Additional Settlement of the Raft-Pile Foundation, Taking into Account the Deformations of the Pile Under Cyclic Loading

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Abstract. The aim of the work is to study the additional settlement of the raft-pile foundation under cyclic loading due to the deformation of the reinforced concrete pile material under the conditions of redistribution of the compression forces of the reinforced concrete pile, taking into account the redistribution of forces between the reinforcement and the concrete of the pile, as well as the pile and the surrounding soil. There are no research results on this problem in the existing literature. Theoretical studies are carried out and the redistribution of forces between the main elements of the raft–pile foundation is considered. The change in the stress-strain state of a compressed reinforced concrete element due to the manifestation of deformations of the vibro-creep of concrete and reinforcement under cohesive conditions is considered. Based on the research, the equation of changes in stresses and constrained deformations of concrete and pile reinforcement under cyclic loading is proposed for the development of a method for calculating the settlement of a raft-pile foundation. For the first time the proposed method allows us to estimate the settlement of the raft-pile foundation taking into account the deformation of the reinforced concrete pile and the compression of the pile under cyclic loading, which is a significant contribution to the theory of calculating pile foundations and provides concrete savings of up to 15% compared to the standard method.

Keywords: Raft-pile foundation · Reinforced concrete pile · Concrete · Reinforcement · Vibration creep · Constrained deformations · Settlement · Soil · Cyclic loading

1 Introduction

In the general case, the settlement of the raft-pile foundation is represented as the sum of: the settlement of a conditional foundation, the pressure and the deformed compression of the reinforced concrete pile [1–5]. The settlement due to the compression of the pile depends on the conditions of joint deformation of all elements of the system «pile cap – piles – soil of the inter-pile space – soil below the pile toe», on the strength and deformation properties of concrete and reinforcement of the pile, on the parameters of cyclic

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loading. In the case of cyclic loading, the regularities of the formation and development of the raft-pile foundation settlement due to the compression of the reinforced concrete pile have not been studied [6–10]. In this regard, the aim of the study is to develop a method for calculating the settlement of the raft-pile foundation due to the deformation of the pile under cyclic loading [11]. At the same time, we have to establish the regularity of the development of the raft-pile foundation settlement by the compression of the pile under cyclic loading; to develop the equation of joint deformation of concrete and reinforcement of the pile and the surrounding soil; to develop the calculation model of piles as a part of a raft-pile foundation under cyclic loading.

2 Materials and Methods

Under the action of cyclic loads, the deformation of the pile leads to the appearance and development of additional settlement of the raft-pile foundation caused by deformations of the concrete pile during the first loading cycle and deformations of the vibration creep of the concrete during subsequent loading cycles.

This process is considered in the tridimensional formulation, taking into account the joint deformation of all elements of the system «pile cap – piles – soil of the inter-pile space – soil below the pile toe» with a rigid connection of the piles and the pile cap. When determining the stresses in piles we take into account following aspects: the redistribution of forces between the elements of the system in the process of cyclic loading; the joint deformation of the pile cap; piles; the soil of the inter-pile space and the soil below the pile toe; as well as the manifestations of deformations of the vibro-creep of the soil and concrete piles in cramped conditions (Fig. 1).

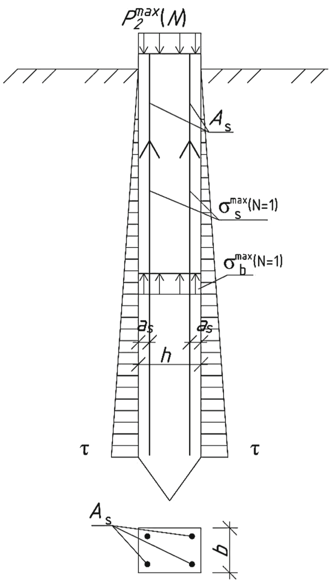

Fig. 1. Stress state of a reinforced concrete pile at the first loading.

In this case, two stages are considered. The first stage corresponds to the first loading cycle up to the maximum load of the cycle and the calculations are made as for static loading. The longitudinal deformations of the reinforcement and concrete piles in conditions close to the central compression due to the adhesion of the materials will be the same (1). Stresses in the reinforcement are calculated by (2).

$$\varepsilon_s^{max}(N=1)=\varepsilon_b^{max}(N=1)=\frac{\sigma_b^{max}(t,t_0)}{\mathrm{E_b}},\tag{1}$$

$$\sigma_s^{max}(N=1)=\varepsilon_s^{max}(N=1)\cdot E_s=\sigma_b^{max}(N=1)\cdot\frac{\alpha}{V},\tag{2}$$

where $\alpha=\frac{E_s}{E_b}$, E_S is the Young modulus of steel, E is the Young modulus of concrete, V is the elasticity coefficient of concrete.

The role of transverse bars is reduced to ensuring the stability of the longitudinal compressed bars and therefore does not affect the development of vertical deformations of the pile. The equilibrium equation of external loads and internal forces in concrete and reinforcement of the pile:

$$\begin{aligned}N_2^{max}(N=1)&=\sigma_b^{max}(N=1)\cdot A_p+\sigma_s^{max}(N=1)\cdot A_s\\&=\sigma_b^{max}(N=1)\cdot A_p\left(1+\frac{\mu\alpha}{V}\right)\end{aligned}\tag{3}$$

where $\mu=\frac{A_s}{A_p}$ is the percentage of longitudinal reinforcement of the pile, A_p is the cross-sectional area of the pile.

Hence the compressive stress in the concrete at the first loading up to the maximum load of the cycle is:

$$\sigma_{(N=1)}^{max}=\frac{P_2^{max}(N=1)}{A_p\left(1+\frac{\mu\alpha}{V}\right)},\tag{4}$$

At the second stage, the influence of the vibration creep deformations of the reinforced concrete pile on the increase in the total deformations of the pile and, as a result, additional settlement of the raft-pile foundation due to the compression of the pile is considered (Fig. 2).

The vibration creep deformations of the reinforced concrete pile are a consequence of the vibration creep of the concrete pile. Steel reinforcement becomes an internal bond that prevents free deformations of the concrete's vibration creep. In a reinforced concrete pile under load, the redistribution of forces between the reinforcement and the concrete of the pile is a consequence of the constrained vibration creep of the concrete.

Constrained deformations of concrete vibration creep lead to the appearance of internally balanced stresses in the reinforced concrete pile: stretching in the concrete and compressing in the reinforcement (5). Under the influence of the deformation difference of the free vibration creep of concrete $\varepsilon_{b\,pl}^{vib}(N)$ and constrained vibration creep of the reinforced element $\varepsilon_{pl}^{vib}(N)_{bs}$ the tensile stresses in the concrete arise (6).

$$\varepsilon_{b\,pl}^{res}(N)=\varepsilon_{b\,pl}^{vib}(N)-\varepsilon_{pl}^{vib}(N)_{bs,}\tag{5}$$

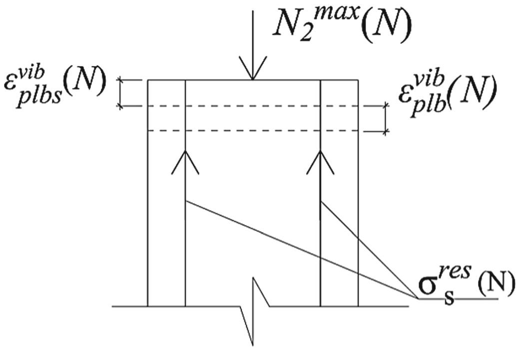

Fig. 2. Residual stress state in the pile cross section under cyclic loading.

$$\sigma_{bt}^{add}(N) = \varepsilon_{b\,pl}^{res}(N) \cdot E_b(N), \tag{6}$$

where $E_b(N)$ is the Young modulus of concrete under cyclic loading.

The highest stress values are located in the area of contact with the reinforcement. Deformations for rebar $\varepsilon_{pl}^{vib}(N)_{bs}$ are elastic and therefore compressive stresses occur in it:

$$\sigma_s^{res}(N) = \varepsilon_{pl}^{vib}(N)_{bs} \cdot E_S. \tag{7}$$

The equilibrium equations of internal forces of a concrete pile with two-sided symmetrical reinforcement have the form:

$$\sigma_s^{res}(N) * A_s = \sigma_{bt}^{add}(N) \cdot A_p. \tag{8}$$

Residual $\sigma_s^{res}(N)$ stresses in the rebar are determined from Eq. (9).

$$\sigma_s^{res}(N) = \sigma_{bt}^{add}(N)\frac{A_b}{A_s} = \frac{\sigma_{bt}^{add}(N)}{\mu}. \tag{9}$$

Substituting in (9) the deformations expressed in terms of the stress in (6)–(8):

$$\frac{\sigma_{bt}^{add}(N)}{E_b(N)} = \varepsilon_{b\,pl}^{vib}(N) - \frac{\sigma_{bt}^{add}(N)}{\mu E_s}. \tag{10}$$

After the transformations from (10), we determine the value of the additional tensile stresses in the concrete, Eq. (11). Based on Eq. (5), we determine the constrained deformations of the vibration creep of the concrete pile under cyclic loading, Eq. (12). Deformations of the free vibration creep of concrete piles are determined by the method proposed by I.T. Mirsayapov [14–16], Eq. (13).

$$\sigma_{bt}^{add}(N) = \frac{\varepsilon_{b\,pl}^{vib}(N) \cdot E_s}{\frac{1}{\mu} + \frac{\alpha}{V_p}}, \tag{11}$$

$$\varepsilon_{pl\ bs}^{vib}(N) = \varepsilon_{b\ pl}^{vib}(N) - \varepsilon_{b\ pl}^{res}(N) = \varepsilon_{b\ pl}^{vib}(N) - \frac{\sigma_{bt}^{add}(N)}{E_b(N)}, \tag{12}$$

$$\varepsilon_{b\ pl}^{vib}(N) = \sigma_b^{max}(t, t_0) \cdot C_\infty(t, \tau) \cdot \left\langle \begin{matrix} \left[1 - \mathrm{e}^{-\gamma(t-t_0)}\right] \cdot \rho_b + \\ +\left[1 - (1-a)^N\right] \cdot (1 - \rho_b) \end{matrix} \right\rangle \cdot S_k\left(\frac{\sigma_b^{max}}{R_b}\right) \cdot f\ (N), \tag{13}$$

where $\sigma_b^{max}(t, t_0)$ is the maximum compressive stress in the pile concrete under cyclic loading, $C_\infty(t,\tau)$ is the ultimate measure of concrete creep, $\rho_b = \frac{\sigma_b^{min}}{\sigma_b^{max}}$ is the asymmetry coefficient of the stress cycle in the concrete, a and γ are creep parameters, $S_k\left(\frac{\sigma_b^{max}}{R_b}\right)$ is the creep nonlinearity function of concrete deformations, m_n and η_n are non-linearity parameters, *f (N)* is the growth function of the nonlinear part of the vibration creep deformations.

The modulus of concrete deformation under cyclic loading is determined in accordance with the method proposed by I.T. Mirsayapov according to the Eq. (14).

$$E_b(t, \tau) = \frac{\sigma_b^{max}(t, \tau)}{\varepsilon_{be} + \varepsilon_{b\ pl}^{vib}(N)}, \tag{14}$$

where $\sigma_b^{max}(t, \tau)$ is the maximum stress in the concrete pile at time $t = N$ (where N is the number of loading cycles), ε_{be} and $\varepsilon_{b\ pl}^{vib}(N)$ are elastic and plastic deformations of the pile at the same time, respectively.

Given the formula (13) and that $\varepsilon_{be} = \frac{\sigma_b^{max}(t,\tau)}{E_b(t_o)}$, the expression (14) after some transformations is reduced to the form (15).

$$E_b(t, \tau) =$$
$$E_b(t_0) \cdot \left\{1 + C_\infty(t, \tau) \cdot E_b(t_0) \cdot \left\langle \left[1 - e^{-\gamma(t-t_0)}\right]\rho_b + \left[1 - (1-a)^{N_i}\right](1 - \rho_b) \right\rangle \cdot S_k\left(\frac{\sigma_b^{max}}{R_b}\right) \cdot f(N) \right\}^{-1}, \tag{15}$$

where $E_b(t_0)$ is the initial Young modulus of concrete.

3 Results and Discussions

Taking into account the above information, we obtain the equation of additional precipitation due to compression of the pile trunk under cyclic loading $\Delta S_C(N)$. In this case, the additional sediment $\Delta S_C(N)$ is represented as the sum:

$$\Delta S_C(N) = \Delta S_{C1} + \Delta S_{C2}(N), \tag{16}$$

where ΔS_{C1} is the additional settlement of the pile at the first loading to the maximum load, $\Delta S_{C2}(N)$ is the additional settlement of the pile under cyclic loading due to the development and accumulation of constrained deformations of concrete vibration creep.

In general, the additional settlement $\Delta S_C(N)$ (the additional settlement at the maximum load of the cycle is considered) is represented as:

$$\Delta S_c(N) = \left[\varepsilon_b^{max}(N=1) + \varepsilon_{pl\ bs}^{max}(N)\right](l - a_c), \tag{17}$$

where l is the length of the pile, a_c is the size of the cross-section of the pile.

Then taking into account (1), (4), (11)–(13) the expression (17) is reduced to the form:

$$\Delta S_c(N) = \left\{ \frac{P_2^{max}}{A_{\mathrm{CB}}\left(1 + \frac{\mu\alpha}{V}\right) \cdot E_b(t_0)} + \frac{P_2^{max}(N)}{A_{\mathrm{CB}}\left(1 + \frac{\mu\alpha}{V}\right)} \cdot c_\infty(t,\tau) \cdot f(N) \cdot S_k\left(\frac{\sigma_b^{max}}{R_b}\right) \cdot \right.$$
$$\left. \left\langle \left[1 - \mathrm{e}^{-\gamma(t-t_0)}\right] \cdot \rho_b + \left[1 - (1-a)^N\right] \cdot (1 - \rho_b) \right\rangle \cdot \left[1 - \frac{E_S}{\left(\frac{1}{\mu} + \frac{\alpha}{V}\right) \cdot E_b(N)}\right] \right\} \cdot (l - a_c), \tag{18}$$

where P_{2max} is the longitudinal force in the pile at the first loading up to the maximum load of the cycle, P_{2max} (N) is the longitudinal force in the pile under cyclic loading, at $N > 1$ cycle.

4 Conclusions

The theoretical studies of the stress-strain state of a reinforced concrete pile as part of a raft-pile foundation allowed us to determine the main regularities of the development of the pile shaft settlement under cyclic loading conditions, according to which the settlement due to the deformation of the pile shaft occurs because of the cyclic deformation of the compression of concrete and the reinforcement of the pile in cramped conditions. In this case, there is a redistribution of forces between the concrete and the reinforcement of the pile.

Equations for the development of raft-pile foundation settlement are developed, taking into account the compression of the pile shaft under cyclic loading. The resulting equation of the development of raft-pile foundation settlement describes the main characteristic features of the behavior of such foundations observed in laboratory and field experimental studies, and allows us to reliably estimate the settlement of the raft-pile foundation due to the compression of the pile shaft under cyclic loading.

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