Parametric model of cement soil

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Annotation. The article discusses the conditions for the construction of pile foundations. The interconnection between the structures of pile foundations and soil properties is analyzed. Special attention is paid to the properties of loess subsidence soils. A comparison is made between bored and bored ones. The task of developing a parametric model of a cementitious soil is formulated. A parametric model of the cement soil has been developed. The results of applying of the parametric model of cement-soil for solving practical construction problems are considered. The economic efficiency of the installation of mixing piles in comparison with bored piles has been illustrated.

Keywords: pile foundations, bored piles, loess soils, subsidence soils, cement soils, parametric model, soil strength.

1. Introduction

For new construction usually allocate territories that were not previously built up due to the complexity of geotechnical conditions. In this regard, piles are used in the design of building foundations. Need to improve the production technology. Pile foundations erected on soils with insufficient bearing capacity and in permafrost conditions are widespread. The use of pile foundations is facilitated by the introduction of industrial construction methods and the equipping of construction organizations with mobile equipment for the production of pile works [1-3].

With significant thicknesses of subsiding soils, bored piles are most effective, because when drilling a well, the soil near the pile space is compacted and the bearing capacity of the pile increases [6, 7]. The main disadvantage of bored piles is the need for concreting them in the field and heating the concrete mixture in winter. There is also quality control of the construction of bored piles.

Among the bored piles, a special place is occupied by piles made by the drilling-mixing method. For this method use drilling rigs and drilling machines. All types of weak and unstable soils can be fixed using the mixing method. The drilling-mixing method is the most promising in foundation construction due to the use of local soils directly at the construction site, low cost and complete mechanization of work with the prospect of fixing loess subsidence soils [8, 9].

Favorable physical and chemical properties of loess soils, a small content of clay particles, an alkaline reaction of the environment and a small amount of readily soluble salts caused the use of loess soils for the construction of cement soil foundations. The most suitable for strengthening with cement are soils based on light loam and sandy loam, which have high strength and frost resistance due to the presence of calcium carbonates in them [10, 11]. From which it follows that the cementitious soils used for the construction of foundations must have high strength and frost-resistant characteristics.

When developing land under construction sites that were not previously built up due to the complexity of engineering and geological conditions due to heterogeneity of soils. Design organizations are increasingly using piles in the construction of foundations of buildings and structures.

Recently, various designs and piling technologies have been used. Factory-made piles were widely used: screw, driven, and other designs.

There are various technologies for making piles directly at the construction site. Consider one of these technologies in Figure 1.

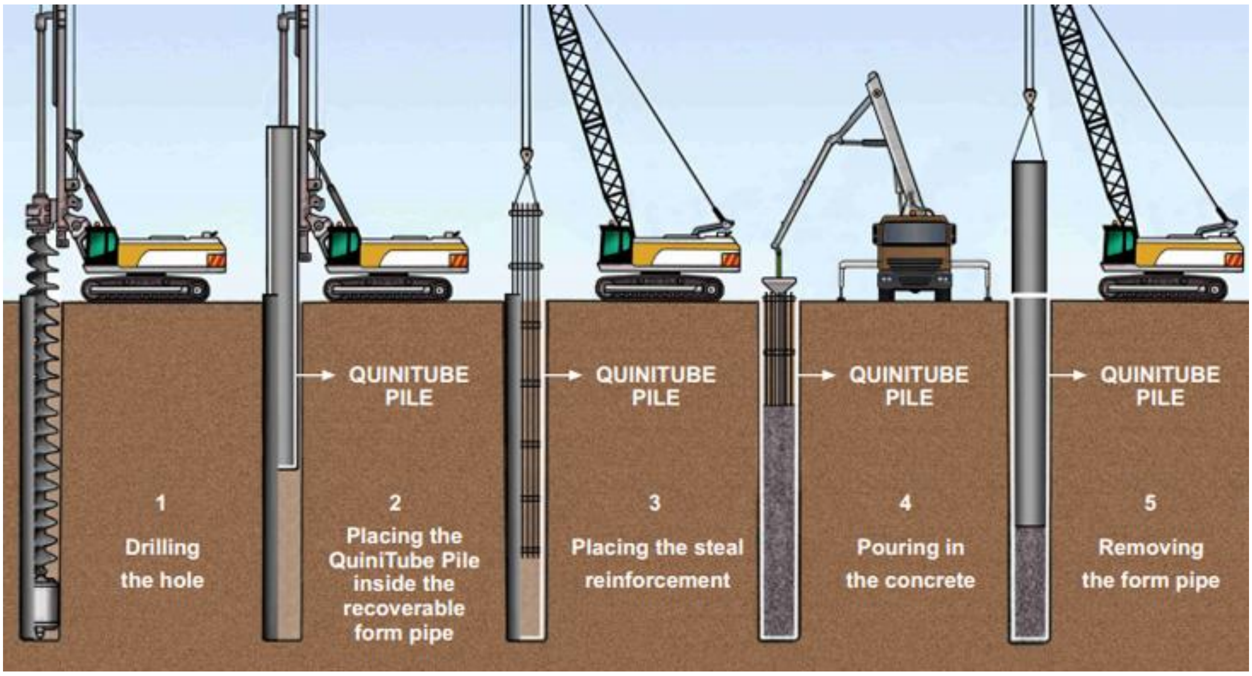


Fig. 1. Manufacturing technology of the pile foundation at the construction site.

The manufacturing process of the pile foundation at the construction site, shown in Figure 1, consists of five stages. At the first stage, the drilling rig forms a well in the ground under the future pile. At the second stage, a pipe of the corresponding diameter, which serves as the formwork, is immersed in the well obtained at the first stage of the technological process. At the third stage, a steel reinforcing cage is placed in the pipe. At the fourth stage, the steel reinforcement cage is poured with concrete mixture. The concrete mixture is sealed with a vibrator. Without waiting for the curing of the concrete mixture, not the fifth stage, a pipe is removed from the raw concrete solution. After curing the concrete mixture, the resulting pile is ready for the further construction of the foundation.

The advantages of the considered technology for manufacturing a pile foundation include:

- the ability to build the foundation of a building under construction or structures near existing buildings, as this technology belongs to the category of unstressed;
- the foundation obtained by this technology has a large bearing capacity;
- there is the possibility of building the foundation for this technology in any soil conditions.

The disadvantages of the considered technology for manufacturing the pile foundation are the need for heating the concrete mixture in winter, so concreting occurs in the field, and the complexity of controlling the quality of well formation.

However, during the construction of buildings and structures, especially on heterogeneous soils in difficult engineering and geological conditions, pile foundations account for approximately 25% of the total volume of constructed foundations. Therefore, research to improve the technology of their construction today is very relevant. Especially technologies that, while ensuring the strength and reliability of pile foundations, reduce the complexity and cost of manufacture.

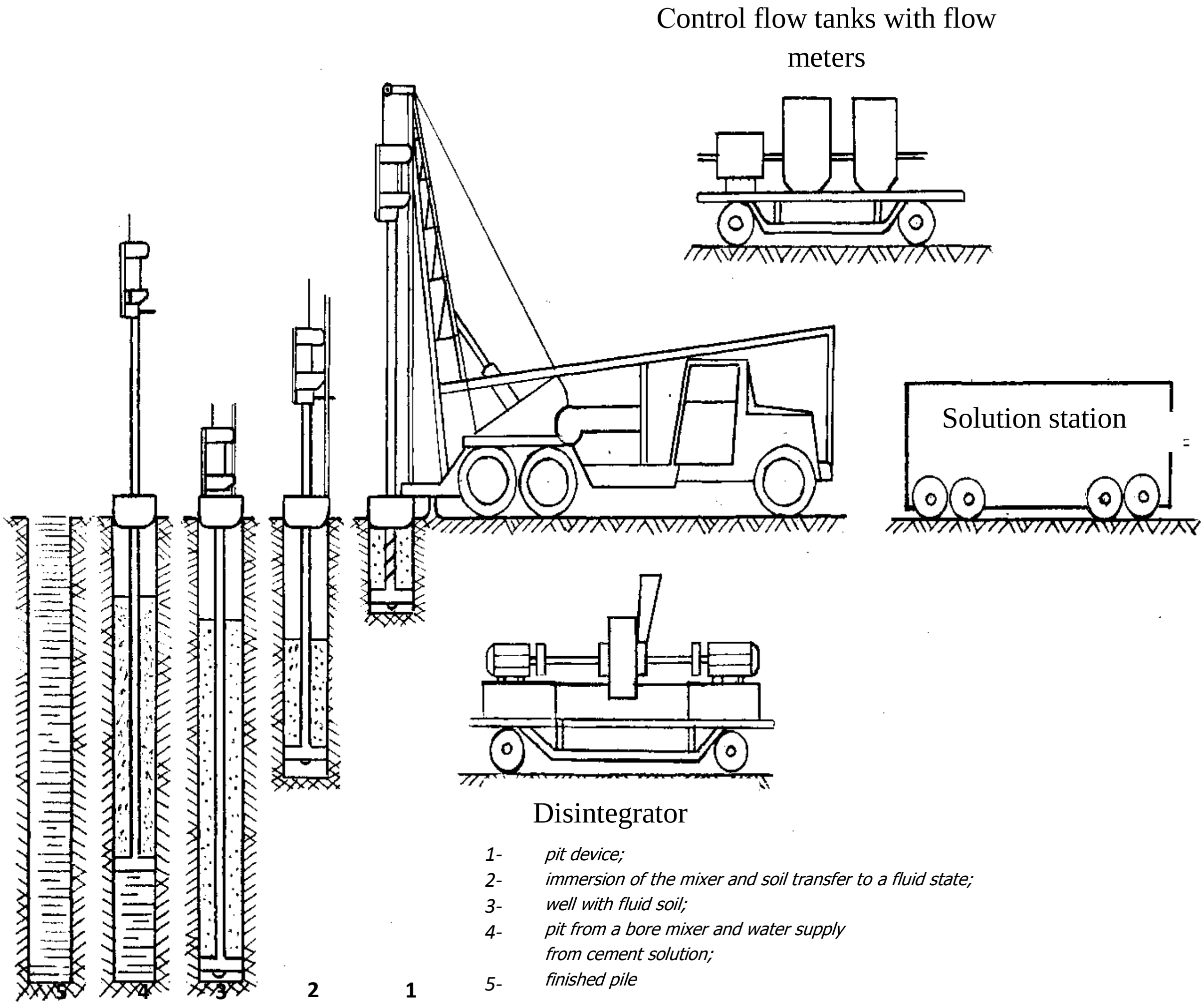
One of the most promising methods of constructing pile foundations is the mixing method [1]. The drilling mixing method of constructing pile foundations allows fixing all types of structurally unstable and weak soils regardless of their moisture and the location of the groundwater horizon. The mixing method is quite economical, thanks to:

- the use of local soil piles as part of the material;
- low cost of the process;
- a high level of mechanization of work;
- the prospect of fixing soils under the object under construction, such as filler soils of any moisture and activity, clay flowing and fluid-plastic soils, as well as loose water-saturated sands.

This method is characterized by environmental cleanliness and the possibility of application, both for the construction of foundations of new buildings and structures, and for the reconstruction of existing ones.

Many years of experience in strengthening soil confirms the need to improve methods for improving the properties of cement-soil pile foundations [1]. One of them is the method of mechanical activation of soils, which allows to reduce cement consumption and increase the strength of cement-pile pile foundations.

A drilling mixing method for constructing pile foundations with mechanical activation of soils can be implemented by using drilling mixing machines, drilling rigs, as well as hollow drill rods providing for the forced supply of the drilling composition (Fig. 2).



1- *pit device;*
2- *immersion of the mixer and soil transfer to a fluid state;*
3- *well with fluid soil;*
4- *pit from a bore mixer and water supply from cement solution;*
5- *finished pile*

Fig. 2. The technological scheme for the manufacture of cement piles by the mixing method using mechanical activation.

The technological scheme for the manufacture of cement piles by the mixing method using mechanical activation of the soil consists of the following operations (Fig. 2):

1) pit device;
2) immersion of the mixer and transfer of soil to a malleable state;
3) Filling the well with a soil of viscous consistency;
4) Deepening of the mixer and the supply of water-cement mortar.

The pit device is drilled by a receiving well with a diameter of 0.1 meters greater than the diameter of the piles being constructed and a depth of 0.5 - 2 meters, depending on the length of the future pile and the physical and mechanical properties of the soil. The receiving well is designed to receive the excess cement-soil mixture that arose when water and cement were pumped into the ground. The soil extracted from the well is used to prepare a mechanically activated cement-soil mixture. Depending on the physical and mechanical properties of the soil and the amount of binder introduced, determine the depth of the well.

The immersion of the mixer and the transfer of soil into a malleable state is performed by drilling the soil with a paddle mixer and water supply to transfer the crushed soil into a malleable state.

A well is filled with a soil of a viscous consistency by supplying water when the mixer is immersed in the soil. In this case, two processes occur simultaneously: cutting the soil and its moistening to a malleable state.

The boring mixer is deepened and the water-cement-cement mortar is supplied by removing the boring mixer with the simultaneous supply of the water-cement mixture in the required volume for the estimated amount of cement to enter the ground mass.

The construction of a pile foundation in fluid mixtures, compared with plastic ones, reduces the immersion and removal times of the mixer by three times by increasing the speed to 130 rpm and reduces the cutting force of the soil by two to three times. And also, the development of the soil with a mixer with the supply of a given volume of water to the well to transfer the soil to a malleable state allows you to get the soil of the required degree of grinding.

The main advantages of the drilling mixing method for constructing pile foundations with mechanical activation of soils are the use of local soil extracted directly from the well as the material of the piles, and the possibility of installing piles near existing foundations and other underground structures without damaging them.

2. Materials and methods

The macrostructure of the cement soil is formed in two stages. At the first stage, the soil is mixed. At the second stage, fine grinding is preliminarily carried out, and then the soil is compacted. The process of enveloping the soil with mixing proceeds with a decrease in surface energy. And external energy is spent on overcoming internal friction and on mixing the soil.

The adhesion between the binder and the soil is formed in the adhesive-active centers of the surface in the presence of wetting due to the forces of dispersion or chemical interaction. The larger the specific surface area of the soil, the more adhesive-active centers and the higher the strength of the soil, provided that the specific content of the binder is preserved per unit surface.

At high rates of chip formation, which take place in cement soils, amorphous structures are formed, which have low plasticity, but high heterogeneity in strength.

The strength of the material of soil solids R, depending on the porosity, is expressed by the dependence:

$$R=f\,(\Pi^{-n}), \tag{1}$$

where:
Π – the porosity of the solid material;
n – an index that ranges from 3 to 6.

The mathematical description of the dependence of material strength R on the size of soil units is as follows:

$$R=R_0\,d^{-1/m}, \tag{2}$$

where:
R_0 –strength of hardened soils from units smaller than 1 mm;
d – unit diameter in mm;
$1/m$ – an index characterizing the homogeneity of the hardened soil.

From formula (2) we can see that the smaller the absolute value of 1 / m, the greater the strength of the hardened soil. That is, the strength of a given type of material is less dependent on the size of the units, and to a greater extent depends on its homogeneity. This conclusion suggests itself from the fact that formula (2) does not reflect the essence of the process of forming the structure of these materials. Therefore, we will consider the strength of materials based on soils, taking into account the patterns of the formation of structures in the process of its hardening.

Units with a dimension less than 1 mm have the largest area in the structure of soils, and in the range of grain sizes from 0 to 300 mm, granulometry does not affect the work of mixing. The area of the resulting surface with the thickness of the bonding layer h is found by the formula:

$$S_{sp}=\pi h(d-h), \tag{3}$$

where:
d – unit diameter.

If we assume that soil units have a spherical shape with a diameter d, then the soil surface area will be in cm^2/g:

$$S_{sp}=N\pi d^2, \tag{4}$$

where:
N – number of units in one gram of soil.

Number of units in one gram of soil N is defined by formula:

$$N = 6/\pi d^3\rho_{gr}, \tag{5}$$

where:
ρ_{gr} – average density of the soil structure.

Considering formulas (4) and (5) get the formula for calculating diameter of units:

$$d=6/S_{sp}\rho_{gr}. \tag{6}$$

And formulas (5) and (6) make it possible to calculate the formula for the number of units in one gram of soil N:

$$N=S^3_{sp}\rho^2_{gr}/36\pi. \tag{7}$$

Assume that the thickness of the layer gluing the soil grains is equal to the thickness of the binder layer evenly distributed over the surface of the soil units of the mix. Then the formula for calculating the thickness of the adhesive layer h will be:

$$h = 1/100\rho_b S_{sp}, \tag{8}$$

where:
ρ_b – density of the binding material in g/cm^2.

In the case of hexagonal packing, each soil unit has six points of contact with other units.
Then the value of the entire area of contact between the units in one gram of soil will be:

$$S_c=6N\pi h(d-h), \tag{9}$$

$$S_c =\rho^2_{gr}S_{sp}/600\ \rho_b\,(6/\rho_{gr}\ -\ 1/100\ \rho_b) \tag{10}$$

In the average density of the soil structure ρ_{gr} is equated to 1,8 gr/cm^3, and density of the binding material ρ_b is 3,1 gr/cm then the value of the entire contact area of the units in one gram of soil S_c will be:

$$S_c=0,00174S_{sp}-(3.3-0.0032S_{sp}), \tag{11}$$

or in general:

$$S_c=b_1S_{sp}-(b_2-b_3S_{sp}), \tag{12}$$

where:
b_1, b_2 and b_3 – indexes equal to 0.00174, 3.3 and 0.0032.

Since b_2 is almost 1 000 times larger than b_1, hen the surface area of the bonding layer can be considered proportional to the specific surface area:

$$S_c= BS_{sp}. \tag{13}$$

The total strength of the soils strengthened with this binder depends on the area of the binder layer that glues the soil units together. Then, dividing S_{sp} by the actual strength of the soil material R, the following mathematical expression:

$$L_R =S_{sp}/R, \tag{14}$$

where:
L_R – structural criterion of soil material strength.

The structural criterion of the strength of the soil material L_R depends on the specific surface area of the soil unit S_{sp} and on a number of technological factors T_F. Such as the quality of mixing K_p, the quality of compaction P and the conditions for the hardening of the cement soil t_c.

Based on this, the structural criterion for the strength of the soil material L_R will be:

$$L_R = f(T_F)/R, \tag{15}$$

where:
$T_F = f\,(K_n, P, t_c)$.

The technological factor of the quality of mixing of the cement-soil K_p manifests itself at the beginning of the technological process, the quality of compaction P and the conditions for the hardening of the cement-soil t_c manifest themselves at the end of the technological process. This allows us to write the structural criterion of the strength of the soil material L_R as follows:

$$L_R = (C_R S_{sp} + M)/d, \tag{16}$$

where:
C_R – coefficient of variation characterizing the homogeneity of the strength of the resulting cement soil material;
M – a value characterizing the degree of aggregation of the adhesive layer of the material after compaction and subsequent curing of the cement-soil mixture.

A joint consideration of mathematical expressions (15) and (16) allows one to obtain the desired value of the strength of the material of solid bodies of soil R:

$$R = S_{sp} \cdot d/(C_R S_{sp} + M). \tag{17}$$

The mathematical expression (17) is a parametric model of a cement soil, the analysis and application of which will be considered in the next section of this scientific work.

3. Results and conclusions

Analyzing the parametric model of the cement soil (17), it can be concluded that the main role in the formation of the quality of the cement soil belongs to the dispersion of the soil filler S_{sp}. And the coefficient of variation C_R, which characterizes the homogeneity of the strength of the resulting material of the cement soil, and the value of M, which characterizes the degree of aggregation of the adhesive layer of the material after compaction and subsequent hardening of the mix of cement soil, have a certain dependence on the dispersion of the soil filler S_{sp}.

An increase in the dispersion of the soil to be strengthened at the beginning contributes to an increase in the strength of the cement soil material, and after a certain level of dispersion, the quality of the material deteriorates.

This happens for the following reasons:

- insufficiency for the increasing surface, the introduced amount of binder;
- increased by several times the difficulty of uniform distribution of the mineral binding material in the volume of the ground filler.

In the process of work, the required level of soil dispersion was investigated to obtain material grade 60. To perform analytical studies, the parametric model of cement soil (17) was transformed with respect to the specific surface of the material per unit volume S. And, omitting intermediate transformations, the mathematical dependence took the following form:

$$S = M/(d/R - C_R). \tag{18}$$

Number of contacts per unit area χ in cm^{-2} depends on unit diameter d in cm:

$$\chi = 2.67/d^2. \tag{19}$$

In theory, soil units are generally spherical. Therefore, the value of M, which characterizes the degree of aggregation of the adhesive layer of the material after compaction and subsequent curing of the cement-soil mix, is equal to:

$$M = 6/d^2. \tag{20}$$

Replacing in formula (20) the diameter of the aggregate d in cm by the number of contacts per unit area χ in cm^{-2} from formula (19), the following dependence was obtained:

$$M = \sqrt{(36\chi / 2{,}67)}. \quad (21)$$

Based on the average value of the number of contacts per unit area χ, equal to 120 000 cm^{-2}, the value M was obtained, which characterizes the degree of aggregation of the adhesive layer of the material after compaction and subsequent hardening of the cement soil, equal to 1 270 cm^{-1}.

For further calculations using formula (18), the experimental values of the remaining quantities are taken. As a result of the substitution of the calculated and experimental values of the quantities, the value of the specific surface area of the material per unit volume S was obtained, equal to 3 772.277 cm^{-1}.

To convert the specific surface area of the material per unit volume S (cm^{-1}) into the specific surface area of the soil unit S^{sp} (cm^2/gr), it had to be divided by the density of the material equal to 1.85gr/cm^3. As a result, the specific surface area of the soil filler is S_{sp} = 2 039.069 cm^2/gr.

As a result, it can be concluded that to obtain grade 60 material, the dispersion of the soil filler is required within the range S_{sp} = 2000 cm^2/gr. And this is possible only with preliminary crushing of the soil to the specified dimensions of the units *d*.

For this purpose, taking into account the significant volume of work on crushing the soil, it is necessary to use high-performance disintegrators.

A comparative economic analysis of the effectiveness of the use of mixing piles based on cement soils, regardless of their manufacturing technology, shows that they are more than two times cheaper than bored piles (Fig. 3).

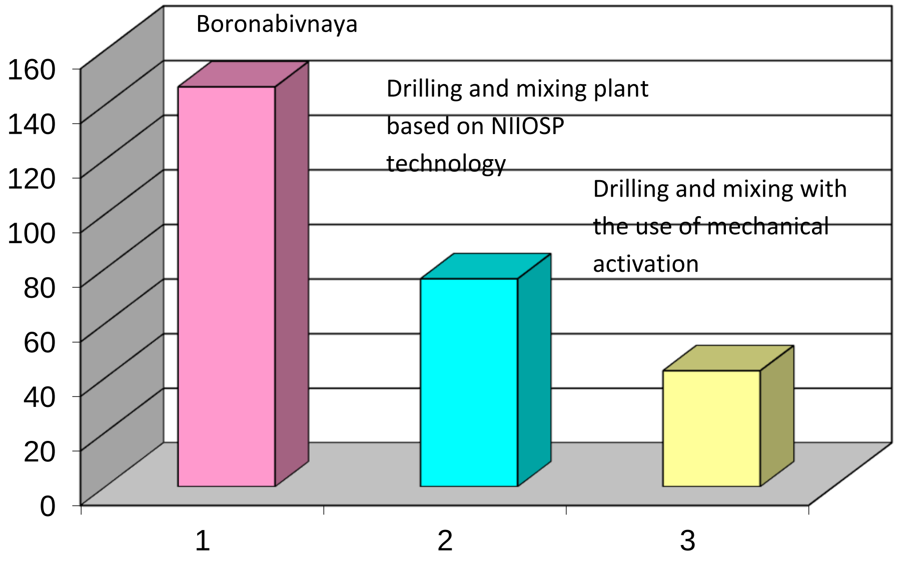


Fig. 3. Economic efficiency of the device of drilling piles in comparison with bored piles.

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