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Combined massive and plate foundations under machines with dynamic loadings

Des fondations combinées à blocs et plaques pour des machines avec charges dynamiques

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ABSTRACT: A new type of foundation under machines with dynamic loading is presented. The combined massive and plate foundation consist of deepened rigid solid mass and attached thin horizontal plates. Finite element analysis of the combined massive and plate foundation under machines with periodic loading is conducted. The analytical method of dynamic analysis of combined massive plate foundations under impact, rotating and reciprocal machines under dynamic loadings is applied. Experimental investigation of the combined massive and plate foundation interaction with a soil base was performed on large-scale models in the open ground. The analytical and numerical results are compared with large-scale models. It was shown that the combined massive and plate foundations are much more efficient compared to conventional block-type foundations under dynamic machines, such as turbo-pumps, compressors, fans, centrifuges, etc.

RÉSUMÉ: Il est proposé un nouveau mode de fondation pour des machines supportant des charges dynamiques appelée "la fondation combinée à blocs et plaques". Elle consiste en un bloc rigide, relié à des plaques de faible épaisseur noyées dans le sol. Il a été réalisé des calculs de "fondations combinées à blocs et plaques" pour des machines soumises à des charges périodiques par la méthode des éléments finis. Les méthodes analytiques du calcul dynamique des "fondations combinées à blocs et plaques" ont été développées pour des machines subissant des impacts, des machines comportant des organes en mouvement rotatif et des bielles. L'interaction des "fondations combinées à blocs et plaques" et du sol a été étudiée expérimentalement à l'aide d'essais à grande échelle sur chantier. Les résultats des calculs analytiques et numériques sont comparés aux résultats des essais de modèles à grande échelle. Il est montré que des "fondations combinées à blocs et plaques" sont beaucoup plus efficaces que les fondations à blocs traditionnelles pour les turbopompes, les compresseurs, les ventilateurs, les centrifugeuses.

KEYWORDS: vibrations of foundations, dynamic loading, combined massive and plate foundations, dynamic analysis.

1 INTRODUCTION

Heavy machinery with rotating, reciprocating or impacting masses requires a foundation that can resist dynamic loadings and the resulting vibrations. A properly designed foundation is one that transfers the dynamic load on the soil without high vibration level. Depending on the types of load or dynamic equipment various types of foundations are used. A block-type foundation under machinery is simple and in common used. Its response depends on the foundation mass and area of foundation base (Barkan D.D.1962 and Brajama M.D., Bamana G.V. 2011). A heavy loaded foundation has extremely big weight and as a result its natural frequency is very low. Therefore, such foundation under low-frequency loading can have a very high level of vibration. Furthermore, in case operation of impact machines, it can be dangerous for building with low resonance frequency. No changes of dimensions of such foundations enable geotechnical engineers to decrease considerably the vibration level.

In the article new forms of foundations under machines with low dynamic loadings are presented. They were named «Combined massive and plate foundations» (Fig. 1). Foundations such as these consist of deepened rigid solid mass and attached to it in soil thin horizontal plates (Kirichek Y. 2011). Its natural frequencies can be set in a wide frequency range by changing dimension and location of attached thin horizontal plates in soil. As a result natural frequency of such foundation can be significantly higher in amount than of block-type foundation and vibration level of the combined massive and plate foundations under low-frequency loading and impacting machinery generally is considerably lower.

2 LARGE-SCALE FIELD TEST

For studying behavior of the combined massive and plate foundations under low-frequency loading large-scale field tests

were conducted. The comparison of the footing vibration tests with theory was done. For these tests, the vertical and horizontal dynamic forces on footing were generated by rotating mass vibrators. The large-scale models were 1.5 m in wide and 3.71 m in length (See Fig.2).

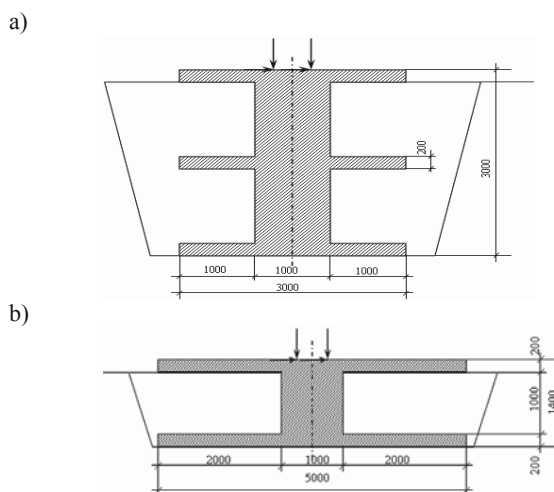


Figure 1. Combined massive and plate foundations: a – a solid block and three plates, b – a solid block and two plates.

Figure 2 shows the large-scale model of massive and plate foundations with the plate on the top or at the foot.

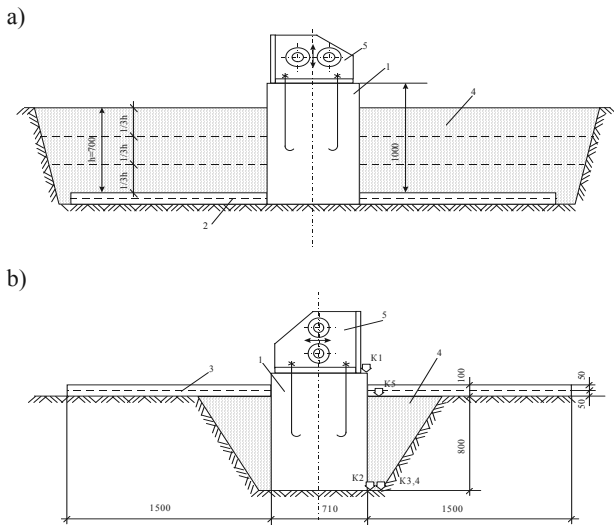


Figure 2. Large-scale models of combined massive and plate foundations: a – the plate is on the top of foundation, b – the plate is at the bottom of foundation. 1 – block, 2 – lower plate, 3 – upper plate, 4 – soil, 5 – vibrator.

The tests were performed on the silty clay with unit weight 19.7 KN/m^3 , natural water content 0.22, voids ratio 0.85, Young's modulus 10 MPa. The block was 1 m high with the area of its foot equal 1 m^2 . The plates thickness was $h=0.05 \text{ m}$ and $h=0.1 \text{ m}$. The area of the plates was $F=2.13 \text{ m}^2$ and $F=4.5 \text{ m}^2$. The foundations were placed at the centre of a hole excavated to the desired depth. Cyclic load was applied $12.7 - 25.4 \text{ KN}$ under frequency 50 Hz . The amplitude-frequency responses of the combined massive and plate foundations under horizontal and vertical periodic loadings are shown in Figures 3 and 4.

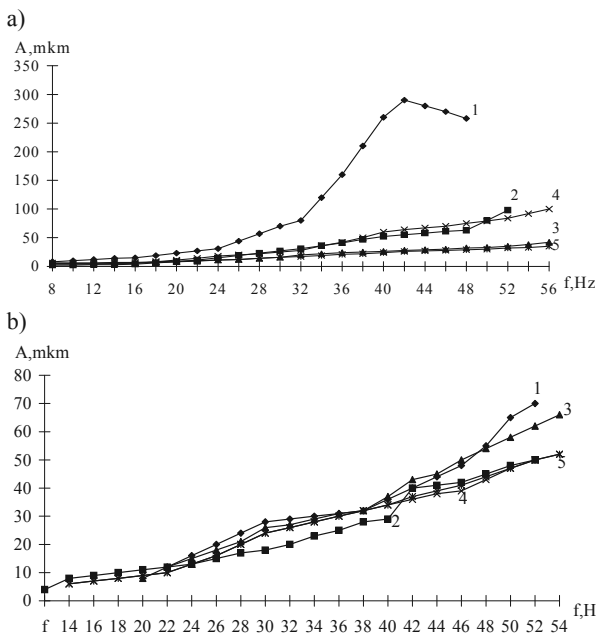


Figure 3. Amplitude-frequency responses of the combined massive and plate foundations with the plate on the top of the foundations: a – horizontal periodic load, b – vertical periodic load, 1 – amplitude-frequency response of the block, 2 – $F=2.13, h=0.05$, 3 – $F=4.5, h=0.05$, 4 – $F=2.13 \text{ m}, h=0.1$, 5 – $F=4.5 \text{ m}, h=0.1 \text{ m}$.

a)

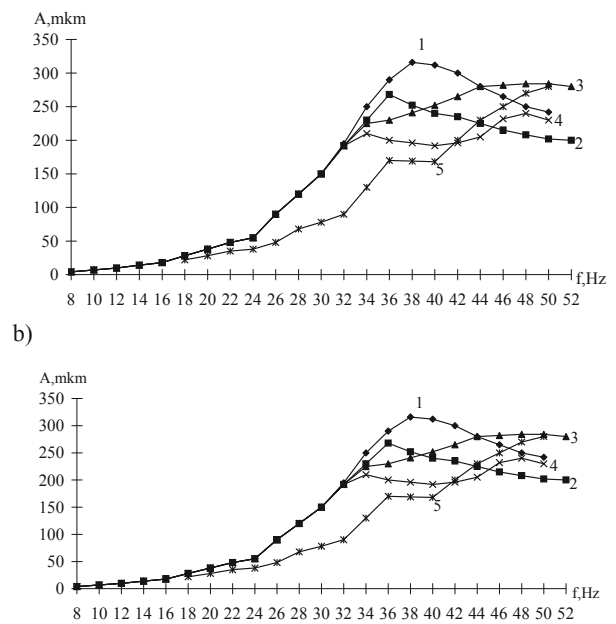


Figure 4. Amplitude-frequency responses of the combined massive and plate foundations with the plate at the bottom of foundations: a – horizontal periodic load b - vertical periodic load, 1 – the amplitude-frequency response of the block, 2 – $F=2.13, h=0.05$, 3 – $F=4.5, h=0.05$, 4 – $F=2.13 \text{ m}, h=0.1$, 5 – $F=4.5 \text{ m}, h=0.1 \text{ m}$.

The comparison of the amplitude-frequency responses of the combined massive plate foundations enable to evaluate influence of the dimension of plates on responses of foundation. We note that the vibration amplitude decreases half as much with increasing of the plate area twice as many. The plate thickness has less effect on the responses of foundation. It was experimentally determinate, that the effect of top plates was bigger under horizontal dynamic loading and the effect of bottom plates was bigger under vertical dynamic loading.

A thin plate on the soil can significantly reduce the vibration level of the block foundation. Figures 5 and 6 present the results of such large-scale field test. Responses of the deepened block-type foundation with dimension $1 \text{ m} \times 1 \text{ m} \times 1 \text{ m}$ became quite different after attaching a thin plate lying on the soil. So resonance frequencies became 42%-64% higher. As a result the high-frequency vibration amplitude decreased 3 – 4 times.

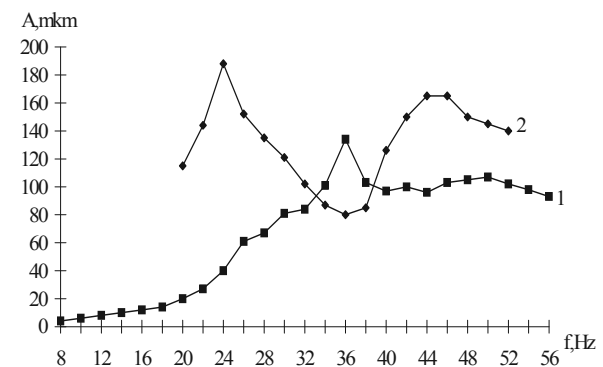


Figure 5. The amplitude-frequency responses of the block-type foundations under horizontal periodic loading: 1 – the plate with area 8 m^2 is on the top of foundation, 2 – no plate.

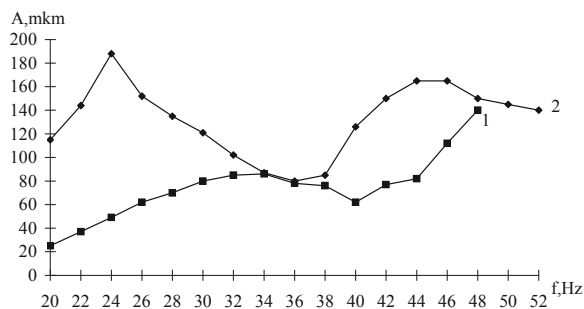


Figure 6. The amplitude-frequency responses of the block-type foundations under horizontal periodic loading: 1 – the plate with area 12m² is on the top of foundation, 2 – no plate.

The vibration level of the plate extremely reduced with increasing the distance from the block. Figure 7 shows measuring on the large-scale model of block-type foundation with attached thin plate lying on the soil. Similar effect we can see on the slab around the block-type foundation of industrial machinery (See Fig.8).

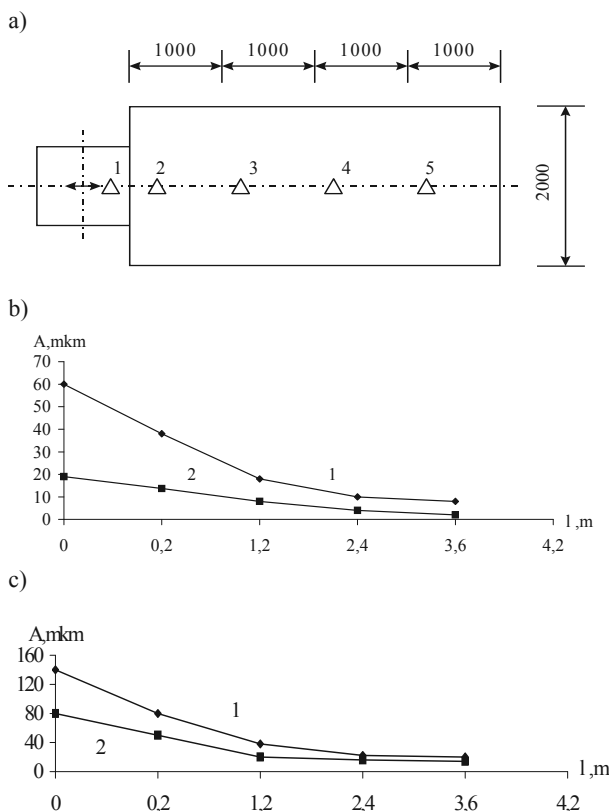


Figure 7. Decline of the vibration amplitude of the plate away the block: a – the large-scale model, b - vertical vibration amplitude, c - horizontal vibration amplitude, 1 – vibration frequency 40 Hz, 2 – vibration frequency 20 Hz.

The large-scale test results and the finite element analysis (Kirichek Y. 2000) present, that the combined massive and plate foundations have advantage over type-block foundations in frequency range 9 – 30 Hz, as their vibration level is considerably less. The slabs bring positive influence on the vibration level of block-type foundations in the low-frequency range. The vibration level of type-block foundations reduced two or three times as a result of increasing the natural frequency of system “block – slab”.

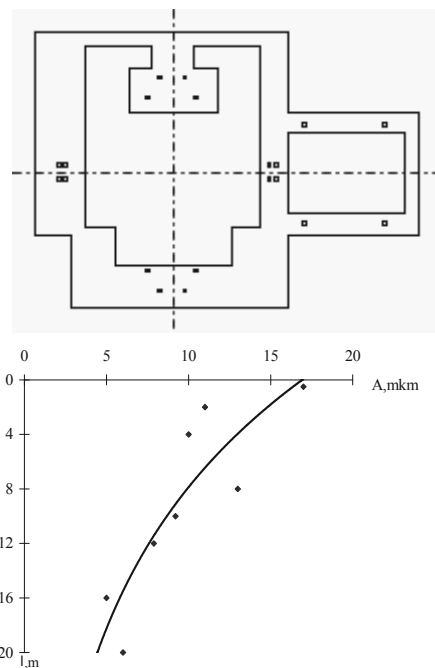


Figure 8. Decline of the horizontal vibration amplitude of the slab away the block-type foundation.

3 ANALITICAL SOLUTION

The mathematical model of the combined massive and plate foundations is a concentrated mass with either plates or beams on a viscoelastic base. Integral transformations for vertical and horizontal oscillations of the block and plates are considered as a problem of beams or plates on a viscoelastic base using asymptotic and transformation methods. The analytical

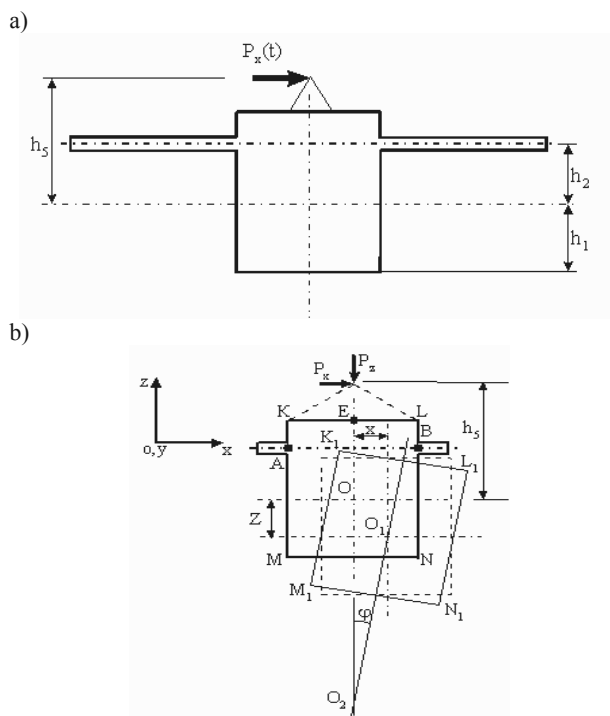


Figure 9. Design model of the combined massive and plate foundation

derivation of the complex problem is also given using a elementary system (Barkan D.D. 1962. and Verruijt A. 2010). Figure 9 shows the system consisted of a mass and some beams, supported by a linear springs.

Theoretical solution for such foundation subjected to sliding and rocking forced vibration is presented below. The vibration amplitude and natural frequencies of the block can be derived from displacement equation (see Eq. 1).

$$\begin{aligned}
 m \ddot{x} + (K_x + K_{xn}) \cdot x - [K_x h_1 - (-1)^k K_{xn} h_2] \varphi &= P_x(t) \\
 \theta \ddot{\varphi} + (K_\varphi + K_x h_1^2 + (-1)^k K_{xn} h_2^2 - Qh_1) \varphi + & \\
 + (K_{xn} h_2 - K_x h_1) x &= M_y [P_y(t)]
 \end{aligned}
 \tag{1}$$

Where: m – mass of block;
 K_x, K_{xn} – sliding subgrade modulus of the block and plate;
 K_φ – rocking subgrade modulus of the block;
 For vibration amplitude the solution to Eq.1 can be given as:

$$A_x = \frac{P}{\alpha} \left[1 + \frac{\alpha h_5 + \varepsilon}{\alpha \gamma - \beta \varepsilon} (\beta + h_5 \alpha) \right]
 \tag{2}$$

Where:

$$\begin{aligned}
 K_x + K_{xn} - m\omega^2 &= \alpha; \\
 K_x h_1 - (-1)^k K_{xn} h_2 &= \beta; \\
 K_\varphi + K_x h_1^2 + (-1)^k K_{xn} h_2^2 - Qh_1 - \theta\omega^2 &= \gamma; \\
 K_x h_1 - K_{xn} h_2 &= \varepsilon
 \end{aligned}$$

The solution to Eq.1 of natural frequencies (see Eq. 3) can be written as

$$\lambda_{1,2} = \sqrt{\frac{1}{2} \left(A \pm \sqrt{A^2 - 4B} \right)}
 \tag{3}$$

Where

$$\begin{aligned}
 A &= \frac{K_x + K_{xn}}{m} + \frac{K_\varphi - Qh_1 + K_x h_1^2 + (-1)^k K_{xn} h_2^2}{\theta}; \\
 B &= \frac{2(-1)^k K_x K_{xn} h_1^2 + (K_x + K_{xn})(K_\varphi - Qh_1)}{\theta \cdot m}
 \end{aligned}$$

Figure 10 shows the comparison of analytical solution (see Eq. 2) to field test result. The amplitude-frequency responses of the combined massive and plate foundation are shown. The plates with area 2.13 m² and 4.15 m² were located on the soil at the top of the foundation. This simple spring-mass system can be used for definition vibration level of the combined massive and plate foundation on the understanding that properties of dynamically loaded soil must be correctly evaluated.

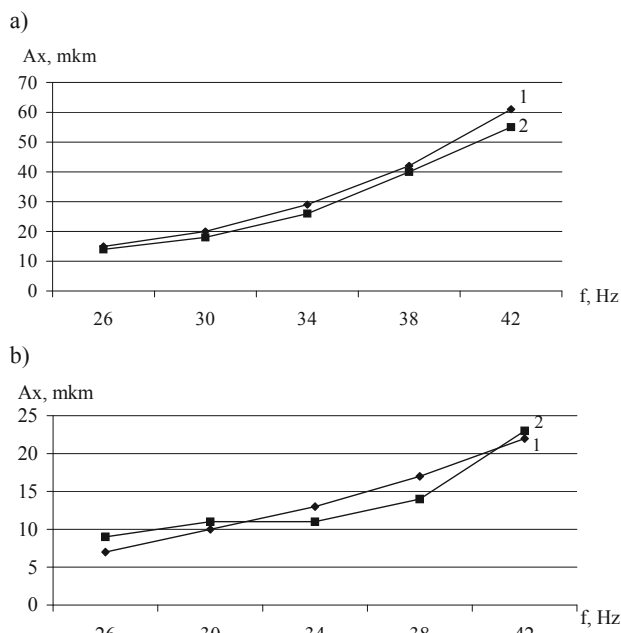


Figure 10. Comparison of analytical solution to field test result, amplitude-frequency responses of the combined massive and plate foundation with the plates on the top of foundation: a – area of the plate is equal 2.13 m², b – area of the plate is equal 4.15 m², 1 – analytical solution, 2 – field test result.

4 CONCLUSION

The new type of foundation under machinery with dynamic loading was developed. It was named the combined massive and plate foundation. The foundation consists of deepened massive block and attached in soil one or more horizontal plates. Finite element analysis and experimental investigation showed that the combined massive and plate foundations have advantage over block-type foundations in low-frequency range, as their vibration level is considerably less. The slab brings positive influence on vibration level of type-block foundations, their vibration levels get two or three times reduced and their natural frequency increases. For most problems the analytical derivation of solution is given using asymptotic and perturbation methods. The mathematical models for the oscillation of the combined massive and plate foundation are a lumped mass with beams or plates on the viscous-elastic basis. Integral transformations, Fourier series, averaging methods are applied for solution to such equations. The analytical and numerical results are compared with large-scale modeling test data.

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