Forecast of settlement of single pile based on hereditary creep

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Abstract. The various calculation models are proposed in the literature for the purpose of description the creep behavior of soil bases. The objective of the paper is to develop an algorithm to predict long-term settlement of piles based on the rheological deformation model using Koltunov’s creep kernel. The paper discusses the results of single pile tests on weathered claystones and sandstones. Based on experimental results and theoretical study the author developed an automated algorithm for the calculation of settlement of pile on weathered claystones and sandstones. The following tasks are solved: 1) to describe the research technique; 2) to analyze the results of testing single piles; 3) to perform numerical calculation of settlement of piles; 4) to describe the capabilities of the developed algorithm for the calculation of pile settlement; 5) to compare the results of field tests, numerical simulation and calculation of the proposed method; 6) to state conclusions. The result shows that the proposed method is an excellent option for identifying the parameters of creep core for the prediction of long-term settlement of piles on claystones and sandstones.

1. Introduction
Many researchers have been involved in foundations on sandy and clay soils [1-8]. It was proved that settlements occur mainly due to creep for foundations on hard clays, gravel soils, claystones, sandstones [9-13]. Rheological processes in soils do not stop with the completion of filtration consolidation and continue for a long time. When plastic-viscous flow of the soil occurs, damping creep is typical for loads not exceeding the limit values. A characteristic feature of creep curves is that 90% of visco-elastic deformations develop in the first hours of loading, but then their growth slows down significantly, and the curves asymptotically tend to a certain limit which depends on the value of the load. It was proved that the settlement of pile on Vendian clay increases twofold in 16 days [6]. Much attention should be given to the speed and degree of development of irregular settlement of foundations on soil bases with rheological properties [1,11,14]. It is necessary to predict the long-term interaction of a pile foundation and a soil base.

In the investigations [15-24] it was proved that the most reliable theory that connected stress, deformation and time for viscous media was the phenomenological theory of hereditary creep. The expressions are complex and the collection of above mentioned soil parameters is not easy in engineering practice.

When analyzing the creep behavior of soils the associated model parameters should be determined in advance. In the work [15] the main relationships between stresses and strains were presented. Traditionally, the graphical method was used for determine the rheological parameters of materials. In the case of coincidence of the experimental and theoretical curves, the known deformation parameters...
of the theoretical curve can be assigned to the experimental one. The solution of the equation has been automated by many authors [1, 16]. It has shown good results for different materials. But at present, there are no verified solutions for the forecast of long-term settlement of piles on claystones and sandstones. Therefore, the solution to this problem is relevant.

2. Purpose and objectives
The purpose of the investigation is to develop the methodology for calculation of settlement for pile based on claystones and sandstones. The objectives are: 1) to review existing theoretical and experimental research; 2) to describe the capabilities of the developed calculation methodology; 3) to analyze the results of calculation of settlement for single piles obtained by the numerical method and the proposed method; 4) to describe the findings.

3. Theoretical research
The Boltzmann-Volterra equation is used to describe creep phenomena:

$$\varepsilon(t) = \frac{\sigma(t)}{E} + \int_0^t k(t-\tau)\sigma(\tau)d\tau$$  \hspace{1cm} (1)

where $\sigma(t)$ and $\varepsilon(t)$ – stresses and strains at the time $t$ under a uniaxial stress state, accordingly; $\tau$ is the time preceding $t$, $E$ is the elasticity modulus, $k(t-\tau)$ is an influence function (creep core).

Equation (1) is used for modelling of the viscoelastic behavior of materials and in the calculation of constructions using various numerical methods.

The most common singular core of heredity is the Koltunov-Rzhanitsyn core:

$$\Gamma(t) = Ae^{-\beta t}t^{a-1}$$ \hspace{1cm} (2)

where $0<\alpha<1$; $\beta$ - attenuation parameter.

The accuracy of solving the hereditary creep problem depends on the correct choice of the core. The accuracy of the approximation of the core should be checked by comparing it with the experimental curve.

Assuming that the pile on soil base is simulated by rheological deformation model using Koltunov’s creep kernel type. In the research, the expression proposed in work [15] for nonlinear relations of the theory of creep was used:

$$S(t) = \psi(\sigma_i) \cdot (1 + \int_0^t K(t)dt)$$ \hspace{1cm} (3)

where: $\psi(\sigma_i)$ is the similarity coefficient, $K(t)dt$ is the function of influence (Koltunov’s creep kernel).

The method for determining the rheological characteristics of core parameters by four values of the experimental curve “time-settlement” is proposed. The process of finding the coefficient of similarity was automated. The author developed an automatic algorithm for the calculation of pile settlement. The sequence of actions in the developed algorithm:

1. load, time and values of settlements for short-term tests of piles are entered as input parameters;
2. the search for a theoretical curve similar to the experimental one and the calculation of the deviations of the experimental values from the theoretical ones are performed;
3. the determination of parameters for Koltunov’s creep kernel ($\alpha$, $\beta$, $A$) is performed;
4. the results in the form of curves "time - settlement" and "load - settlement" with taking into account hereditary creep are shown.

This algorithm makes it possible to perform the calculation of long-term settlements of piles on weathered claystones and sandstones. Data from widely used field tests of piles is used as input. The
author believes that the application of this automatic algorithm is a simple and effective way to improve the accuracy of calculation of long-term settlement of piles.

4. Methodology of experimental research

4.1. General information
In the research, the settlements of pile obtained by experimental method, numerical simulation and calculation method were considered. The experimental time-settlement curves were compared with the theoretical ones in order to expose similarities and adjust the theoretical solutions. For piles on claystone and sandstone, the values of parameters for Koltunov’s creep kernel type were determined from eleven short-term pile tests.

4.2. Methodology of field investigation
The study reviewed field test results of single piles on layered clay base. The layered clay base consisted of Quaternary clays and Early Permian claystones and sandstones. Claystone and sandstone can be described as highly weathered and softenable rock that consists of clastic grains consolidated by clay-chlorite, ferrous and carbonate cement. Macroscopically Permian claystone and sandstone across the terrestrial Permian-Quaternary boundary is a dense clay and sand rock of brown and grey color [3, 4]. On the test sites, these deposits are covered by layers of modern sandy-clay soils with a thickness of 5.0 to 13.0 m.

The values of some physical and mechanical properties for Quaternary soils and Permian claystones and sandstones are presented in table 1.

Table 1. Mean value of the parameters for Quaternary soils and Permian claystones and sandstones.

| Soil type            | Specific gravity, kN/m$^2$ | Void ratio | Plasticity index, % | Liquidity index, % | Secant stiffness in standard drained triaxial test, kN/m$^2$ | Tangent stiffness for primary oedometer loading, kN/m$^2$ | Cohesion intercept, kN/m$^2$ | Angle of internal friction, ° |
|----------------------|-----------------------------|------------|---------------------|-------------------|-------------------------------------------------------------|-------------------------------------------------------------|-----------------------------|--------------------------------|
| Stiff and soft-firm loam (QIV) | 20                          | 0.81       | 13                  | 32–74             | 13000                                                        | 9290                                                        | 31                          | 21                             |
| Very stiff sandy loam (QIV)      | 19                          | 0.60       | 14                  | -2                | 26561                                                        | 23000                                                       | 30                          | 10                             |
| Stiff clay (QIV)             | 20                          | 0.72       | 18                  | 5                 | 25000                                                        | 18000                                                       | 25                          | 20                             |
| Claystone (P1)              | 20                          | 0.65       | 20                  | 15                | 10342                                                        | 10483                                                       | 23.3                        | 37                             |
| Sandstone (P1)             | 20                          | 0.48       | -                   | -                 | 13640                                                        | 12667                                                       | 29                          | 27                             |

The study analyzed the settlements in time of full-scale driven and bored piles with claystone and sandstone bases. The dimensions of the piles were the following: the cross-section of driven piles was 0.3x0.3 m, the diameter of bored piles was 0.63 m. The penetration of the driven piles into claystones and sandstones ranged from 1.0 to 2.0 m, and that of the bored piles was from 2 to 6 m. The depth of the driven pile tests was 8–10 m, whereas the depth of the bored pile tests was 15–20 m.

4.3. Methodology of numerical investigation
Numerical calculations of these tests of piles were performed using the commercial PLAXIS 3D software. The physical and mechanical parameters of soils were determined from triaxial and oedometer tests. Results of laboratory tests were adjusted in the SoilTest (Plaxis 3D). The initial data of the geological conditions of full-scale tests of piles were used for modeling “ground base – pile foundation” system. In accordance with previous studies [25], the Hardening Soil model was applied for Quaternary and Permian soils. A linear-elastic model was used to model the pile material. Piles
were loaded stepwise in numerical modeling. The step value of the load stage was similar to that in the field pile tests.

5. Results and discussion
In the course of testing the piles, the bearing capacity of claystones and sandstones was not exhausted, but the ultimate strength of the pile material was reached. The obtained curves of all pile settlement in time were of damping creep. The settlement of piles on claystones and sandstones in time can be divided into two parts. The settlement under load dominates in the first phase for about 3 hours for weathered claystones and sandstones. Then creep deformations develop, under which the pile settlement velocity varies from 0.023 mm/min and tends to zero. Values of settlements for piles on claystones and sandstones are presented in table 2 and table 3, respectively. Results are given for maximum loads when testing bored and driven piles.

### Table 2. Values of the long-term settlement of piles on claystones.

| No. Pile | Experimental short-term settlement from pile tests, mm | Settlement obtained by Plaxis 3D, mm | Settlement obtained by the proposed method, mm |
|----------|------------------------------------------------------|--------------------------------------|-----------------------------------------------|
|          |                                                      | Driven piles                         | Bored piles                                   |
| 407      | 2.2                                                  | 27.2                                 | 10.1                                          |
| 403      | 3.4                                                  | 14.8                                 | 11.6                                          |
| 587      | 3.1                                                  | 33.4                                 | 8.4                                           |
| 592      | 2.3                                                  | 16.2                                 | 16.8                                          |
| 1        | 7.6                                                  | 99.0                                 | 12.1                                          |
| 2        | 6.1                                                  | 55.5                                 | 9.6                                           |

### Table 3. Values of the long-term settlement of piles on sandstones.

| No. Pile | Experimental short-term settlement from pile tests, mm | Settlement obtained by Plaxis 3D, mm | Settlement obtained by the proposed method, mm |
|----------|------------------------------------------------------|--------------------------------------|-----------------------------------------------|
|          |                                                      | Driven piles                         |                                               |
| 381      | 7.3                                                  | 25.5                                 | 11.7                                          |
| 469      | 4.0                                                  | 30.7                                 | 14.8                                          |
| 541      | 14.9                                                 | 65.2                                 | 19.6                                          |
| 201      | 6.6                                                  | 52.3                                 | 9.4                                           |
| 437      | 0.9                                                  | 84.1                                 | 3.2                                           |

The results in table 2 and table 3 show that the settlements of piles obtained by numerical method exceed the settlements of piles obtained by proposed method. The settlements obtained by the proposed method are close to the experimental settlements from pile tests.

Pile tests with long durations are of interest in civil engineering applications. The results of the research showed the same trend with Bartolomey’s experimental investigation of long-term settlements of pile [1]. The study [1] showed that the long-term settlement of a single pile exceeds the short-term settlement of the pile by 2 - 4 times for the case of damped creep. Hence, commonly used isotropic hardening models are inadequate to describe the behaviour of single piles on claystone and sandstone. It can also be seen that the proposed method of calculation seems to predict fairly well the behaviour of pile on claystone and sandstone.

Based on these results, it was found that the deformations of piles on claystones and sandstones should be calculated using parameters of Kolotunov’s creep kernel type which can capture both the vertical deformation and time effect. Based on a set of measurements from pile tests, the proposed
automated algorithm can be employed to effectively identify the optimal parameters for piles on claystone and sandstone.

6. Conclusion
The forecast of settlement of pile foundation is important in engineering practice. Data from the pile tests of Early Permian claystones and sandstones were collected in the case study. In this research, the solution is presented for estimation the long-term settlement of pile based on the rheological deformation theory using Koltunov’s core parameters. A probabilistic method of identifying the creep parameters and investigating the efficiency of isotropic hardening model in the prediction of the deformation of claystone and sandstone from pile tests was presented. Based on the developed method, eleven experimental and numerical tests with piles on claystones and sandstones were studied. The calculation results were verified with the experimental tests of piles, which indicates that the creep behavior of pile on claystone and sandstone was successfully captured. Numerical results of the calculations in Plaxis 3D were also investigated and compared with experimental tests. It was shown that the settlements of piles obtained by numerical method exceed the settlements of piles obtained by proposed method. This approach is useful in the engineering practice; engineers can adopt the present automated algorithm to identify the parameters for a given soils for the prediction of long-term creep behavior. Moreover, this method is simple and easy in calculation but is still consideration to all necessary parameters of hereditary creep.

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