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Procedia Engineering 152 (2016) 182 – 189

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Oil and Gas Engineering, OGE-2016

Theoretical researches of rammer's operating element dynamics in a soil foundation of oil and oil products storage tank

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Abstract

The development of technologies for a directional soil compaction is a new prospective task which solving will enable to obtain the required carrying capacity of soil foundations with a rational use of construction materials and to provide a trouble-free operation of engineering structures. Theoretical researches were carried out to study characteristics of physical and mechanical processes of an impact action for rammers operating elements on foundation soils for oil and oil products storage tanks. In the course of the conducted analytical studies of the dynamics for a conic model impact action on a dispersed noncohesive soil we obtained the dependence of the model's motion velocity change on impact parameters. The increase of the model impact velocity from 0.47 to 1.40 m/s resulted in the reduction of interaction process duration in a «model-soil» system from 90 to 56 ms.

Keywords: operating element dynamics; analytical studies; soil foundation; tank

1. Introduction

The problem of reinforcement of bases and foundations for oil and gas facilities to improve their reliability in the operation process, especially in Far North conditions, has been and remains extremely important, as the regions under development are characterized by hard engineering-geological, climatic and seismic conditions [1-6]. Underestimation of specific construction conditions and operation of transport facilities and liquid hydrocarbons storage, as a rule, results in serious ecological consequences. That holds true for oil and oil products storage tanks.

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doi:10.1016/j.proeng.2016.07.689

Many reasons determine technology choose or a way of reinforcement of tanks' bases and foundations. For example, the choice of a flowchart depends on the quality of facility's complex engineering surveys, structure type, its design, loadings affecting the basis and foundation, etc. However, the main goal of this technology is providing the required characteristics of reliability and reduction of material inputs and duration of work due to forming by special operating elements sets the directional compaction zones in a soil, taking into account soil properties, basis and foundation design and loadings affecting them [7-10]. To ensure the necessary operational reliability of oil and oil products storage tanks and to enhance their service life while loads on the bases and foundations increase, the problem of their reinforcement comes to a brand new level and requires new scientifically based technological solutions [11-15].

The development of new technologies of soil compaction requires understanding of physical and mechanical processes during the impact of operating elements of construction machines on oil and oil products storage tanks foundation soils. The research of impact action dynamics characteristics of construction machines operating elements on foundation soils will enable to estimate technology development prospects of the directional soil compaction.

2. Study subject

The dynamics of a rammer's operating element in a dispersed noncohesive foundation soil of oil and oil products storage tanks is the study subject.

3. Methods

In the course of conducted studies, the problem of research of operating element dynamics of a conic-shaped construction machine in the process of its impact on a soil was solved. A rammer operating element model (Fig. 1) [16] based on key principles of professor Balovnev's similarity theory was built. Theoretical and experimental studies of the conic model impact action on the soil were performed to analyze the impact dynamics.

Based on the structural model (Fig. 2) for the conic-shaped model the equation of its motion in the soil was derived:

$$m\ddot{z} = Q - N \cdot \sin\alpha - F_{Fr} \cdot \cos\alpha \,, \qquad (1)$$

where m is a model mass, Q is a model weight, N is a normal reaction force of a soil to a model's side surface, F_{Fr} is a model's side surface friction force on the soil, α is an angle between a generatrix side surface and a cone axis.

The normal reaction force of soil to the model's side surface equals:

$$N = \sigma \cdot S \,, \qquad (2)$$

where σ is a normal stress on a conic model's side surface, S is an area of the model side surface plunged in a soil.

Fig. 1. The rammer’s operating element model.

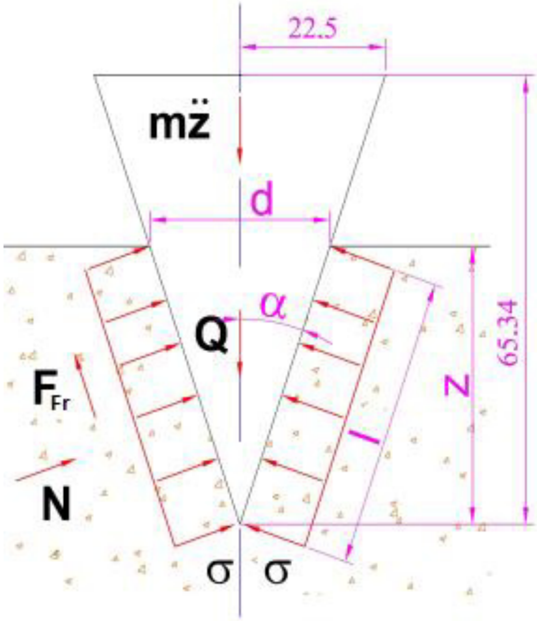

Fig. 2. The structural model of forces affecting the conic model.

We accept the normal stress σ on a cone side surface in assumption of the structural model as a constant, which equals maximum, i.e. amplitude, value of a contact pressure, growing in the course of impact [17]:

$$\sigma = \frac{a \cdot m \cdot V_{\mathrm{Im}}^{N}}{S \cdot \tau} = \frac{a \cdot m \cdot V_{\mathrm{Im}} \cdot \sin\alpha}{S \cdot \tau} = \frac{a \cdot m \cdot V_{\mathrm{Im}}}{S_{\max}^{\mathrm{Pr}} \cdot \tau}, \quad (3)$$

where a is a dimensionless coefficient (Table 1) considering deformations development lag from contact pressure changing [17]. V_{Im} is a model's velocity at the moment of impact in a soil, V_{Im}^{N} is normal to the side surface model's velocity component, at the moment of impact in a soil, $S_{\max}^{\mathrm{Pr}}$ is a projection area on a soil’s day side of the side surface plunged into the soil during the conic model impact, τ is the impact time.

Table 1. A coefficient values.

Velocity at the moment of impact, m/s	Die mass (kg) per 1 m^2 of a contact surface			
	500	1500	2000	4500
1	1.5	1.3	1.2	1.1
2	1.8	1.5	1.3	1.2
3	2.0	1.7	1.4	1.2
5	2.5	2.0	1.7	1.4
10	3.0	2.5	2.0	1.7

The impact time τ is closely connected with a soil deformation duration and therefore depends on the same factors affecting this duration. This includes the deformation value itself and its current velocity. The deformation developing during the impact, is defined by the soil flexibility degree to external loadings and depends on the soil's condition and type, and first of all on its density and moisture (Table 2) [17].

Table 2. The impact time τ (s) for optimum moisture soils.

Specific impulse, (H·s/m²)	Soil relative density ρ/ρ_{max}				
	0.80	0.85	0.90	0.95	0.98
5 000	0.040	0.030	0.020	0.015	0.010
10 000	0.070	0.050	0.030	0.020	0.015
15 000	0.090	0.065	0.040	0.025	0.015
20 000	0.110	0.080	0.050	0.030	0.015
25 000	—	0.095	0.060	0.035	0.020

The area S of the model's side surface plunged in the soil equals:

$$S = \frac{\pi \cdot d}{2} \cdot l = \pi \cdot z \cdot tg\alpha \cdot \frac{z}{\cos\alpha} = \pi \cdot z^2 \cdot \frac{tg\alpha}{\cos\alpha}, \tag{4}$$

where d is a foundation diameter of the conic model part plunged in the soil, l is a length of the side surface generatrix of the cone plunged in the soil, z is a height of the conic model part plunged in the soil.

A conic model's side surface friction force on the soil F_{Fr} is:

$$F_{Fr} = \mu \cdot N, \tag{5}$$

where μ is a coefficient of sliding friction.

The equation (1) considering equations (2), (4), and (5) can be written as:

$$m\ddot{z} = mg - \pi \cdot \sigma \cdot z^2 \cdot tg^2\alpha - \mu \cdot \pi \cdot \sigma \cdot z^2 \cdot tg\alpha = mg - \pi \cdot \sigma \cdot z^2 \cdot (tg^2\alpha + \mu \cdot tg\alpha) \tag{6}$$

For convenience to perform analytic transformations and calculations, we introduce additional notation of constants:

$$\begin{cases} A = \dfrac{\pi \cdot \sigma}{m} \cdot (tg^2\alpha + \mu \cdot tg\alpha) \\ B = g \end{cases} \tag{7}$$

Then the equation (6) taking into account (7) takes the form:

$$\frac{d^2 z}{dt^2} + A \cdot z^2 = B \tag{8}$$

In analytic form, it is possible to solve the equation (8) with respect to the first derivative:

$$\frac{dz}{dt} = \sqrt{-A \cdot \frac{2}{3} \cdot z^3 + 2 \cdot B \cdot z + 2 \cdot C} \tag{9}$$

It is clear, that

$$\frac{dz}{dt} = V, \tag{10}$$

where V is a the model's current velocity in the soil.
At the moment of conic model's impact in the soil:

$$\begin{cases} z = 0 \\ V = V_{\text{Im}} \end{cases}, \tag{11}$$

Substituting of (10) and (11) in the equation (9) allowed us to define C coefficient value:

$$C = \frac{V_{\text{Im}}^2}{2} \tag{12}$$

Thus, the equation (9) taking into account (7), (10) and (12) can be written as:

$$V = \sqrt{-\frac{2 \cdot \pi \cdot \sigma}{3 \cdot m} \cdot (tg^2\alpha + \mu \cdot tg\alpha) \cdot z^3 + 2 \cdot g \cdot z + V_{\text{Im}}^2} \tag{13}$$

4. Results and discussion

The obtained relationship (13) enabled to investigate the effect of a conic model's free fall height on the nature of its velocity change in a soil (Fig. 3). The conic model has the following parameters: the weight equals 0.56 kg, the cone angle with 2α=38° vertex, the foundation diameter d=45 mm [18]. The analysis of the data obtained defines two phases of the model's motion in the soil: acceleration and deceleration.

The first phase «Acceleration» is characterized by model's motion velocity increasing with growing of depth of its plunging in the soil – from the soil impact velocity to a certain maximum value exceeding the impact velocity (Fig. 4). For example, when conic model falls from the height of 1.6 cm its velocity at the moment of impact will be 0.470 m/s, and a maximum velocity in the soil will make 0.747 m/s that is 1.589 times higher than the velocity in impact (Table 3). While the conic model falls from 5.0 cm height its velocity at the moment of impact will be 0.936 m/s, and the maximum one in the soil will be 1.100 m/s that is 1.175 times higher than the velocity at the moment of impact.

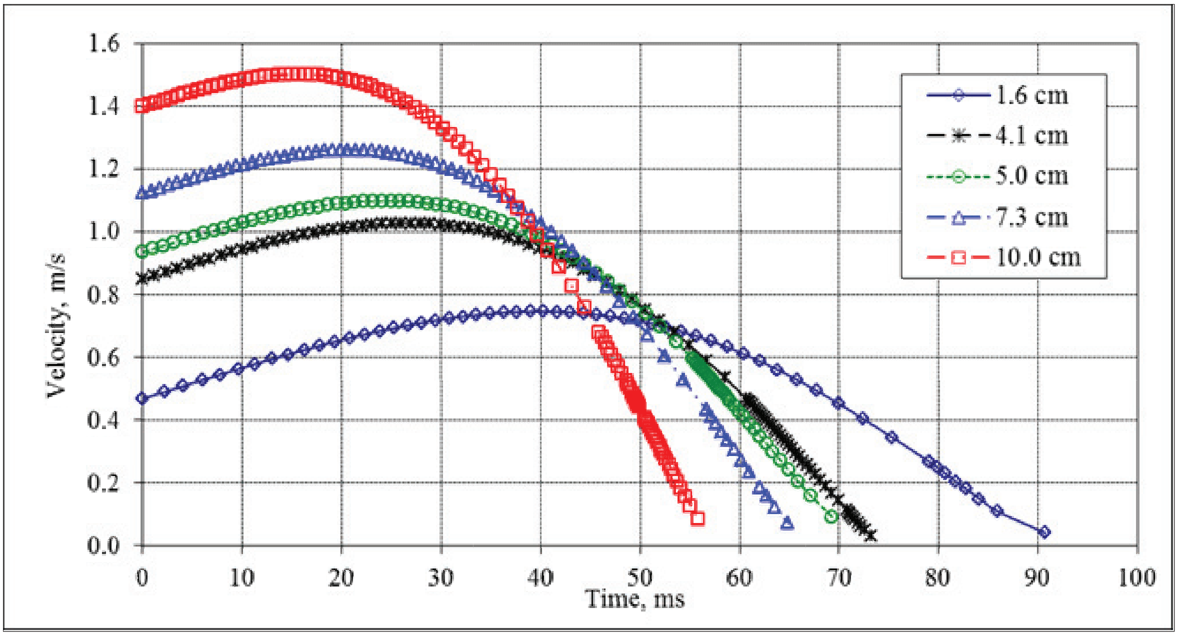

Fig. 3. Velocity changing of a conic model's motion in a soil for various values of a free fall height.

While conic model falls from the height of 10.0 cm its velocity at the moment of impact will make 1.400 m/s, and the maximum one in the soil will be 1.504 m/s that is 1.074 times higher than the velocity at the moment of impact. Thus, impact velocity increasing of the conic model in the soil results in its growth reducing in the «Acceleration» phase. «Deacceleration», the second phase of the conic model motion in the soil is characterized by decrease of the model motion velocity from maximum to zero.

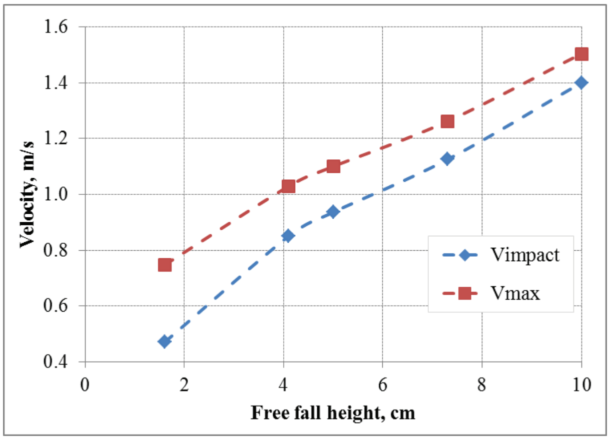

Fig. 4. The effect of the model's fall height on its velocity.

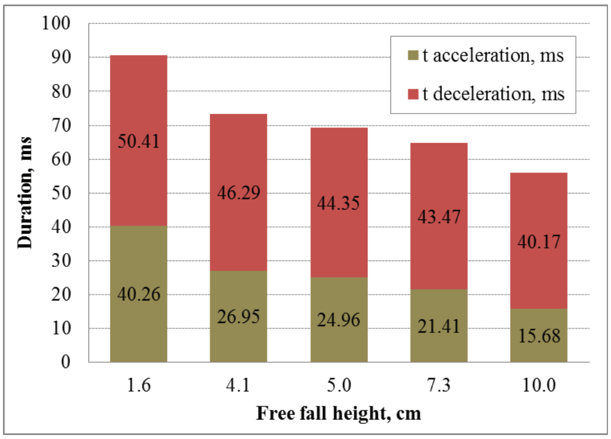

Fig. 5. The effect of the model's fall height on the phases duration.

The model's motion duration in the soil has been found during theoretical calculations (Fig. 5). For example, when the conic model falls from 1.6 cm height, the impact duration is about 90.7 ms, where the «Acceleration» phase duration is 40.3 ms and the «Deceleration» phase is 50.4 ms (Table 3). The «Deceleration» phase duration by

1.25 times exceeds the «Acceleration» phase duration. At the same time while the conic model falls from the height of 10.0 cm, the impact duration is about 55.9 ms, where the duration of «Acceleration» phase is 15.7 ms, and the «Deceleration» phase is 40.2 ms. The «Deceleration» phase duration by 2.56 times exceeds the «Acceleration» phase duration. Thus, increase of the model free fall height from 1.6 cm to 10.0 cm results in decrease of the model motion duration in the soil by 1.62 times. The main contribution to the model's motion time reduction in the soil is due to the reduction of «Acceleration» phase duration from 40.3 ms to 15.7 ms (24.6 ms increase). From the given data, it is clear that the «Acceleration» phase share in a total model's motion duration in the soil while increasing the model's free fall height from 1.6 cm to 10.0 cm has reduced from 44% to 28%. Thus, the «Deceleration» phase duration decreases from 50.4 to 40.2 ms (10.2 ms increase).

Table 3. Model's impact parameters on the soil.

Characteristic	Free fall height, cm				
	1.6	4.1	5.0	7.3	10.0
Impact velocity, m/s	0.470	0.850	0.936	1.125	1.400
Maximum velocity, m/s	0.747	1.029	1.100	1.262	1.504
Duration of the «Acceleration» phase, ms	40.3	27.0	25.0	21.4	15.7
Duration of the «Deceleration» phase, ms	50.4	46.3	44.4	43.5	40.2
Duration of the model's motion in the soil, ms	90.7	73.3	69.4	64.9	55.9

5. Conclusion

The development of new methods and improvement of existing technology of preparation of oil and oil products storage tanks soil foundations remains an urgent problem and its solution can allow us to increase oil industry profitability. The most efficient and low-cost existing technologies are those focused on a controlled change of soil's construction properties in the process of its local compaction [8-10]. The identification of a stress resultant vector direction both for compacted zones forming in the soil and for achieving the required carrying capacity for a specific engineering structure will enable one to solve the task most completely.

A preliminary generalization of theoretical research results allows to conclude that a compaction process as a way of achieving the required capacity of bases and foundations is quite complex. We have found in the course of theoretical studies of impact compaction dynamics of soil foundation for oil and oil products storage tanks:

- the conic model impact on the soil consists of two phases «Acceleration» and «Deceleration», characterized by the model motion velocity increase in the soil to a maximum value and its subsequent reduction to zero;
- the increase of the conic model impact velocity on the soil results in the reduction of the velocity growth after model's motion starting in the soil;
- the increase of the conic model impact velocity on the soil results in the reduction of the model's motion duration in the soil;
- the reduction of the model's motion duration in the soil if its impact velocity increases, occurs mostly due to the decrease of the «Acceleration» phase duration.

Experimental studies with models of rammers' operating elements used to prepare soil foundations of oil and oil products storage tanks will be performed to verify the correctness of the obtained theoretical results.

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