Experimental study of full-scale piles on the vertical load in clay soil

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Abstract. This paper presents the results of field researches the engineering and geological conditions of the construction site, conducting full-scale parametric studies of changes in the bearing capacity of piles in Jurassic clays using various methods. The results obtained were generalized with the data of other authors. They show that in the process of changing the stress-strain state of the soil around the pile during the migration of pore water, the bearing capacity of the pile in these soil conditions increased from 1.1 to 6.0 times during the "rest" period. When investigating the causes of these processes, existing methods for determining changes in the bearing capacity of piles in time were considered and compared with the experimental results obtained. The article presents a method for optimizing the design solutions of pile foundations and provides recommendations for the use of pile foundations in similar ground conditions.

1. Introduction

When piles are submerged in clay soils, structural connections are destroyed in them. The dynamic impact of the hammer on the base changes the mechanical properties of soils based on their thixotropic properties. When a pile is submerged, water moves along its "trunk" [3] and is squeezed out from under the compacted layers of soil. The soil around the pile reduces its strength characteristics. It takes considerable time to restore water-colloidal bonds. The issue of thixotropic hardening [1] of the soil is relevant in the production of construction and installation works. The time of soil hardening depends on the genesis and processes of diagenesis. The main factor in this process is the number of dusty particles in the base. According to [9], the maximum "rest" time of the pile is 6-20 days. As a result of a break in production, the duration and cost of testing increases. Reducing the time of "rest" leads to underutilization by 20-30% of the load-bearing capacity of piles and increasing the estimated cost of construction of the object.

Many scientists, including K Terzaghi [3], M Yu Abelev [13], A A Bartolomey [9-11], B V Bakholdin [24-27], B M Gumensky [5-6], H B Seed [10], R M Narbut [2], G F Novozhilov [7], A E Radugin [8], Yu K Zaretsky [33], G A Sanglerat [4], A B Ponomarev [10,13], A Zhussupbekov [34,35], M F Randolf [45], M I Hoit [15], D M Dhwakar [17,18], Y Kim [19,20], C J F Clausen [36], C H Chen [38], D M Holloway [39], S T Hsu [41,42], Y Khodair, [47], A Boominathan [49] and others, were engaged in research of pile's work.

Currently, the authors use various models to describe the behavior of soils during hammering of piles in water-saturated soils and during the subsequent time. We have accumulated some experience in constructing buildings in similar ground conditions. Despite the existence of a number of methods...
for calculating the bearing capacity of the pile taking into account the time factor [2, 4-8, 11-13, 18, 19, 40, 41] currently, there are no normative documents that allow predicting this process.

The above methods are of a recommendatory nature, cause discussions in the scientific community, and the final decision is made after repeated tests of piles after their «rest».

The article presents the results of the study of the bearing capacity [13, 16, 17, 26, 34, 35, 36, 38, 40, 44, 45] at various stages of interaction between the pile and the soil base, and compares the results of field research with the results of engineering methods of calculation.

2. Methods
In the city of Vladimir, static and dynamic tests of square-section driven prismatic piles were performed on the territory of the chemical plant for the construction of foundations of the workshop for the production of water dispersed polymers. Piles with a cross section of 35x35 cm and a length of 14 m (C14-35 TK-2) were used as foundations on the site. The piles material is B30 class concrete.

The piles reinforcement is made according to the 3.500.1-1.93 series. The estimated permissible load on a single pile is 472 kN. The mark of the "head" of the pile is 91.03 m. under the lower end of the pile there are upper Jurassic clays, semi-hard (IGE-5). Piling was performed with a hydraulic hammer "HHK 6 AS" on the basis of the installation "Junttan PM 20 LC" (see figure 2) with the mass of the impact part of 60 kN. The total weight of the hammer is 101 kN.

In geomorphological terms, the site is confined to the left Bank of the first over-floodplain terrace of the Klyazma river (Russia). The natural absolute marks of the terrace vary from 105.12 to 107.48 m. the Terrain of the site is relatively flat, with a slight slope in the South-West direction, towards the Klyazma river (Russia). Absolute surface marks are 107.42-109.19 m. surface water Flow is free at the site.

Modern Quaternary (QIV), upper Quaternary (Qm), and upper Jurassic deposits participate in the geological structure of the site at a depth of 24.0 m (see figure 1).

Modern Quaternary deposits, represented by technogenic soil (tQIV), are deposited from the surface. The capacity of the bulk soil is 1.5-2.3 m under the bulk soil, there are upper-Quaternary deposits represented by alluvial loam (aQm). In the lower part of the section, there are dusty Sands with a capacity of 3.1 m. the Total capacity of Quaternary deposits varies from 15.9 to 17.1 m. from absolute levels of 90.62 – 93.24 m, there are upper Jurassic deposits (J3), represented by clay, the opened capacity of which is 6.9-7.4 m.

Hydrogeological conditions of the site are characterized by the presence of an aquifer confined to upper-Quaternary alluvial deposits. The water level during the survey was found at a depth of 4.8-5.0 m, at absolute levels of 102.82-104.30 m. Water-containing soils are alluvial loam and dusty sand. The upper Jurassic clay serves as a water barrier, the roof of which lies at a depth of 15.9-17.1 m. the flow of underground water is directed to the South-West towards the Klyazma river (Russia), where it is discharged.

Based on the analysis of spatial variability of particular indicators of soil properties and statistical processing of the results of laboratory and field studies (see table 1 and figure 1) at a depth of 24 m, 5 engineering-geological elements (EGE):

- EGE-1. The technogenic soil.
- EGE-2. Loam gray, yellowish-gray, soft-plastic, sandy, with spots of ferruginization, heterogeneous, alluvial.
Figure 1. Geological sections of the construction site.

Table 1. Design values of soil characteristics

| №№  | EGE name of soil  | ρ, g/cm³ | w | I_p | I_L | e | S_r | K_f | E_o | С | φ, deg.
|------|-------------------|---------|---|-----|-----|---|-----|-----|-----|---|-------|
| 1    | The technogenic soil (tQTV) | not normalized |   |     |     |   |     |     |     |   |       |
| 2    | Loam (aQIII) | 1.97 | 0.250 | 0.144 | 0.64 | 0.644 | 1.00 | 0.022-0.037 | 10 | 9.4 | 13 |
| 3    | Loam (aQIII) | 1.97 | 0.273 | 0.146 | 0.78 | 0.715 | 1.00 | 0.022-0.037 | 4 | 7.0 | 18 |
| 4    | Sand (aQIII) | 2.01 | 0.241 | - | - | 0.640 | 1.00 | 0.1-1.0 | 22 | 4.4 | 31 |
| 5    | Clay (J3) | 1.73 | 0.436 | 0.467 | 0.08 | 1.179 | 0.97 | 0.012-0.017 | 19 | 29.4 | 12 |
- EGE-3. Gray loam, fluid-plastic, sometimes in the roof with layers of fluid, sandy, with spots of ferruginization, heterogeneous, alluvial.
- EGE-4. Sand is powdery, gray, quartz, medium density, water-saturated, with frequent layers of loam, alluvial.
- EGE-5. The clay is dark gray, semi-hard, with layers of solid, with remnants of fauna, upper Jurassic.

According to the data of engineering and geological surveys, the tip of the piles is buried in the EGE-5 soils-upper Jurassic semi-solid clay at 0.28-1.45 m. since the EGE-5 soils are water-resistant and, consequently, their consistency and strength characteristics in the roof are reduced and increase with depth. When assigning the length of the piles, it should be borne in mind that the mark of the IGE-5 roof is variable, varying from the absolute mark of 90.62 m to 92.24 m. In this case, it is advisable to perform zoning of the construction site when designing the foundations of the building with the appointment of piles of different lengths as part of the "pile field".

It is widely known that the bearing capacity of piles changes over time, after their driving, most often, increases [18, 35, 36, 40].

At immersion of piles in weak water-saturated silty-clay soils under the influence of hammer blows (especially severe in our case) changes of mechanical properties [5] (total volume up to 50% at a distance of up to 2 cross-sectional dimensions of the pile) caused by the movement of water along the pile shaft, thinning the surrounding soil, which facilitates immersion piles. In addition, the soil experiences thytrotrophic decompression, which leads to the destruction of structural bonds. Subsequent compaction of the soil around the pile occurs due to the ongoing consolidation, thixotropy, dispersion of excess pore pressure and water compression. In the process of "rest" according to [1, 2, 3], free water is transformed into physically connected water with simultaneous immobilization of free water. Together with the interaction between individual particles, this creates the necessary conditions for restoring structural bonds in the soil (hardening). Processes of consolidation and thytrotrophic hardening "in pure form" never occur around piles. Consolidation involves a decrease in humidity and density, and with thytrotrophic hardening, these indicators are unchanged, and there is a restoration of coagulation bonds that break down during consolidation. The increase in the bearing capacity of the pile is uneven and follows an exponential law. When predicting precipitation, it is possible to apply the phenomenological theory of hereditary soil creep.

It should be noted that the available methods for predicting changes in the bearing capacity of piles after their immersion do not have sufficient reliability for practical purposes. There are several explanations for the increased bearing capacity of piles over time. One explanation for this is the phenomenon of ground thixotropy under mechanical influence. It is not possible to fully explain the practical increase in the bearing capacity of piles over a long period of time. As an alternative, the proposal of Seed and Reese [10, 40] on the possibility of applying the theory of consolidation to explain the increase in the bearing capacity of piles in time can be considered. Their work is of great practical importance, but it does not have a significant gap - it does not clearly reflect the physical meaning of the phenomenon. According to Seed and Reese [10] the skeleton of the soil immediately after the dive of the pile turns out to be almost completely and finally compressed embedded in it piles.

As a result of studies carried out by Baholdin B.V. [24, 26, 27, 29] it was found that during the pile scoring the water-saturated clay soil is displaced in the sides, the soil is compacted, the porosity decreases, the pore water does not have time to filter, which leads to an increase in pressure in the pore water. These phenomena cause filtration of ground water, resistance of friction forces on the side surface of the pile is reduced until the end of the process of relaxation of excessive pore pressure.

In this regard, a number of experimental studies have been carried out to improve the behavior of piles.

Initially, the piles were tested with dynamic loads without recording the elastic part of the failure. Immediately after the dive, dynamic load tests were performed on 4 piles (see figure 2). The residual part of the "false" failure was 1.67-2.94 cm. The bearing capacity of the pile was 116-254 kN. The permissible design load on a single pile is 131 kN.
Subsequent tests were carried out after the "rest" of the piles. The residual part of the failure to "rest" piles for 10-12 days changed to 0.50 – 0.86 cm. The determination of the limit resistance of piles was performed using the method [23]. The partial values of the pile limit resistance vary from 355 to 661 kN. The bearing capacity of a single pile S14-35 TZ-2 with abs. The point mark of 91.03 m on the axial pressing load is 355-472 kN. According to the results of dynamic tests, the permissible load transferred to a single pile with an absolute "tip" mark of 91.03 m is 254 kN. The bearing capacity of piles during the "rest" increased by 1.9 – 3.1 times.

To clarify the permissible load on the pile, static tests of the piles were carried out (see figure 3) for the action of the axial pressing load. Pile tests were performed after the "rest" of the piles for 10-11 days and a set of concrete piles of standard strength. The load on the pile was transferred in stages and maintained until conditional stabilization in accordance with [22] and [23].

For a particular value of the limit resistance of the pile Fu to the pressing load, the load is taken, under the influence of which the tested pile will receive a draft equal to \( S = \xi \cdot Su,mt \) where \( \xi = 0.2 \), \( Su,mt = 150 \text{ mm} \) [23]. Hence, \( S = 0.2 \cdot 150 = 30 \text{ mm} \).

During the tests, the pile sediment increased smoothly and did not reach the critical point corresponding to a continuous increase in the sediment without increasing the load.

Private values of the ultimate resistance of the piles amounted to 491-506 kN. The permissible design load transferred to a single pile with a point mark of 91.03 m is 409 kN.

Static tests made it possible to take into account the factors affecting the load-bearing capacity of the pile more accurately than dynamic tests. Despite the increase in the bearing capacity of the piles after the "rest", the calculated pressing loads on the C14-35 TK-2 piles adopted in the project exceed the permissible loads on these piles obtained from dynamic and static tests.

Figure 2. Hydraulic hammer "HHK 6 AS" based on the installation «Junttan PM 20 LC».
For a more complete assessment, the results of static soil sensing were analyzed. Particular values of ultimate resistance at the “tip” mark of piles amounted to 736–813 kN. The permissible calculate load (based on the results of static sounding) transmitted to a single pile with a tip mark of 589–650 kN.

3. Results and Discussion

Based on the data obtained, it was decided to increase the "rest" time and conduct repeated static tests of the piles. As a result, the "rest" of the piles were 27-28 days.

During repeated static tests (see figure 4), the partial values of the pile limit resistance increased from 612 to 784 kN. The bearing capacity of a single pile S14-35 TZ-2 with abs. the point mark of 91.03 m on the axial pressing load was 647 kN. According to [10], the calculated load transferred to a single pile is 462 kN.
In the considered soil conditions, increasing the "rest" time of piles has a significant impact on their load-bearing capacity. In our case, the bearing capacity of the piles increased by 3.8 – 4.9 times during the "rest" period. As a result of additional research, it was possible to preserve the original design solution.

In addition, analytical calculations were made for changes in the bearing capacity of piles over time using currently existing methods [2, 5-7]. For different authors, the duration of the "rest" should be from 25 to 180 days for soils similar to this construction site. According to [9] when cutting through clay soils of soft and fluid-plastic consistency, the duration of "rest" is at least 20 days. In our case, it is advisable to rest for 30 days.

Figure 5. Graph of changes in the bearing capacity of the pile over time.

During the "rest" period, the load-bearing capacity of piles according to [2, 7, 8, 9] increases 1.1 – 6.0 times depending on the type of soil.

The study considered the methods of G F Novozhilov [7], E A Radugin [8], and R K Narbut [2]. The results are shown in table 2 and figure 5.

Table 2. Comparison of the results of determining the change in the bearing capacity of the pile over time with data from field tests.

| pile          | The load capacity of the pile after a «rest» |
|---------------|-------------------------------------------|
|               | According to the results of a static test method | By the method of Novozhilov G F | By the method of Radugin A E | By the method of Narbut R M |
| C14-35T3-2    | 131                                       | 462                          | 387                          | 421                          | 406                          |

The deviations of the results of determining the bearing capacity of piles, taking into account the time factor, from the results of field tests are 9-16%, which indicates their high convergence. These
methods should be used in the preliminary calculation of the load-bearing capacity of piles in similar ground conditions at the stage of design work, which will reduce the likely understatement of the load-bearing capacity of piles, especially during dynamic tests of test piles.

Clay soils in natural occurrence provide a solid basis of buildings and structures possess sufficient strength and low compressibility. The high content of lamellar clay minerals with sliding crystal lattice and of organic matter determines the high dispersion of clays, their hydrophilicity and the presence of coagulation-soil of structural ties. The microstructure of Jurassic clays, roughly, lamellar. All these features of the material composition and structure determine their specific physical and mechanical characteristics - low values of angle of internal friction, a long process of deformation, the slow recovery of the destroyed structural relations, as well as low water permeability and the anisotropy of properties. Characteristics of Jurassic clays uneven within the soil column. The worst indicators are noted in the roof of the reservoir, which is a confinement and increase with depth. For individual clays, the ultimate strength is reduced to 30%. Over time, the soil of the active zone hardens, but also with steady creep, it can also soften. Almost non-deformable at pressures \( \sigma < \sigma_{\text{str}} \), they are highly compacted at high pressures. Compression curves are essentially non-linear and are fairly well described by the semilogarithmic equation. Excess pore pressure can be determined by methods of the theory of filtration consolidation. Sometimes, simplifying the task, it is permissible to take excess pore pressure equal to the total normal stresses \( \sigma \) along the sliding areas (\( \mu = \sigma \)) or assign design values \( \varphi \) and \( c \) corresponding to the non-stabilized state of the soils, determining them according to the non-consolidated quick shift.

In a short period of time, when the pile is hammered, the soil is compacted, but the pore pressure does not have time, which leads to a decrease in friction forces on the side surface of the pile. Resistance on the side surface of the pile is reduced up to the end of the process of pore pressure reduction.

Reducing the "rest" time of piles leads to an underestimation of their load-bearing capacity and an increase in the estimated cost of construction.

4. Conclusions

The experimental studies carried out in this work, the testing of developments in real conditions, made it possible to formulate the following conclusions:

1. According to the results of static testing of piles by pressing loads, the permissible load on a single pile S14-35TK-2 with a mark of the bottom of the pile of 91.03 m is 462 kN (see table 2 and figure 6). In these ground conditions, increasing the "rest" time of piles significantly affects their bearing capacity (up to 4.9 times according to experimental data). Additional research has made it possible to more accurately determine the bearing capacity of the pile and more fully use the strength characteristics of the base, while maintaining the original design solution.

2. It is recommended to immerse piles with minimum required hammer impact energy or by pressing. When piles are clogged into water-saturated clay soils, "failure" can increase with depth of diving and pile "fails." This phenomenon is due to the fact that the pile contour creates excessive pore pressure and water films are formed in the clay soil along its side surface, which significantly reduce friction, and due to dynamic (vibration) effects of clay becomes a fluid state, its strength is reduced. After rest of the pile, the soil is consolidated, and clay having a high adhesion coefficient envelopes the pile body (the phenomenon of "pile sucking"), which leads to an increase in its bearing capacity. When the pile is submerged by pressing the above-described phenomena, no phenomena occur. The main advantage of this method is that the pile is immersed in the ground as a result of static action, so the pressure force actually corresponds to the bearing capacity of the pile on the ground, without changing its physical and mechanical characteristics during diving.

3. It was experimentally established that the normative weekly value of the “rest” period is not enough to restore structural ties in the active zone for the full realization of the bearing capacity of the pile on the soil. Recommended «rest time» should be at least 30 days (see figure 4, 5).

4. The results of analytical calculations show high convergence with the results of experimental studies and can be used for preliminary prediction of changes in the bearing capacity of piles over...
time. The bearing capacity of the pile \([2, 5, 6, 10, 11]\) of interest to the builders should be determined as: \(F_d = F_{d,o} \cdot (1 + \tau) \cdot k_c\), where \(F_{d,o}\) - the bearing capacity of the pile immediately after immersion, \(\tau\) - the degree of hardening of the piles, depending on the type of soil (0.5-4.0), \(k_c\) - the degree of restoration of structural bonds (0.5-1.0; determined on the basis of field studies of soil characteristics).

5. The results of the studies allow us to optimize design solutions for pile foundations in water-saturated clay soils.

References

[1] Vyalov S S 1978 Rheological foundations of soil mechanics (Moscow: High school) p 448
[2] Narbut R M 1972 Work of piles in clay soils (Leningrad: PH Literature on construction) p 160
[3] Terzaghi K 1942 Discussion on the progress report of the Committee on the Bearing of pile foundations J of Soil Mechanics and Foundation Engineering Division 68 2 311-323
[4] Sanglerat G 1984 Practical problems in soil mechanics and foundation engineering Ph. Char. of Soils, Plasticity, Settlement Calculations, Interpretation of in-Situ 1 1-285
[5] Gumensky B M 1950 Driving piles into thyrotrophic soils J Equipment of Railways 3 (Moscow)
[6] Gumensky B M and Novozhilov G F 1961 Soil thixotropy and its accounting in the construction of roads and bridges (Moscow: Autotransmit) p 108
[7] Novozhilov G F Phenomena occurring in clay soils during sinking and resting of piles, their influence on the process of increasing the resistance of hanging piles over time Col. of works LIRE 234
[8] Radugin A E 1966 Investigation of the influence of "rest" piles on their load-bearing capacity J OFMG 6 16-17
[9] Bartholomey A A, Omelchuk I M and Yushkov B S 1994 Prediction of the sediment pile foundations (Moscow: Stroyizdat) p 184
[10] Bartolomey A A, Omelchak I M, Ponomaryov A B and Bakholdin B V 1997 Calculation of pile foundations on limiting states: Russian practice ed De Cock F and Legrand C Design of axially loaded piles: European practice (ERTC3 Sem. on Design of Axially Loaded Piles – European Practice: Brussels, Belgium) pp 321-336
[11] Bartolomey A A, Ponomaryov A B and Yushkov B S 2000 The basic achievement and problems pile foundations building, ed M Mets (Baltic geotechnics. Proc. 9th Baltic Geotechnical Conf.: Parnu, Estonia) pp 274-278
[12] Seed H B and Reese L C 1955 Pressure distribution along friction piles Proc. ASEC Eng. 55
[13] Ponomarev A B and Bezgodov M A 2014 Load-bearing capacity of driving piles in weak water-saturated soils taking into account the time factor J Construction and architecture 1 7-15
[14] Ponomarev A B and Sychkina E 2016 Verification of the Results of Numerical and Analytical Estimates of the Settling of a Single Pile in Argillite-Like Clay J Soil Mechanics and Foundation Engineering 53(2) 78-81
[15] Wu G and Finn W D I 1997 Dynamic nonlinear analysis of pile foundations using finite element method in the time domain Canadian Geotechnical J 34 44–52
[16] Banerjee P K and Davis T G 1978 The behavior of axially and laterally loaded single piles embedded in non-homogeneous soils Geotechnique 28(3) 309-326
[17] Dewaikar D M, Salimath R S and Sawant V A 2009 A modified p-y curve for the analysis of a laterally loaded pile in stiff clay J Australian Geomechnic 44(3) 91-100
[18] Dewaikar D M, Chore H S, Goel M D and Mutgi P R 2011 Lateral resistance of long piles in cohesive soils using p-y curves J Structure Engineering-ASCE 38(3) 222-227
[19] Kim Y, Jeong S and Lee S 2011 Wedge failure analysis of soil resistance on laterally loaded piles in clay J Geotechnic Geoenvironmental Engineering 137(7) 678-694
[20] Kim Y and Jeong S 2011 Analysis of soil resistance on laterally loaded piles based on 3D soil-pile interaction J Computers and Geotechnics 38(2) 248-257
[21] Lee S, Kim Y and Jeong S 2010 Three-dimensional analysis of bearing behavior of piled raft on soft clay J Computers and Geotechnics 37(1-2) 103-114
[22] GOST 5686-2012 2012 Soils. Methods of field testing with piles (Moscow) p 47
[23] SP 24.13330.2017 2017 Pile foundations. (Updated version of SNIIP 2.02.03-85) p 86
[24] Bakholdin B V and Trufanova E V 2010 Resistance of piles to horizontal loads J OFMG 6 8-13
[25] Trufanova E V and Yastrebov P I 2014 Experimental investigation of soil plasticity J NIC Construction 143-153
[26] Bakholdin B V and Bolshakov N M 1973 Research on the stress state of clay grounds when driving piles J OFMG 5 7-9
[27] Bakholdin B V, Bessmertny A V and Yastrebov P I 2017 Increased bearing capacity of piles driven in clay J Soil Mechanics and Foundation Engineering 54 97–101
[28] Trufanova E V and Yastrebov P I 2014 Experimental studies of soil plasticity J NIC Construction 10 143-153
[29] Baholdin B V, Bessmetrtya A V and Yastrebov P I 2017 Study of the nature of increasing the bearing capacity of piles submerged in clay soils J OFMG 2 pp 18-21
[30] Paramonov V N and Dunaevskya T A 2004 Change of bearing capacity of clogged piles in time on open areas and loaded structures J Reconstruction of cities and geotechnical construction 8 pp 102-106
[31] Paramonov V N and Tikhomirova L K 2000 Changing the bearing capacity of driven piles in time J Reconstruction of cities and geotechnical construction 1 pp 127-131
[32] Gumensky B M 1965 Fundamentals of the physical chemistry of clay soils and their use in construction (Moscow: Stroyizdat) p 255
[33] Zaretsky Yu K 1988 Viscoplasticity of soils and structural strength (Moscow: Stroyizdat) p 349
[34] Zhussupbekov A Zh, Lukpanov R E and Omarov A R 2016 The Results of Dynamic (Pile Driving Analysis) and Traditional Static Piling Tests in Capital of Kazakhstan Mat. 13th Baltic Sea Region Geotechnic Conf. (Vilnius, Estonia) pp 201-205
[35] Zhussupbekov A Zh, Syrlybaev M K, Lukpanov R T and Omarov A R 2015 The applications of dynamic and static piling tests of Astana Mat. 15th Asian Regional Conf. on Soil Mechanics and Geotechnic Engineering ARC 2015: New Innovations and Sustainability pp 2726-2729
[36] Clausen C J F and Aas P M 2001 Capacity of driven piles in clays and sands on the basis of pile load tests Proc. of the 11th Int. Offshore and Polar Eng. Conf. ISOPE vol II pp 581-586
[37] Burland J B Shaft friction of piles in clay a simple fundamental approach J Ground Engineering 6 3 30-42
[38] Chen C H, Perng T D, Hwang J H and Chang I T 2000 Analyses for load test data of PC piles on west-coast reclaimed areas of Taiwan J of the Chinese Institute of Civil and Hydraulic Engineering 12 1 29-40
[39] Holloway D M, Clough G W and Vesic A S The effects of residual driving stresses on pile performance under axial load Proc.10th Offshore Technology Conf. vol 4 (Houston, USA) pp 2225-2236
[40] Coyle H M and Reese L C 1996 Load transfer for axially loaded piles in clay J Soil mechanics and foundation division ASCE 92 2 1-26
[41] Hsu S T 2011 Numerical simulation of driven piles in alluvial soil Applied Mechanics and Materials 105 1415-1419
[42] Hsu S T 2014 Behaviors of large-scale driven PC piles J of Marine Science and Technology 22 4 487-497
[43] Randolph M F, Carter J P and Wroth C P 1979 Driven piles in clay-the effects of installation and subsequent consolidation J Geotechnique 29 4 361-393
[44] Randolph M F and Wroth C P 1978 Analysis of determination of vertically loaded piles J of the Geotechnical Engineering Division 104 12 1465-1488
[45] Chandler R and Martins J 1982 An experimental study of skin friction around piles in clay J Geotechnique 32(2) 119-132
[46] Yang Z and Jeremić B 2014 Study of soil layering effects on lateral loading behavior of piles *J of Geotechnical and Geoenvironmental Engineering* **131**(6) 762-770
[47] Khodair Y and Abdel-Mohti A 2014 Numerical Analysis of Pile–Soil Interaction under Axial and Lateral Loads. *Int. J of Concrete Structures and Materials* **8**(3) 239-249
[48] Hong Y, He B, Wang L et al 2017 Cyclic lateral response and failure mechanisms of semi-rigid pile in soft clay: Centrifuge tests and numerical modeling *Canadian Geotechnical J* **54**(6) 806-824
[49] Boominathan A and Ayothiraman R 2007 An experimental study on static and dynamic bending behaviour of piles in soft clay *J Geotechnical and Geological Engineering* **25**(2) 177-189
[50] Verruijt A 2018 *Consolidation* (Springer Int. Publ.) pp 123-129
[51] Pan A, Goh A, Wong K et al. 2000 Model tests on single piles in soft clay *Canadian Geotechnical J* **37**(4) pp 890-897