Experimental studies of the working process of compaction of sand with a vibrating plate

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Abstract. The paper investigates the process of compaction of a sand layer with a manual vibroplate under various technological conditions. The moisture content of the sand layer was previously determined in accordance with the accepted methodology. Then, as a result of preliminary experiments, the authors selected the limits of variation of some technological parameters of the vibroplate. To reduce the volume of experiments and increase their accuracy, the authors used an almost rotatable three-level non-factorial plan. The obtained experimental data were processed using the Statistika.exe software. As a result, the obtained mathematical models describe the dependences of the density of the sand layer on the mass of the additional load and the speed of the vibroplate, as well as on the frequency of rotation of its unbalanced shaft. The results are presented in the form of three-dimensional graphs and equations describing the compaction process. The paper analyses the research results and conclusions. They will allow to determine some optimal technological parameters of the vibroplate during the compaction of the sand layer.

Key words: vibroplate, sand layer, compaction, vibration frequency.

1 Introduction

The density of sand or soil, located in the reinforcing layer when creating coatings for roads or streets, should not be less than specified in the standards. For the main part of the created embankments and excavations, the compaction coefficient is not less than 0.95 in the lower, and 0.98 in the upper layer of the subgrade or sand. Undercompaction can lead to a decrease in the service life of coatings, as well as post-construction deposits of the created layer, followed by deformation, sometimes destruction of road or street surfaces, as well as engineering networks and structures [1, 2].

Sometimes the use of heavy compaction equipment is not economically feasible, and sometimes it is not technologically justified, or simply impossible (for example, in case of insufficient space near structures or for safety reasons) [3, 4].

In such cases, for compaction of sand, bonded soil or gravel, as well as for compaction of asphalt mixtures, it is good to use vibroplates or rammers [5-8].

The efficiency of the vibroplate is ensured by the combined action of vibration (mechanical shaking of sand or soil particles) and dynamic pressure. It is generally accepted that as the static pressure of the vibrating plate increases, the value of the dynamic pressure and its effect in the degree of compaction will increase, which will lead to an increase in the working efficiency of the vibrating plate. In this case, the effectiveness of compaction to a greater extent will be manifested in the
compaction of fine-grained and weakly bonded materials. This means that the degree of compaction should depend on the magnitude of the dynamic and static pressures, as well as on the frequency of vibration. Therefore, increasing the efficiency of the plate compacting sand requires determining the optimal values of these parameters of the plate for a particular type of compacted material [9-12].

The number of loading cycles of the compacted material depends on the frequency of vibration, the speed of movement and the number of passes of the plate. The value of static pressure, in turn, depends on the weight of the plate. The speed of movement and the number of passes of the vibroplate affect the productivity of compaction work [13-15].

Therefore, in this study, the task was to determine the influence of vibration frequency, speed, and weight of the plate on the degree of compaction of sand.

The aim of the study is to investigate the technological process of compaction of sand with a vibroplate and determine the dependence of the degree of compaction of sand on the speed of movement, vibration frequency and weight of the vibrating plate.

2 Materials and methods

The experimental vibrating plate (figure 1) is driven by a three-phase electric motor. The vibration frequency equal to the rotational speed of the unbalanced shaft was regulated by changing the frequency of the current supplying the drive electric motor. For this purpose, we used a three-phase frequency controller. The speed of movement of the plate was regulated by changing the speed of the cable of the traction winch, and with the help of another frequency controller. Three plates with holes for welding additional loads are welded on each side of the plate. The loads had a mass of 4 kg and their maximum weight installed in a vibrating plate was 24 kg.

To conduct sand compaction experiments, we made a canal 1 m wide, 0.5 m deep and 9 m long. The canal was filled with washed river sand.

Method for determination of moisture and density of sand:

After each compaction experiment, sand samples were taken using a PG-200 sampler (figure 2). Subsequently, we determined its density and humidity [16, 17]. All samples were weighed on electronic scales with an accuracy of 1 gram. Samples were dried in an oven in the laboratory of the Institute of Transport Structures of KSUAЕ.
Figure 2. PG-200 sampler ring: 1 – cutting ring; 2 – a cover for a ring; 3 – anvil handle.

Table 1. Matrix plan and levels of factor variation.

| Level and interval of factor variation | Factor          |  |  |  |
|--------------------------------------|-----------------|---|---|---|
|                                      | Vibrator shaft rotation frequency, \( n, \text{ rpm} \) | Speed of movement \( v, \text{ m/s} \) | Additional load weight \( m, \text{ kg} \) |
| Upper level (+)                      | \( x_1 \)       | \( x_2 \)       | \( x_3 \)       |
| Main level (0)                       | 3000            | 0,20           | 24              |
| Lower level (-)                      | 2400            | 0,15           | 12              |
| Variation interval                   | 1800            | 0,10           | 0               |
|                                      | 600             | 0,05           | 12              |
| Experiment plan                      |  |  |  |
| 1                                   | +               | +             | 0               |
| 2                                   | -               | -             | 0               |
| 3                                   | +               | -             | 0               |
| 4                                   | -               | +             | 0               |
| 5                                   | +               | 0             | +               |
| 6                                   | -               | 0             | -               |
| 7                                   | +               | 0             | -               |
| 8                                   | -               | 0             | +               |
| 9                                   | 0               | +             | +               |
| 10                                  | 0               | -             | -               |
| 11                                  | 0               | +             | -               |
| 12                                  | 0               | -             | +               |
| 13                                  | 0               | 0             | 0               |
| 14                                  | 0               | 0             | 0               |
| 15                                  | 0               | 0             | 0               |

Preparation for drying and determination of density was carried out in the following order:  
1) for each experiment, we took three samples of sand in the boxes;  
2) each sample was weighed on an electronic balance, excluding the weight of the box;  
3) after weighing, all data was recorded in a table.
4) the samples were placed in a heated drying oven. the sand was dried to constant weight at a temperature of (105±2)°C.

5) after drying, the samples were also weighed, minus the weight of the weights.

6) based on the results obtained, calculations were made of the values of humidity and density of sand, as well as their arithmetic average value.

7) we calculated and entered the values of the density of sand in table 1.

Assessment of the quality of compaction of soil or sand is made by comparing the compaction coefficient of soil or sand in the embankment \( k_y \) with its required values of \( k_{tr} \). The requirement for a high-quality compaction is the fulfillment of the condition:

\[
k_y \geq k_{tr}.
\]

The actual value of the compaction coefficient is determined by the ratio of the density of dry soil or sand in the embankment \( \rho_d \) to its maximum standard density obtained in the laboratory device SoyuzdorNII \( \rho_{d(max)} \) according to [18] (in foreign countries - Proctor device [19]). Therefore, the compaction coefficient is determined by the formula:

\[
k_y = \frac{\rho_d}{\rho_{d(max)}}.
\]

The soil compaction coefficient is the most important characteristic that is carefully monitored, determining the density of dry soil in the body of a soil or sand sheet and the maximum standard density.

To reduce the amount of work and save time when conducting experiments, the density of the compacted layer of sand after each experiment was taken as the output parameter, instead of the compaction coefficient. Density was defined as the ratio of the mass of the sand sample inside the PG-200 sampler ring to its volume.

The method of preliminary experiments:

During preliminary experiments, it is necessary to determine the limits of change in the frequency of vibration, speed, and also the weight of the plate.

The limits of change in the speed of movement of the plate are selected based on the characteristics of these types of plate and the recommended values in the studies, from 0.15 to 0.3 m/s. The limits of change in the mass of additional cargoes, based on preliminary experiments, varied from 0 to 24 kg. With a further increase in cargo mass, loading and burying phenomena may occur.

To determine the lower and upper limit of changes in the vibration frequency, we conducted the experiments at rotation frequencies of the unbalanced shaft from 600 to 3000 rpm. Driving was carried out with an average value: the mass of additional loads – 12 kg and the speed of movement – 0.225 m/s.

The methodology of the main experimental studies:

To reduce the volume of experimental studies and increase the accuracy of their results, we used the experimental planning method.

To obtain a mathematical model, a three-level almost rotatable Boks-Benkin second-order plan was implemented [20]. The planning matrix and levels of variation by factors are given in table 2.

**Table 2. The results of the preliminary experiment.**

| № of experiment | Vibration frequency, \( n \), rpm | Density \( \rho_{dav} \), g/cm³ |
|-----------------|----------------------------------|-------------------------------|
| 1               | 600                              | 1,59                          |
| 2               | 1200                             | 1,62                          |
| 3               | 1800                             | 1,67                          |
| 4               | 2400                             | 1,71                          |
| 5               | 3000                             | 1,69                          |

The experiments in the implementation of the plan were carried out with triplicate. The adequacy of the mathematical model was checked by Student's criteria.
During the implementation of the matrix, as in the preliminary experiments, the vibroplate was drilled along a pre-prepared, 9-meter platform with a layer of sand. After each penetration using the PG-200 sampler, samples were taken for further processing. The output parameter was the density of sand. The obtained experimental results were processed by the data processing software STATISTIKA. As a result of processing, we obtained regression equations describing a model of the process of compaction of sand with a vibrating plate.

3 Results

Results of the preliminary experiments. The results of preliminary experiments to determine the upper and lower levels of the frequency of rotation of the vibrator shaft are given in table 2.

As can be seen from table 2, the results of preliminary experiments show that for optimal volumes for compacted river sand with a natural moisture content of 14...16% having a density of 1.5 to 1.6 g/cm$^3$ (according to GOST 22733-2002), further experiments need to be carried out when the rotational speed of the vibrator shaft $n$ is from 1800 to 3000 rpm.

Results of the main experiments:
The results of the implementation of the experimental matrix (Table 1) are shown in table 3. Here, instead of the compaction coefficient, the density $\rho$ of sand was also recorded after compaction by the vibroplate.

| № of experiment | $x_1$ | $x_2$ | $x_3$ | $y$ |
|------------------|------|------|------|-----|
|                  | $n$, rpm | $v$, m/s | $m$, kg | $\rho_{ср}$, g/cm$^3$ |
| 1                | 3000 | 0.15 | 12 | 1.74 |
| 2                | 1800 | 0.3  | 12 | 1.59 |
| 3                | 3000 | 0.3  | 12 | 1.65 |
| 4                | 1800 | 0.15 | 12 | 1.66 |
| 5                | 3000 | 0.225| 24 | 1.67 |
| 6                | 1800 | 0.225| 0  | 1.67 |
| 7                | 3000 | 0.225| 0  | 1.66 |
| 8                | 1800 | 0.225| 24 | 1.66 |
| 9                | 2400 | 0.15 | 24 | 1.69 |
| 10               | 2400 | 0.3  | 0  | 1.61 |
| 11               | 2400 | 0.15 | 0  | 1.69 |
| 12               | 2400 | 0.3  | 24 | 1.68 |
| 13               | 2400 | 0.225| 12 | 1.67 |
| 14               | 2400 | 0.225| 12 | 1.69 |
| 15               | 2400 | 0.225| 12 | 1.68 |

The results were processed in Statistica.exe.

Figures 3, 4 and 5 are three-dimensional graphs of the dependence of the density of sand $\rho$ on the rotational speed of the unbalanced shaft $n$, the penetration rate of the vibrating plate $v$ and the mass of the additional load $m$.

Figure 3 shows a graph of the dependence of the density of sand $\rho$ on the frequency of rotation of the unbalanced shaft $n$, the speed of penetration of the vibroplate $v$. 
Figure 3. Three-dimensional image of the dependence of the density of sand $\rho$ on the rotational speed of the unbalanced shaft $n$ and the speed the vibroplate $v$.

The regression equation determining the dependence of the density of sand $\rho$ on the frequency of rotation of the unbalanced shaft $n$ and the speed of penetration of the vibrating plate $v$ has the form:

$$\rho = 1.3899 + 0.0002 \cdot x + 0.5269 \cdot y - 3.0449E^{-8} \cdot x \cdot x - 0.0001 \cdot x \cdot y - 1.5043 \cdot y \cdot y.$$  \hspace{1cm} (3)

As can be seen from figure 3, with an increase in the vibration frequency $n$ up to 3000 rpm, the sand density $\rho$ increases, and an increase in the speed of penetration of the vibrating plate $v$ leads to a decrease in density.

This graph shows that optimal compaction is achieved with a vibrator shaft speed closer than $n = 3000 \text{ rpm}$ and a penetration speed of about $v = 0.15 \text{ m/s}$. With an increase in penetration rate, the degree of compaction will deteriorate, and the higher the vibration frequency, the density decreases more with an increase in penetration rate.

Figure 4 shows a graph of the dependence of the density of sand $\rho$ on the rotational speed of the unbalanced shaft $n$ and the mass of the additional load $m$.

The regression equation determining the dependence of the density of sand $\rho$ on the speed of the unbalanced shaft $n$ and the mass of the additional load $m$ has the form:

$$\rho = 1.4436 - 0.0004 \cdot x + 0.0002 \cdot y - 2.1365E^{-5} \cdot x \cdot x - 0.0001 \cdot x \cdot y - 1.5043 \cdot y \cdot y.$$  \hspace{1cm} (4)

Figure 4 shows that at low rotational speeds of the vibrator shaft, an increase in the mass of the load hardly affects the amount of compaction. However, with an increase in the vibration frequency $n$ to 3000 rpm, the density of sand $\rho$, as in figure 3, increases, and an increase in the mass of the additional load $m$ leads to a more intensive increase in the density $\rho$. This can be explained by the fact that with the growth of $n$, dynamic forces also quadratically grow, which can no longer be leveled by the large mass of the plate. Therefore, at frequencies close to $n = 3000 \text{ rpm}$, it is advisable to increase the mass of the load to 20 kg.

Figure 5 shows the dependence of the density of sand $\rho$ on the penetration rate of the vibrating plate $v$ and the mass of the additional load $m$. 
Figure 4. Three-dimensional image of the dependence of the density of sand $\rho$ on the rotational speed of the unbalanced shaft $n$ and the mass of the additional load $m$.

Figure 5. Three-dimensional image of the dependence of the density of sand $\rho$ on the speed of the vibroplate $v$ and the mass of the additional load $m$. 
The regression equation determining the dependence of the density of sand $\rho$ on the speed of the vibroplate $v$ and the mass of the additional load $m$ has the form:

$$\rho = 1,4436 - 0,0004 \cdot x + 0,0002 \cdot y - 2,1365 \cdot E^{-5} \cdot x \cdot x - 0,0001 \cdot x \cdot y - 1,5043 \cdot y \cdot y. \quad (5)$$

As can be seen from figure 5, with an increase in the mass of the additional load $m$ up to 24 kg, the degree of compaction of sand almost ceases to respond to an increase in the speed of penetration of the vibroplate. This can be explained by the fact that here compaction is caused more by the amplitude of the oscillations, and not due to the number of influences. As can be seen from the graph, the maximum density value with this type of compaction is low.

4 Conclusions

As a result of processing these experiments with the Statistika.exe program, we obtained regression equations. The regression equation determining the dependence of the density of sand $\rho$ on the frequency of rotation of the unbalanced shaft $n$ and the speed of the vibroplate $v$ has the form:

$$\rho = 1,3899 + 0,0002 \cdot x + 0,5269 \cdot y - 3,0449 \cdot E^{-8} \cdot x \cdot x - 0,0001 \cdot x \cdot y - 1,5043 \cdot y \cdot y. \quad (6)$$

An analysis of the equation, as well as the obtained three-dimensional graphs, shows that the highest density $\rho$ is achieved at a rotational speed of the vibrator shaft of about $n = 3000$ rpm and a speed close to $v = 0.15$ m/s. In this case, the best compaction is achieved when loading the plate with an additional load weighing up to 20 kg.

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