Significant Development of the Explosive Compaction Method for Sandy Foundations

Développement significatif de la méthode de compactage explosif pour les fondations sablonneuses

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ABSTRACT: The explosive compaction method used for sandy water-saturated soils of foundations and structures has an outstanding history in construction industry. This paper describes the results of a theoretical study, field tests and experimental compacting under field conditions, which for the first time have proved the substantial efficiency of the consecutive firing technique in comparison with simultaneous firing when compacting. In addition to a higher degree of compaction, the consecutive firing technique makes it possible to decrease considerably the extents of dynamic impact from firing on weak clay soils of a natural foundation, when the built-up solid mass of sandy soils of foundations is being compacted, as well as on the nearby buildings and structures. It has been discovered by the author that, as a result of vibrodynamic compaction, there is achieved a significant increase in the physical and mechanical properties of sandy foundation soils: the modulus of elasticity E from 6…12 MPa to 24…60 MPa, angle of internal friction φ from 26-28 to 34-38 degrees, and relative density I_D from 0.1…0.2 to 0.48…0.82. This ensures the capacity of sandy foundation soils of buildings and structures to resist most types of vibrodynamic impact, including the seismic one.

RÉSUMÉ : La méthode de compactage explosif utilisée pour les sols sableux saturés de fondations et de structures a une histoire exceptionnelle dans l'industrie de la construction.La méthode de compactage explosif utilisée pour les sols sableux saturés de fondations et de structures a une histoire exceptionnelle dans l'industrie de la construction. Cet article décrit les résultats d'une étude théorique, des essais sur le terrain et du compactage expérimental dans des conditions de champ, qui ont démontré pour la première fois l'efficacité substantielle de la technique de tir consécutive par rapport à la cuisson simultanée lors du compactage. En plus d'un degré de compactage plus élevé, la technique de cuisson consécutive permet de diminuer considérablement l'intensité de l'impact dynamique de la cuisson sur des sols argileux faibles d'une fondation naturelle, lorsque la masse solide accumulée des sols sablonneux des fondations est compacte , Ainsi que sur les bâtiments et les structures à proximité. Il a été découvert par l'auteur que, grâce au compactage vibrodynamique, on obtient une augmentation significative des propriétés physiques et mécaniques des sols de fondation sablonneux: le module d'élasticité E de 6 ... 12 MPa à 24 ... 60 MPa, l'angle De friction interne de 26-28 à 34-38 degrés et densité relative ID de 0,1 ... 0,2 à 0,48 ... 0,82. Cela garantit la capacité des sols sableux de fondation de bâtiments et de structures à résister à la plupart des types d'impact vibrodynamique, y compris le séisme.

KEYWORDS: explosion method, soil liquefaction, density increase, reduction in vibrodynamic impact

1 INTRODUCTION

Explosive soil compaction is a world-known method serving to improve the physical and mechanical properties of foundation soils, to eliminate the sagging of soils and to ensure the vibrodynamic and seismic safety of a structure, as well as its ability to resist man induced impact.

The author is familiar with the experience of applying the explosive soil compaction method in the USA (1939-1940), Canada, France, Poland, Pakistan, Ukraine, Tadzhikistan, Uzbekistan and other countries.

In Russia the first experiments on water-saturated sands under field conditions were carried out by P.L. Ivanov, supervised by V.A. Florin, Associate Member of the USSR Academy of Sciences, in 1949, while Volzhskaya hydro power plant was being constructed, and in the ensuing years - under the guidance of Professor P.L. Ivanov at various objects of hydropower and other types of construction, including the alluvial territories on Vasilyevsky Island, Saint-Petersburg, created in order to build a new residential area(Florin and Ivanov, 1949).

Explosive soil compaction method means placing explosive charges (EC) at given intervals and at a given depth of the compacted site of a foundation and their subsequent explosion.

There exist two ways of explosive soil compaction: using simultaneous and consecutive firing technique (Ivanov and Krutov 1980, Minaev1993).

The present paper is aimed at identifying the efficiency of the consecutive firing technique in comparison with the traditional simultaneous one when compacting sites of foundation soils.

2 THEORETICAL JUSTIFICATION

In his theoretical research the author considered the task of consecutive explosion of two neighboring charges placed in the same tier in terms of depth and in terms of layout at a certain distance, with a given time interval, including the stage of partial soil consolidation caused by the explosion of a previous charge. At the same time it was supposed that the weakening of the structure of the foundation soil solid mass, resulting from the filtration forces developing during the consolidation caused by the explosion of a previous charge, added to the efficiency of the impact of the next explosion.

The calculations feature the dependencies for the explosion of a single or several charges (at the same place when arranged at one tier in terms of depth or in two or three, etc. when arranged at several tiers), when the structure of foundation soil is either intact or damaged as a result of the previous explosion (Ivanov,1980).

The following ratio was used to characterize the change in the stress state of the foundation soil skeleton caused by the explosion wave

$$\Delta = \frac{\sigma(p_{\max})}{\sigma(\gamma_{\text{soil}})} \qquad (1)$$

where σ (p_{max}) refers to maximal pressures of the explosive wave influencing the foundation soil skeleton.

A special case of the absence of trapped gas in foundation soil according to V.A. Florin

$$\sigma(p_{\max}) = \frac{(\beta_{MP}m+\beta_w n)p_{\max}}{(\beta_{MP}m+\beta_w n+\beta_{SK})} \qquad (2)$$

where $m = 1 - n$; β_{MP}, β_W, β_{SK} are the bulk compressibility ratios of the mineral particles, water and foundation soil skeleton respectively.

According to G.M. Lyakhov, in a special case for water-saturated sands with an insignificant amount of trapped gas the dependency for the maximal pressure of the explosion wave in foundation soils is the following

$$p_{max} = 60.0\left(\frac{3\sqrt{C}}{R}\right)^{1.05} \qquad (3)$$

where p_{max} is maximal pressure, MPa; C is the mass of the charge, kg; R is the distance from the center of the charge, m.

The vertical tensions in the foundation soil skeleton at the depth Z are defined in the following way taking into account the weighing factor of water

$$\sigma(\gamma_{soil}) = (\gamma_s - \gamma_w)(1-n)Z \qquad (4)$$

where γ_s, γ_W are the specific weights of the particles of the soil and water, n is soil porosity.

Judging by the results of test explosions of deep charges in fine water-saturated foundation sands, the value of Δ_K can be adopted as equal to 5–15 when their consistency is fluffy and 15–30 when the density is average.

Using the formula of V.A. Florin it is possible to identify the time of compaction t_{COM} of a foundation soil layer in the following way

$$t_{COM} = \frac{\gamma_w}{\gamma_{SUS}}\frac{h_{COM}}{K_p}\frac{n_1-n_2}{1-n_1} \qquad (5)$$

where γ_w is the specific weight of water; γ_{SUS} is the specificweight of the soil suspended in water; h_{COM} is the capacityof the compacted layer of the foundation soil; K_p is the permeability ratio of the compacted soil; n_1 is the initial soil porosity; n_2 is soil porosity after compaction.
Settlement of the surface of foundation soil layer

$$S = \frac{n_1-n_2}{1-n_2}h_{COM} \qquad (6)$$

Thus, from (5) and (6)

$$T_{COM} = S/K_p . \qquad (7)$$

The characteristic results of the calculations according to formulae (1) - (4) are shown in Fig. 1 and Fig. 2.

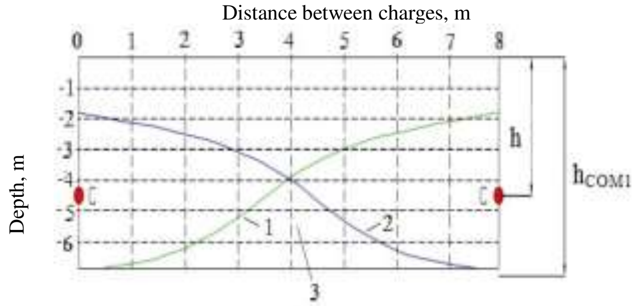

Fig. 1. Graphs showing the dependency of soil liquefaction depth on the center of the explosion when the consecutive firing technique is applied for two neighboring charges at a time interval $\Delta t \geq t_{com}$: *1* is the zone of soil liquefaction caused by the explosion of the first charge, *2* is the same for the second charge, *3* is the "dead zone" not exposed to soil liquefaction

Fig. 1 proves that when two charges are exploded consecutively with an interval of $\Delta t \geq t_{com}$ in the lower part between the charges there is a significant "dead zone" not exposed to complete soil liquefaction (Minaev, 2014).

During the soil consolidation process the border r_1 of the liquefied layer moves up to the surface, and the process stops completely if $r_1 = h_{COM1}$. At the same time the subsequent explosion of the charge placed near at a time interval $\Delta t < t_{COM1}$ enables not only ensuring soil liquefaction in this zone that has not been liquefied, but also impacting on foundation soils again exposed to the impact of the previous explosion. This leads to multiple soil liquefaction between charges repeated during subsequent explosions

With the help of a specially designed PC program calculations were made for the typically used charges with a mass of 5 kg placed at a distance of 8-10 m, and for a different border r_1 of the zone of soil particles relaying in the process of consolidation caused by the previous explosion (Minaev and Uzdin, 2014).

The calculations have shown (Fig. 2) that maximal efficiency of the subsequent explosion contributing to the destruction of the soil structure and repeated (multiple) impact on foundation soils is achieved when the ratio of the border r_1 of the soil consolidation zone caused by the previous explosion to the depth of soil compaction h_{COM1} varies between 0.25-0.3.

Consequently, calculated as the time of a soil layer consolidation r_1 according to dependency (5) $\Delta t = (0.25 - 0.3)$ t_{COM1}.

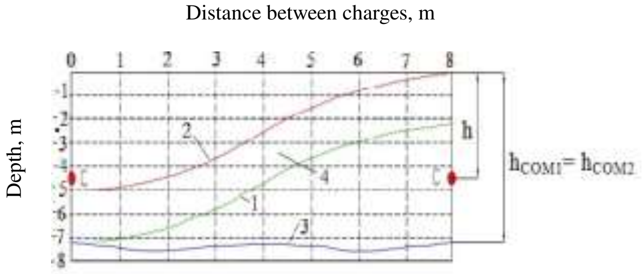

Fig. 2. Graphs showing the dependency of soil liquefaction depth on the center of the explosion when the consecutive firing technique is applied for two neighboring charges at a time interval $\Delta t \leq t_{com}$
1 is the zone of soil liquefaction caused by the explosion of the fir st charge; *2* is the same during soil consolidation process within time Δt after the first explosion; *3* is the zone of soil liquefaction caused by the second explosion with an interval of $\Delta t = 0.3 t_{com}$; *4* is the zone of the repeated soil liquefaction

Analogous calculations for the simultaneous explosion of two neighboring charges testified that in this case the "dead zone" of the foundation soils with intact structure between the neighboring charges can be practically eliminated due to amplification of counter running deformation waves and their superposition. However, at the same time the effect of repeated destruction of the soil foundation structure cannot be achieved when the subsequent charge is exploded.

3 EXPERIMENTAL TESTS

In order to carry out field tests two adjacent sites of the dam were selected, the layer thickness of fine and medium technical sands being up to 7-7.5 m at both. When the blasting works were being carried out the dam had been filled up to average values of +1.2 and +1.4 m at the first and the second site respectively.

Taking into account the foundation layer thickness and explosion containment, the mass of a charger was set to be 6 kg, the charge being placed at the depth of 4.5-5.5 m. The distance between charges equaled 10 m, and the number of explosions equaled 4.

64 charges were submerged at each site of the foundation (Fig. 3).

At the first site 16 charges were exploded simultaneously; they had been joined together with the help of a detonating cord (DC). At the second site of the foundation each charge in a round was exploded separately using the consecutive firing technique for all places where the charges had been submerged (Fig. 3). The time interval between the explosions of separate charges varied from 3 to 5 min (up 10 min).

After each round of explosions the layer thickness was checked through the settlement of surface landmarks and with the help of static penetration tests.

Geodetic measurements of the settlement showed that at the site of consecutive firing after four rounds the average total settlement of the foundation surface equaled 23 cm (see Fig. 3), whereas at the site of simultaneous firing the settlement was only 21 cm (the maximal average settlement during the second round of explosions was 6 cm, and the minimal settlement during the fourth round was 4.2 cm). In addition, the maximal settlements at the first site were 34-36 cm, while at the second one they reached 38-42 cm.

Taking into account the fact that at the first site the layer thickness of the compacted foundation comprised, on average, 5.5 m, and 4.7 respectively at the second site, the value of the relative settlement equaled 0.038 and 0.049 for average settlements at the foundation compaction site, and 0.064 and 0.085 for maximal settlements. Thus, the relative settlements of the compacted layer increased by 25-30% at the second site, in comparison with the first one.

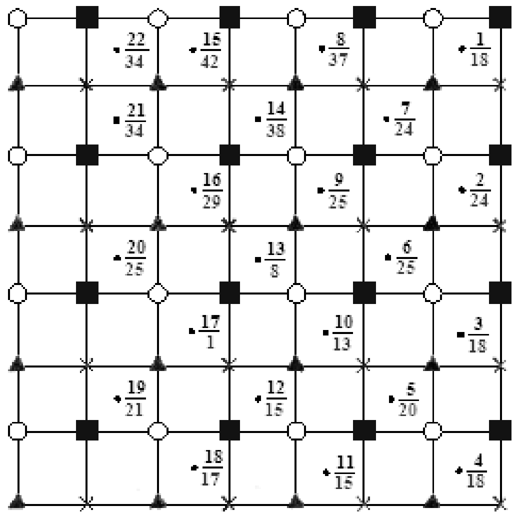

Fig. 3. Layout of the test site where foundation soil compaction was carried out using consecutive firing technique. Symbol legend: circles [O] are charges of the 1st round, squares [□] are charges of the 2nd round, crosses [X] are charges of the 3rd round, triangles [Δ] are charges of the 4th round. Numerical designation: in the numerator there are the sequence numbers of surface landmarks, in the denominator there is the total settlement of the soil of the foundation surface after four rounds of explosions, cm.

The static penetration test yielded especially positive results. At the first site resistance to the penetration of the probe point changed from 2 up to only 6-8 MPa, whereas at the site of consecutive firing – up to 10-16 MPa (Fig. 4), which testified the fact that the foundation soil had been significantly compacted.

According to the research, the permeability ratio K_p at the test sites was 2 meters per day (0.0023 cm per second) for fine sands and 10 meters per day (0.012 cm per second) for medium sands.

Using the above-mentioned values of the surface foundation soil settlement at the site of simultaneous explosions in series, and with the help of formula (7) the average value of consolidation time t_{COM} can be calculated for fine and medium sands, which equals 22.1 min. The results of the experimental tests helped to state that Δt ratio had changed from 0.14 to 0.23 (up to 0.45) t_{COM}, which accords with the data received during theoretical research.

On the whole, according to the results of the static penetration test carried out only at one dam, where more than 1 mln m^3 had been compacted using the consecutive firing technique, the values of q_p varied from 8 to 18 MPa (10 MPa and more with 90% coverage), which testified the fact that fine and medium sandy soils had positively achieved the condition of medium density and the dense one.

It has been discovered by the author that, as a result of vibrodynamic compaction, there is achieved a significant increase in the physical and mechanical properties of sandy foundation soils: the modulus of elasticity E from 6…12 MPa to 24…60 MPa, angle of internal friction φ from 26-28 to 34-38 degrees, and relative density I_D from 0.1…0.2 to 0.48…0.82.

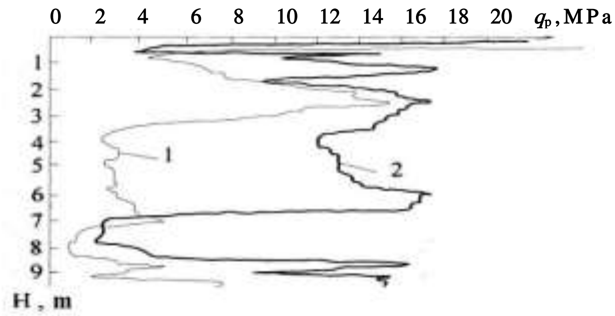

Fig. 4. Graphs showing the dependencies of resistance q_p to the penetration of the probe point on the depth H of its penetration according to the results of the static penetration test using the consecutive firing technique:
1 – before the explosion; 2 – after the explosion of all charges

This ensures the capacity of sandy foundation soils of buildings and structures to resist most types of vibrodynamic impact, including the seismic one (Seed and Idriss 1982, Ishihara 1996, Idriss and Boulanger 2008, Stavnitser 2008, Uzdin and Belash 2011, Towhata 2014, Zhussupbekov and Tanaka 2015).

By the present day, the total amount of the proved introduction according to the author's developments has been more than 10.0 million m^3 of soil of foundations and structures, including cases when sand cushions are build instead of weak clay soils of foundations, dam bodies in the foundations of highways, bridge pillars and buildings, etc.

4 CONCLUSION

The theoretical research and experimental tests under field conditions have enabled the author to prove for the first time the efficiency of compacting fine and medium water-saturated sandy foundation soils using the consecutive firing technique, in comparison with simultaneous firing. It appeared that this compaction technique enables increasing the relative settlements of the compacted layer by not less than 25-30% and achieving a considerably greater density of foundation soils.

In addition, the consecutive firing technique enables reducing significantly the values of vibrodymanic impact, caused by explosions, on weak clay foundation soils, as well as on the nearby buildings and structures.

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