Analysis of the Pile Foundation Calculation Results Given the Action of an Earthquake and Soaking of the Loess Base

Nyamdorj Setev and Dashjamts Dalai

Abstract Purpose and task: On the territory of Mongolia, loess type subsiding soils are widespread and where seismic activity is 6–9 points according to the modified scale of Giuseppe Mercalli (Charles Richter) system. During the calculation of piles, the goal was to analyze the reduction in the bearing capacity of the pile foundation, depending on the activity of the earthquake and the water saturation of the soil of the building base in the operational stage. Brief description of the methodology: Based on the results of the analytical calculation, a comparative analysis of the reasons for the decrease in the bearing capacity of the pile foundation under action 6 was carried out; 7; 8 and 9 points and in the condition Wsat. A method was used to predict the probability of a risk from unacceptable and uneven settlement of buildings and structures. Results and conclusions: A quantitative assessment of the reduction in the bearing capacity of the pile foundation was obtained and the inequalities of the boundary conditions were revealed based on the results of comparative analyzes of numerical values, relevant factors of influence, such as an earthquake and wetting of the subsiding soil of the base. Conclusions are drawn on the basis of a quantitative assessment and comparative analyzes that when designing pile foundations in a mandatory laying, consider the problem of reducing and increasing uneven settlements, and make a design decision taking into account the coefficient of reduction in the bearing capacity of the foundation.

Keywords Humidity · Water saturation · Subsiding soils · Bearing capacity · Settlement

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1 Introduction

According to the requirement of the development of urban planning and the development of a new territory where structurally unstable soils are common, such as subsidence loessal, swelling, bulk, seasonal and permafrost soils, the optimal use of pile foundations, taking into account the high activity of the earthquake according to the modified scale of Giuseppe Mercalli (Charles Richter), is acute. The experience of using pile foundations for buildings and engineering structures in the above-considered engineering geological conditions of Mongolia shows that there are certain opportunities to increase the economic efficiency of investments, reduce the duration of the zero-cycle technological work, complete mechanization, most importantly, ensure reliable stability of the base and foundation of the structure under construction and operational suitability during the estimated period.

According to the results of field tests of reinforced concrete piles of various lengths in low-moisture subsidence dusty sandy loam soil of the territory of the city of Darkhan, the bearing capacity decreases by 1.14–2.59 times after soaking to the state of water saturation in terms of moisture (Nyamdorj [1]).

2 Brief Description of the Methodology

Abelev Yu.M., Y., Broms B.B., Vesic A.S., Bakholdin B.V., Ishihara K., Grigoryan A.A., Kulhawy F.H., Nordlund R.L., Dashzhamts D., Ilyichev V.A., Stavnitser L.R., Tomlison M.J., Krutov V.I., Mangushev R.A., Jian Chu., Gotman A.L. and others studied the features of the work of piles and pile foundations in subsidence soils during soaking, taking into account earthquake activity and developed a theoretical justification for their calculation. Currently, more than 200 different types of piles have been developed and used in the world, and new research is ongoing to find better options. This circumstance confirms that the most effective constructive and technological options for pile foundations have not yet been found (Mangushev [2]; Ishihara [3]; Dashzhamts [4]).

In 1997, in the city of Hamburg, the Germans, leading researchers and specialists in the field of pile foundation engineering, set the goal at a meeting of the Technical Committee (TS-18) of the International Association for Soil Mechanics and Geotechnics (ISSMGE) as follows: "by modeling the calculation method of a pile foundation and designing according to optimal design solutions, save material costs and reduce the total estimated cost of buildings and structures".

For example, in the soil conditions of the territory of Mongolia, piles are driven and embedded in subsiding soil with natural low humidity, in the future, in a long operational period, the moisture content of the base soil increases due to technogenic soaking, in other words, there is a high probability of increasing the degree of humidity to the value of water saturation ($Sr \geq 0{,}8$). If, under this condition, a seismic event occurs, that is, an earthquake, there can be great risk. At the current level of development of geotechnical science in modeling using the finite element method, it is more possible to predict the patterns of subsidence deformation and changes in bearing capacity (Ilyichev [5]; Stavnitser [6]). The seismic behavior of piled foundations during soaking of the base soil and earthquake is widely discussed by many researchers from different countries in order to design more safely and economically.

Ishihara and Asuyuki Koga [7] studied the conditions of soil liquefaction and destruction of buildings and structures during the 1964 Nigata earthquake. Tokimatsu and Asaka [8] studied the negative effects of soil movements caused by liquefaction on the work of piles during an earthquake, established the causes of the destruction of the building and engineering communications of the city of Hyogoken-Nambu (Kobe) in 1995. Motosaka and Somer [9] established ground motion characteristics and structural damage of liquefied soils during the 1999 Kocaeli earthquake in Turkey. Motosaka and Wang [10] studied the vibration characteristics to the ratio of damage to the pile heads at the joints with the grillage structure of a high-rise building with a large span and a pile foundation based on microtremor observations of the Sendai (Fukoshimo) earthquake in 2011. It was established that soil liquefaction is the main cause of damage to building structures in seismically active areas.

Finn and Fujita [11] in his work "Pile in liquefying soils: seismic analysis and design issues" specific design cases are considered and illustrated. One is the reaction of the pile to a strong earthquake, accompanied by the development of high pore water pressures or liquefaction during shaking, and the other is the reaction to pressure caused by the lateral movement of the liquefied soil. An analysis was made of the results of model tests of pile foundations, which are used to demonstrate the current process of reducing the bearing capacity during strong shaking. Boulanger et al. [12] investigated the causes of damage to bridge support structures after an earthquake, that is, as a result of liquefaction of the soil of the base of the supports. Rostami et al. [13]. The regularities of the loss of the bearing capacity of the pile and the nature of the damage were studied and the place of formation of plastic hinges along the length of the pile was determined. The results of parametric studies have shown that a plastic hinge is formed at the boundaries of the fluidized and non-liquefied layers; however, many factors can influence the location, such as material properties, pile length, and thickness of the liquefied soil layer.

Janalizadeh and Zahmatkesh [14]. Studies were conducted using three-dimensional (3D) numerical modeling to determine various parameters such as soil stratification, kinematic and inertial forces, pile head boundary conditions, soil surface slope, and pile response. Comparing the results of numerical analyzes with the results of laboratory flume tests, it was concluded that the use of the p-y curve method for liquefied sand gives satisfactory results. In the work of Stolyarov [15] analyzes the effect of residual seismic soil displacements on the operation of traditional foundations, as well as on pile foundations with an intermediate cushion. It is proposed to use seismic-resistant foundations in seismic regions with an intensity of 7–9 and 9–10 points, the size of which takes into account the magnitude of residual soil displacements, It is shown that the accepted standard accuracy of setting the intensity of an earthquake for settlements $-\Delta I = 1$ point, at which seismic displacements change by a factor of 6, is unprecedentedly low for science and technology. It is desirable to bring it to the Japanese accuracy of 0.1 points. Wang [16] investigates the seismic response of single piles in liquefying soil by testing on a laboratory shaker and numerical simulation. The main factors of influence on the behavior of piles in liquefied soil, as well as the dynamic connection of the inertial interaction of the structure and the pile, the mechanism of kinematic soil-pile interaction were established.

From the considered and cited works of researchers, it can be seen that the problem of the interaction of a pile and a liquefied soil is very complex and depends on many factors. Including the volume of laboratory and field work performed to determine the calculated physical and mechanical indicators, their reliability is very important. The clarity of the assignment for the performance of engineering–geological work is very important, it must be certain, subsequent work depends heavily on the reliability of certain calculated indicators of soil conditions until the expiration of the operational suitability of the constructed buildings and structures.

3 Methods and Materials

According to the methodology specified in BNbD 50.01-16 [17] and SP 24.13330–2011 [18] to determine the area of the base of the conditional pile foundation of buildings and structures built on subsidence soils, taking into account soaking to the value of W_{sat} and $S_r \geq 0.8$, in Depending on the activity of the earthquake, the angle of internal friction decreases as follows: with a 7-point earthquake, the values of φ^{II} by 2°; at 8 points by 4° and at 9 points by 7° (where φ^{II}–is the angle of internal friction of water-saturated soil). As a result of the latter, the area of the base of the conditional pile foundation decreases to a certain extent, in such a case, in order to provide the criteria for calculating I for strength and II for deformation limit states, increase the depth of the piles and the distance between the piles that are part of the pile cluster foundation.

Developed a calculation scheme in accordance with the methodology under consideration, taking into account the moisture content of the base soil soaking and earthquake activity (Fig. 1). For the purpose of comparative analysis and identification of the dynamics of the decrease in bearing capacity, calculations were carried out in accordance with this methodology, taking into account the liquefaction of silty sandy loamy soil and an increase in seismic activity from 6 to 9 points, the results of which are analyzed and shown in the next part.

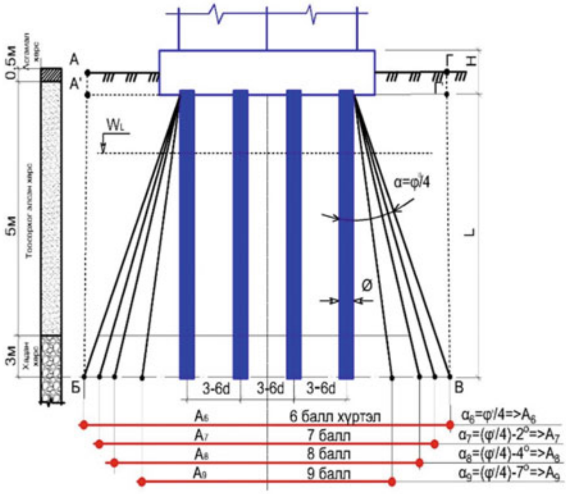

Fig. 1 Calculation scheme for determining the area of the base of a conditional piled pad foundation under the conditions of increasing seismic activity

4 Results of the Analytical Calculation

Let's consider an example of calculating the bearing capacity (F_d) of a bored pile with a length of 8.0 m and a diameter of 0.6 m in subsiding dusty sandy loamy soil of the city of Darkhan, taking into account the water saturation of the base soil from technogenic soaking in the operational period and 7-point seismic activity according to microzoning according to the formula Grigoryan [19] and according to Appendix E of the SP norm [18], formula 16: The calculated characteristics of the soil condition are obtained from table 2 from (Nyamdorj et al. [20]).

$$F_d = \gamma_c (F_{1H} + F_{2H}); \tag{1}$$

where γ_c—is the working condition coefficient, $\gamma_c = 1.0$.

F_{1H}–$F_d = \gamma_c (F_{1H} + F_{2H})$; lateral resistance coming to the length $l_0 + l_H$,

$$F_{1H} = A_1 = U\left[\ell_0\left(0.5\xi \cdot \gamma \cdot \ell_0 \cdot tg\varphi'' + c\right) + \left(\xi \cdot \gamma \cdot \ell_0 \cdot tg\varphi'' + c\right)\ell_2\right]; \tag{2}$$

$$\text{U} = 1.884;\ \xi = 0,5;\ \varphi'' = 17^{\circ} - 2°{=}15°;\ \text{c}'' = 6.8\,\text{k}\pi\text{a},\ l_2 = 7.7 - 1.0 = 6.7\text{m}$$

$$l_2 = l + 2/d - l_0 - b - a = 7.7 + 0.6/2 - 2.0 - 0.23 - 1.0 = 4.77_{\text{M}}$$

$l_0 = l_1 - a = 3.0 - 1.0 = 2.0$ M; $\text{tg}15° = 0,32$; $\text{ctg}15^{\circ} = 3.12$;
$l_1 = 12d$ or accepted not less than 6.0 m, accepted $l = 3.0$ M.

$$b = d/2 - (ctg\alpha - 1)ctg\varphi'' = 0.6/2 - (3.126 - 1) \cdot 3.126 = 30 - 6.65 = 23.35\,\text{cm}$$

Table 1 Results of calculating the dependence of the bearing capacity and settlements of bored piles on seismic activity

Seismic activity, Q	Length and diameter of piles, m	φ_{sat} soaked soil	The area of the sole of the conditional foundation-A, m^2	Bearing capacity of piles-F_d, tons	Decrease in bearing capacity Δ, in time
6 points	L = 8.0, ∅ = 0.6	17°	23.75	71.97	1.0
7 points	L = 8.0, ∅ = 0.6	15°	20.92	63.14	1.14
8 points	L = 8.0, ∅ = 0.6	13°	16.46	52.48	1.64
9 points	L = 8.0, ∅ = 0.6	10°	9.16	27.79	2.59

$\alpha = 45^\circ - \varphi - \mathrm{x} \cdot c = 45^\circ–15^\circ - 0.2 \cdot 5.0 = 29^\circ$, $ctg\alpha = \frac{0.674}{0.485} = 1.802$, $x = \frac{k}{l_0} = \frac{1,0}{5,0} = 0,2$

$F_{1H} = 1.884[2.0(0.5 \cdot 0.5 \cdot 16.5 \cdot 2.0 \cdot 0.32 + 6.8) \cdot 4.77] = 12.46$ mn

$$F_{2H} = k\delta_1 A; \quad (3)$$

$F_{2H} = 3.0 \cdot 59.69 \cdot 0.283 = 50.68_{\mathrm{TH}}$, if $k = 3.0$

$$\delta_1 = \frac{\delta_3(1 + sin\varphi) + 2c\,cos\varphi}{1 - sin\varphi} = \frac{16.5(1 + 0.485) + 2 \cdot 6.8 \cdot 0.874}{1 - 0.485} = 59.69$$

$$\delta_3 = \xi\gamma l_0 = 0.5 \cdot 16.5 \cdot 2.0 = 16.5.$$

$$F_d = 1,0(12.46 + 50.68) = 63.14_{\mathrm{T}}$$

The results of calculations performed in accordance with the above methodology to determine the dependence of the bearing capacity and settlement of bored piles on the angle of internal friction (φ_{sat}) and seismic activity are shown in Table 1.

5 Analysis of the Results

When the value of the angle of internal friction of subsidence low-moisture (i.e. with natural moisture) silty sandy loamy soil at φ = 17° and Q = 6 points, $A_6 = 23.75$ m^2, $F_{d;6} = 71.97$ tons, when it decreases by 2° at $\varphi_{sat} = 15^\circ$ and Q = 7 points, it turns out $A_7 = 20.92$ m^2 and therefore $F_{d;7} = 63{,}14$ tons or the bearing capacity decreases by 1.14 in times. For other cases, similar calculations were carried out: at

Q = 8 points $A_8 = 20.92\ m^2$; $F_{d;8} = 43.88$ tons or 1.64 times; with Q = 9 points $A_9 = 16.46\ m^2$; $F_{d;9} = 27.79$ tons or 2.59 times respectively decrease (Figs. 2, 3 and 4).

In the work of Ter-Martirosyan et al. [21] presented approximately similar results of a comparative analysis of analytical calculations and numerical solutions of the interdependence of a pile and a water-saturated base soil, taking into account soil liquefaction during an earthquake.

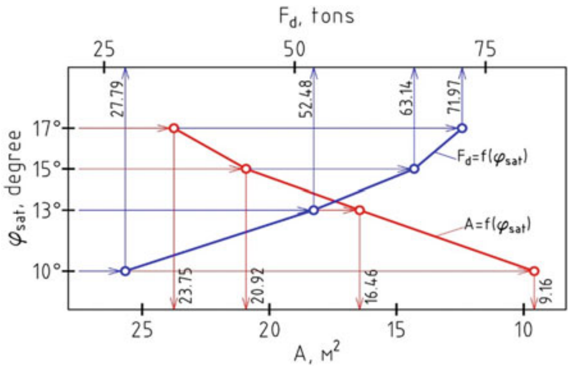

Fig. 2 Diagrams of the dependence of the area of a conditional pile foundation on the angle of internal friction, taking into account the activity of seismic A = f(φ_{sat}), (red curve) and the bearing capacity on the angle of internal friction, taking into account the activity of seismic F_d=f(φ_{sat}), (blue curve)

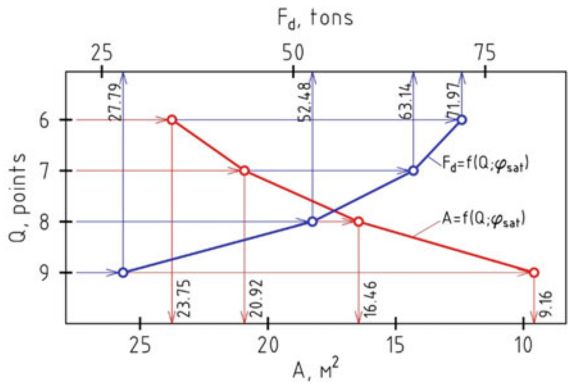

Fig. 3 Diagrams of the dependence of the area of a conditional pile foundation on the intensity of seismic, taking into account the angle of internal friction A = f(Q), (red curve) and the bearing capacity of the pile foundation on the intensity of seismic F_d = f(Q), (blue curve)

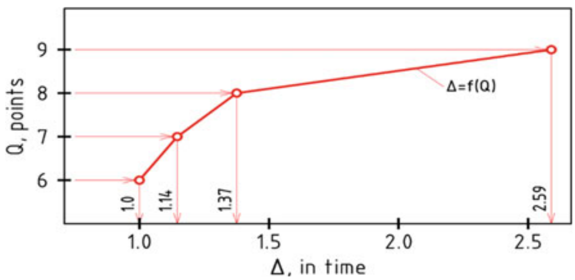

Fig. 4 Variation curve (Δ) of A and F_d values versus Q and φ_{sat} values

Based on the results of the calculation, diagrams were constructed for a preliminary assessment of the dependence of the decrease in the area of the base of the conditional foundation and the bearing capacity of bored piles with a length of 8.0 m and a diameter of 0.6 m in subsidence soils on seismic activity and the angle of internal friction of the soaked soil.

The main reason for the decrease in the bearing capacity of piles is the process of liquefaction of sandy-argillaceous soil with high humidity during an earthquake, which is shown in Fig. 3. The quantitative assessment of the negative impact of soil liquefaction on the calculated bearing capacity of a pile foundation under seismic impacts is not fully understood.

According to the results of the calculation and their analysis, it was established that the values of the numerical values of the variability (Δ) of the area (A) and the bearing capacity (F_d) depending on the seismic intensity (Q) and the angle of internal friction (φ_{sat}) are equal to.

The boundary condition of the bearing capacity determined by this calculation method is written:

$$F_{d;6} > F_{d;7}^{sat} > F_{d;8}^{sat} > F_{d;9}^{sat}; \tag{4}$$

where–$F_{d;6}$; $F_{d;7}^{sat}$; $F_{d;8}^{sat}$; $F_{d;9}^{sat}$ –bearing capacity pile according to 6 –9 points.

As shown in Fig. 1, the numerical value of the area of the base of conditional pile foundations corresponds to the $A_6 > A_7 > A_8 > A_9$, then the following boundary conditions for calculating the settlement of the pile foundation should be provided:

$$S_u < S_6 < S_7^{sat} < S_8^{sat} < S_9^{sat}, \tag{5}$$

where $S_6 - S_9$–pile foundation settlement, corresponding to 6–9 points, S_u–maximum allowable settlement.

The pile foundation is designed according to the conditions for fulfilling the criteria of these mathematical inequalities of the boundary conditions for calculating the bearing capacity and settlement. An analysis of the results shows that the fulfillment of the inequality criteria makes it possible to ensure the operational reliability of buildings and structures.

6 Conclusion

1. According to the results of calculation and analysis, it is established that there are many causes of the destruction of buildings and structures under the action of 7 and greater seismicity, but among them the most significant reasons are the liquefaction of the soaked soil of the pile foundation during an earthquake. In order to prevent this kind of risk, it is necessary to avoid fulfilling the inequality criterion (4) and (5).

2. Comparative analysis shows that under the condition of 6 point seismic, the bearing capacity of the pile foundation, without taking into account the influence of base soaking and earthquake, is 1.14 times greater than the bearing capacity determined taking into account soaking and 7point earthquake, and also at 8 and 9 points respectively 1.64 and 2.59 times more.
3. The main reason for the decrease in the bearing capacity of piles is the process of liquefaction of sandy-argillaceous soil with high humidity during an earthquake.
4. The use of the proposed diagrams is correct provided that the geometric characteristics of the pile and the calculated corresponding soil parameters of the foundation, taking into account the regional features of this territory of Mongolia.
5. The risk from an earthquake depends on many factors, including the possibility of a decrease in the bearing capacity with 7, 8 and 9 seismic points, from which great risks can be created. Unfortunately, in recent years, some strong earthquakes have occurred in different countries of the world and there have been huge risks, on the basis of the latter, it is necessary to draw the appropriate conclusions and make decisions on the obligatory consideration of these circumstances in the construction project.

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