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INTERACTION OF GRAVEL PILES WITH THE SURROUNDING SOIL AND RAFT

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This paper provides a quantitative assessment of the stress-strain state of the "crushed stone pile–surrounding compacted soil–grillage" (cell) system under static and variable loads, taking into account the elastic and elastic-viscous properties of the pile and the surrounding soil. The potential for defining the parameters for deformability and viscosity of the cell, required for carrying out simplified calculations for the foundation known as "piles under the slab," is illustrated. The influence of the pile on the dynamic properties of the base (without piles), including the dynamic response factor, dependent on the frequency of the natural oscillations of the cell, with and without the influence of the pile, is evaluated.

Introduction

It is well-known that a pile-slab foundation is often used given the limited thickness of weak, water-saturated clay and sandy soils with underlying, relatively dense soils.

The design of foundations such as these requires an assessment of the distribution and redistribution of the static load on the grillage (plate) between the pile and the surrounding soil, as well as the rate of settlement for the slab foundation.

The paper examines the presentation of, and the solution to, the problem of interaction between the component parts of the "pile–surrounding soil–grillage" cell, under static and variable loads, on grillage, taking into account the elasticity, creep, and vibrocreep behavior of the surrounding soil.

The elastic, and elastic-viscous Kelvin-Voigt model is used to describe soil and pile creep; the parameters of the model are set using static, kinematic, and triaxial compression tests of sandy and clay soils. The investigation was conducted at the Research and Education Center "Geotechnical Engineering" of Moscow State (National Research) University of Civil Engineering (NRU MGSU) over the course of the last 10 years. The stress-strain state (SSS) of pile foundation is examined as it interacts with crushed stone or cement piles made using different technology [1-4]. During the manufacturing process, the pile and the surrounding soil are compacted and reinforced.

The "end-bearing pile" scheme is used to calculate the SSS of the cells, assuming the gravel pile does not push through the underlying, relatively dense soil (Fig.1).

Accounting for the Elasticity Properties of the Pile and the Surrounding Soil

It is known [5] that in the simplest case of a uniformly distributed static impact on the grillage, the load p is distributed and redistributed in time between the pile and the surrounding soil. Under the

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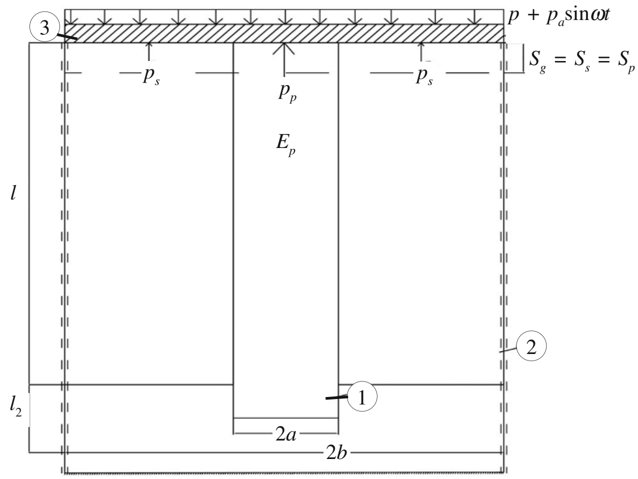

Fig.1. Design drawing showing the interaction of crushed stone piles (1) with a surrounding thick-walled soil cylinder (2) and grillage (3) as a component of a pile-slab foundation, with static and variable loads acting on the grillage.

assumption of compression loading conditions for the pile and the surrounding soil given the linear dependence $\varepsilon - \sigma$, the following conditions are realized:

– *equilibrium*

$$p = p_p\Omega + p_s(1 - \Omega), \tag{1}$$

where p_p and p_s are loads, acting on pile and soil, respectively, $\Omega = a^2/(b^2 - a^2)$, and a and b are the radii of the pile and the soil cylinder;

– *the equality of the sediment of the grillage, piles, and soil*

$$S_g = S_p = S_s \tag{2}$$

or

$$m_p p_p = m_s p_s = m_g p_g, \tag{3}$$

where m_p, m_s, and m_g are the coefficients of relative compressibility of the pile, soil, and grillage, respectively.

Thus, it follows that

$$p_p = p\frac{E_p}{E_p\Omega + E_s(1-\Omega)}; p_s = p\frac{E_s}{E_p\Omega + E_s(1-\Omega)}, \tag{4}$$

where E_p and E_s are the deformation coefficients.

In this case, the reduced deformation module of the cell is defined as

$$E_{re} = E_p\Omega + E_s(1 - \Omega). \tag{5}$$

Taking into account the elastic-viscous properties of the pile and the surrounding soil, it is obvious that the settlement for both the pile and the grillage will develop with time.

The Elastic-Viscous Kelvin-Voigt Model

The dependence $\varepsilon(t) - \sigma$ in the simplest case is written

$$\sigma = \varepsilon E + \dot{\varepsilon}\eta, \tag{6}$$

where η is viscosity.

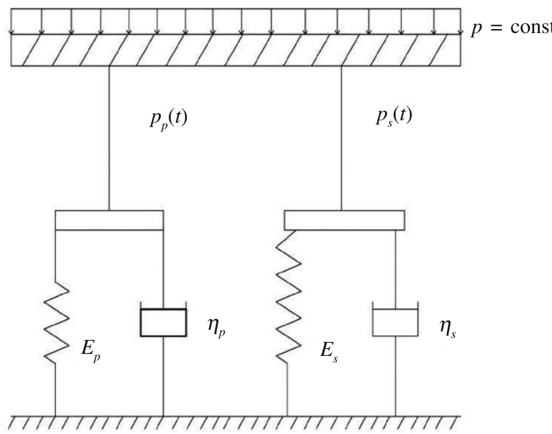

Fig. 2. Computational model of interaction between a crushed stone pile and the surrounding soil under compression conditions in accordance with the Kelvin-Voigt model.

The model of interaction between the crushed stone pile and the surrounding soil that is compressed in accordance with the Kelvin-Voigt model is shown in Fig. 2.

The equilibrium condition in the course of the development of the grillage settlement is

$$p = p_p(t)\Omega + p_s(t)(1 - \Omega), \tag{7}$$

where p, $p_s(t)$, and $p_p(t)$ are the pressures acting on the grillage, soil, and pile, respectively.

Taking into account the following,

$$p_s(t) = (\varepsilon_s E_s + \dot{\varepsilon}_s \eta_s), p_p(t) = \varepsilon_p E_p + \dot{\varepsilon}_p \eta_p, \tag{8}$$

as well as the condition (7), we get

$$p = (\varepsilon_s E_s + \dot{\varepsilon}_s \eta_s)(1 - \Omega) + (\varepsilon_p E_p + \dot{\varepsilon}_p \eta_p)\Omega . \tag{9}$$

Under the strain equality condition: $\varepsilon_s = \varepsilon_p$ and $\dot{\varepsilon}_s = \dot{\varepsilon}_p$ it follows that

$$p = \varepsilon(E_s(1 - \Omega) + E_p\Omega) + \dot{\varepsilon}(\eta_s)(1 - \Omega) + \eta_p\Omega, \tag{10}$$

where $\varepsilon = \varepsilon_s = \varepsilon_p$ and $\dot{\varepsilon} = \dot{\varepsilon}_s = \dot{\varepsilon}_p$.

Equation (10) is represented as

$$\dot{\varepsilon} + \varepsilon P = Q, \tag{11}$$

where

$$P = \frac{E_s(1 - \Omega) + E_p\Omega}{\eta_s(1 - \Omega) + \eta_p\Omega}, \; Q = \frac{p}{\eta_s(1 - \Omega)\eta_p\Omega}. \tag{12}$$

The solution (11) is presented as follows:

$$\varepsilon(t) = e^{-\int P dt}\{\int Q e^{\int P dt} + C\}, \tag{13}$$

and then

$$\varepsilon(t) = \{Q + Ce^{-Pt}\}. \tag{14}$$

From the initial condition $t = 0$, $\varepsilon(0) = 0$ it follows that $C = -Q + \varepsilon(0)$.

Substituting C into the original equation, we get

$$\varepsilon(t) = Q(1 - e^{-Pt}). \tag{15}$$

It therefore follows that $\varepsilon(0) = 0$ when $t = 0$, and $\varepsilon(\infty) = Q$ when $t \to \infty$.

To determine the reduced rigidity parameters E_{re} and the viscosity η_{re} of the cell as a whole, we cite the equation for the grillage settlement, assuming that it proceeds in accordance with the Kelvin-Voigt model, i.e.,

$$p = \varepsilon E_{re} + \dot{\varepsilon}\eta_{re}. \tag{16}$$

Then

$$\dot{\varepsilon} + p'\varepsilon = Q', \tag{17}$$

where

$$p' = \frac{E_{re}}{\eta_{re}},\ Q' = \frac{p}{\eta_{re}}. \tag{18}$$

Comparing (16) and (10), we have

$$E_{re} = E_s(1 - \Omega) + E_p\Omega,\ \eta_{re} = \eta_p\Omega + \eta_s(1 - \Omega). \tag{19}$$

This result allows us to solve the problem of interaction of the pile with the surrounding soil and grillage under static and dynamic loadings, including the oscillations of the system under consideration, namely, a heterogeneous soil base that is accommodating the pile. To do this, it is sufficient to have a solution for a homogeneous soil base (without piles). Replacing E by E_{re} and η by η_{re} we will obtain the required solution to the problem of the oscillation of the foundation on a nonhomogeneous soil–pile base.

Oscillations of the Foundation on a Homogeneous and Heterogeneous Base

To fix this problem, the equation [2] is finally solved as

$$\ddot{z} + 2n_z\dot{z} + \lambda_z^2 z = p_z(t)/m, \tag{20}$$

where $\lambda_z = \sqrt{C_z F/m}$ (1/sec) is the circular frequency of the vertical self-oscillations, showing the number of oscillations for the grillage of 2π sec; F is the grillage area, $C_z = E_{re}/h$, and m is the mass of the foundation.

The self-oscillation frequency of the grillage is related to λ_z as follows:

$$f_z = \frac{\lambda_z}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{C_z F}{m}}. \tag{21}$$

The oscillation period T_z (sec) is determined using the formula

$$T_z = \frac{1}{f_z} = 2\pi\sqrt{m/C_z F}. \tag{22}$$

The damping coefficient n_z caused by the inelastic (viscous) resistance n_z and the magnitude of the damping φ_z is

$$n_z = \frac{\eta_z}{2m} = \frac{\varphi_z\lambda_z^2}{2}. \tag{23}$$

The solution (20) without the right hand side, corresponding to the free oscillations of the grillage under initial conditions $t = 0 \to z = z_0$, $\dot{z} = \dot{z}_0$, at $n_z = 0$, is

$$z = \frac{\dot{z}_0}{\lambda z}\sin\lambda_z t + z_0\cos\lambda_z t. \tag{24}$$

At $n_z \neq$ and $n_z < \lambda_z$, the free oscillations are

$$z = e^{-\eta_z t}\left[\frac{\dot{z}_0}{\lambda' t}\sin\lambda_z' t + z_0(\cos\lambda_z' t + \frac{n_z}{\lambda_z'}\sin\lambda_z' t)\right], \tag{25}$$

with the self-frequency, taking into account the damping

$$\lambda_z' = \lambda_z\sqrt{1 - n_z^2/\lambda_z^2}. \tag{26}$$

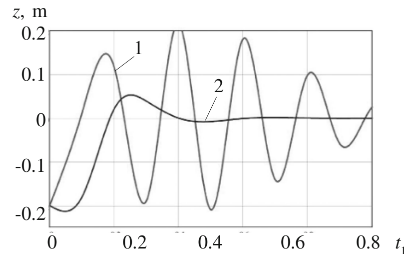

Fig. 3. Free oscillation of the "grillage–base" system without (1) and with (2), taking into account the pile influence.

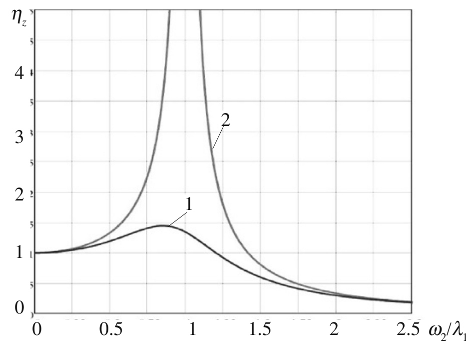

Fig. 4. The dependence of the dynamic response factor on ω/λ_z for homogeneous (1) and heterogeneous pile (2) bases.

Note that the solution (20) can be obtained using MathCAD software under the appropriate initial conditions $z'(0)$ and $z(0)$ and using different initial data m, F, C_z, λ_z and n_z. This was conducted for m = 10 tons, F = 6 m^2, $z'(0)$ = 20 m/s, and $z(0)$ = −0.2 m (Fig.3).

It is evident that the grillage oscillations on homogeneous (1) and inhomogeneous pile (2) bases differ significantly, and in the latter case there is an aperiodic oscillation.

One of the solutions of the Eq. (20) for forced oscillations when exposed to grillage by the law $p_z(t) = p_z(0)\sin\omega t$ corresponds to free oscillations and takes the form (25).

Another solution characterizes forced oscillations and can be represented as

$$z = A_z^* \sin(\omega t + \delta),$$

where A_z^* is the amplitude of forced oscillations, and δ is the phase shift between the amplitudes of the disturbing force and the displacements of the grillage

$$A_z^* = \frac{p_z(0)}{m\lambda_z^2} \frac{1}{\sqrt{(1-\frac{\omega^2}{\lambda_z^2}) + 4(\frac{n_z}{\lambda_z})^2 \omega^2}} = A_{z,st}\eta_z^*, \tag{27}$$

where $A_{z,st} = p_z(0)/m\lambda_z^2 = p_z(0)/C_zF$ is settlement of the grillage under a static disturbing force, and η_z^* is the dynamic response factor

$$\eta_z^* = \frac{1}{\sqrt{(1-\frac{\omega^2}{\lambda_z^2})^2 + 4(\frac{n_z}{\lambda_z})^2 \omega^2}}. \tag{28}$$

The dependence of the dynamic response factor η_z on the calculated values $\omega\lambda_z$ without and with taking into account the influence of the pile is shown in Fig.4.

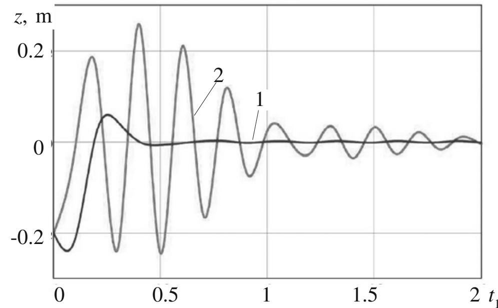

Fig. 5. Forced grillage oscillations on homogeneous (1) and heterogeneous pile (2) bases.

Note that the solution (20) can also be obtained directly using MathCAD software. This was done with the same parameters as in Fig. 3, assuming that $p_z(t) = p_0 + p_a \sin\omega t$, where $p_0 = 60$ tons, $p_a = 0.3$ tons, and $\omega = 30$ Hz (Fig.5).

Conclusions

1. When a crushed stone pile interacts with the surrounding weak soil, compacted during the process of pile manufacture, there is a complex, heterogeneous SSS in the "pile–surrounding soil–grillage" system (cell). The load acting on the grillage is distributed and redistributed with time between the pile and the surrounding soil in accordance with their rigidity and viscosity.

2. The solution of the problem of the interaction of the "end-bearing pile" with the surrounding soil and grillage under compression, with static and variable impacts on the grillage, enables a definition of the deformability and viscosity parameters of the cell as a whole. It greatly simplifies the solution of static and dynamic problems in the design of slab foundations on a pile base.

3. Numerical calculations using MathCAD software showed a significant difference between the free and forced oscillations of the grillage on a homogeneous and heterogeneous pile foundation, as well as the influence of the dynamic response coefficients for the foundations under these conditions.

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