Design soil resistance for deep foundation

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ABSTRACT

The following article represents various methods for soil resistance – R identification under single pile, based on the Republic of Kazakhstan guidelines. Analytical values obtained from formulas and empirical values based on plate load and CPT tests for deep foundation bearing capacity design. To study and evaluate design soil resistance – R just beneath the footing, theoretical calculations executed, at the same time, set of plate load test probing carried out on the depth 7.0 – 11.0 m, with diameter of the cross section plate equals to 30 cm. Furthermore, dynamic and static test took place for single pile bearing capacity identification. Consequently, code of practice values validated with obtained experimental values. The pile cross section is 30 x 30 cm and length is 8.0-10.0 m. The physical and mechanical soil properties on the depth of 8.0 – 12.0 m state that bearing layer underneath the pile toe is loam with following design characteristics: cohesion = 27 - 41 kPa, angle of friction = 23 - 26 degrees, density = 19.2 – 19.5 ton/m3. It has to take into account that soil is saturated and the site located in impounded area. Load – settlement figure states that factored bearing capacity is 403 – 784 kN. Dry resistance unit soil results of CPTs for loam is 241 and 582 kN, with bearing capacity equals to 658 kH. Dynamic tests results reveal bearing capacity of the pile 606 kN. Plate load test results perform settlement of 0.58 cm in the range of 0.1 – 0.5 MPa loading. The modulus of deformation is 12.0 MPa. Settlement – loading figure and plate load test curve is linear at 10.2 m depth. Comparative results of single pile bearing capacity perform difference between design values of soil resistance underneath the pile toe in terms of shaft surface in analytical and experimental approaches.

Keywords: resistance, design, bearing capacity, single pile, deep foundation

1. INTRODUCTION

Introduction of Building Norms in the Republic of Kazakhstan with regard to the principles of Eurocode "Geotechnics-7" in 2015-20 determines the need to revise and clarify the provisions of building codes and national standards for the design of pile foundations. Building norms of pile foundation design developed nearly 40 years ago for the vast territory of the USSR taken without considering the behaviour of soil conditions on the territory of Kazakhstan. Results of geological engineering survey analysis represent that the foundation soil in many design parameters are different. In recent years, the government set a problem for building committee to adapt existing regulations to the basic principles of basement and foundations design of Eurocode "Geotechnics-7". Comparative results conducted by the authors show that the calculation and design of pile foundation different in:
- the choice of safety factors for the foundation soil;
- determining the design resistance of soil under pile foot and around the shaft of piles;
- selection of test methods for the pile bearing capacity determination;
- determining the distance between piles in the design and dimensioning of the pile cap.

Thus, to shift to the main aspects of international norms it is necessary to adapt basic principles of basement and foundation design. Taking into account particular geological conditions on the vast territory of Kazakhstan design characteristics of foundation soils need to adopt as well.

http://doi.org/10.3208/jgssp.KAZ-09 350
2. FOUNDATION SOIL FEATURES

Because of complex engineering and geological surveys in the Central Kazakhstan and their subsequent generalizations found that majority of buildings and structures, foundations are of continental sedimentary unconsolidated Quaternary rock origin.

Zoning of Quaternary soils revealed a commonality of basic engineering-geological conditions. Standardisation accomplished selection the rational type of foundations for all construction areas. Quaternary soil types are alluvial in origin. Building Norms of RK 5.01-01 (2002) provides a feature of the buildings’ and structures’ design foundation erected on the alluvial soils. Alluvial clayey soils are made up of loose structured loam and clay. Foundations composed by alluvial soils designed taking into account their specific characteristics:
- heterogeneity of composition with a large spread of values of strength and deformation characteristics;
- variability of physical and mechanical properties of loamy soils during saturation.

Analysis of the physical - mechanical properties of soils sampled at depths of 8.0 - 12.0 m in the cities of Central Kazakhstan revealed that the bottom layer under the pile foot is semisolid loam. Physical and mechanical properties of loam given in Table 1. Consequently, semisolid, unsaturated loamy soils and test region relates to impounded areas.

3. DESIGN FOUNDATION SOIL RESISTANCE

In the design of foundations, the computed resistance of soil basement correspond to such pressure under the pile foot and the surrounding area in which the zone of plastic deformations develop at a limited depth and this pressure is in the early phases of area displacement formation. The design resistance of soil foundation coefficients meet only negligible by size plastic strain region.

Design foundation soil resistance equals to the shaft and pile foot pressure, when zone of plastic deformations propagates up to limited depth and following pressure is in the early phase of shift zones development. Herewith, design foundation soil resistance coefficients is in charge of negligible in size plastic deformation region.

3.1. Pile foot

The design resistance - R under the pile foot depends on the soil (density and type of sandy soils and clayey soils flow index), as well as on depth of pile foot penetration. Following number evaluated from Building Norms of RK 5.01-03 (2002). International practice accepted following formula:

Sandy foundations

\[ R = N_q \sigma, A_B \]  

Clayey foundations

\[ R = 9 c A_B \]

where, 
\( \sigma \) = \( \gamma' h \) – effective stress under pile foot due to soil self-weight;
\( N_q \) – single pile bearing capacity coefficient depending on the angle of friction - \( \varphi' \);
\( A_B \) – pile toe cross section area
\( C \) – soil cohesion

3.2. Pile shaft

Shaft resistance depends on type of sandy soil, clayey soil flow index, layer depth of taken as representative angle of friction, evaluating from the Building Norms RK 5.01-03 (2002). According to international standards, shaft resistance depends on the size of cohesion and the angle of internal friction of soil.

Scientific approach determining the design resistance of the soil under pile foot and the pile shaft shows that there is a difference between the regulations of the Republic of Kazakhstan and international standards. If Building Norms of RK 5.01-03 (2002) recommend to choose the values from the table based on the types of soil (sand or clay), the international standards determining with help of formulas, based on the estimated physical and mechanical properties (density, cohesion and angle of internal friction).
4. PILE BEARING CAPACITY

4.1. Analytical methods

Bearing capacity of driven standing pile determines through analytical methods of static and dynamic experiments, and CPT.

Bearing capacity of driven standing pile working in compression determined as sum of design soil resistances under pile foot and around the shaft, according to Building Norm of RK 5.01-03(2002), Ukhov S.B. and others.

\[ N = F_d = \gamma_c \cdot (\gamma_{cR} \cdot R \cdot A + u \sum \gamma_{cf} \cdot f_i \cdot h_i) / \gamma_R \]  

where,
\[ \gamma_c = 1 \text{ coefficient of work conditions in soil;} \]
\[ R \text{ - design soil resistance of pile toe, kPa;} \]
\[ A \text{ - area of soil contact with a pile, m}^2; \]
\[ u \text{ - cross sectional outer perimeter of pile shaft, m;} \]
\[ f_i \text{ - i-th layer design soil resistance on a shaft surface of pile, kPa;} \]
\[ h_i \text{ - i-th layer thickness in contact with pile's shaft surface, m;} \]
\[ \gamma_{cR}, \gamma_{cf} \text{ - soil work condition coefficient under pile foot and around the shaft, taken from the table;} \]
\[ \gamma_R \text{ - factor of safety.} \]

International standards determine the bearing capacity \( R_{c,d} \) as:

- For sandy foundations
  \[ R_{c,d} = [N_q \cdot \sigma, A_B + (K \cdot \sigma, \tan \delta \cdot A_p)] / \gamma_R \]  
- For clayey foundations
  \[ R_{c,d} = q_{ek} + q_{sk} = [9cA_B + \alpha cA_p] / \gamma_R \]

\( K \) - coefficient of horizontal pressure on the pile shaft;
\( A_p \) - area of shaft surface;
\( \alpha \) - cohesion.

Therefore, analysis reveal that calculation methods for design bearing capacity of a single standing pile is different in formulas and in approaches stated in Building Norms of RK and international standards.

4.2. Pile tasting methods

Building Norm of RK 5.01-03(2002) suggests two ways of pile tasting for bearing capacity determination: static and dynamic methods. Dynamic method is confined in bearing capacity evaluation in pile-driving resistance.

Static method using settlement-loading graph to find ultimate loading which creates 20% of ultimate building settlement.

The ultimate loadings divided by a safety factor equal to 1.2 or 1.4. Ultimate pile resistance in international standards apart the static method determine using a dynamic driving formula and the results of wave equation solutions. In static method, the settlement-loading schedule provides ultimate resistance of piles, causing settlement equal to 10% of pile toe diameter, EN Eurocode 7 (1997). The ultimate resistance of piles divided by a safety factor of 3.0

5. RESULTS ANALYSIS

According to international standards for the jacking of driven piles, the critical limit is determined by the resistance-loading curve that has the continuous curvature. In this case, the criterion for "destruction" is taking the settlement of pile head, equal to 10% of pile toe diameter. Then, as of Building Norm of RK 5.01-03 (2002) take the condition that ultimate value for settlement of the tested pile is determined by following equation:

\[ S = \zeta S_{u,mt} \]

where,
\[ \zeta \text{ - conversion factor from the average value of foundation settlement or the structure } S_{u,mt} \text{ to the tested settlement by SACLT. According to the requirements conversion factor shall be taken as } \zeta = 0.2 \text{ in case of aforementioned stabilization criteria.} \]

\( S_{u,mt} \) - is maximum allowable foundation settlement value of the designed building or structure, and is vary depending on type of designed building or structure:

\( S_{u,mt} = 8 \text{ cm in case of industrial and civil buildings and constructions with a reinforced concrete frame.} \)

(Figure 1. Pile settlement under jacking load.)
Results of calculated soil resistances under pile foot and around the shaft, bearing capacity of piles, various analytical and field tests in consideration with safety factors given in the Table 2.

Table 2. Bearing capacity piles.

| Method       | \(q_{dk}\) (kN) | \(q_{dk}\) (kN) | \(R_{sd}\) (kN) | \(\gamma_d\) | \(E_d\) (kN) |
|--------------|-----------------|-----------------|-----------------|--------------|--------------|
| BN RK        | 387             | 521             | 908             | 1.4          | 648          |
| EU           | 33.21           | 442.8           | 476             | 1.4          | 340          |
| ST BNRK      | -               | -               | 1098            | 1.2          | 784          |
| ST EU        | -               | -               | 1210            | 3.0          | 403          |
| DT BNRK      | -               | -               | 849             | 1.4          | 606          |
| CPT          | 241             | 582             | 823             | 1.25         | 658          |

Results analysis reveals that there are significant differences between the analytical methods for determining the bearing capacity of piles and the design resistance of soil under pile foot and around the shaft. Calculations show that the resistance of the soil under pile foot by BN RK 5.01-03 (2002) is equal to 387 kN. According to international standards, Tomlinson (2001), this figure is 10 times smaller and is equal to 33.21 kN. Resistance on shaft surface is different in 78.2 kN. The results of static tests of driven piles show that the difference in critical limits soil resistivity is 112 kN. Taking into account that the safety factors of pile bearing capacity is equal to 381 kN. It means the difference nearly doubled. It should be noted that the safety factor of BN RK 5.01-03 (2002) is equal to 1.4, according to international standards EN Eurocode 7 (1997) FOS reaches 3.0.

The bearing capacity of driven piles according to results of dynamic testing and static probing shows that the difference is 52.0 kN and the design resistance of soil without safety factor is 26.0 kN. It should be noted that in dynamic tests soils are characterized only by the magnitude of pile-driving resistance. Therefore, the design resistance at pile foot and around the shaft is not possible to evaluate. During the static soil test, resistance value at pile foot and around the shaft measured simultaneously, but without pore pressure effect. According to the results of CPT within a range of 0.1-0.5 MPa load, the settlement is 0.58 cm. Furthermore, the deformation modulus is in the range of 12.0 -16.0 MPa. Settlement-loading curve at 10.0 m depth is linear.

6. CONCLUSION

Shift to the main provisions of international standards requires the adaptation of the basements and foundations design, taking into account features of engineering-geological soil conditions in Kazakhstan.

In result of complex engineering-geological surveys, areas of Central Kazakhstan and their subsequent generalizations, found that majority foundations of buildings and structures are of continental sedimentary unconsolidated Quaternary rocks origin. These geotechnical investigations and laboratory testing results show that the soils have relatively high density and low void ratios. The laboratory studies confirm an increase in water content of soils and the transition from a semi-solid to a low-plasticity consistency.

Design resistances of soil under the pile toe and around the shaft selected from BN of RK tables and based on the types and state of the soil. International standards’ approach based on physical and mechanical properties of a soil and following formulas evaluation. Analytical study of calculation methods for the bearing capacity of piles represent that there is a difference in between the formulas and approaches.

Analytical method for determining the bearing capacity of piles perform almost doubled difference in results.

According to the results of static tests of piles, bearing capacity varies also almost in two times due to the safety factor, which sometimes accepted by international standards as 3.0. Bearing capacity analysis points that the results of static probing and dynamic tests of piles are nearly identical.

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