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Automatic Calculation Techniques for Soil Digging Force Applied by Bucket Swing

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Abstract

The article describes the procedure of automatic calculation techniques for soil digging force applied by a bucket swing using Mathcad software. There are also foundations of calculation of soil digging force applied by a bucket swing depending on swing angle provided. The digging force is one of important parameters of a single-bucket excavator attachment and depends on the dimensions of the components of working attachment, their angles of swing and C is a number of blows by dynamic densimeter (DorNII rammer); s is a thickness of side plate (cm); α is a digging angle (degree); $\beta 0$ is a side plate tapering factor; μ is a soil excavation technique factor. $\mu = 1$ (for locking excavation) and others parameters of soil.
In a digging operation using a bucket swing relative to joint *Ok* its teeth travel along a circle arc, and the bucket rotates by the angle φ determined by the equation of volume of displaced part of drag prism having *bk* high and characterized by a segment-shaped cross-section and the volume of soil in the filled bucket. The bucket-filling angle is determined by the successive approximations method.
The developed procedure makes such calculation and various investigations possible given with minimum expenses and maximum visualization.

Keywords: single-bucket excavator; digging force; bucket swing ; method and calculation.

1. Introduction

The volume of cylindrical soil segment V separated by digging and characterized by flat surface can be defined by the formula, as follows:

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$$V = q \cdot \frac{Cf}{Cs} = bk \cdot \frac{Rk^2}{2} \cdot (\phi - \sin(\phi)) \cdot \frac{Cf}{Cs}, \tag{1}$$

where: *q* is a bucket capacity (cu m); *Cf* is a bucket fill factor; *Cs* is a soil swell factor; *bк* is a width of attachment cutting edge (m); *Rk* is a kinematic length of bucket (m); φ is an angle of bucket swing (rad).

In one operation of digging by a bucket swing relative to joint *Ok* its teeth travel along the arc of a circle, and the bucket rotates by the angle φ determined by the equation of volume of displaced part of drag prism having *bk* high and characterized by a segment-shaped cross-section and volume of soil in the bucket upon filling it up (1):

$$\varphi = \sin(\varphi) + \frac{2 \cdot q}{bk \cdot Rk^2}. \tag{2}$$

The bucket-filling angle is determined by the method of successive approximations, i.e. by inserting of previously calculated parameter into the same formula. The desired number of iterations is defined in conditions where maximum difference between two sequentially determined values is 0.001.

The thickness of the cut slice of soil is defined by a current angle of swing φ. If the angle of swing φ changes from 0 to φmax, than the thickness of cut slice of soil (depth of cut) increases from 0 to *hmax,* and then decreases down to 0 again, as follows:

$$h_{\max} = l\kappa \cdot [\cos(\varphi - \varphi \max) - \cos(\varphi \max)]. \tag{3}$$

The maximum thickness of cut slice of soil *hmax* (m) can be reached at $\varphi = \varphi max$, as follows:

$$h_{\max} = l\kappa \cdot (1 - \cos(\frac{\varphi \max}{2})). \tag{4}$$

2. Theoretical basis

The theory of soil digging by N. A. Zelenin, a Member of Academy of Science [1-4], states the issue, as follows:

- the digging force applied by a bucket swing $P(\varphi)$ (kN) without considering teeth parameters as a function of the angle of bucket swing φ (degree) is determined by the formula, as follows:

$$P(\phi) = 10 \cdot C \cdot (h(\phi) \cdot 100)^{1.35} \cdot (1 + 2.6 \cdot bk) \cdot (1 + 0.03 \cdot s) \cdot (1 + 0.0075 \cdot \alpha) \cdot \beta 0 \cdot \mu, \tag{5}$$

where: C is a number of blows by dynamic densimeter (DorNII rammer); s a thickness of side plate (cm); α is a digging angle (degree); β_0 is a side plate tapering factor; μ is a soil excavation technique factor. $\mu = 1$ (for locking excavation).

The digging force applied by a bucket swing $Pz(\varphi)$ (kN) considering teeth parameters as a function of the angle of bucket swing φ (degree) is determined by the formula, as follows:

$$Pz(\phi) = 10 \cdot C \cdot (h(\phi) \cdot 100)^{1.35} \cdot (1 + 2.6 \cdot bk) \cdot (1 + 0.0075 \cdot \alpha) \cdot z \cdot \mu, \tag{6}$$

where *z* is a factor considering position of teeth on lateral bars. $z = 1$.

In accordance with the theory of soil digging by professor Y. A. Vetrov [5], the digging force applied by a bucket swing $P01(\varphi)$ (kN) is determined by the formula, as follows:

$$P01(\varphi) = k1 \cdot Rk \cdot bk \cdot (1 - \frac{\cos(\frac{\varphi \max}{2})}{\cos(\varphi)}) \cdot (1 + m \cdot (\frac{1 + \cos(\psi)) \cdot \cos(\varphi)}{1 + \cos(\psi - \varphi)} - 1)), \tag{7}$$

where: *k1* is a specific resistance to excavation; ψ is a sum angle (digging angle δ, angle of internal friction ϕ and angle of wall friction ρ); *m* is a soil density factor.

3. Calculation by Mathcad software

The procedure and results of calculation of digging force applied by a swing of bucket of single-bucket hydraulic excavator equipped with backhoe using Mathcad software [6-20] are given below.

Table 1. Input data.

Operation factors	Vaiue
type of excavated soil	loam
number of blows by DorNII rammer	C:=12
specific resistance to excavation (N/sq m)	*kl*:= 200000
bucket fill factor	*Кн*:=1
soil swell factor	*Kp*:= 1
kinematic length of bucket (m)	*Rk*:=1.638
bucket width (m)	*bk*:= 1.237
bucket capacity (cu m)	*q*:=1.4
transfer factor considering tangential digging force to normal (cm)	ξ:=0.15
thickness of bucket side plate (cm)	*s*:=1.5
digging angle (degree)	α:= 52
side plate tapering factor (for blunt teeth)	$\beta 0$:=1.05
soil excavation technique factor (for locking excavation by the bucket equipped with one lateral bar and two side plates)	μ:= 1
factor considering position of teeth on lateral bars	z:= 1
angle of wall friction (degree)	ρ:= 14
angle of internal friction (degree)	ϕ:= 14
soil density factor	*m*:= 0.8

3.1. Calculation procedure:

Calculation of maximum angle of bucket swing φmax (rad. degree) and volume of soil cut by a bucket swing $V(\psi)$ (cu m):

- initial angle of bucket swing φmax (rad. degree) φ_0:=0
- computer program for calculation of maximum angle of bucket swing φmax (rad, degree), fig. 1.
- angle of bucket swing variation ranging from φmin to φmax (degree):

$$\varphi \min := 0 \qquad \varphi := \varphi \min, \ \ \varphi \min \ + \ 1 ... \varphi max_1$$

- maximum angle of bucket turn about X axis (degree)

$$\varphi\max_1 := round(\varphi\max_1) \; = 104$$

$$\varphi max := \left| \begin{aligned} & for \;\; i \in 0..\, 10 \\ & \quad \varphi 0 \leftarrow sin(\varphi 0) + \frac{2 \cdot q}{(bk \cdot Rk^2)} \\ & \varphi 1 \leftarrow \varphi 0 \cdot \frac{180}{\pi} \\ & \varphi \leftarrow \begin{pmatrix} \varphi 0 \\ \varphi 1 \end{pmatrix} \end{aligned} \right. \qquad \varphi max = \begin{pmatrix} 1.814 \\ 103.945 \end{pmatrix}$$

Fig. 1. Computer program for calculation of maximum angle of bucket swing by Mathcad software.

- volume of soil cut by a bucket swing V (cu m) (fig. 2 a) and depth of cut h (m) (fig. 2 b) as a function of the angle of bucket swing φ (degree):

$$\begin{aligned} & V(\varphi) := bk \cdot \frac{Rk^2}{2} \cdot (\varphi \cdot \deg - \sin(\varphi \cdot \deg)) \\ & h(\varphi) := Rk \cdot \left(\cos\left(\varphi \cdot \deg - \frac{\varphi\max_0}{2} \right) - \cos\left(\frac{\varphi \cdot \max_0}{2} \right) \right) \end{aligned} \tag{8}$$

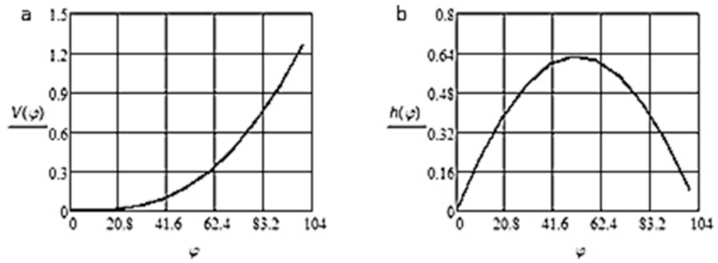

Fig. 2. (a) volume of soil cut *V(φ);* (b) depth of cut *h(φ).*

Calculation of digging force as per the theory developed by A.N. Zelenin [2-5]:

- analytic representation of digging force *P(φ)* (N) applied by a bucket swing without considering teeth parameters as a function of the angle of bucket suing φ (degree)

$$P(\varphi) := 10 \cdot \mathrm{C} \cdot (h(\varphi) \cdot 100)^{1.35} \cdot (1 + 2.6 \cdot bk) \cdot (1 + 0.03 \cdot s) \cdot (1 + 0.0075 \cdot \alpha) \cdot \beta 0 \cdot \mu \tag{9}$$

- analytic representation of digging force *P(φ)* (N) applied by a bucket swing with considering teeth parameters as a function of the angle of bucket swing φ (degree)

$$Pz(\varphi) := 10 \cdot \mathrm{C} \cdot (h(\varphi) \cdot 100)^{1.35} \cdot (1 + 2.6 \cdot bk) \cdot (1 + 0.0075 \cdot \alpha) \cdot z \cdot \mu \tag{10}$$

- graphical representation of digging force *P(φ)* (N) (fig. 3 a) applied by a bucket swing with and without considering teeth parameters *Pz(φ)* (N) (fig. 3 b) as a function of the angle of bucket swing φ (degree).

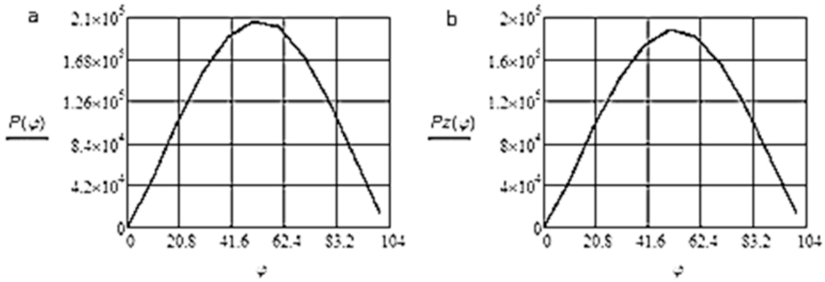

Fig. 3. (a) digging force *P(φ)*; (b) digging force *Pz(φ)*.

- analytic representation of digging force *Pzc(φ, C)* (N) applied by a bucket swing considering teeth parameters as a function of the angle of bucket swing φ (degree) and *C* parameter (number of blows by DorNII rammer)

$$Pzc(\varphi, C) := 10 \cdot \mathrm{C} \cdot (h(\varphi) \cdot 100)^{1.35} \cdot (1 + 2.6 \cdot bk) \cdot (1 + 0.0075 \cdot \alpha) \cdot z \cdot \mu \tag{11}$$

- graphical representation of digging force *Pzc (φ, C)* (N) (fig. 4) applied by a bucket swing considering teeth parameters as a function of the angle of bucket swing φ (degree) and *C* parameter (number of blows by DorNII rammer)

$$\varphi min := 0 \qquad \varphi := \varphi min, \varphi min + 1 \,..\, \varphi max_1$$

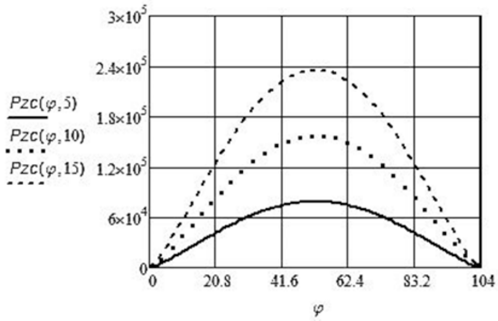

Fig. 4. Digging force *Pzc(φ,c)*

Calculation of digging force as per the theory developed by Y.A. Vetrov [1]:
- angle of bucket swing variation ranging from *φmin* to *φ*max (degree)

$$\varphi := a + \phi + \rho \qquad \psi := \psi \times deg \qquad \varphi min := 0 \qquad \varphi := \varphi min, \varphi min + 1 \,..\, \varphi max_1$$

analytic representation of digging force *P01(φ)* (N) applied by a bucket swing as a function of the anqle of bucket swinq φ (deqree)

$$P01(\varphi) := k1 \cdot bk \cdot Rk \cdot \left(1 - \frac{\cos\left(\frac{\varphi \max_0}{2}\right)}{\cos\left(\varphi \cdot \deg - \frac{\varphi \max_0}{2}\right)}\right) \cdot \left(1 + m \cdot \left(\frac{(1+\cos(\psi)) \cdot \cos\left(\varphi \cdot \deg - \frac{\varphi \max_0}{2}\right)}{1 + \cos\left(\psi - \left(\varphi \cdot \deg - \frac{\varphi \max_0}{2}\right)\right)}\right)\right) \tag{12}$$

- graphical representation of digging force $P01(\varphi)$ (N) applied by a bucket swing as a function of the angle of bucket swing φ (degree) fig. 5

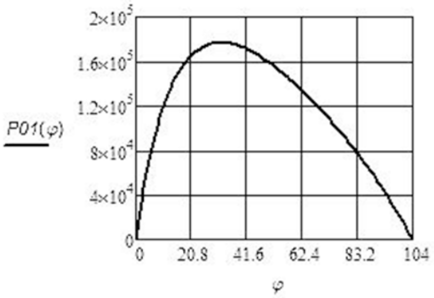

Fig. 5. Digging force $P01(\varphi)$

Required parameters:
- initial angle of bucket swing $\varphi := 0$
- angle of bucket swing providing maximum depth of cut (degree) $\varphi max := Maximize(P01, \varphi) = 31.88$
- maximum tangential digging force applied by a bucket swing (N) $P01max := P01(\varphi max) = 1.769\times10^5$
- maximum perpendicular digging force applied by a bucket swing (N) $P02max := P01max\cdot\xi = 2.654\times10^4$
- maximum digging force applied by a bucket swing (kN) $P0\max := \sqrt{P01\max^2 + P02\max^2} = 1.789\times10^5$

These problems can be research others methods and systems [9-20], but it less efficiently.

4. Conclusion

The proposed procedure of calculation of digging force applied by a swing of bucket of a single-bucket excavator equipped with backhoe using Mathcad software enables to decrease by an order of magnitude the time of labour inputs of such calculation, as well as pursue investigations related to changing parameters of attachment components.

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