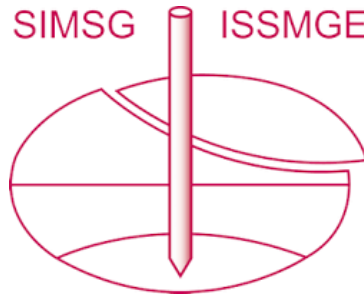


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Russian heavy mass tampers for consolidation of thick mass foundation soils

Rammers lourds russes pour la consolidation des sols des fondations d'une couche épaisse

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ABSTRACT: Today, it is common practice to use single mass tampers which are basically slabs with a round or polygonal lower base for dynamic compaction of foundations. The disadvantage of using heavy single mass tampers is that they render it impossible to deepen the compaction zone of the foundation without increasing their weight or drop height. Besides, the interaction of such tampers with the surface layer of foundation soils results in significant displacement areas, which causes soil uplifting and loosening to a depth of over 2-3 m and to considerable ineffective losses of the impact energy of the tamper on the soils of the foundation compacted. In Russian proposes a breakthrough design of the heavy tamper and a new method of soil compaction that involves using it. This “mass beater” consists of two impact masses, subsequently interacting with the soil of the foundation with a given time interval. The paper presents the main results of the comparative study of heavy single and dual mass tampers and operational experience of using the latter to compact the foundations of soil structures. The term “mass beater” was introduced for the first time in the world practice by the author of the paper instead of the traditionally recognized “tamper”. Its principle definition is given in the text of the paper.

RÉSUMÉ À l'heure actuelle, des rammers lourdes à masse unique sous la forme d'une plaque de base circulaire ou polygonale sont utilisées dans le monde entier pour le compactage dynamique des bases. L'inconvénient des rammers lourdes mono-masse est l'impossibilité d'augmenter la profondeur de compactage de la base sans augmenter leur masse ou hauteur de déversement. De plus, lorsque ces rammers interagissent avec la couche superficielle des sols de base, des zones de cisaillement importantes se forment, conduisant à un soulèvement et un ameublissement du sol à une profondeur de 2-3 m ou plus et à des pertes inefficaces importantes de l'énergie d'impact de la rammer sur les sols de la base compactée. En Russie, une conception fondamentalement nouvelle d'un rammer lourd a été proposée et une nouvelle méthode de compactage du sol en l'utilisant a été développée. Ce «bateur de masse» se compose de deux masses de choc, interagissant de manière constante avec le sol de base à un intervalle de temps donné. L'article présente les résultats d'études comparatives de perceurs mono et bi-masse et l'expérience pratique de l'utilisation de ces derniers pour le compactage des fondations dans les structures du sol. Le terme «bateur de masse» a été introduit pour la première fois dans la pratique mondiale par l'auteur de l'article au lieu du rammer de nom traditionnellement reconnu, son explication fondamentale est donnée dans le texte de l'article.

KEYWORDS: Russian heavy mass tampers; single mass tampers; dual mass tampers; “mass beater”; deformation shock waves; motions of soil mass; consolidation of foundation soils; thick mass of soil

1 INTRODUCTION.

A method for compacting foundation soils with heavy free-falling tampers was first introduced by Russian specialists, поэтому они получили название за рубежом как «русские трамбовки». Initially, Russians used heavy tampers to compact slightly damp foundation soils with average or little cohesion after they had been saturated to reach the optimum moisture content.

In the 1970s, and in the last decades, a French company in Australia called Louis Ménard started to make the extensive use of heavy tampers to ensure dynamic consolidation of water-saturated foundation soils (Ménard 1979; Hamidi & Varaksin 2011). It should be pointed out that long before that the liquefaction-based technique of dynamic consolidation of saturated soils had been applied in Russia by Prof. Ivanov in the explosive compaction method (Ivanov 1949; Minaev 1993).

According to Menar, it is recommendable to set the time sequence Δt between tamper drops so that the subsequent tamper is dropped only after the consolidation of loose soil due to the previous tamper drop.

The author of the paper proposes a new structure of heavy tampers and a new method of soil compaction using it (Minaev 2011, 2014). This tamper consists of two shock masses consistently interacting with the ground base with a predetermined time interval.

This paper presents the results of the comparative study of heavy single and dual mass tampers and operational experience of using the latter for the compaction of the foundations of soil structures.

2 MATERIALS AND METHOD

2.1 Heavy dual mass tampers

The use of large capacity cranes allows using heavy tampers of 10-30 tons. (Figure 1). The crane equipment available in Russia can be used to lift such weights at a height of 15-25 m. The designed depth of compaction can be increased up to 11-18m or more.

The impact of such heavy weights dropped from a big height changes in a qualitative way the nature of their influence on the soil foundation from local plastic deformations of compaction to the formation of intensive impact deformation waves in the soil mass that is being compacted (up to 1000 cubic meters and more). It is no longer a tamper, but rather a kind of “beater”, whose deformation waves spread from the site of impact in the foundation soils to considerable distances of dozens of meters, increasing due to the reflection from the bed rocks of the natural foundation. These impact waves will cause vibrational motions of the soil mass, its vibro-dynamic compaction (Minaev 2011) on a considerable scale, causing the motions of the soil mass comparable to the level of seismic impact during an earthquake.

Today, single mass tampers with circular or polygonal lower base, normally of 2-3 meters in diameter are used everywhere in the world (Minaev 2014).

Their main disadvantage is that it is impossible to increase the depth of tamping without enlarging the mass of tampers or the drop height. As a result, more powerful, expensive and unique cranes are required for the operation.

Furthermore, the interaction of tampers with the surface layer of soil foundation generate significant shear zone, resulting in bulging and loosening of soil to a depth of 2-3 meters. This results in a significant loss of impact energy due to inefficient compaction on soil compacted base and the need for subsequent compaction of the loosened surface soil layer.

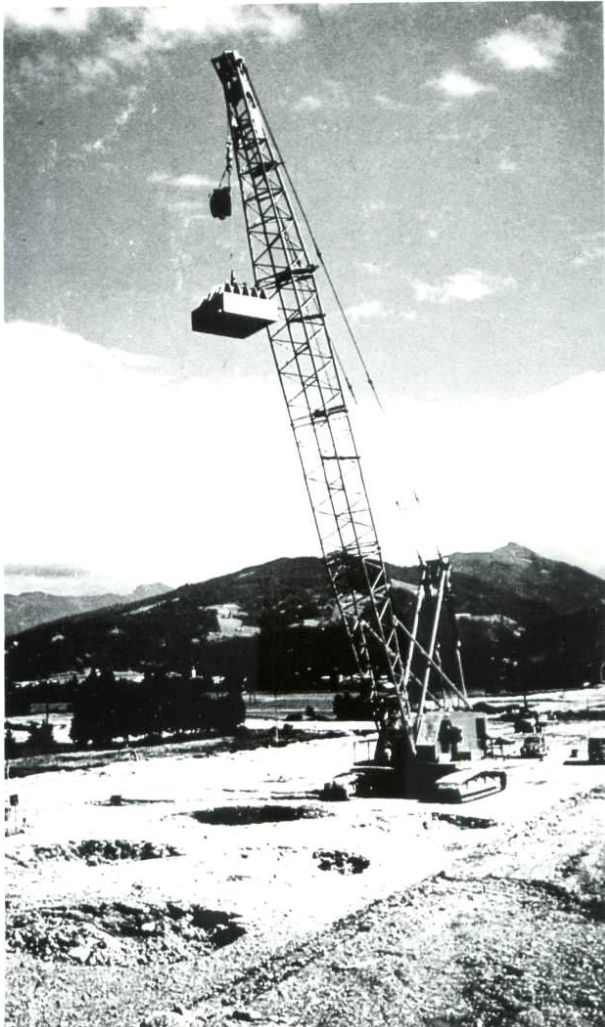


Figure 1. A high capacity crane for dropping a 25-ton tamper from the height of 20 m

To test and compare various configurations of heavy tamper, an experimental model of a heavy dual mass tamper was specially designed and built.

Its construction design provided for two operating modes: single mass and dual mass tamping.

It enabled two possible positions of a resettable backing frame: the lower position, when the frame was fixed close to internal shock mass, and the higher, with the distance between the frame and the internal mass equal to 1 m.

When fixing the frame in the lower position, both tamper masses are lifted simultaneously for the subsequent drop, thus implying that the frame works as a single tamper.

Dual mass tamper work was set by fixing the frame in the higher position. The external mass was lifted only after the internal mass was fixed close to a backing frame while moving along the uprights. A general view of a dual mass tamper at the moment of dropping at the experimental site is shown in Fig. 2.



Figure 2. The moment of dropping the experimental variant of a heavy dual mass tamper

The depth of the foundation soil depression under the tamper was 0.4–0.6 m, with practically no bulging and loosening of foundation top soil layer in the intervals between subsidence craters (Figure 3).



Figure 3. The general view of the foundation site after being treated with the designed variant of a dual mass tamper with a view of soil settlements under its sole

The area of underwater dumping of small and medium sand into the dam body varied from 0.0 to (2.8 ... 4.5) meters (increasing to water area of the Finnish Gulf), with the water area – from 1.0 to 1.5 meters, in some places up to 2 meters and more.

The dual mass tamper compacted the dam body at the groundwork base of the express road (Figure 4), at the abutments of the dam to the culverts and other foundations and buildings at the construction site of the Saint-Petersburg flood prevention facility complex.



Figure 4. A view of the current state of the high-speed highway on the Complex of Structures of the City of St. Petersburg from Floods

The full scope of implementation was no less than 1 mln cu m of compacted soil.

2.2 Justification of advantages of dual mass tampers

2.2.1 Theoretical Justification

When choosing the method of sand soil foundation compaction at depth, the attainable compaction depth h_{tamp} of the foundation is considered to be the main factor that depends on the value of the vibrodynamic effect.

When the dynamic consolidation method is applied for the compaction of saturated sandy foundation soils, the depth of the zone of compaction is determined from the critical ratio Δ_c (cyclic load ratio) between the shock-wave pressure and static pressures in the soil skeleton at a specified depth of foundation compaction, which is expressed by the equation :

$$\Delta_c = \frac{\sigma(p_{\max})}{\sigma(\gamma_{gr})} \quad (1)$$

where $\sigma(p_{\max})$ – the maximum shock-wave pressures transferred to the foundation soil skeleton, $\sigma(\gamma_{gr})$ – the vertical static pressures in the foundation soil skeleton at a depth Z of the foundation being compacted.

$\sigma(\gamma_{gr})$ is a vertical pressure in the foundation soil skeleton at the depth Z of the compacted foundation that is expressed by the formula:

$$\sigma(\gamma_{gr}) = (\gamma_s - \gamma_w)(1 - n)Z \quad (2)$$

where γ_s, γ_w - are specific weights of soil and water, n - is foundation soil porosity.

It is recommended to assume the value Δ_c equal to 5–15 for loose sands and 15-30 for sands of average density.

The value of the maximum shock-wave pressure $p_{\max}$ is derived from the equation:

$$p_{\max} = 10,0 \left(\frac{\sqrt{Q \cdot H}}{R} \right)^{1,05}, \quad (3)$$

where $p_{\max}$ – the maximum pressure in MPa, Q – the weight of the tamper in kN, H – the height from which the tamper is dropped in m, R – the distance from the centre of percussion in m. In practical calculations, the value $\sigma(p_{\max})$ may be taken equal to 0.01 ($p_{\max}$).

A theoretical study determined the depth of foundation soil compaction induced by single and dual (each part weighing 5 t) mass tampers weighing 10 t dropped from a height of 10 m. In these calculations, the value of Δ_c can be taken equal to 15. The results of calculations following (1), (2) and (3) are displayed in Fig. 5 and 6, where γ_w denotes the specific weight of water suspended in the ground.

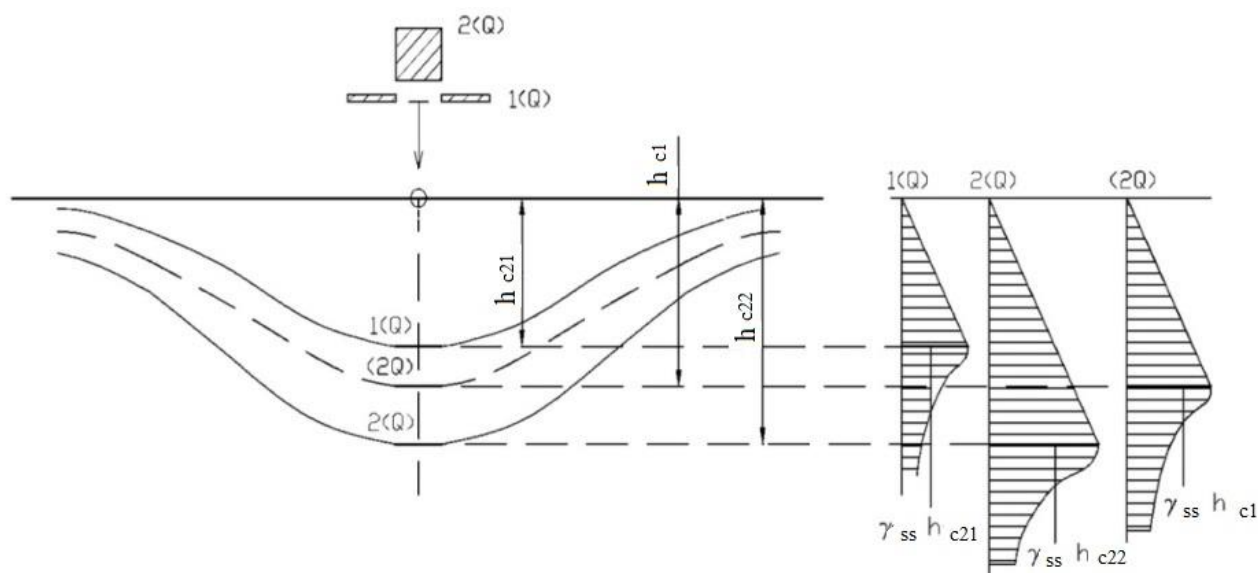


Figure 5. The zones of soil liquefaction under the impact of the first (1) and second (2) parts of a dual mass tamper each weighing Q with a small interval Δt and one impact of a dual mass tamper weighing $2Q$ and the distribution diagrams of excessive pressures in pore water corresponding to them

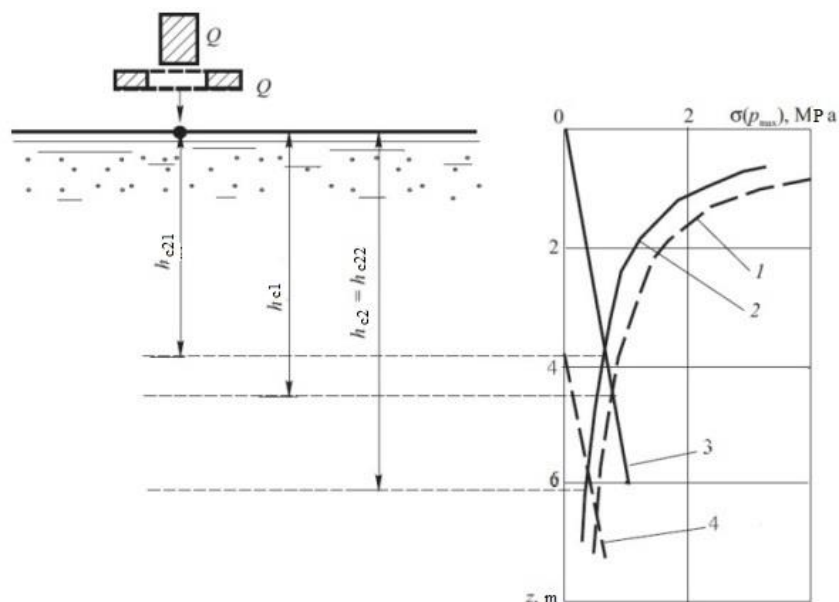


Figure 6. Varying depths of the zones of soil structure breakdown at the blow of the first (h_{c21}) and the second (h_{c22}) part of a dual and single mass tamper (h_{c1}).

Legend: 1 and 2 are the maximum pressures of the impact wave transferring to the soil skeleton along the depth of the foundation being compacted from the impact of a single mass tamper (1) and individual beating parts (2) of a dual mass tamper; 3,4 are the vertical dynamic stresses in the soil skeleton of the foundation at the depth Z of the foundation being compacted when there is an impact on the non-consolidated soil foundation (3) and in the process of soil liquefaction (4), equal to $\gamma_{ss} Z \Delta_c$ and $\gamma_{ss} (Z - h_{c21}) \Delta_c$, respectively, where γ_{ss} is the specific weight of suspended soil.

Theoretical research shows that deloading the underlying layer of foundation soil accompanied with the liquefaction of the overlying layer induced by the first part of the dual mass tamper results in a 1.3 times increase in the depth of compaction of foundation soil when there is a dual mass tamper used instead of a single mass one, even if they weigh the same and are dropped from the same height.

According to theoretical studies, the same single mass tamping depth can only be obtained by increasing the mass of the tamper or the higher drop by 1.5-2 times.

On the other hand, plastic deformations of soil in the site where the tamper falls occur in a much smaller zone and contribute to the compaction of the surface layer of soil, when the impact is made only immediately below its sole. In the bulging zones the soil can soften, rather than be compacted. On the other hand, tamping efficiency depends strongly on the

relationship between the amount of energy expended in vibrating the soil mass and in local plastic deformations.

Correspondingly, the effective impact of the tamper can be improved all other things equal due to a transfer to dual mass tampers. Thus it becomes possible to get energy from the impact of the second part of the tamper on the formation of waves spreading from the site of the impact after a time interval.

2.2.2 Experimental Tests

The comparative tests of various heavy tampers in real conditions were carried out on sandy water-saturated soil on the dam construction site in St. Petersburg.

The total weight of the tamper was 10 t, including 5.5 t of its external and 4.5 t of its internal sections. The tamper was dropped from the arm of a crane that was 15 m in length. The tests were carried out at a dam where the depth of the underwater sand or sand-gravel soil fill was 3.5...4.0 m and of the above-water one – 1.0... 1.5 m.

Two adjacent plots measuring 30x30 m were prepared for the trials. The tamper was dropped at a sequence of five times onto the centre of each plot.

The effectiveness of tamping was calculated with the help of geodetic observations of the soil surface layer displacements; by measuring excess pressure in water by pore pressure sensors and with the help of static probing.

Pore pressure sensors were placed at different depths in the radius of 3 meters from the percussion center. Their readings were recorded on the oscilloscope.

Observations over the surface displacement of the foundation soil showed that dual mass tamping always depresses the surface soil under the tamper less than single mass tamping. Yet, the latter causes more significant soil bulging around the tamper.

Computing displacements of soil surface allowed for estimating the volume of the displaced soil right under the tamper: it was 2.4 m³ in the single mass tamping mode and 2.0 m³ in the dual mass one; the volume of the uplift was 1.0 and 0.2 m³, respectively. Hence, the volume of the rammed soil in the dual mass tamping mode was 1.8 m³, while it was 1.4 m³ at single tamping.

The compaction was followed by pore water squeezing from soil. Thus, all sensors recorded the increase and then gradual decrease of pore pressure after each tamper drop on both sites.

At the same time, pore pressure sensors indicated that at dual mass tamping there was a greater excess pressure in the water as compared to single mass tamping (Fig. 7), and its increase occurred at great depths of the stratum being compacted.

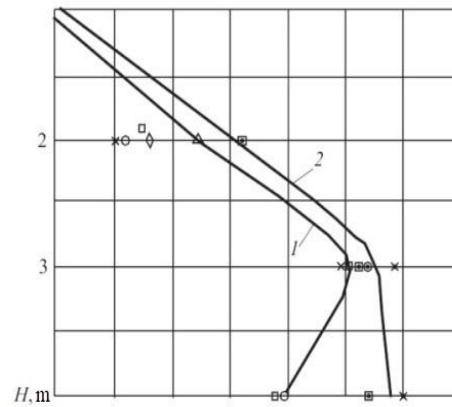


Figure. 7. The graph of maximum pore pressure values in relation with tamper compaction. 1—single mass tamper; 2 — dual mass tamper. The tamper drops are marked by: circle — 1; rhombus — 2; triangular — 3; square — 4; cross — 5; for single mass tamper compaction. Same symbols are used for dual mass tamping.

The results of static probing proved that with single mass tamping there is larger bulging and loosening of top soil layer, including top water saturated layer, than with dual mass tamping of foundation soil.

3 PRACTICAL OUTCOMES

The experimental compaction of water saturated sand foundation soils with the developed sample of a heavy dual mass tamper was conducted by dropping the dual mass tamper weighing 10 tons, which was lifted at a height of 8-10 meters. The tamper was dropped along a mesh at a pitch not exceeding 3.5-4 meters, and with the number of impacts being 6-8 in one wake.

The results of static probing of experimental compaction on the operational site are presented in figure 8.

Cone penetration testing showed that the resistance to penetration of the pointed cone q_c had increased from loose and average consistency to the compactness of 14...20 MPa throughout the whole depth of the sandy foundation.

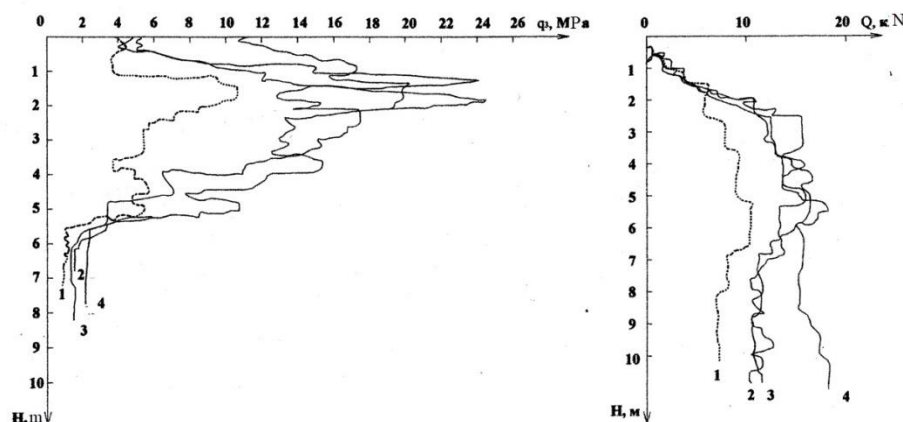


Figure 8. Results of compacting a dam with a dual mass tamper: q_c is the resistance to the penetration of the probe point; Q_c is the total friction along the lateral surface of the rod: 1 – before the compaction; 2–4 – after the compaction

Taking into account that dry soil density of loose structure was equal to $\rho_d^{\text{loose}} = 1,46\text{--}1,52 \text{ g/cm}^3$, according to lab tests, and $\rho_d^{\text{firm}} = 1,78\text{--}1,83 \text{ g/cm}^3$ - for soil firmness, the relative density of soil base was equal to $I_D = 0,64 \dots 0,82$ (Minaev 2014).

The obtained values of q_c after compacting were also indicative of an increase in the sandy soil modulus of deformation E to 42...60 MPa and in the internal friction angle φ - to 35...38 degrees, which proves the significant compaction effectiveness and it is in accordance with the current standards for construction engineering and geological research in Russia.

The calculations of reduced sediment in the entire compacted grounds (taking into account the distance between centers of subsidence craters) is not less than 0,16...0,25 meters. This accounts for 4,3...6,8 % of the relative sediment for the middle layer of underwater dumping, and 9 % for the minimal layer.

There is a high probability that such compaction can lead to the solution of the tasks of vibrodynamic and seismic safety of buildings and structures (Ilichev & Stavnitser 1995; Uzdin & Belash 2011).

4 CONCLUSIONS

The impact of heavy and super heavy weights dropped from a big height changes in a qualitative way the nature of their influence on the soil foundation from local plastic deformations of compaction to the formation of intensive impact deformation waves in the soil mass that is being compacted. It is no longer a temper, but rather a kind of "beater", whose deformation waves spread from the site of impact in the foundation soils to considerable distances of dozens of meters, increasing due to the reflection from the bed rocks of the natural foundation. These impact waves will cause vibrational motions of the soil mass on a considerable scale, causing the motions of the soil mass comparable to the level of seismic impact during an earthquake:

- Today, single mass heavy tampers are used for dynamic compaction everywhere in the world. This method of water saturated foundation soil tamping has some disadvantages.
- The author of the paper proposes the new structure of a dual mass tamper that consists of two shock masses, interacting successively with the foundation soil at a given time interval. Such dual mass tamping allows implementation of a new compaction method for water saturated foundation soil.
- Today, there are real conditions in Russia and abroad for the wide application of dual mass tampers of 20-30 tons dropped from the height of 15-25 meters. The compaction depth to firm soil can be up to 10 meters or more.
- In prospect, "dual mass beaters" can be effectively used to consolidate sand, subsiding and other soils of foundations and structures of thick mass.

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