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Development of calculation and practice of implementation for berth wall under seismic load

O. P. Minaev
Peter the Great St. Petersburg Polytechnic University, Saint-Petersburg, Russia, minaev.op@bk.ru

A. Zh. Zhussupbekov
Eurasian National University. Astana, Republic of Kazakhstan

A. S. Zhakulin
Karaganda Technical University, Karaganda, Republic of Kazakhstan

ABSTRACT: A retaining wall is a basic enclosing element of hydraulic structures (Figure 1). The author suggests a classical theory for calculating the gravity retaining wall of the berth based on a principle preventing the process of liquefaction of structurally unstable sandy soils under seismic load. The dynamic stability of the soil structure during the liquefaction process is estimated using a coefficient of cyclic loading, which links the dynamic stresses under seismic action and static stresses in the soils of the base. A higher dynamic stability of the soil structure during the liquefaction process can be effectively achieved by increasing the density of the soil composition. In addition, the author suggests considering the decreasing angle of internal friction of the soil against the rear surface of the retaining wall during seismic action, depending on the earthquake intensity. The paper presents the calculations of gravity retaining walls for seismic load on the soils of the natural foundation base and pile foundation. The calculations were made for various types of retaining walls, a reinforced concrete corner wall with a front console and a massive reinforced concrete wall. The calculations consider a wide range of dimensions of retaining walls and characteristics of backfill soils comprising sandy soils on weak clay soils of the base. In order to achieve the required soil density, which excludes the process of liquefaction of sandy soil structure, the author proposes his own effective methods of dynamic consolidation of sandy soils with shock, explosive and vibration effects.

KEYWORDS: berth, wall, liquefaction, dynamic, consolidation.

1 INTRODUCTION

The gravity retaining wall (Figure 2) serves as the primary structure for enclosing berthing structures in seaand river ports, cargo and passenger terminals, city embankments, and elements of dams.

The classical theory for calculating the gravitational retaining wall of a berth is based on the principle of preventing the liquefaction of structurally unstable sandy soils under seismic load (Minaev 2019a, 2019b, Minaev O.P., Zhussupbekov A.Zh. 2025). This phenomenon, when it occurs in water-saturated soils, can result in a catastrophic loss of the wall's stability and bearing capacity (Florin & Ivanov 1961, Ivanov 1966, 1980, Seed. & Idriss 1982, Ishihara 1996, Idriss & Boulanger 2008, Towhata 2014, Kokusho 2020).

Figure 1. Port "Marine Facade" of the Big Port of St. Petersburg

Figure 2. Sea breakwater wall of shore protection in Yalta

Additionally, the author suggests taking into account the reduction in the angle of internal friction of the soil against the wall, based on the intensity level of earthquakes (Minaev 2023).

Traditionally, calculations assume the angle of friction of the soil against the retaining wall is equal to the angle of internal friction of the backfill soil or half of it.

However, considering the wave-like nature of dynamic impacts on the retaining wall, such an assumption is unlikely to hold when calculating seismic loads.

Furthermore, there was a misconception that the decrease in the angle of internal friction of the soil under seismic load solely caused the decrease in shear resistance. Professor Ivanova P.L. argues that the mistake lies in the ignorance of the change in the stress σ during the period of dynamic wave load action.

When subjected to vibrations and seismic impacts, the shear stability of structures should be checked by considering the dynamic component of stresses while maintaining a constant value for the internal friction angle of the soil based on static tests (see Fig. 3).

Designations in the figure: (τ_{stat} - $\Delta\tau_{\text{dyn}}$) is the least resistance to soil shear against the rear surface of the wall under dynamic (seismic) action, kN/m^2; σ_{stat} is normal stresses of soil on the retaining wall under operational (static) load, kN/m^2; $^+_-\Delta\sigma_{\text{dyn}}$ is the change in normal stresses of soil under dynamic (seismic) action kN/m^2; φ is the angle of internal friction of backfill soil, degree; *T* is the time of soil oscillations under seismic impact, c.

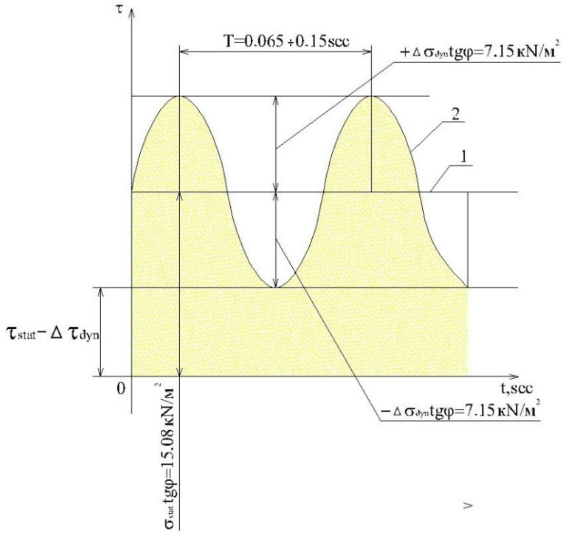

Figure 3. Graph of dynamic wave impact on the retaining wall at seismic intensity of 7 points: 1 – resistance to soil shear against the retaining wall under static load; 2 - change in resistance to soil shear under soil oscillations under seismic load

The paper presents calculations for gravitational retaining walls under seismic load on natural foundation soils and pile foundations. The calculations were performed for reinforced concrete retaining walls.

To prevent the liquefaction of sandy soil structures, the author proposes the use of effective methods of dynamic consolidation, employing shock, explosive, and vibration effects (Minaev 2011, 2014).

2 THEORETICAL DEPENDENCIES

The coefficient of active lateral pressure λ_α^s given angle ω of soil friction against the retaining wall under seismic impact is determined according to the dependence

$$\lambda_a^s = \frac{cos^2(\varphi - \varepsilon)}{\left(1+\sqrt{z}\right)^2 \cos\varepsilon} \tag{1}$$

where

$$z = \frac{\sin(\varphi - \varepsilon)\sin(\varphi + \omega)}{\cos(\omega + \varepsilon)} \tag{2}$$

In order to calculate the angle ω, which represents the friction between the soil and the retaining wall during seismic activity, a specific formula is applied. The formula, denoted as equation (3), is as follows:

$$\omega = arctg\left(2 - \frac{E_a^S}{E_a}\right)tg\varphi, \tag{3}$$

Within this equation, E_a refers to the force of lateral soil pressure exerted on the retaining wall under static load, measured in kilonewtons (kN). On the other hand, E_a^s represents the force of lateral soil pressure on the retaining wall during seismic loads, while φ represents the internal friction angle of the backfill soil.

If the expression within the parentheses yields a negative value, the angle ω is assumed to be 0. This scenario implies that, under the influence of seismic forces, the soil could potentially slide along the rear surface of the retaining wall.

According to the existing norms for calculating a retaining wall for seismic load, the most hazardous is the horizontal direction of the seismic pressure of soil. In this case

$$\gamma^s = \frac{\gamma_i}{\cos\varepsilon} \tag{4}$$

where $\varepsilon = arctgAK_1$ is the angle of deviation from the vertical of the specific gravity equilibrium γ_i of soil and seismic force $y_i^s AK_1$, A is the coefficient whose values should be taken as equal to 0.1; 0.2; 0.4, respectively, for the calculated seismic intensity of 7, 8 and 9 points, K_1 is the coefficient considering the admissible damage to buildings and structures, taken for hydraulic structures as equal to 0.25.

In the case the lateral active pressure of water-saturated soil on the retaining wall under seismic effects is determined, the weight of submerged soil ysb should be introduced into the formulas, just as in case of operational load, while seismic force ysaturAK1 should be determined according to the density of saturated soil ysatur. In this case, the deviation angle of the resultant is determined by the following formula

$$\varepsilon_{satur} = arctg\frac{\gamma_{satur}}{\gamma_{sb}}AK_1 \tag{5}$$

The value of the force E_a^s of the active lateral pressure on the retaining wall under seismic load is determined as the area of the active lateral pressure diagram e_a^s , and the height of application from the soil foundation is proportional to the areas of the diagram e_a^s in separate sections along the height of the retaining wall.

In order to determine the conditions under which water-saturated soils of the foundation become dangerously diluted under dynamic influence, Professor Seed (Seed. & Idriss, 1982) proposed a coefficient $\Delta_к$ of cyclic loading, relating the shifting dynamic stresses τ_{dyn} from external loads to the static stresses σ_{stat} in the foundation soil skeleton. This coefficient is defined as

$$\Delta_k = \frac{\tau_{\text{dyn}}}{\sigma_{\text{start}}} \leq 0.6\ldots0.65 \tag{6}$$

When checking the stability of the foundation soil directly under the sole of the retaining wall, expression (9) is modified to the following formula:

$$\Delta_{k}^{sol} = \frac{\tau_{\text{dyn}}}{\sigma_{\text{start}}} = \frac{E_a^S}{N_{\text{экс}}}, \tag{7}$$

where E_a^s represents the force of lateral active impact on the retaining wall under seismic action, and N_{expl} is the vertical force from the combined weight of the retaining wall and backfill soil. This includes accounting for the weight of water for sections located below the water level in the water area, measured in kilonewtons.

Similarly, the stability of the sand filling is assessed by applying the ratio:

$$\Delta_{К}^{fil} = \frac{\tau_{\text{dyn}}}{\sigma_{\text{start}}} = \frac{e_a^S}{\sigma(\gamma_{gr})}, \tag{8}$$

where e_a^s is the ordinate of the lateral pressure of soil and water per unit volume of soil, and $\sigma(\gamma_{gr}) = (q + \sum \gamma_i y_i)$ represents the vertical stresses in the soil skeleton at a given depth of the filling soil. The calculation also takes into account the effects of the payload q on the soil surface.

3 INITIAL PARAMETERS AND LOADS

The study considered retaining walls with heights ranging from 6.6 to 9.7 meters. The water depth h_b at the embankment varied from 4.8 to 7.5 meters, and the elevation h_0 of the wall above the water level ranged from 1.3 to 2.2 meters. Backfill soils consisted of large and medium-sized sands with specific gravities of 17.2 to 20.5 kN/m^3 and moisture levels w from 6% to 18%. The foundation of the retaining walls comprised water-saturated fine sands, powdery sands, or clay soils (sandy loam or loam) with specific gravities between 18.8 to 20.7 kN/m3. The sandy soils had moisture levels ranging from 21% to 28%, while the clay soils had liquidity boundaries at W_L between 0.23 to 0.35 and plasticity boundaries at W_p between 0.16 to 0.20.

The calculated angle of internal friction φ of medium and coarse sandy soils of the backfill was from 32^0 to 38^0 and sandy soils (fine and dusty sands) of the base 26^0-28^0 at adhesion from 0 to 1.33 kPa, and clay soils of the base varied from 14^0 to 23^0 at adhesion from 4.0 to 24.9 kPa. The modulus of elasticity E of sandy backfill soils ranged from 30 to 50 MPa, and sandy and clay base soils ranged from 9.2 to 24.8 MPa.

The value of the payload q on the base surface (on the cordon) varied from 14 to 31 kPa depending on the calculation variant.

The calculations were carried out at seismicity of the construction area from 7 to 9 points.

4 MAIN CALCULATION RESULTS

Checking the stability of the retaining wall for sliding in flat shear in the plane of the footing under the action of seismic loading showed that the values of the stability factor K_f in flat shear at seismicity of the construction area of 7 points and sufficiently strong base soils is from 1.18 to 1.50.

When the wall is constructed on weak foundation soils in areas with seismicity of 8, especially 9 points, the values of the stability factor K_f are reduced.

As a result of the calculations of the retaining wall for deep shear, an even greater reduction of the stability factor K_d was revealed.

At the same time, the construction of a sand cushion over the entire width of the retaining wall with a layer thickness of 3.71 and 5. 21 m, allowed increasing the stability factor up to 1.30 and 1.18, respectively, for the retaining wall with the height of 7.1 and 9.5 m and seismicity of the construction area of 8 and 9 points, what depends on both the height of the retaining wall and seismicity points. Characteristic plots of the load-bearing capacity of the foundation under the foot of the retaining wall are presented in Figure 15.

The evaluation of the possibility of liquefaction of the sand cushion soils has shown that the values of the coefficient of cyclic loading vary from 0.26 to 0.46.

In all cases, the stability of the structure of the sand cushion soils to the liquefaction process without loss of the bearing capacity of the foundation is ensured.

Analogous assessment of the possibility of liquefaction of the sand fill soils showed that the values of the coefficient of cyclic loading vary from 0.42 to 0.68. In most cases, the stability of the structure of the sand fill soil to the liquefaction process is ensured.

The main results of the calculation of the retaining wall on a pile foundation showed that the number of piles was from 29 to 92 pieces per 10 linear meters of retaining wall.

The pile foundation at the base of the retaining wall allowed significantly increasing the values of the K_{gl}^{sv} coefficient of stability reserve on dee shear.

However, liquefaction of the backfill can lead to a complete loss of bearing capacity and a significant reduction in the K_{gl}^{sv} coefficient of stability reserve for deep shear of the pile foundation.

If soil liquefaction is possible, additional compaction of the sand cushion and backfill is necessary to increase the angle of internal friction of the soil by 2-4° (up to 34-36°).

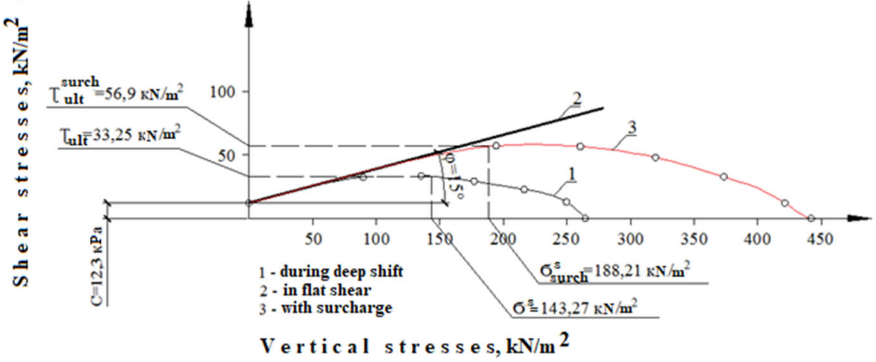

Figure 4 Graphs of the bearing capacity of the reinforced concrete corner retaining wall deep shear

According to the results of comparative calculations, it was found that the calculation of the bearing capacity and stability of the retaining wall for a seismic load of 9 points can be carried out without taking into account the friction of the soil on the rear surface of the wall.

At the seismic load of 7 and 8 (and less) point the angle of soil friction on the rear surface of the retaining wall should be determined by dependence (3).

5 DYNAMIC SOIL CONSOLIDATION

The author has proposed fundamentally new methods and designs of compacting shells for dynamic consolidation of structurally unstable sandy soils.

The efficiency of the method of sequential explosion of charges in comparison with the one-time explosion is provedю The method allows increasing the density of foundation soils. In addition, the method of sequential explosion of charges allows significantly reducing the dynamic impact of explosions on the underlying rock (Minaev 2014, 2017).

The proposed new two-mass tamper allows to eliminate loosening of the surface soil layer and to increase the depth of compaction of the foundation by 30% (Minaev 2014, 2022).

As a result of dynamic consolidation of fine and medium sands by the developed methods a significant increase in the physical and mechanical properties of base soils has been observed: the deformation modulus E from 6...20 MPa to 24...60 MPa, the angle of internal friction φ from 26-30 to 34-38 degrees and relative density I_D from 0.1...0.3 to 0.48...0.82.

6 CONCLUSIONS

Based on the classical theory of the calculation of a gravity retaining wall of a pier, the author for the first time established the principle of preventing the process of liquefaction of structurally unstable sandy soils of the backfill and at the base of the retaining wall under seismic loading.

The author of the article also obtained for the first time a dependence of the angle of friction of the soil on the back of the retaining wall on the intensity of the seismic impact.

The author proposed fundamentally new methods and designs of compacting shells for dynamic consolidation of structurally unstable sandy soils, the implementation of which allows significantly improving physical and mechanical properties of soils.

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