

Analysis of possible performance increase of open-pit excavators by elimination of soil adhesion to excavator bucket

S A Zenkov

Bratsk State University, 40, Makarenko St., Bratsk, 665709, Russia

E-mail: mf@brstu.ru

Abstract. Soil adhesion to open-pit excavator buckets significantly reduces their performance and affects friction force between soil and the bucket. Thermal and vibrothermal methods are the most efficient among all ways to reduce soil adhesion under subzero temperatures. Performance analysis of single-bucket open-pit excavators and soil frictional resistance inside the bucket was carried out. A coefficient of proportionality and superficial friction factor f_{sf} account for shift characteristics when calculating friction force of soil to metal surface, while its magnitude consists of deformation and adhesion components and depends on the same parameters as shift resistance, which are as following: contact time t and pressure P , soil humidity W and dispersability D , temperature T in shear plane, metal surface condition. By the experimental approach, on a special shift stand, the coefficient of proportionality magnitudes was calculated depending on temperature in a shear plane both without antiadhesion intensifiers and under thermal and thermoacoustic exposure. This will enable one to calculate friction force of the metal surface of working body taking into account adhesion and intensifier effect and using resulting data to choose an intensifier type.

1. Introduction

Adhesion and freezing of soil to working bodies of machinery during exploiting wet cohesive grounds significantly reduces performance (especially under temperatures below zero). A performance decrease is caused by the reduction of useful capacity of a bucket and by incomplete unloading, an increase of front resistance to cutting (digging) as a consequence of wet ground adhesion to a working body, an increase of a ram drag of a bucket and longer downtime caused by necessity to clean working bodies [1-7].

The experiments were carried out on excavators operating under different climate conditions of open pits in Siberia. Excavated solids were represented by loams and clays with sandstones and argillites of 19...22% wet, siltites with loams of 14...15% wet.

Analysis of resulting data proved that soil adhesion to a bucket starts after three to five cycles, and after loading a locomotive carriage with capacity of 220...320 m³ (approximately 50...60 cycles), soil remainder occupies 6...9% of total bucket capacity. The teeth root surface and the front wall of a bucket are the most prone to adhesion regardless of its geometric dimensions. The maximum solid remainder (layer 25...30 cm thick) is concentrated in the center of the bucket front wall and along the line of its connection to side walls (figure 1). The bucket bottom is a mechanically moving part and is almost unaffected by adhesion. Inconsiderable adhesion was also detected on inner surface of the rear wall.



Among all known methods of reduction of soil adhesion to excavator buckets, the most efficient ones are thermal and thermoacoustic (vibrothermal) intensifier exposure techniques [3].



Figure 1. EKG-10 excavator bucket with frozen over soil (Korshunovski MCC).

2. Formulation of the problem and the method of solution

Excavator technical performance is defined by the following equation (N. Dombrovski formula):

$$B_{T.P.} = \frac{3600 \cdot q \cdot K_P \cdot k_f \cdot k_{adh.}}{t_c}, \quad (1)$$

where:

q – bucket capacity, m³;

K_P – influence coefficient of soil puddling;

$$K_P = \frac{1}{k_P};$$

k_P – soil puddling coefficient;

k_f – bucket fill factor;

t_c – cycle duration, s;

$k_{adh.}$ – coefficient of adhesiveness to internal sliding surface of wet ground;

$k_{adh.} = 0.7 \dots 1.0$;

$$k_{adh.} = \frac{q - q_{adh.}}{q},$$

where:

$q_{adh.}$ – volume of soil that adheres to the internal bucket surface;

$q - q_{adh.}$ – actual volume of soil unloaded from the bucket.

An increase in excavator performance caused by elimination of soil adhesion can be implemented by means of a digging force reduction, an increased volume of collected ground, shorter cycle duration if no time is needed to clean the bucket.

N. Dombrovski suggested that digging soil with the excavator bucket causes three types of resistance:

$$P = P_D + P_S + P_C,$$

where:

P_D – cutting resistance;

P_S – shift resistance to drag prism;

P_C – shift resistance of soil cuttings shift inside the bucket.

After transforming to unit-area resistance, the equation can be defined as follows:

$$K' = K_D + K_S + K_C,$$

with the same components accordingly.

According to I. Nedorezov, excavator buckets resistances K_S and K_C compose 70...30% of K' in inverse proportion to ground strength.

All the techniques of eliminating soil adhesion to excavator buckets partly or entirely remove resistance to soil friction in the bucket P_C .

Adhesion is connected to friction. According to R. Zadneprovski, friction force composes 30...60% of total digging resistance. Friction force of soil along the sliding plane with account of adhesion is defined as [2]:

$$F = f \cdot P + f_1 \cdot \rho_{adh} \cdot S, \quad (2)$$

where:

P – resultant force of contact normal pressure;

ρ_{adh} – specific adhesion force, Pa;

f – proportionality coefficient for the deformation component of friction force;

f_1 – proportionality coefficient for the adhesion component of friction force;

S – contact area.

When $f = f_1$, the equation transforms to renowned Deryagin-Krotova formula.

Specific adhesion force ρ_{adh} depends on pressure, contact duration, soil type and condition [2] and can vary up to 150 times.

According to Terzaghi-Bowden theory of friction, skin-friction force equals shear resistance of adhesive bonds appeared in points of plain contact and is defined as:

$$F = \tau \cdot S, \quad (3)$$

where:

τ – shearing resistance (stress) that takes adhesive bonds into account;

S – contact area.

Setting right parts of (2) and (3) equations equal each other:

$$\tau \cdot S = f \cdot P + f_1 \cdot \rho_{adh} \cdot S, \quad (4)$$

therefore shift resistance equals:

$$\tau = \frac{f \cdot P + f_1 \cdot \rho_{adh} \cdot S}{S}. \quad (5)$$

Analysis of formula (5) proves that shearing resistance (stress) to the metal surface consists of deformation ($f \cdot P$) and adhesion ($f_1 \cdot \rho_{adh} \cdot S$) components and depends on contact pressure and duration, properties of shearing surfaces, specimen velocity.

Having divided both parts of equation (4) by resultant force of contact normal pressure P :

$$f_{np} = \frac{r \cdot S}{P} = f + f_1 \cdot \rho_{adh} \frac{S}{P}. \quad (6)$$

The proportionality coefficient or superficial friction factor f_{np} accounts for shearing peculiarities when defining soil friction force along the metal surface, while its magnitude consists of deformation and adhesion components and depends on the same parameters as shift resistance, which are as follows: contact time t and pressure P , soil humidity W and dispersability D , temperature T in shear plane, metal surface condition.

3. Results and discussion

Let us state that formula (5) defines shearing resistance when soil freezes over the sliding plane as well. Therefore proportionality coefficient f_{np} accounts for adhesion effect under subzero temperatures and is defined by comparing analytical formula (5) to equations [8-13] resulted from experiments on special shift stand [14], where $\tau = f(D, F, P, W, T, t)$.

Shearing stress τ , contact area S and pressure P can be measured which enables us to define superficial friction factor f_{sf} when soil freezes over the metal surface of the working body.

Based on [3] without intensifiers exposure:

$$f_{sf} = (6670,25D + 10,95p + 16,96W - 1,34T + 7,79t - 6,52 \cdot 10^6 D^2 - 0,81p^2 - 0,09W^2 - 0,042T^2 - 0,1t^2 - 409,5Dp - 718WD + 484,5DT + 82,5Pt + 0,09WP - 0,07PT - 0,36WT + 0,13Wt - 0,11tT - 648,92) \cdot \frac{S}{P}. \quad (7)$$

Based on [8-10] under thermoacoustic exposure:

$$f_{sf} = (4,42 + 0,15p + 0,2W + 0,58T - 0,07t + 330,5D - 24DT + 59Dt + 0,01pW - 0,01pT - 0,03WT - 19 \cdot 10^4 D^2 - 0,01p^2 - 0,02W^2 - 0,01t^2) \cdot \frac{S}{P}. \quad (8)$$

Based on [11-14] under thermal exposure:

$$f_{sf} = (0,82p + 1,62W + 1,22T - 0,26t + 3,41 \cdot 10^3 D - 0,52 \cdot 10^6 D^2 - 0,03p^2 - 0,06W^2 + 0,003T^2 - 0,01t^2 - 0,07 \cdot 10^3 DW - 0,05 \cdot 10^3 Dt + 0,1 \cdot 10^3 Dt + 0,02PW - 0,02PT - 0,05WT - 11,27) \cdot \frac{S}{P}. \quad (9)$$

Resulting dependencies of the proportionality coefficient on temperature (7-9) are presented in table 1.

Table 1. Approximate proportionality coefficients f_{sf} depending on temperature in shearing area

Temperature, °C	+5	- 5	-15	-25	-35
Without any exposure	2.43	6.09	9.33	12.14	14.53
Under thermoacoustic exposure	0.19	0.29	0.39	0.48	0.58
Under thermal exposure	0.67	0.83	0.95	1.05	1.12

The magnitudes of f_{sf} are calculated under the following conditions: soil dispersability $D_S = 5 \cdot 10^{-3}$ mm, pushing pressure $P = 20$ kPa, humidity $W = 17.5\%$, contact duration $t = 20.5$ min.

Analysis of resulting values of proportionality coefficient f_{sf} proves that when temperature of contacting surfaces drops from +5°C to -35°C, f_{sf} increases 3 times under thermoacoustic exposure,

1.7 times under thermal exposure and 6 times without any exposure. Absolute values of the superficial friction factor under thermoacoustic exposure become 25 times lower and rise with heating. Thermal exposure results into f_{sf} decrease 12 times in average. The degree of f_{sf} decrease under thermoacoustic and thermal exposure rises with negative relation to temperature.

4. Conclusion

Resulting formulae (7-9) enable one to calculate the value of the proportionality coefficient with given outside factors (operating conditions) and define friction force between soil and the metal surface of the working body taking freezing adhesion and outside exposure into account.

Digging resistance and energy capability of ground exploiting with the excavator bucket are to a great extent defined by processes caused by cut ground movement inside the bucket.

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