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Justification and static calculation of the adaptive moving counterweight of a single-bucket excavator

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Abstract. The results of an analytical study of the effect of loads on the equipment of a single-bucket excavator are presented, and an analysis of previous studies is performed.

The work highlights that the work process of a universal single-bucket excavator is a cycle of performing operations - digging and transporting soil.

Universal excavators can perform work above and below the level of their parking lot with the working equipment of forward and reverse shovels or with the help of additional interchangeable equipment.

During the work process, static and dynamic loads occur on the machine and mechanisms, which affect the stability of the machine and safety on the work site.

To increase the stability of single-bucket universal excavators when working on an inclined plane and increase the efficiency of the machine in quarries, construction sites, when disassembling rubble after man-made disasters, accidents, and military operations, it is necessary to create a balancing mechanism of automatic action.

The calculation of the stability of a universal single-bucket excavator with an adaptive movable counterweight with working equipment forward and reverse shovel in the basic calculation positions, which are performed when calculating universal single-bucket excavators, has been developed. For an excavator equipped with a reverse shovel, the calculation is made for two positions. Calculation of the stability of an excavator with straight shovel equipment, performed for four positions.

Due to the adaptive movable counterweight, an additional, adjustable, arm appears, which automatically balances the system when necessary.

Thanks to the automatic system, the single-bucket excavator can work and move on a more inclined plane, the moving counterweight will balance the machine itself, and it is also possible to increase the holding moment and prevent the excavator from tipping over.

The expediency of using an adaptive moving counterweight for single-bucket excavators is described. Examples of the use of a movable counterweight in other machines are given. The analysis of related studies was performed and the expediency of using an adaptive moving counterweight in them was substantiated. Preliminary studies in the development of a movable counterweight for single-bucket excavators are provided. The calculation of the stability of a single-bucket excavator with an adaptive movable counterweight in the main design positions has been developed.

Keywords: adaptive moving counterweight, stability, holding moment, overturning moment.

INTRODUCTION

More than 90% in our country perform work with universal excavators. Universal single-bucket excavators perform work in quarries, construction sites and in urban conditions. They are widely used for dismantling the rubble of buildings and structures after disasters, accidents and hostilities

Single-bucket excavators can have one type of working equipment or be equipped with variable types installed on the machine depending on the work being performed. In the first case, excavators are called special, and in the second - universal.

Universal excavators can perform work above and below the level of their parking lot with the working equipment of forward and reverse shovels or with the help of additional interchangeable equipment.

A single-bucket excavator is one of the main machines used to dismantle debris during rescue and recovery work [7].

To increase the working area, for example, in the development of large pits, on loading and unloading, as well as on excavation work, dragline work equipment is installed on excavators. [1]

The development of deep excavations, pits, wells is carried out using the working equipment of a grab, for planning works - special planning equipment. Excavators can also be equipped with cranes, pile breakers, and other interchangeable work equipment. more than 40 species in total.[1]

On hydraulic excavators, during operation, a large force is exerted on the teeth and the cutting part of the bucket due to the rigid articulation of the elements of the working equipment with each other and with the base part of the machine, which works in terms of stability as a single unit. This makes it possible to hang buckets with a larger capacity on hydraulic excavators - on average by 60% compared to the buckets of rope excavators, in strong, even conditions. [1]

The working process of a universal single-bucket excavator is the cyclical performance of operations - digging and transporting soil. During the work process, static and dynamic loads occur on the machine and mechanisms, which affect the stability of the machine.

With this, the load on the parts and mechanisms of the machine increases, which can lead to their destruction, and also reduces the stability and balance of the machine as a whole.

In order to ensure stability under the maximum possible loads on the excavator, increase the slope of the working platform, and increase the efficiency of the machine, it is advisable to develop an adaptive movable counterweight, which will automatically compensate the load on the rotary platform mechanism and prevent the machine from overturning.

THE GOAL OF THE WORK

Analytical study of dynamic and static loads on a single-bucket excavator and attachments and their impact.

SCIENTIFIC NOVELTY

Study of power parameters and modes of motion of a movable counterweight. Creation of means of ensuring stability and increasing the efficiency of a single-bucket excavator due to a movable counterweight. Study of an adaptive system for ensuring the balance of a single-bucket excavator.

PROBLEM

One of the consequences of Russia's full-scale armed aggression, which began on February 24 last year. As of November 2022, the damage caused to the housing stock of Ukraine amounts to $52.5 billion. Currently, the share of the housing stock in the total amount of damage is 38.6%. The number of destroyed and damaged private and apartment buildings increased by 8 thousand to 143.8 thousand compared to September 2022. Of them, 126.7 thousand were private (individual) houses; 16.8 thousand — multi-apartment buildings; almost 0.3 thousand are dormitories[6].

Various means of mechanization are used to dismantle rubble, mainly construction machines, which do not always meet the requirements of these works.

To increase the stability of single-bucket universal excavators when working on an inclined plane and increase the efficiency of the machine in quarries, construction sites, when disassembling rubble after man-made disasters, accidents, and military operations, it is necessary to create a balancing mechanism of automatic action. Dismantling the rubble of buildings and structures under the rubble of which the victims are located is especially relevant at the moment.

A single-bucket excavator is one of the main machines used to dismantle debris during rescue and recovery work [7]. Single-bucket excavators with attached equipment in the form of hydraulic hammers, hydraulic chisels, disc saws, loosening teeth, hydraulic chippers, grab buckets for lumpy and bulk materials are used for the elimination of simple and medium-sized piles. Before disassembling complex rubble, long-dimension reinforced concrete structures are cut (sliced) with hydraulic chippers or disc saws, which are installed on excavators or instead of dumps of engineering machines, with subsequent transportation of structures by road pavers or grab machines [8].

Performing work with a single-bucket universal excavator requires timely preparation of the work site, transportation over unevenness, inclined planes, which in critical and emergency situations is not always possible or requires additional time. All this increases the time and complexity of the work.

In order to ensure stability under the maximum possible loads on the excavator, increase the holding moment, increase the efficiency of the machine, and increase safety at the work site, it is advisable to develop an adaptive movable counterweight, which will automatically compensate the load on the rotary platform mechanism and prevent the machine from overturning.

PRELIMINARY RESEARCH

In the patent for a useful model of a single-bucket excavator, which is highlighted in Fig. 1, the problem of the stability of the excavator is solved. It was found that the center of mass changes on an inclined plane, which reduces the stability of the machine, and during operation, the stability of the machine against overturning was ensured [5].

The bodies of hydraulic cylinders are horizontally attached to the rotary platform in directions with the possibility of longitudinal movement. The rods are fixed to the counterweight.

During the operation of the working equipment, the center of mass is shifted to the front, in order to avoid overturning the machine, the driver switches the distributor that pushes the counterweight until the excavator takes a horizontal position.

Let's consider the hydraulic scheme of advancing the counterweight in Fig. 2. A pressure line 6 and a drain line 7 are connected to the two-position distributor 8 with manual control. The outlet nozzles of the distributor 8 are connected to a three-position, two-line distributor 9 with hydraulic control. The outlet pressure nozzle of the distributor 9 is connected through the flow divider 10 to the piston cavities of the hydraulic cylinders 3, and the drain nozzle is connected to the rod hydraulic cylinders [5].

The hydraulic control chambers 11 of the distributor 9 are connected by hydraulic lines to the piston cavities of the vertical hydraulic cylinders 12, which are mounted on the platform with their housings, and the hydraulic

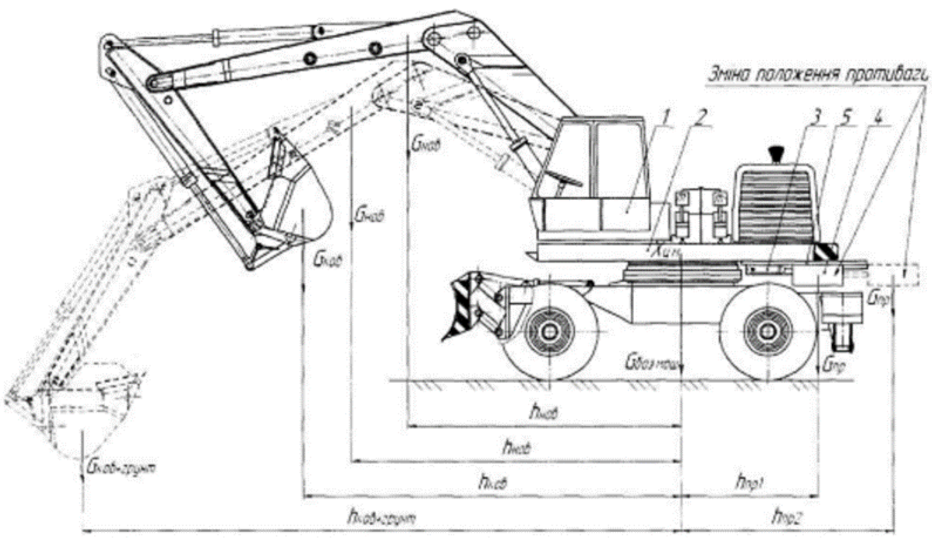

Fig. 1. A useful model of a single-bucket excavator with a movable counterweight

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cylinders 12 are located in the plane of the longitudinal axis of the excavator, and the rod cavities of these hydraulic cylinders are interconnected. The same masses 13 and 14 are installed on the rods of hydraulic cylinders 12, which are fastened together by a rocker arm 15, which rests with its middle part on a stop 16 with the possibility of rotation around it.[5]

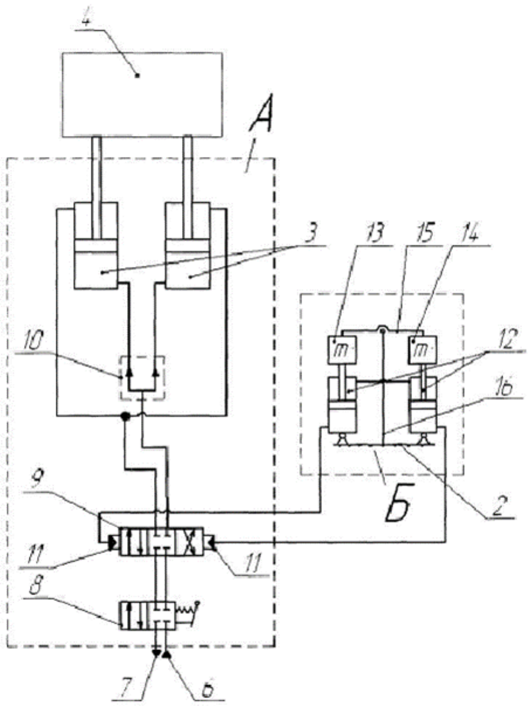

Fig. 2. Metal structures of the working equipment of a single-bucket excavator

The disadvantage of this design is that the system is not automatic and adaptive, the counterweight is extended only longitudinally, only along one line.

It is advisable to develop an adaptive movable counterweight system that would adapt to external conditions, ensure the stability of a single-bucket excavator without the assistance of a driver, and reduce the effect of static, dynamic loads on the working equipment, nodes and rotary platform, move around the rotary platform and longitudinally.

In the analytical study of related developments and researches in the field of increasing the efficiency of single-bucket excavators in disassembling rubble and emergency rescue work, such as a single-bucket excavator with a spatially oriented boom [9].

The proposed design of the boom system of the excavator makes it possible to manipulate the working body in compressed conditions of rubble of destroyed buildings, reducing the danger of finding rescuers in these conditions. In addition, the productivity of performing rescue operations from one car parking place increases. [9].

It was determined that the excavator during operation has a probability of loss of stability and there are risks of the machine tipping over, it is proposed to modernize the machine with a movable counterweight.

In the research and development of a single-bucket excavator with telescopic working equipment, it was determined that the use of working equipment with a two-section telescopic boom and a traditional handle allows you to increase the digging depth by 17.7% by pushing out one boom telescope and by 36% in the case of pushing out both boom telescopes, while achieving an increase in soil volume by 29% and 51%, respectively, when digging from one excavator stand. The calculations performed using the proposed method of integral calculations confirm the efficiency of the structure. The use of the proposed working equipment allows you to increase the volume of the developed soil from one parking lot of the excavator, as well as to expand the functional capabilities and the range of performed works [10].

When the handle is increased, the shoulder and overturning forces increase, which significantly affect stability, the risks of the excavator tipping over and the machine's carrying capacity decrease. To ensure the stability, efficiency and safe use of the development, the development of an adaptive movable counterweight is required, which would adjust the counterweight to the normal conditions of stability of the machine when the reach of the boom is increased.

APPLICATION OF MOVABLE COUNTERBALANCE IN OTHER MACHINES

A movable counterweight is used in pipelayers, which positively contributes to increasing the efficiency and maintaining the stability of the machine. The machine has a counterweight that can be thrown away - this is a rational design, because when working with a load, the counterweight can be thrown away, which in turn increases the load moment of the structure.[3]

There are also successful developments of mobile counterweights for the modernization of mobile cranes to increase machine productivity. The movable counterweight increased the load characteristics, without a significant change in the design. The drive of the movable counterweight is low-power, so it can be introduced into the system without replacing the last elements [4].

STABILITY CALCULATION OF A UNIVERSAL SINGLE-ARM EXCAVATOR WITH A MOVABLE COUNTERBALANCE

The stability of the excavator is the ability of the machine to resist external loads, including the gravity of the soil in the bucket, as well as the component parts of the excavator, the resistance of the soil to digging, and the forces of inertia that prevent the excavator from tipping over and moving the supporting part of the excavator relative to the soil base [2].

The static calculation includes a check of the general stability of the excavator and the balancing of the platform.

The stability of the excavator is characterized by the coefficient of stability

$$K_y = \frac{M_y}{M_n},$$

where M_y – the moment of all the forces keeping the excavator from overturning;

M_n – the moment of all the forces contributing to the overturning of the excavator.

For different types of variable working equipment and different modes of operation, their limits of the stability coefficient are recommended. For normal conditions $K_y = 1{,}1 \div 1{,}2$.

The stability of the excavator is divided into two groups - the stability of the machine when digging the soil and all other states of the excavator.

In calculating the stability of a single-bucket excavator with a movable counterweight, we will use the basic calculation provisions that are used to calculate the stability of this type of machine.

The calculation of the excavator with the reverse shovel equipment is performed for two positions:

1. The excavator is on a horizontal plane, the bucket is separated from the soil at the edges of the face under the action of maximum forces, which are generated by lifting the boom (Fig. 3). The direction of soil reaction on the bucket teeth is perpendicular to the line connecting the center of rotation of the boom and the cutting edge of the bucket. The movable counterweight is automatically moved as close as possible to the rotary platform.

$$R = \frac{1}{r_R} = P_{цmax} r_ц - g_к r_к - g_р r_р - g_с r_с,$$

Stability reserve coefficient for the first position, taking into account the movable counterweight:

$$K_y = \frac{G_м r_м + G_п r_п + g_{пр} r_{пр} + g_{рп} r_{рп}}{R l_R + g_к r_к + g_с r_с + g_р r_р}.$$

where $g_{рп}$– the weight of the movable counterweight;

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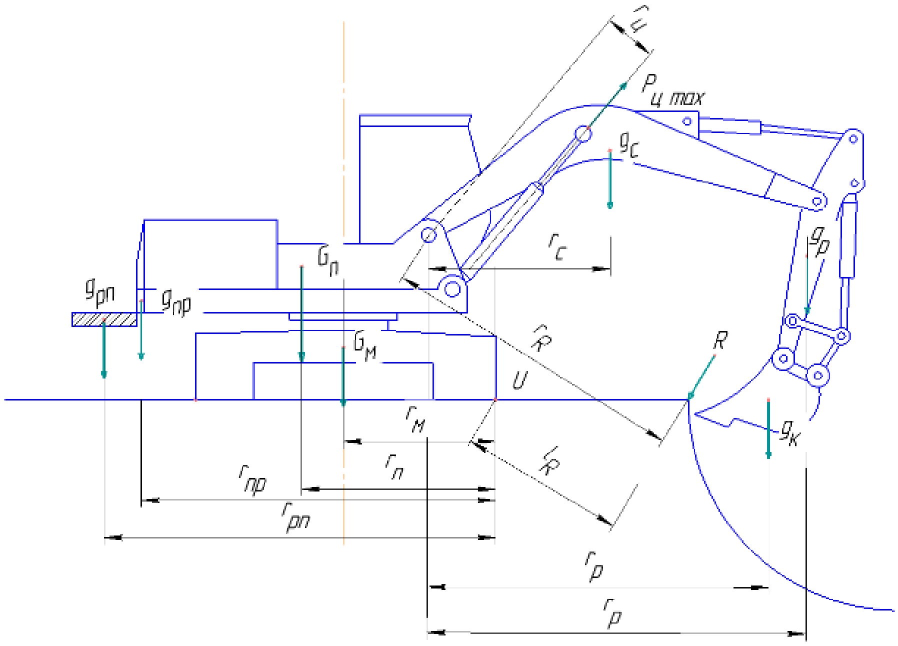

Fig. 3. Scheme for determining the stability of an excavator with a movable counterweight, equipped with a reverse shovel, at the calculated position 1

2. The machine is located on a surface that is inclined to the horizon at an angle of 12°. Cohesive soil is unloaded at the maximum reach of the bucket (Fig. 4). The movable counterweight is extended to the maximum distance from the rotary platform.

The stability margin factor will be

$$K_y = \frac{A}{(A + D)\, tg\alpha + g_{кг} l_к + g_p l_p + g_c l_c},$$

where $A = G_m h_m + G_n h_n + g_{np} h_{np} + g_{pn} h_{pn}$; $D = g_{кг} h_к + g_p r_p + g_c h_c$; $K_y \geq 1{,}15$.

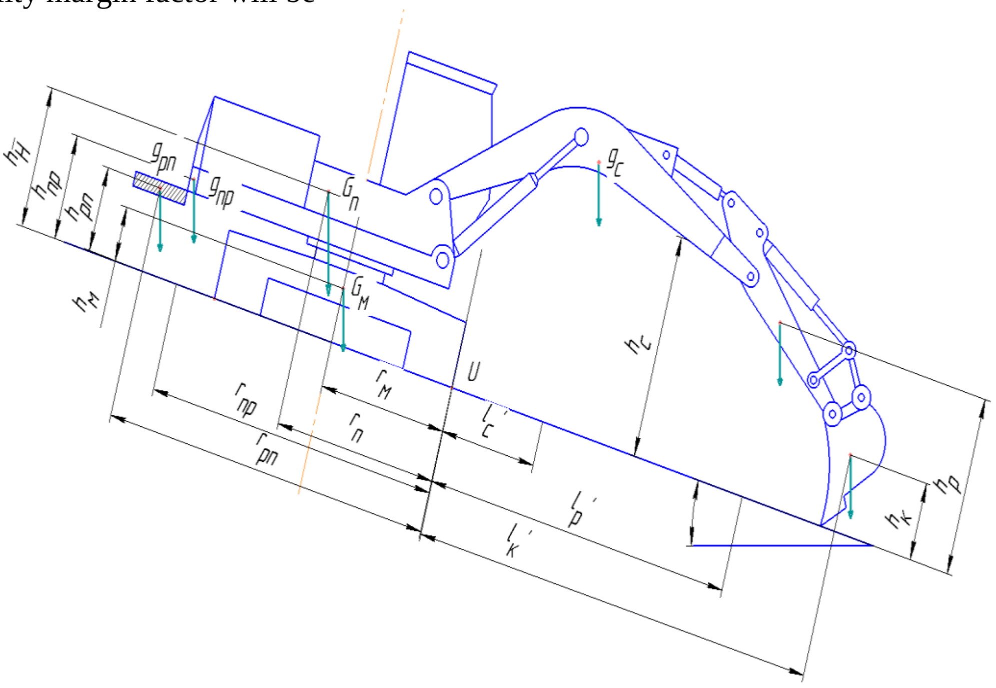

Fig. 4. Scheme for determining the stability of an excavator with a movable counterweight, equipped with a reverse shovel, at the calculated position 2

The stability of an excavator equipped with a straight shovel is perform for four positions:

1. The machine is installed on a horizontal plane, the working equipment is installed at 90° relative to the running device, the bucket is empty, the teeth of the bucket are located at the level of the pressure shaft, the boom is inclined at 45° from the horizon (Fig. 5). The force on the teeth of the bucket is equal to the pressure of the safety valve of the hydraulic system. This case leads to the likely overturning of the excavator relative to the outer faces of the outriggers, support rollers, pneumatic tires. Therefore, the movable counterweight, in this case, will be automatically located under the support contour and moved as much as possible to the rotary platform.

The stability margin factor will be calculated as follows:

$$K_y = \frac{M_y}{M_{пер}}$$

$$K_y = \frac{G_в r_в + G_п r_п + g_{пр} r_{пр} + g_{рп} r_{рп}}{P_{max} l_з + g_к l_к + g_р l_р + g_с l_с},$$

where P_{max} - the maximum vertical force on the cutting edge of the bucket, determined from the condition of equilibrium of the handle, H; $G_в$ – the force of gravity of the trolley chassis, H; $g_р, g_к, g_с$ - gravity of the handle, bucket and boom, H; $G_п$ – the force of gravity of the rotary platform with the devices located on it, $H \cdot м$; $g_{пр}$ – gravitational force of the counterweight, H; $g_{рп}$ – the force of gravity of the moving counterweight;

shoulders $r_в$, $r_п$, $r_{пр}$, $r_{рп}$, $l_з$, $l_к$, $l_р$, $l_с$.

The stability margin coefficient is in the interval 1,05 – 1,1.

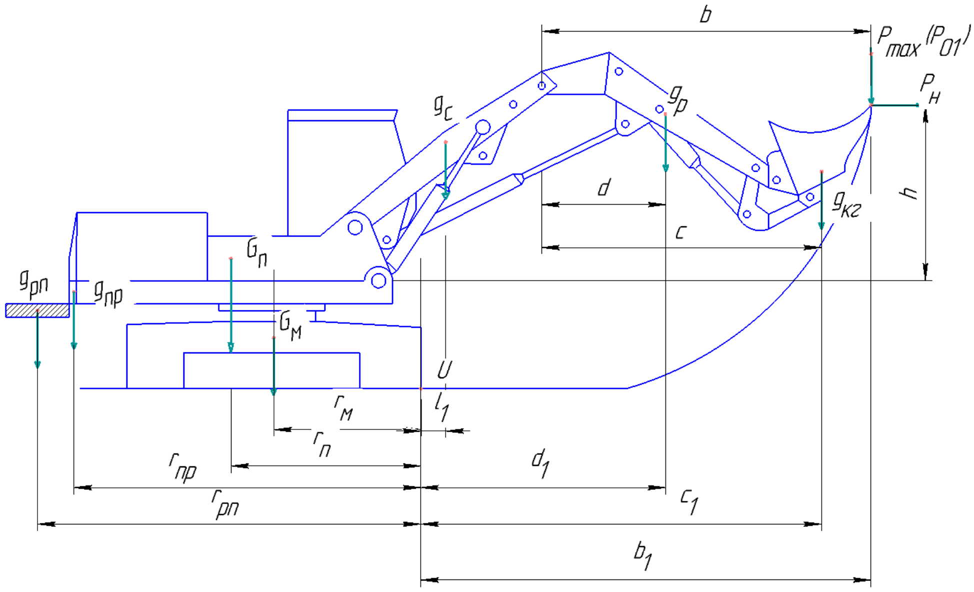

Fig. 5. Scheme for determining the stability of a single-bucket excavator with a movable counterweight, equipped with a straight shovel, in the working process

2. During normal operation, the machine is installed on a horizontal plane, the working equipment is located perpendicular to the undercarriage, the handle is horizontal and maximally extended, the boom is located at an angle of 45° from the horizon, the bucket is full (Fig. 3). First of all, for hydraulic excavators, the force P_1, is calculated, the rotation of the handle relative to the boom under the action of forces in the cylinders that correspond to the nominal pressure in the hydraulic system is considered. The value of the effort P_2 directed from itself, is determined based on the implementation of the nominal oil pressure in the boom hydraulic cylinders with the already found value of P_1. The adaptive movable

counterweight is on the opposite side of the overturning forces at the maximum distance.

Overturning is possible relative to the outer faces of support rollers, outriggers or pneumatic tires. To prevent loss of stability and overturning of the machine in automatic mode, the movable counterweight is located on the opposite side of the overturning forces.

$$К_у = \frac{М_у}{М_{пер}}$$

$$К_у = \frac{G_т r_т + G_п r_п + g_{пр} r_{пр} + g_{рп} r_{рп}}{P_1 l'_з + P_н r_н + g_{кг} l'_к + g_р l'_к + g_с l_с}.$$

Values included in the upper equality P_1, P_H set from the balance equation of the handle with the bucket relative to the axis of the pressure shaft:

$$P_1 = \frac{S_{ц.р} a - g_{кг} c - g_р d}{b};$$

$$P_и = \frac{B + g_{кг} c_1 + g_р d_1 + g_с l_1}{h},$$

where $B = P_{ц.с} a_1 - P_{max} b_1$; $P_и$ – centrifugal force from the rotation of the platform, which passes through the center of gravity of the bucket and crosses the axis of the platform at an angle of 90°; $P_и$, $P_п$ – forces in hydraulic cylinders for turning the handle and boom, H; $g_{кг}$ – the force of gravity of the bucket with the soil, H.

The stability margin coefficient is in the interval 1,05…1,1.

3. The equipment with fixed in the transport position. The machine moves uphill (Fig. 6). The overturning of the machine is facilitated by the air load. The calculation of stability is carried out for the maximum inclined support surface of the movement. The maximum angle of elevation is in the conditions of maximum traction of tracks (wheels) with the road or traction force:

$$arctg\varphi_c \geq \alpha_{max} \leq \alpha_N,$$

where φ_c – traction coefficient of tracks (wheels) with the road; α_N – the angle of elevation determined by the traction calculation:

$$sin\alpha_N = \frac{N_n}{G_e v_{min}\left(1 + f^2\right)} - f\sqrt{\frac{1}{1+f^2} - \left[\frac{N_n}{G_e v_{min}\left(1+f^2\right)}\right]^2}$$

where N_n - the power of the power plant, W; v_{max} – the maximum speed of the excavator, m/c; G_e – gravity of the entire excavator, H; f – coefficient of movement resistance; η – transmission efficiency.

Loss of stability of the excavator in this case is possible relative to the rear wheels. To balance the machine, the movable counterweight in automatic mode is set as close as possible to the rotary platform. Excavator safety factor:

$$K_у = \frac{M_у}{M_{пер}} = $$

$$= \frac{G_e r_e cos\alpha_{max} + G_{рп} r_{рп} cos\alpha_{max}}{G_e h_ц sin\alpha + G_{рп} h_{црп} sin\alpha + k_e F_{бр} k p_в r_в}$$

$$K_у \geq 1{,}2,$$

where $h_ц$ – height of the excavator's center of gravity, m; $h_{црп}$ – height of the center of gravity of the moving counterweight, m; r_e – the distance between the direction of the overturning axis, taking into account the selected position of the working equipment and the component $G_e cos\alpha$, m; $r_{рп}$ – the distance between the direction of the overturning axis, taking into account the selected position of the working equipment and the component $G_{рп} cos\alpha$, m; $F_{бр}$ – the area of the windward surface of the excavator, limited by its contour, m^2; k_e – the filling factor of the windward surface of the excavator, $k_e = 1$; k – drag coefficient, $k = 1{,}2$; $p_в$ – calculated wind pressure equal to 250 Pa.

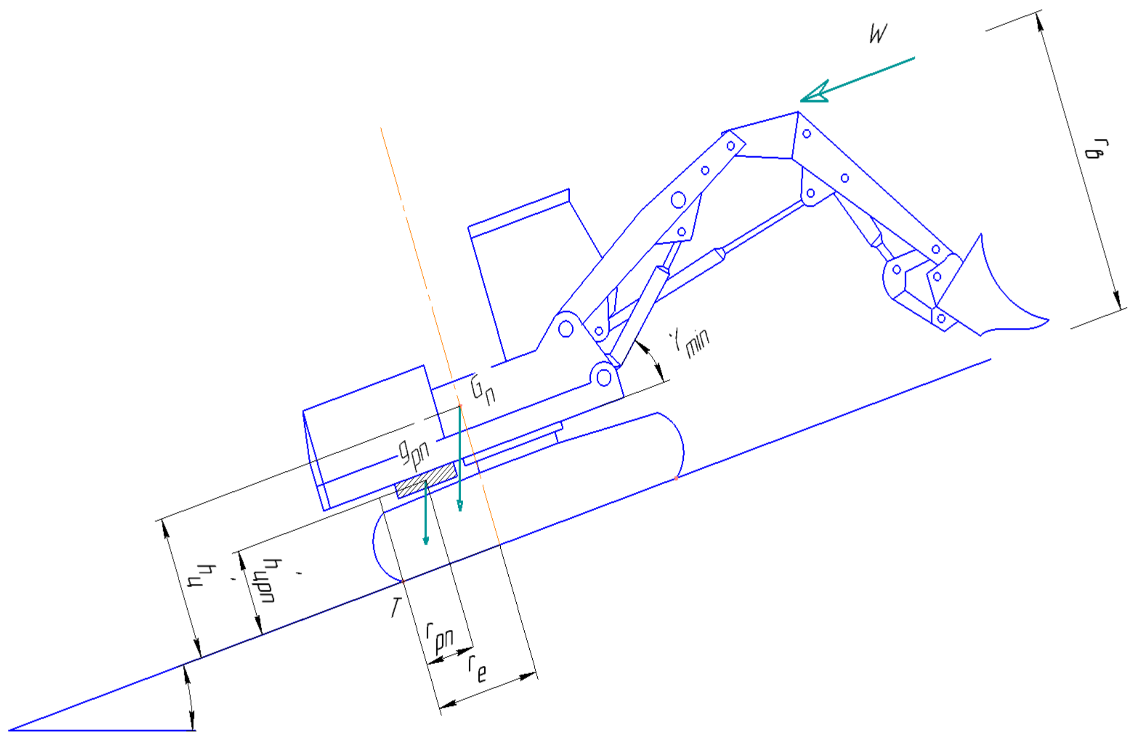

Fig. 6. Scheme for determining the stability of a single-bucket excavator with a movable counterweight, equipped with a straight shovel, when moving uphill

4. The working equipment with fixed in the transport position. The direction of the wind against the movement of the car, and will be equal to 250 Pa. The excavator moves down at an angle (Fig. 7). To prevent the machine from overturning, the movable counterweight is extended to the maximum distance from the rotary platform. Overturning in this case is possible relative to the front wheels or the front part of the tracks. The coefficient of stability of the excavator was calculate according to the formula:

$$K_y = \frac{M_y}{M_{пер}},$$

and

$$K_y \geq 1{,}2,$$

where

$$M_y = G_e r'_e cos\alpha_{max} + G_{рп} r'_{рп} cos\alpha_{max} ;$$

$$M_{пер} = G_e h'_ц sin\alpha + G_{рп} h'_{црп} sin\alpha + k_e F'_{бр} k p_в r'_в;$$

r'_e, $h'_ц$, $F'_{бр}$, $r'_в$, $r'_{рп}$, $h'_{црп}$ – values, as in the previous formula, but we accept the value taking into account other positions of the bucket and tipping point.

Due to the adaptive movable counterweight, an additional, adjustable, arm appears, which automatically balances the system when necessary.

The main advantage of this calculation for the stability of a single-bucket excavator with an adaptive movable counterweight is that it covers all critical positions in which the excavator may find itself in difficult operating conditions.

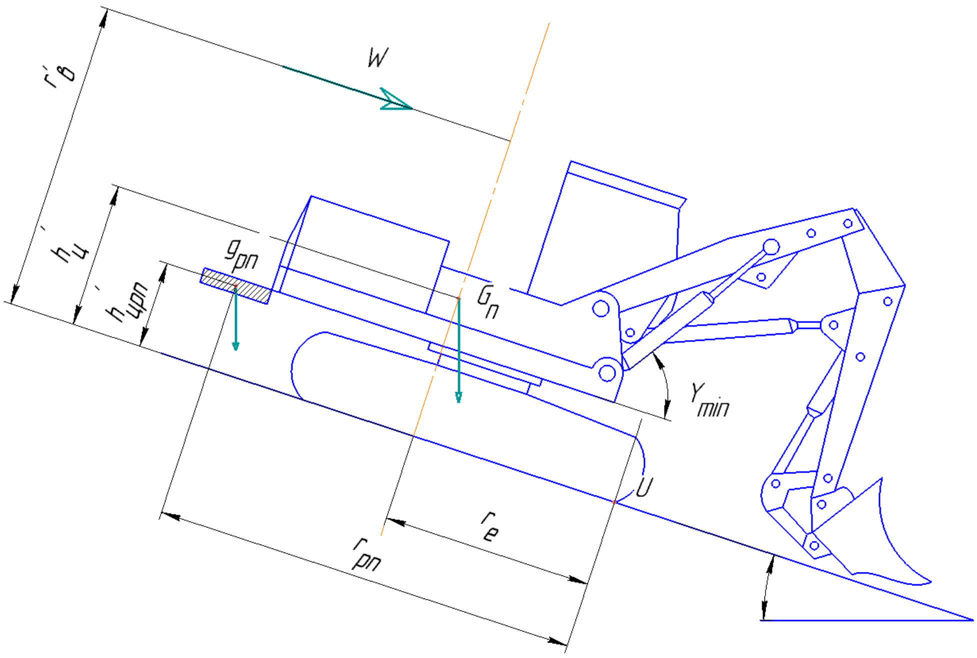

Fig. 7. Scheme for determining the stability of a single-bucket excavator with a movable counterweight, equipped with a straight shovel, when moving at an angle

CONCLUSIONS

On the basis of the conducted analytical analysis, it is proposed to use one of the methods of counteracting the overturning of a single-bucket universal excavator in the working and transport position, which consists in the use of an adaptive movable counterweight by balancing the rotary platform and the machine as a whole. The movable counterweight moves in the opposite direction from the overturning forces, which balances the system. Due to the additional movable counterweight, it is possible to increase the load on the working body without losing the stability of the machine, thereby increasing the efficiency of the working equipment. Thanks to the automatic system, the single-bucket excavator can work and move on a more inclined plane, the movable counterweight will balance the machine itself.

This method consists in the fact that due to the movable counterweight, it is possible to increase the holding moment and prevent the excavator from overturning in automatic mode.

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Обґрунтування та статичний рахунок адаптивної рухомої противаги одноківшевого екскаватора

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Анотація. Представлені результати аналітичного дослідження дії навантажень на обладнання одноківшевого екскаватора, виконано аналіз попередніх досліджень.

В роботі висвітлено, що робочий процес універсального одноківшевого екскаватора являється циклічність виконання операцій – копання і транспортування ґрунту.

Універсальні екскаватори можуть виконувати роботу вище та нижче рівня своєї стоянки робочим обладнанням прямої та зворотної лопат чи за допомогою додаткового змінного обладнання.

Під час робочого процесу виникають статичні та динамічні навантаження на машину та механізми, які впливають на стійкість машини та безпеку на робочому майданчику.

Для збільшення стійкості одноківшевих універсальних екскаваторів при роботі на похилій площині та підвищення ККД машини в кар'єрах, будівних майданчиках, при розбиранні завалів після техногенних катастроф, аварій, бойових дій потребується створення врівноважуючого механізму автоматичної дії.

Розроблено розрахунок на стійкість універсального одноківшевого екскаватора з адаптивною рухомою противагою з робочим обладнанням пряма та зворотна лопата в базових розрахункових положеннях, які виконуються при розрахунку універсальних одноківшевих екскаваторів. Для екскаватора з обладнанням зворотна лопата, розрахунок виконаний для двох положень. Розрахунок на стійкість екскаватора з обладнанням пряма лопата, виконаний для чотирьох положень.

За рахунок адаптивної рухомої противаги з'являється додаткове, регульоване, плече, яке в автоматичному режимі зрівноважує систему, коли це необхідно.

Завдяки автоматичній системі, одноківшевим екскаватором можливо працювати та переміщатися на більш похилій площині, рухома противага сама збалансує машину, а також можливо збільшити утримуючий момент та запобігти перекиданню екскаватора.

Описана доцільність використання адаптивної рухомої противаги для одноківшевих екскаваторів. Наведено приклади використання рухомої противаги в інших машинах. Виконано аналіз супутніх досліджень та обґрунтовано доцільність використання адаптивної рухомої противаги в них.

Надані попередні дослідження в розробці рухомої противаги для одноківшевих екскаваторів. Розроблено розрахунок на стійкість одноківшевого екскаватора з адаптивною рухомою противагою в основних розрахункових положеннях.

Ключові слова: адаптивна рухома противага, стійкість, утримуючи момент, перекидний момент.