Accounting of the dynamic pressure of bulk on the side surface in the world practice of designing building structures

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Abstract. This paper contains research of the seismic effects on the design of retaining walls. The present state of the technique of determining the pressure of the bulk medium on the side surface is analyzed. The basic theory of soil pressure on the retaining walls in static formulation is the Coulomb theory, according to which the pressure of the bulk medium on the lateral surface is determined by the condition of static equilibrium of a rigid wedge formed in the layer between the rear face of the structure and the sliding surface. In the works of Okabe and Mononobe, the proposed theory has evolved in the direction of dynamic influence accounting. To date, these studies are at the heart of current regulations. The issue of seismic component consideration in the calculation of retaining walls in the world design practice was analyzed. The differences between the calculated dependencies of the US, Ukraine and Eurocodes codes are given. The reasons for the analyzed differences are identified and recommendations for their correction are offered.

1 Introduction

As a rule, accounting dynamic pressure of soil on the lateral surface based on Coulomb's static theory. In [1], proposed an approach for accounting the seismic effect of soil on retaining walls, whereby two changes compared to the static approach: the angle of internal friction of the soil (φ) conditionally decreases by the seismic angle (θ) and the bulk density of the soil was conditionally increases as:

$$\varphi_d = \varphi - \theta$$

$$\gamma_d = \frac{\gamma}{\cos \theta}$$

where, $$\theta = \arctan \frac{\tau_0}{g}$$ - angle of seismicity, $$\tau_0$$ - seismic acceleration; $$g$$ – acceleration of gravity.

In the works of Okabe and Mononobe, the dependencies obtained from a consideration of the inertial and gravitational forces acting in the backfill soil were calculated. Therefore, the soil pressure diagrams from seismic effects did not differ in form from the static pressure diagrams [2, 3]. A number of modern studies are devoted to the search for methods for taking into account the dynamic impact of friable on the side surface, including the seismic effect of soil on retaining walls. An example of this can be the work of Mikola and Sitar (USA), where the results of the experimental dynamic pressure of the soil on
the lateral surface are displayed [4]. The authors obtained updated data regarding the point of application of the resultant load and the shape of the lateral pressure diagram. Soubra and Macuh (France) in [5] proposed a kinematic method for determining the active and passive lateral pressure coefficient, while the sliding surface of the backfill soil considered curvilinear, having a logarithmic outline. Ghosh and Sengupta (India) in works [6-8] offer an alternative method for determining the lateral pressure coefficient. The authors obtained analytical dependencies that allow determining the specified coefficient within the error of no more than 10% compared with the Mononobe-Okabe theory. Nimbalkar (Australia) proposed a pseudo-dynamic method for determining soil pressure on retaining walls [9]. The author postulates the nonlinear nature of the lateral pressure distribution. Wu and Finn (Canada) in [10, 11] describe a study whose results differ from the Mononobe-Okabe theory. Sugano (Japan) in [12] describes the consequences of the Kobe earthquake, the nature and causes of the destruction of pressure-receiving loose structures. Jahangir and Soleymani (Iran) in [13] give an analysis of the seismic effects of soil on sheet piling walls. In works [14-17] proposed methods of rational design of retaining walls, in particular, perceiving seismic load.

2 Accounting for seismic pressure of soil on retaining walls in regulatory documents

Despite a significant amount of advanced research of the direction under discussion, in current regulatory documents, guidelines for calculating retaining structures for dynamic effects still based, as a rule, on the Mononobe-Okabe theory [2, 3]. The main parameter in determining the pressure of the soil on the retaining wall is the coefficient of lateral pressure bulk, which is in trigonometric dependence on a number of soil characteristics and structural parameters: the angle of internal friction of the bulk, friction of the soil on the wall material, the angle of backfill, the angle taking into account the seismic effect. This approach is standard, but there are certain discrepancies in the method of determining the lateral pressure of the bulk in the regulatory documents. Below are expressions for determining the coefficient of lateral pressure of soil and the accepted notation (Table 1, Fig. 1), used in the codes of the European Union, the USA and Ukraine [18-20].

\[
K = \frac{\sin^2 \left( \psi + \phi' - \theta \right)}{\cos \theta \sin^2 \psi \sin (\psi - \theta + \delta_y) \left[ 1 + \frac{\sin (\phi' + \delta_y) \sin (\phi' - \beta - \theta) \sin (\psi + \beta)}{\sin (\psi - \theta - \delta_y) \sin (\psi + \beta)} \right]^{1/2}} \quad \text{EU (3)}
\]

Figure 1. To the determination of the seismic effect of soil on the retaining wall.
The expression (4) also occurs in the codes of Canada, India, Australia, New Zealand, and others [21]. The difference in the expressions for the lateral pressure coefficient of soil in the USA and Europe predetermined by the basic reference of the angle of slope of the back surface of the wall (Fig. 1). In the American and Ukrainian codes in the calculations, the actual value of the angle of internal friction of loose and friction of the soil on the wall surface is used. In European codes, these values are taken with a certain margin:

\[
\varphi_d = \tan^{-1}\left(\frac{\tan \varphi}{\gamma_\phi}\right)
\]

\[
\delta_d = \tan^{-1}\left(\frac{\tan \delta}{\gamma_\phi}\right)
\]

where \(\varphi_d, \delta_d\) – design values; \(\varphi, \delta\) – actual values; \(\gamma_\phi\) – safety factor.

**Table 1.** Designations in regulatory documents.

| Designations                                           | Regulatory document |
|-------------------------------------------------------|---------------------|
| The earth pressure coefficient                        | \(K_{AE}\)          | \(K\)          | \(\lambda\) |
| The angle of internal friction                        | \(\varphi_d\)       | \(\varphi\)    | \(\varphi\) |
| The angle of the backfill slope                       | \(\beta\)           | \(i\)          | \(\rho\)    |
| The angle of slope of the back surface of the wall    | \(\psi\)            | \(\beta\)      | \(\epsilon\) |
| Friction angle between the ground and the retaining wall | \(\delta_d\)       | \(\delta_a\)   | \(\delta\)  |
| The angle of deviation of the resultant weight of the soil from the vertical, considering the seismic effects | \(\theta\)          | \(\theta\)     | \(\omega\) |

The deflection angle of the resultant weight of the soil from the vertical, considering the seismic impact in American and European codes, is defined as:

\[
\tan \theta = \frac{k_h}{1 \pm k_v}
\]
where $k_h$; $k_v$ – vertical and horizontal seismic coefficients, respectively (determined by national standards).

In Ukrainian norms, this parameter is defined as:

$$\omega = \arctan (AK_1)$$  \hspace{1cm} (9)

According to [20], when calculating retaining walls and basement walls, the product $AK_1$ should be taken 0.04, 0.08 and 0.16 with a calculated seismicity, respectively, 7, 8 and 9 points.

3 Numerical analysis

To determine the quantitative discrepancy between the above dependencies, let us define arbitrary values: the volume weight of the soil $\gamma = 18 \text{ kN/m}^3$; wall height $H = 10 \text{ m}$; the angle of deviation of the resultant weight of the soil from the vertical, considering the seismic effects $\theta(\omega) = 5.93^\circ$ ($k_h = 0.1; k_v = 0.33$); safety factor for expression (3) $\gamma_0 = 1.1$; friction angle between the ground and the retaining wall $\delta_d = 0^\circ$. There is no load on the backfill surface.

The graphs (Fig. 2-4) show the dependences of the resulting lateral pressure of the soil depending on the angle of internal friction of the bulk, the angle of slope of the back surface of the wall and the angle of the backfill slope.

**Figure 2.** Resulting lateral pressure divergence chart depending on the angle of internal friction (the angle of slope of the back surface of the wall – $15^\circ$; the angle of the backfill slope – $0^\circ$).

**Figure 3.** Resulting lateral pressure divergence chart depending on the angle of slope of the back surface of the wall (the angle of internal friction – $30^\circ$; the angle of the backfill slope – $0^\circ$).
Figure 4. Resulting lateral pressure divergence chart depending on the angle of the backfill slope (the angle of internal friction – 30°; the angle of slope of the back surface of the wall – 15°).

The maximum discrepancies between the results, within the limits of the variable values under consideration, are present in Table 2. It should be noted that the discrepancy between expressions (3) and (4) is due to the adopted coefficient $\gamma = 1.1$. If, in the calculations, it is assumed that the design value of the angle of internal friction of the bulk material is equal to the calculated one, in all cases the comparisons of expression (3) and (4) represent the same result.

Table 2. Discrepancy between regulatory documents.

| Variable parameter                      | EU $(E_d)$ ~ USA $(P_{45})$ | USA $(E_d)$ ~ UA $(E_{45})$ | USA $(P_{45})$ ~ UA $(E_{45})$ |
|----------------------------------------|-----------------------------|-----------------------------|---------------------------------|
| The angle of internal friction         | 7.85                        | 10.99                       | 3.53                            |
| The angle of slope of the back surface of the wall | 4.63                        | 17.41                       | 15.57                           |
| The angle of the backfill slope        | 12.55                       | 15.53                       | 3.53                            |

4 Conclusion
From the analysis, it follows that the discrepancy between the American and European regulatory guidelines for determining the lateral pressure of the bulk in seismic effects is due only to safety factors. The difference between the normative instructions of Ukraine and the ones mentioned above is of fundamental nature and causes an error in the range of up to 17.4% on the smaller (unfavorable) side in certain circumstances. It can also be noted that the current norms of Ukraine, in this aspect, duplicate the instructions given in the norms of the Soviet Union. In further studies, analytical justification and refinement of the described discrepancies is of some interest.

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