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COMPARATIVE ANALYSIS OF ACCOUNTING DYNAMIC EARTH PRESSURE ON RETAINING STRUCTURES IN REGULATORY DOCUMENTS

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This study research investigated the seismic effects on the design of retaining walls. The basic analysis theory of retaining structures under static load is the Coulomb theory, stating that the pressure of a loose body on the lateral surface is determined from the static equilibrium condition of rigid wedge formed in the bed between backsides of the structure and slipping area, considering the wedge as rigid body. Dynamic pressure of the soil was studied in the works of Okabe and Mononobe. Currently, these studies are basic in the preparation of regulatory documents. However, there are discrepancies between the approaches of Ukraine, Europe, and the United States in this matter. Analyzed regulatory guides for the calculation of these structures for the action of dynamic loads. Assessed the discrepancies between the calculated dependencies established by USA codes, Ukraine codes, and Eurocode. This work shows the relation between the curvature of the back face of the retaining wall, and the lateral pressure diagram of the bulk material due to seismic load.

Key words: lateral pressure; supporting wall; seismic; regulations

Introduction

Historically, the first studies of the soil dynamic pressure are based on the static theory of seismic resistance, which rests on assumptions of the Coulomb theory. In the works of Okabe and Mononobe, the calculated dependencies obtained from a consideration of the inertial and gravitational forces acting in the backfill soil. Therefore, the soil pressure diagrams from seismic effects did not differ in a form from the static pressure diagrams. A number of modern studies are devoted to the search for methods for taking into account the dynamic impact of soil on the side surface, including the seismic effect of the 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. The authors obtained updated data regarding the point of application of the resultant load and the lateral pressure diagram shape. Soubra and Macuh (France) 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) 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. The author postulates the nonlinear nature of the lateral pressure distribution. Wu and Finn (Canada) describe a study whose results differ from the Mononobe-Okabe theory. Sugano (Japan) describes the consequences of the Kobe earthquake, the nature and causes of the destruction of pressure-receiving loose structures. Jahangir and Soleymani (Iran) give an analysis of the seismic effects of the soil on sheet piling walls. In addition to the above, there are many methods of rational design of retaining walls, in particular, perceiving seismic load.

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

Despite the significant amount of advanced research of the direction, in current regulatory documents, guidelines for calculating retaining structures for dynamic effects still based, as a rule, on the Mononobe-Okabe theory. 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, USA and Ukraine.

$$K = \frac{sin^2(\psi + \varphi_d^{¢} - \theta)}{cos\theta sin^2\psi sin(\psi - \theta - \delta_d)\left[1 + \sqrt{\frac{sin(\varphi_d^{¢} + \delta_d)sin(\varphi_d^{¢} - \beta - \theta)}{\sin(\psi - \theta - \delta_d)\sin(\psi + \beta)}}\right]^2}, \text{EU} \quad (1)$$

$$K_{AE} = \frac{cos^2(\varphi - \theta - \beta)}{cos\theta cos^2\beta cos(\beta + \delta_a + \theta)\left[1 + \sqrt{\frac{sin(\varphi + \delta_a)sin(\varphi - \theta - i)}{\cos(\delta_a + \beta + \theta)\cos(i - \beta)}}\right]^2}, \text{USA} \quad (2)$$

$$\lambda^* = \frac{cos^2(\varphi - \varepsilon - \omega)cos(\varepsilon + \delta)}{cos\omega cos^2\varepsilon\, cos(\varepsilon + \delta + \omega)\left[1 + \sqrt{\frac{\sin(\varphi + \delta)\sin(\varphi - \rho - \omega)}{\cos(\varepsilon + \delta + \omega)\cos(\varepsilon - \rho)}}\right]^2}, \text{Ukr} \quad (3)$$

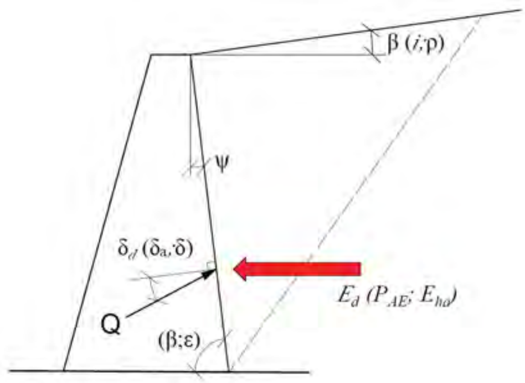

Fig. 1. To the determination of the seismic effect of soil on the retaining wall

Table 1

Designations in regulatory documents

Designations	Regulatory Document		
	EU	USA	Ukraine
The earth pressure coefficient	K_{AE}	K	λ
The angle of internal friction	$\varphi_d^{¢}$	φ	φ
The angle of the backfill slope	β	i	ρ
The angle of slope of the back surface of the wall	ψ	β	ε
Friction angle between the ground and the retaining wall	δ_d	δ_a	δ
The deviation angle of the soil resultant weight from the vertical	θ	θ	ω

The Eq. (2) also occurs in the codes of Canada, India, Australia, New Zealand, and others. The difference in the expressions for the lateral pressure coefficient of soil in the USA and Europe is predetermined by the basic reference of the wall back surface slope angle (Fig. 1). In the American and Ukrainian codes in the calculations, the actual value of the internal friction angle of loose and friction of the soil on the wall surface is used. In European codes, these values are taken with a certain margin, and are defined as:

$$\varphi_d^{¢} = tan^{-1}\left(\frac{tan\varphi¢}{\gamma_{\phi¢}}\right), \quad (4)$$

$$\delta_d = tan^{-1}\left(\frac{tan\delta}{\gamma_{\phi¢}}\right), \quad (5)$$

where $\varphi_d^{¢}$; δ_d – design values; φ; d – actual values and γ_φ – safety factor.

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

$$tan\theta = \frac{k_h}{1 \pm k_v}, \quad (6)$$

where k_h and k_v – vertical and horizontal seismic coefficients, respectively (determined by national standards).

In Ukrainian codes, this parameter is defined as:

$$\omega = arctg(AK_1), \quad (7)$$

According to Ukrainian codes, when calculating retaining walls and basement walls, the product AK1 should be taken 0.04; 0.08 and 0.16 with a calculated seismicity, respectively, 7, 8 and 9 points.

Numerical analysis

To determine the quantitative discrepancy between the above dependencies, let us define arbitrary values: the weight of the soil γ = 18 kM/м^3; wall height H = 10 m; the deviation angle of the soil resultant weight from the vertical, considering the seismic effects θ (ω) = 5.93° (k_h = 0.1; k_v = 0.33); safety factor for expression (1) γ_φ = 1.1; friction angle between the ground and the retaining wall δ_d (δ; δ_a) = 0°. There is no load on the backfill surface.

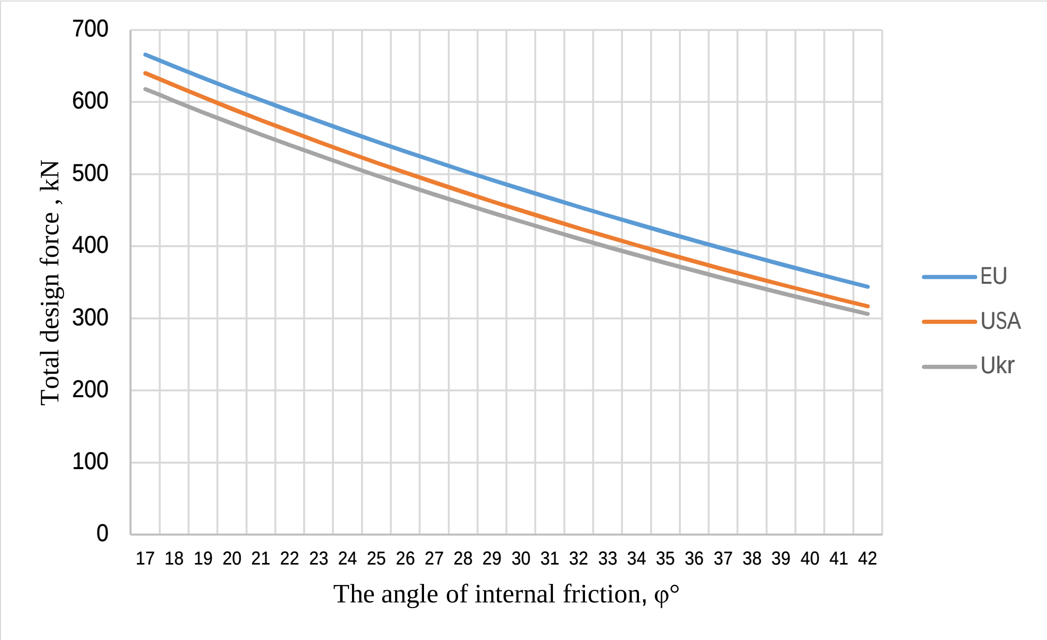

Fig. 2. Resulting lateral pressure divergence chart depending on the angle of internal friction (the angle of slope of the back surface of the wall – 15°; the angle of the backfill slope – 0°)

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 slope angle of the wall back surface and the angle of the backfill slope.

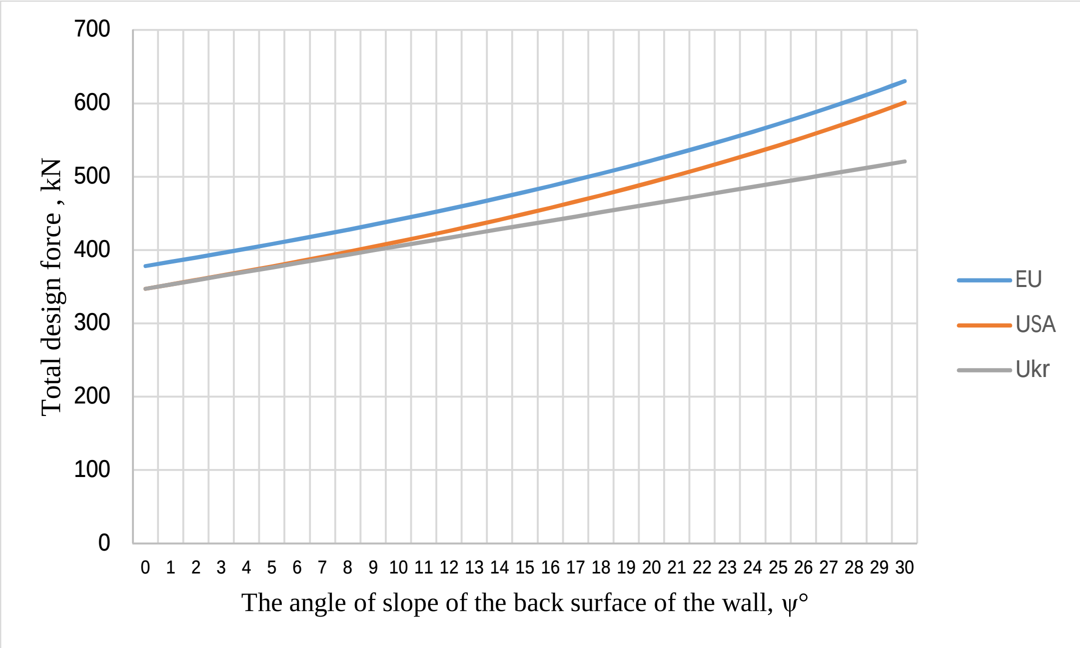

Fig. 3. Resulting lateral pressure divergence chart depending on the angle of slope of the back surface of the wall (the angle of internal friction – 30°; угол the angle of the backfill slope – 0°)

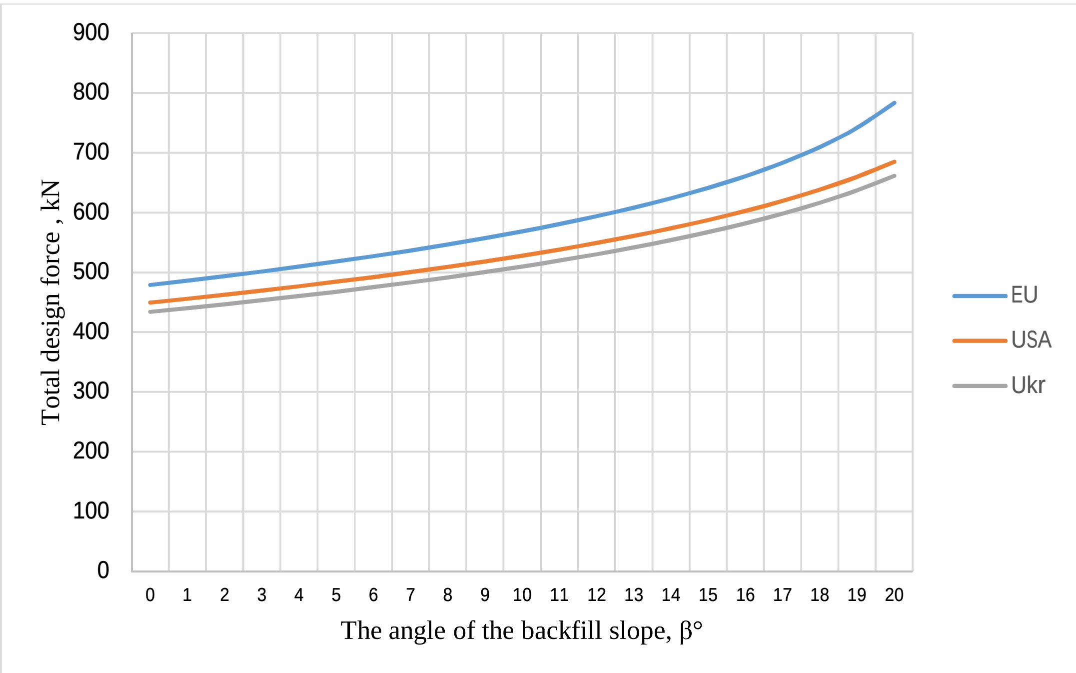

Fig. 4. Resulting lateral pressure divergence chart depending on the angle of the backfill slope (the angle of internal friction – 30°; the angle of slope of the back surface of the wall – 15°)

The maximum discrepancies between the results, within the limits of the variable values under consideration, are presented in Table 2. It should be noted that the discrepancy between Eqs. (1) and (2) is due to the adopted coefficient $\gamma_\varphi = 1.1$. 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 Eqs. (1) and (2) represent the same result.

Table 2

Discrepancy between regulatory documents

Variable parameter	Discrepancy, %		
	EU (E_d) ~ USA (P_{AE})	EU (Ed) ~ Ukr (E_{ha})	USA (P_{AE})~ Ukr (E_{ha})
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

Conclusions

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. The current norms of Ukraine, in this aspect, duplicate the instructions given in Soviet Union codes.

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ПОРІВНЯЛЬНИЙ АНАЛІЗ ВРАХУВАННЯ ДИНАМІЧНОГО ТИСКУ ҐРУНТУ НА ПІДПІРНІ СТІНИ У НОРМАТИВНИХ ДОКУМЕНТАХ

У роботі розглянуто дослідження сейсмічного впливу під час проєктування підпірних стін. Історично перші дослідження динамічного тиску ґрунту базувалися на статичній теорії сейсмостійкості, яка розроблена на припущеннях і передумовах теорії Кулона. У роботах Окабе і Мононобе розрахункові залежності отримано у результаті спільного розгляду інерційних і гравітаційних сил, що діють в ґрунті засипки, тому епюри тиску ґрунту від сейсмічних впливів за формою не відрізнялися від статичних.

Питання пошуку методів урахування динамічного тиску ґрунтів на бічну поверхню, зокрема сейсмічного тиску ґрунту на підпірні стіни, стосується низка сучасних досліджень. Однак у вказівках нормативних документів різних країн світу є деякі розбіжності, що підкреслює неоднозначність наукових поглядів на це питання. Наприклад, у нормативних документах США, Канади, Австралії, Нової Зеландії, Індії вираз рівнодіючої бічного тиску ґрунту за динамічного впливу має однаковий вигляд. У Єврокоді, державних українських нормах залежність для визначення рівнодіючої сили принципово відрізняється від стандартів вищезгаданих країн. В цьому дослідженні здійснено якісне і кількісне оцінювання зазначених розбіжностей. Детально проаналізувавши розрахункові залежності, для визначення бокового тиску ґрунту в нормативних документах США і Європи, можна дійти висновку, що, незважаючи на візуальну розбіжність в аналітичному плані, ці вирази рівнозначні. Кількісна відмінність полягає лише в різних коефіцієнтах запасу. Що ж стосується українських норм – залежності хоч і незначно, але принципово відрізняються порівняно із нормами США і Європи. Відзначено, що ця розбіжність продубльована в державних стандартах України з радянських норм, а це свідчить про те, що за останні роки це питання в Україні не переглядали. Кількісна оцінка результуючого бічного тиску ґрунту обчислена з урахуванням різних нормативних вказівок, залежно від різних факторів. Відмінність нормативних вказівок України від вищезазначених спричиняє похибку в межах до 17,4 % у меншу (несприятливу) сторону.

Ключові слова: динамічний тиск; підпірна стіна; сейсмостійкість; норми.