table also shows that the difference between the calculation results for method 1 and method 2 is quite significant, while it is insignificant between methods 2 and 3. This is clear in the graphs shown in figures 3 and 4.

Figure 3 represents by a diagram the differences in the results of calculating the critical value of the unit angle of gradient between methods 1 and 2 (column 7 in the table).

Figure 4 represents by a diagram the differences in the results of calculating the critical value of the unit angle of gradient between methods 1 and 2, but they are already expressed in degrees.

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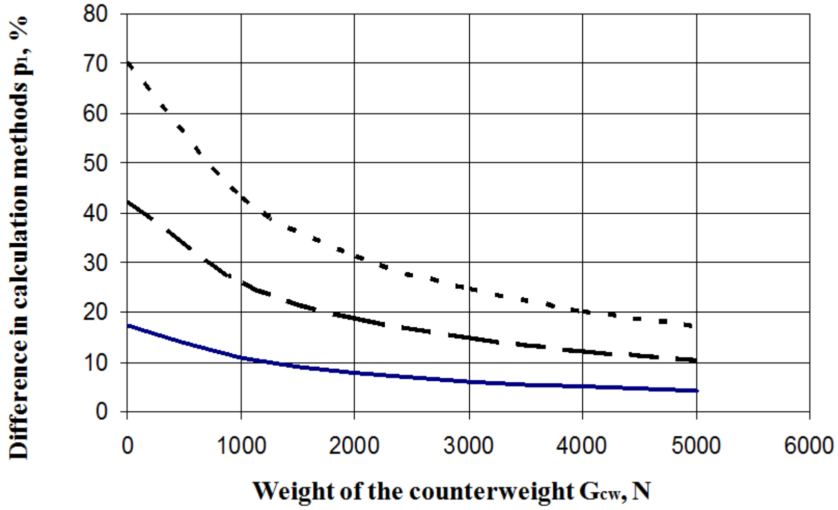

Fig. 3. Differences in the results of calculating the critical value of the angle of gradient for the tractor with the reversible plough p1 (%), obtained by the existing and proposed methods, from the weight of the counterweight with road surfaces of different type

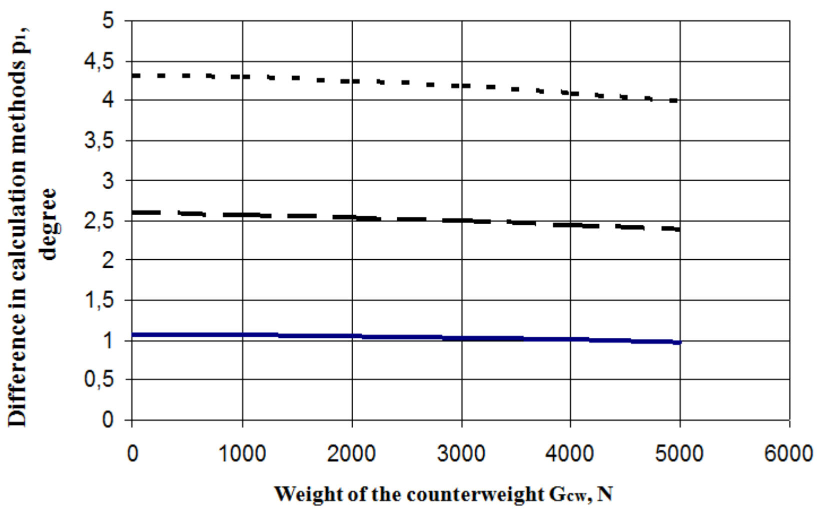

Fig. 4. Differences in the results of calculating the critical value of the angle of gradient for the tractor with the reversible plough p1 (degree), obtained by the existing and proposed methods, from the weight of the counterweight with road surfaces of different type

As graphs show, the type of road surface plays a significant role in calculating the critical value of the angle of gradient for the tractor unit. On the given road surfaces the difference can be 4.3°, i.e. the traditional model provides slightly conservative values of the critical angle of gradient for the unit.

5 Discussion

The research shows that the most convenient for practical calculations to determine the critical value of the unit angle of gradient is the mathematical model relevant to the third calculation method (formula 20). The values calculated using this model are much more accurate, and the model itself should be considered more successful, since it considers such important parameters as the rolling radius of the tractor rear wheels, the rear wheel tire stiffness, and the characteristics of the road surface.

Taking into account the fact that most of the arable land in Russia is located in mountain areas, it is natural that many scientists have studied the issues of longitudinal stability of tractors and their preservation of the necessary conditions for handling [16-20]. If to compare their approach to the theoretical analysis of the lifting process and the resulting mathematical models, it can be stated that our approach covers a far larger number of factors actually affecting the analyzed process and the assumptions made have a slight effect on the accuracy of calculations, meanwhile allowing to maintain the simplicity of the mathematical model.

6 Conclusions

Record of the vertical reactions offset from the vertical axes of symmetry of wheels allows to significantly refine the mathematical model for calculating the critical value of the angle of gradient for the tractor-mounted machine.

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