The results of complex tests of piles during the installation of piled-raft foundations of the grain terminal in difficult soil conditions near the sea coast

O V Novsky¹, M V Marchenko¹, I I Mosicheva* and V O Novsky¹

¹Odessa State Academy of Civil Engineering and Architecture, Odessa, 4, Didrihsona str., Odessa, Ukraine

*E-mail: imosicheva@gmail.com

Abstract. The engineering and geological conditions of the construction site for the designed terminal for processing and transshipment of grain products and its brief structural characteristics were presented; during arranging the zero cycle of the structure for the operative assessment of the accepted parameters of piles and confirmation of their calculated load, a series of dynamic and static tests of prismatic piles were carried out; requirements, normative methods, technology and devices for testing piles were given; calculations and analysis of their results and preliminary assessment of the accepted parameters of the piles were performed; the possibility of operational forecasting and adjustment of the calculated load and parameters of the piles accepted in the project in difficult geological conditions near the edge of the sea coast was shown.

1. Introduction

Due to the growing volume of imports of grain products, there is a need to build in limited areas of seaports, or near them, appropriate complexes of loading and unloading terminals for storage, processing and transshipment of such goods. As a rule, engineering-geological coasts and hydrogeological conditions of the sites allocated for these purposes have a number of negative features, including seismic.

2. Engineering and geological construction of the base

The following structure of engineering-geological layers was recorded at the construction site for the warehouse №1 of the terminal for reception, storage and shipment of grain cargoes and products of their processing in the city of Chernomorsk as a result of surveys and sampling during drilling of eight wells (Figure 1):

layer 1 – bulk layer, represented by sand, clay, greenish-gray and brown loams of hard and soft plastic consistency, with the inclusion of some construction waste;
layer 2 – gray sand, medium density;
layer 3 – greenish-gray loam, silted, plastic consistency;
layer 4 – light loam, brownish-gray, with the inclusion of sludge fluid-plastic consistency;
layer 5 – heavy loam, greenish-gray, with the inclusion of limestone land waste, from semi-hard to stiff consistency;
layer 6 – greenish-gray clay, from semi-solid to solid consistency;
layer 7 – greenish-gray clay of hard or semi-hard consistency with the inclusion of limestone land waste.

In the general assessment of engineering and geological conditions of the selected site, it should be noted that it is located near the sea coast, so soil formation has very significant variability both in depth and in plan, and construction in such conditions can generally be classified as "extremely unsuitable". In addition, the construction site has seismic category of more than seven points on the Richter scale.
3. Design solution of the building foundations

The production and storage facilities are designed as double structures on pile-raft foundations by the project organization "Elevator Technologies of the Future". The total number of piles for the warehouse №1 – 794, of which: piles brands C170.35 – 180 pcs., C180.35 – 12 pcs., C190.35 – 404 pcs. and C200.35 – 198 pcs. (designation: C – prismatic pile; 170/180/190/200 – pile length, dm; 35 – pile cross-sectional size, cm) Piles are accepted as components, the lower part is 12 m long, the upper parts are of variable length.

The piles were immersed with a tubular diesel hammer, the height of the hammer lift was 1.70 m, the total weight of the hammer was 100 kN, the impact part was 50 kN, the rated impact energy was 128 kJ, and the hammer head was made of wood. Connection of piles during process of immersion was made by a welded butt seam on perimeter of final metal bonds with strengthening by figured overlays. The distance between the axes of the extreme piles on the letter axes is 82.00 m, on the digital axes – 34.00 m. The main distance between the axes of the piles located in the pile field on the square grid is 1.70 m.

The value of the estimated allowable load as per project was assumed to be equal to 950 kN. The bearing layer for piles is layer 7 – greenish-gray clay. Engineering-geological section with height reference of piles is shown in Figure 2. Due to special engineering-geological conditions, for prompt adjustment of pile parameters, the designer issued a task to perform dynamic tests of operational piles in the process of pile field formation works.

4. Methods and results of dynamic tests of soils by piles

Dynamic tests of soils by prismatic piles were performed in accordance with the requirements of regulatory documents [1, 2]. According to the technical task, ten piles were tested, from them – six C190.35 and four C200.35. The "recovery" of the piles after the dive was at least fifteen days. The number of blows at the first drive of each pile is accepted equal to three, at the second – five. The value of "failure" was determined by the ratio of the total amount of immersion (subsidence) of the pile to the number of blows. Detailed results of dynamic tests indicating the numbers of operation piles in the pile field, test dates, time of "recovery", number of blows, the value of the total immersion...
of the pile for the cycle of blow and the estimated "failure" for piles C190.35 and C200.35 are shown in Table 1.

Figure 2. Vertical positioning of piles on the engineering-geological section.

The normative algorithm for determining the maximum design load on the pile based on the results of dynamic tests involves the following step-by-step actions:

a) in accordance with the requirements, if the actual "failure" in dynamic tests was \( s_a > 2 \text{ mm} \) (see Tab. 1, for piles \# 46, 180 i 508), the value of the boundary resistance was determined by the formula:

\[
F_s = \frac{\eta A M}{2} \left[ \frac{1}{\eta AS} \sqrt{1 + \frac{4E_d}{m_1 + \varepsilon^2(m_2 + m_3)}} - 1 \right],
\]

where \( \eta \) – tabulated coefficient depending on the pile material, kN/m²;
\( A \) – area limited by the outer contour of a continuous or hollow cross section of the pile trunk, m²;
\( M \) – coefficient taken when blowing the pile with an impact hammer;
\( E_d = G(H - h) \) – the estimated impact energy of the hammer, kJ, where:
\( G \) – weight of the impact part of the hammer, kN;
\( H \) – the height of the fall of the hammer, m;
\( h \) – the height of the first bounce of the impact part for the tubular diesel hammer, m;
\( \varepsilon \) – impact recovery factor when driving reinforced concrete piles with impact hammers using a wooden hammer head;
\( m_1 \) – hammer weight, kN;
\( m_2 \) – weight of head and headgear, kN;
\( m_3 \) – weight of drive head, kN.
Table 1. Results of pile dynamic load test.

| Pile №             | Pile immersion date | Recovery time, days | Number of blows | Total subsidence per cycle, mm | The average failure of one blow, mm |
|-------------------|--------------------|---------------------|-----------------|-------------------------------|----------------------------------|
| №67               | 27.08.18           | 7                   | 3               | 5,0                           | 1,7                              |
| №84               | 27.08.18           | 8                   | 3               | 3,0                           | 1,0                              |
| №46               | 05.09.18           | 15                  | 5               | 6,0                           | 2,0                              |
| №255              | 05.09.18           | 15                  | 3               | 3,0                           | 1,0                              |
| №326              | 05.09.18           | 15                  | 5               | 5,0                           | 1,0                              |
| №389              | 05.09.18           | 15                  | 5               | 7,0                           | 1,4                              |

Failure to drive piles 20 m long

| Pile №             | Pile immersion date | Recovery time, days | Number of blows | Total subsidence per cycle, mm | The average failure of one blow, mm |
|-------------------|--------------------|---------------------|-----------------|-------------------------------|----------------------------------|
| №180              | 27.08.18           | 7                   | 3               | 6,0                           | 2,0                              |
| №222              | 27.08.18           | 8                   | 5               | 12,0                          | 2,4                              |
| №492              | 05.09.18           | 15                  | 3               | 6,0                           | 2,0                              |
| №508              | 05.09.18           | 15                  | 5               | 12,0                          | 2,4                              |

6) bearing capacity of piles according to the results of dynamic tests was determined by the formula:

\[ F_d = \frac{\gamma_c F_u}{\gamma_s} \],

where \( \gamma_c \) – coefficient of operational conditions;

\( \gamma_s \) – coefficient of soil reliability;

\( F_u \) – the value of the boundary resistance of the pile according to the test results.

c) piles allowable design load was determined by the formula:

\[ N = \frac{F_d}{\gamma_k} \],

\( \gamma_k \) – coefficient of reliability, which depends on the method or technique of determining the bearing capacity of the pile.

d) the maximum design load taking into account seismic influences for the city of Odessa, adjusted according to the formula:

\[ N_{eq} = N \cdot \gamma_{eq} \].
where $\gamma_{eq}$ – seismic coefficient.

Thus, taking into account the calculations of the relevant initial values, parameters and accepted coefficients, performed at different stages, the final maximum design load according to the results of dynamic tests was 980 kN, which fully confirmed the design decisions of the choice of bearing layer, prismatic piles size (length and cross section), and also substantiated the accepted value of the piles maximum design load.

5. Methods and results of static tests of soils by piles

Tests of soils by prismatic piles were performed in full compliance with the requirements of regulatory documents [1, 3 and 4]. The "recovery" of the piles after the dive was at least fifteen days. The following equipment, devices and limit values were used during the benchmark static tests of operation piles:

a) axial compressive static load on the piles was transmitted by two jacks equipped with a manometer, using an autonomous manual pumping station;

b) the buffer for the jacks were two metal beams, located crosswise, the ends of which were attached to the reinforcement of the anchor piles (Figure 3);

c) movement (subsidence) of pile heads was measured by two deflection meter of the model with a division value of 0.01 mm;

d) the first criterion was the maximum load on the pile, accepted according to the requirements of the technical task, 1500 - 1600 kN, the second - the maximum subsidence equal to 40 mm.

The method and technology of piles static tests contained the following sequential actions and criterias:

a) the load on the pile was transmitted in stages – the initial stages were 1/5, and the subsequent stages were taken equal to 1/10 of the specified in the test program;

b) readings from the devices were taken: zero – before loading the pile, the first – immediately after the application of the degree of load, the next four – every 30 minutes after, and then every hour of observations until conditional stabilization (deformation damping), which is normalized;

c) the following recommended requirements were observed: discrepancies in the readings of the devices should not exceed 50% – for subsidence less than 1 mm, 30% – for subsidence from 1 to 5 mm and 20% – for subsidence over 5 mm;

![Figure 3](image-url). Photo of soil test by pile.

d) conventional stabilization for each load level was taken as 0.01 mm in the last 60 minutes of observation;
e) in the process of piles test, a working log was kept, and based on the results of fixing the corresponding values, graphs of subsidence dependence on each load stage in time \( S = f(P, t) \) and the resulting pile subsidence by load \( S = f(P) \) were built.

On piles №№ 45, 66 and 85 the ultimate load was brought to the value of 1500 kN, while their stabilized subsidence was 18.87 mm, 17.33 mm and 9.23 mm. On piles №№ 254, 325 and 390, the ultimate load was increased to 1650 kN, and their stabilized subsidence was, respectively, 15.85 mm, 16.26 mm and 12.38 mm. The test results are shown in table 2.

Table 2. The main results of soil static compression load tests by piles.

| №   | Sedimentations of piles (mm) at values of load levels (kN) |
|-----|----------------------------------------------------------|
|     | 300 | 600 | 750 | 900 | 1050 | 1200 | 1350 | 1500 | 1650 |
| № 45 | 0.96 | 2.16 | 3.25 | 4.83 | 6.75 | 9.62 | 13.18 | 18.87 | –   |
| № 66 | 0.82 | 1.80 | 2.95 | 4.50 | 6.26 | 8.45 | 11.94 | 17.33 | –   |
| № 85 | 0.55 | 1.57 | 2.18 | 3.00 | 4.23 | 5.88 | 7.56 | 9.23 | –   |
| № 254| 0.53 | 1.35 | –   | 2.40 | 3.22 | 4.65 | 6.40 | 8.70 | 15.85|
| № 325| 0.85 | 1.68 | –   | 3.17 | 4.15 | 5.51 | 7.57 | 10.35| 16.26|
| № 390| 0.48 | 1.10 | –   | 2.22 | 3.16 | 4.25 | 5.75 | 7.73 | 12.38|

The bearing capacity of prismatic piles according to the results of their tests by static compressive load was determined by the formula [4]:

\[
F_d = \frac{\gamma_c F_{u,n}}{\gamma_g},
\]  

(5)

where \( \gamma_c \) – coefficient of operational conditions; 
\( \gamma_g \) – coefficient of soil reliability; 
\( F_{u,n} \) – the lowest value of the ultimate resistance according to the test results.

Permissible design load on the pile was determined by the formula:

\[
N = \frac{F_d}{\gamma_k},
\]  

(6)

where \( \gamma_k \) – coefficient of reliability.

The maximum design load on the pile, taking into account the seismic effects was determined by the formula:

\[
N_{eq} = N \cdot \gamma_{eq},
\]  

(7)

where \( \gamma_{eq} \) – seismic coefficient.

Thus, based on the results of static tests, taking into account regulatory requirements and calculations according to the above calculation algorithm, as well as taking into account the relevant coefficients, the maximum allowable load on the prismatic piles of the production and storage terminal for receiving, storing and transshipment grain products is 1060 kN, exceeding the design, equal to 950kN.

6. Conclusions

1. Dynamic tests of piles in difficult engineering-geological conditions are an auxiliary element of operative adjustment of the accepted design decisions in the course of production works on the arrangement of pile-raft foundations in especially difficult engineering-geological conditions.
2. At the same time, it should be noted that the necessary reliable justification of the reliability of the design decision is testing of piles by static loads.

3. Static testing of piles in particularly complex engineering and geological conditions is a mandatory regulatory element that confirms the validity of the design decisions in the construction of the zero cycle of the production and storage terminal.

4. To correlate the results of full-scale tests of piles and the real interaction of the system "base-foundation-structure", which is expressed by subsidence, there is such a stage as scientific and technical support of the construction process, including geodetic monitoring.

5. The replenished base of results of static tests in similar difficult engineering-geological conditions should serve as a basis of adjustment of the accepted standard settlement coefficients, and also effective optimization of design decisions of pile foundations.

References
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