A study of dynamics of the operational performance of a single-bucket excavator, taking into account the operating time during construction of transport infrastructure of oil and gas facilities

R F Salikhov\textsuperscript{1}, V B Permyakov\textsuperscript{1}, Yu O Filippov\textsuperscript{2} and M G Grusnev\textsuperscript{3}
\textsuperscript{1}Siberian Automobile and Highway University, 5, Mira ave., Omsk, Russia
\textsuperscript{2}Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia
\textsuperscript{3}Group of companies «Energoservice», 11/1, Volochaevskaya st., Omsk, Russia

Abstract. The paper presents the results of studies of the impact of operating time of single-bucket excavators on their operational performance. The results of production experiments made it possible to establish the dependence of the pressure change in the hydraulic system of the excavator during the process of cutting soil on the operating time. This parameter characterizes the variation value of the cutting resistance of soil at the cutting edge of a bucket, the duration of operation cycle and its operational productive capacity. Based on the results of the study, a technique has been developed that permits to determine economically feasible periods of effective operation of excavators, as well as to establish the optimal technological parameters for cutting soil: the thickness of the soil shavings and speed of its cutting by an excavator.

1. Introduction
The development of the fuel and energy complex is a priority area in the Russian economy. The construction of new oil refining complexes, oil product pipelines, trunk pipelines, railways and highways cannot do without the use of construction equipment. Timely delivery of construction projects increases the requirements for the planning of carrying out mechanized work. Construction and commissioning of facilities on time depends on various factors: climatic, organizational, economic, technical.

Operation of transport and technological machines for a long time leads to a decrease in their potential capabilities, including operational productivity [1-4]. Construction of oil pipelines is a complex technological process that requires usage of various means of mechanization, such as bulldozers, rippers, pipe layers, trench and single-bucket excavators, etc.

During construction and repair of oil and gas field facilities, the bulk of the volume is occupied by the laying or replacement of sections of oil pipelines, gas pipelines. Single-bucket excavators due to their versatility and high productivity in the development of soils of various categories are most widely used in earthworks, including construction, repair of oil and gas facilities [5]. Single-bucket excavators designed for the development of trenches and foundation pits are widely used in repair of pipelines and underground tanks, in construction of highways. Excavators, as a rule, are leading machines in a set with other types of equipment, for example, trucks; therefore, a decrease in their productivity can significantly affect the technological downtime of other types of mechanization means. This can lead to significant production costs, to an increase of lost profits. To solve this problem, it is necessary to improve the existing methods of calculating a change in productivity in order to increase it.
2. Theory
In designing of mechanized work, a decrease in productivity of machines over the course of operating time is rarely taken into account by existing regulatory documents, despite a number of studies devoted to this topic. The operating time is understood as the duration or volume of the machine's operation, which is measured in hours, engine hours, machine hours, hectares, kilometers of run, switching cycles, etc. [6].

The study by professor V G Samoilovich was devoted to taking into account downtime during maintenance and repair, which grows with an increase in the service life. It showed the dependence of the change in the coefficient of decrease in operating performance for some types of construction machines on the service life (Table 1).

| The sequence number of the year of the machine operation |
|---------------------------------------------------------|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Operational degradation factor |
| 0.981 | 0.956 | 0.929 | 0.900 | 0.869 | 0.837 | 0.804 | 0.770 | 0.735 | 0.699 |

This approach takes into account only the effect of changes in the duration of downtime during maintenance and repair associated with ensuring operability depending on the service life of the equipment, on annual productivity.

The second method implies a change in productivity from operating time by taking into account an increase in the duration of the working cycle associated with a decrease in the speed of performing technological operations due to deterioration in the parameters of the technical condition of various units, namely, a decrease in the power of the internal combustion engine, the efficiency of the hydraulic drive, the degree of cutting elements dulling [2, 7–8].

Methods that take into account the effect of changes in the technical state parameters on an increase in the duration of the working cycle in the process of operating are focused only on individual systems and machine units, what does not allow a comprehensive assessment of the overall effect on the change in the duration of technological operations. That is, a complex parameter is needed that takes into account the cumulative effect of the deterioration of the technical condition of machine systems on productivity. The duration of downtime in the maintenance and repair area is also excluded.

The third method takes into account general changes in productivity, both taking into account downtime and reducing the speed of technological operations performing [1]. In this case, the coefficients of deterioration of technical and economic indicators for a year of operation of equipment due to its aging are proposed: $K_{p}$ is the decrease in productivity due to wear of units and assemblies, $K_{p} = 0.5-2.5 \%$; $K_{a.w}$ is the decrease in the annual fund of working time due to failures and repairs, $K_{a.w} = 2-4 \%$. The disadvantage of this method is the indirect account of performance changes. Since the excavator operates in a wide range of loads, the annual change in productivity can exceed 2–4 %, as the change in performance for technical reasons may be non-linear, what also leads to incorrect account of this parameter [1].

To improve the accuracy of accounting a decrease in productivity during operation of excavators, it is necessary to use complex diagnostic parameters able to assess the deterioration of the totality of aggregates. The productivity of the machine significantly depends on the effort developed on the working body, because when it decreases, the power will decrease, and hence the speed of performing technological operations will decrease too.

3. Objects and methods of research
The force on the working body depends on the technical state of an internal combustion engine, the efficiency of a hydraulic drive, the state of cutting elements. To assess the effort on the working body, this paper proposes a complex diagnostic parameter that takes into account the change in pressure in the hydraulic cylinders of the handle, and of the bucket in the process of cutting soil.

To obtain experimental data on the basis of several operational enterprises, a passive statistical experiment was carried out using means of built-in on-board diagnostics, which permits monitoring diagnostic parameters. The experiment was carried out from 2005 to 2007. During the experiment, data were processed on sixteen units of single-bucket hydraulic excavators of ZX 330 models manufactured by Hitachi (Japan), with an internal combustion engine power of 184 kW, with weight of 31 tons, and the bucket capacity of 1.4 m³, according to the parameter “pressure in the hydraulic cylinders of the working equipment during cutting process”. The excavators were operated in a temperate climatic zone, all-the-year-round, during the development of soils of II and III categories, the coefficient of use of the nominal pressure was 0.4–0.57 (the average operating mode of the hydraulic drive) [9].

Excavators of this model are equipped with a built-in system for on-board diagnostics of an internal combustion engine and a hydraulic drive. Such parameters as crankshaft rotation speed, coolant and hydraulic fluid temperatures, the pressure in the hydraulic system during digging and during moving are controlled. Particular attention was paid to the pressure in the hydraulic cylinders of the working equipment during the cutting process, since a change in this parameter directly affects the duration of the digging process. This is one of the most power-consuming operations of the excavation cycle. Built-in pressure sensors are installed in the hydraulic pump body.

4. Experimental results and discussion

Based on the data processing results for each of the machines, the graphical, analytical regression dependencies were obtained, the values of the pressure drop in the hydraulic cylinders of the working equipment were determined at the studied operating time interval, as well as the characteristics of random variables at the beginning of operation, the rate of fall of this parameter (Table 2, figure 1).

Table 2. Statistical characteristics of the pressure during digging in the beginning of operation and the rate of falling this parameter from the operating time.

| Statistical characteristics | Parameter name | The pressure during digging at the beginning of operation (MPa) | The pressure drop rate during soil digging (MPa/hour) |
|-----------------------------|----------------|-------------------------------------------------------------|--------------------------------------------------|
| Mathematical expectation    |                | 16.01                                                       | 3.17 10^-4                                       |
| Standard deviation          |                | 1.50                                                        | 2.2 10^-4                                       |
| Coefficient of variation    |                | 0.09                                                        | 0.69                                             |
The analytical dependence of the pressure change in the hydraulic cylinders of the excavator working equipment is as follows:

\[ P_{\text{hwe}}(t) = -0.0003 \cdot t + 17.884, \]  

where \( P_{\text{hwe}} \) is the pressure in the hydraulic cylinders of the working equipment, MPa; \( t \) is the operating time, hours.

Taking into account the obtained characteristics of the random value of the pressure in the hydraulic cylinders of the working equipment at the beginning of operation and the rate of its fall, the average change in the force at the cutting edge of the excavator bucket during the operating cycle was determined.

According to the results of the analysis, a decrease in the investigated parameter is observed, on average, by 16 % in the interval of operating time from 0 to 8000 engine hours, while the maximum value of the pressure drop is 4.63 MPa, and the minimum is 0.4 MPa.

For a more detailed study of the question posed, a histogram of empirical frequencies of the rate of pressure drop in the hydraulic cylinders of the working equipment was constructed (figure 2).
Taking into account the obtained rates of pressure drop in the hydraulic cylinders of the working equipment, the maximum drop rate of 25–29% was observed in 20% of the examined excavators with operating hours from 6000 to 7000 hours. This is due to the influence of operating conditions (load intensity), the quality of service, the types of operating fluids used, compliance with the rules of production operation by a driver, natural and climatic factors, etc.

According to a well-known technique, calculations were carried out for a new excavator and taking into account the operating time of 8000 engine hours for different methods of digging – with a handle and a bucket [10]. For the calculation, a Hitachi ZX 330 excavator was taken with a handle length of 3.2 m and a bucket with a capacity of 1.15 m³, the category of excavated soil is II.

Determination of the force in the cylinders of the handle and the bucket is determined by the formula:

\[ P_{c.h.}(t) = P_k(t) \cdot F_{c.h.}, \]  
\[ P_{c.b.}(t) = P_k(t) \cdot F_{c.b.}, \]  

(2) (3)

where \( P_{c.h}(t), P_{c.b}(t) \) are functions of efforts from operating time in the hydraulic cylinders of the handle and bucket, kN; \( P_k(t) \) is the function of working pressure arising in the handle and in the bucket of hydraulic cylinders, MPa; \( F_{c.h}, F_{c.b.} \) are areas of pistons of the hydraulic cylinders of the handle and the bucket, m².

Then, from the sum of the moments relative to the points of rotation of the handle and the bucket (figure 3), by the handle and the bucket efforts the tangential efforts at the cutting edge were determined according to the following formulas:

\[ P_{c.h}^b(t) = \frac{1}{R_h} \cdot (P_{c.h}(t) \cdot l_{c.h} - (G_h \cdot l_{c.h} + G_{b+s} \cdot l_{b+s})), \]  
\[ P_{c.b}^b(t) = \frac{1}{R_b} \cdot (P_{c.b}(t) \cdot l_{c.b} - G_{b+s} \cdot l_{b+s}), \]  

(4) (5)
where $P_h^c$, $P_b^c$ are efforts at the cutting edge when digging with a handle and a bucket, kN; $l_{c.h}$, $l_{c,b}$, $l_{b+s}$ are shoulders of forces relative to the points of rotation of the handle, of the bucket, of the bucket with soil, m; $R_h$, $R_b$ are radii of digging with a handle and a bucket, m; $G_h$ is the weight of the handle and $G_{b+s}$ is the weight of the bucket with soil, kN.

Figure 3. The scheme for determining tangential forces on the cutting edge of an excavator bucket when digging by turning: a - handles, b – a bucket.

Figure 4 shows the results of calculating the tangential force at the cutting edge when digging with a handle and a bucket for a new excavator and with an operating time of 8000 operating hours.

Analyzing the dependences obtained, the following can be noted. The largest reduction in the tangential force at the cutting edge after 8000 operating hours in comparison with a new bucket is observed in positions 1–3 of the working equipment position. In positions 4–7, this decrease is noticeably less.
Taking into account the degree of reduction of the force at the cutting edge (figure 4), to overcome the cutting resistance the thickness of the cut shavings will decrease, what means that the digging path will increase, and this will lead to an increase in the duration of the technological operation. From the analysis of statistical observations of the excavators operation during the operating cycle, the authors adopted an approximate distribution of the digging soil duration in a combined way: with a handle – 60 %, with a bucket – 40 %. Taking this into account, the calculation of the average force at the cutting edge was made and the dependence of its change in the course of the operating time was built (figure 5).

![Figure 5. The change in the force at the cutting edge from the operating time with the combined method of digging the soil: 1 – without taking into account the decrease in pressure in the hydraulic cylinders of the working equipment, 2 – taking into account the decrease in pressure in the hydraulic cylinders of the working equipment.](image)

Further, taking into account the obtained dependencies, we determine the duration of digging:

\[
t_c(t) = \frac{q K_f K_1}{N_k(t) K_r} N_k(t)
\]

(6)

where \(q\) is the excavator bucket capacity, m³; \(K_f\) is the coefficient of filling a bucket with soil; \(K_1\) is the coefficient of resistivity to digging, for soil of the II category; \(N_k(t)\) is the function of power from operating time required for digging, kW; \(K_r\) is the coefficient of soil loosening in the bucket.

To determine the power required for digging, we use the following formula:

\[
N_k(t) = P_{med}^k(t) \cdot V_k
\]

(7)

where \(P_{med}^k(t)\) is a function of the average force at the cutting edge from the operating time, kN; \(V_k\) is the speed of movement of the bucket edge at the moment of realization of the maximum effort of digging the soil, m/s (the average speed of digging is taken as 0.4 m/s).

Based on the results of the calculation, graphs of changes in the duration of digging with the course of operating time were obtained. Comparative analysis of the graphs shows that the value of the digging time increases by 19 % in the interval of operating time from 0 to 8000 operating hours (figure 6).
Figure 6. Changing the duration of the excavator digging: 1 – without taking into account a decrease in the pressure in the hydraulic cylinders of the working equipment, 2 – taking into account a decrease in the pressure in the hydraulic cylinders of the working equipment.

The hourly operating performance of a single-bucket excavator is determined by the formula:

$$ P_{\text{hour}}(t) = 60 \cdot \frac{qP_c(t)K_n}{K_r} \cdot K_m(t), $$

(8)

where $q$ is the bucket capacity, m$^3$; $P_c(t)$ is the number of cycles; $K_n$ is the filling factor; $K_r$ is the coefficient of loosening; $K_m(t)$ is the utilization rate of the machine over time.

$$ P_c(t) = \frac{60}{t_c(t)}, $$

(9)

where $t_c(t)$ is the function of the duration of the working cycle, sec.

$$ t_c(t) = t_k(t) + t_{\text{lift}} + t_{\text{unl}} + t_{\text{ret}}, $$

(10)

where $t_{\text{lift}}$ is time of lifting and turning of the working equipment with a loaded bucket, sec; $t_{\text{unl}}$ is time for unloading, sec; $t_{\text{ret}}$ is time to return the working equipment to the face, sec.

The time spent on turning the platform, unloading, returning to the starting position was calculated in the earlier works [11–13]. Therefore, the calculation of the hourly operational productivity was made, taking into account the previous studies and the obtained function of changing the duration of digging from the operating time (figure 7).
The analysis of the presented data indicates that with a decrease in the pressure in the hydraulic cylinders of the working equipment in the process of cutting the soil, on average, the decrease in productivity will be 14 % over the period of operating time from 0 to 8000 hours. The most intense decrease in excavator performance is observed with operating hours of up to 5500 operating hours. Thus, the proposed method for calculating the performance of a single-bucket excavator, taking into account the operating time, makes it possible to assess the competitiveness of machines in comparison with existing approaches more objectively [14].

Adjusted annual operating productivity, taking into account not only downtime during maintenance and repair, but also the degree of productivity loss due to the pressure drop in the hydraulic cylinders of the working equipment in the process of cutting soil from operating time, is calculated by the formula:

\[ p^a_n = p^h_p(t) \cdot t_{a.w.}(t) \cdot K_{t.u.}(t) \cdot K_{a.u.} \]  (11)

where \( t_{a.w.}(t) \) is the function of the annual fund of working time from the operating time, hours, \( K_{t.u.}(t) \) is the function of the coefficient of technical utilization from the operating time; \( K_{a.u.} \) is the coefficient of annual use, excluding downtime due to maintenance and repair.

The resulting dependence can be used to plan the implementation of mechanized work during construction, repair of the transport infrastructure of oil and gas facilities.

5. Conclusions
The conducted research allows us to draw the following conclusions. It is proposed to use the pressure in the cutting process as one of the complex diagnostic parameters characterizing the wear of an internal combustion engine and a hydraulic drive with the course of operating time. It was found that the working pressure in the hydraulic system when digging with an excavator decreases, while the average pressure drop rate is \( 3.17 \times 10^4 \) MPa/hour. It is shown that in the interval of operating time from
0 to 8000 operating hours, the tangential force at the cutting edge of the bucket decreases by 16–19 %, and the duration of digging, taking into account the pressure drop, increases by 19 %. It has been determined that the degree of decrease in the average hourly operational productivity from the operating time is 14 %, and the highest value of this parameter is observed in the interval from 0 to 5500 operating hours. A formula is proposed for calculating the annual productivity taking into account the change in pressure in the hydraulic system during various technological operations and the duration of downtime from operating time.

Thus, the monitoring of diagnostic parameters allows not only to assess the actual technical condition of the machines, but also to accumulate statistical material, the analysis of which will make it possible to predict changes in the parameters of the excavator over time and relate them to technical and economic indicators. Taking into account the change in downtime associated with ensuring the operability of excavators over the course of operating time will make it possible to plan the performance of work during the construction of oil and gas facilities objectively.

6. References

[1] Ivanov V N, Salikhov R F, Grusnev M G 2013 Optimal planning of the functioning of systems of production, technical operation and development of parks of road-building machines (Omsk: SibADI)
[2] Kabashev R A, Kulgildinov M S 1992 Problems of improving and modelling road equipment and technological processes for the construction of highways and vehicles (Alma-Ata) p 183
[3] Kazakova Yu D, Vakhrshev S I 2016 Modern technologies in construction. Theory and practice. 1 310-319
[4] Permyakov V B, Ivanov V N 2002 Efficiency of using mechanization means in construction production (Omsk: SibADI)
[5] Khmara L A, Musiyko V D 2016 Bulletin of the Kharkiv National Automobile and Highway University 73 190-195
[6] Velikanov V S, Dvorina N V, Antropova L I, Zalavina T Y 2019 Journal of Physics: Conference series 1399 4 044067
[7] Vasilchenco V A, Sobolev V O 2008 Construction and road machines 8 32-36
[8] Rynkevich S A, Kutuzov V V 2016 Design, operation and diagnostics of mobile machines (Mogilev: Izd-vo BRU)
[9] Galdin N S, Galdin V N, Khramtsova K I 2009 Bulletin of the Siberian State Automobile and Highway Academy 4(14) 10-14
[10] Pavlov V P 2011 Voronezh State Technical University Bulletin 7 1 185-188
[11] Salikhov R F 2016 Mechanization of construction 1 29-32
[12] Salikhov R F, Popkov V I 2018 Mechanization of construction 4 46-50
[13] Karasev G N 2004 Construction and road machines 2 41-44