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Determination of settlement profiles of foundations composed of weak soils for railway and road embankments, dams, and levees made of earth materials

The article is dedicated to the issue of foundation settlements in railway, road, and other embankments, as well as earth dams and dikes, especially when constructed on weak soils with low deformation modulus. It emphasizes that in such cases, settlements can be comparable to the height of the embankment, requiring settlement profiles to be considered during design. A simple iterative algorithm developed by the authors is proposed for calculating settlement profiles and is recommended for inclusion in the draft Ukrainian State Building Code “Earth Dams. General Requirements.” An example of the algorithm’s application is provided, demonstrating its advantages over conventional graphical and tabular methods. The algorithm ensures simplicity, fast convergence, and results consistent with those obtained using the finite element method. Additionally, the study highlights the limitations of FEM when regulatory guidance on key parameters such as boundary conditions and mesh configuration is lacking. The authors conclude that their proposed algorithm can be effectively implemented in engineering practice for the design of embankments and dams on weak soils with a trapezoidal cross-section.

Keywords: earth dams, embankments, foundation settlement, long embankment, trapezoidal embankment, weak foundation soils, plane strain condition, compressed soil depth, settlement profile, material volume for embankment on weak soils

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Introduction

The determination of settlements of foundations for railway, highway, and other embankments, as well as for earth dams and levees during their design, construction, and operation is a mandatory procedure [1, 2].

If the foundation consists of soils with a low modulus of overall deformation (such as silts, peats, peaty soils, and similar types), it is necessary not only to determine the average settlement and differential settlement (as is typically done for conventional foundations), but also to determine the settlement profiles. This requirement arises because, in such cases, the settlement values can be of the same order of magnitude as the height of the embankment, dam, or levee. Therefore, when calculating the volume of earth material required for constructing such structures, these settlements must be taken into account. Accordingly, it becomes necessary to construct settlement profiles both within the embankment body and beyond its boundaries [1, 2, 3, 4, 5].

This article presents an example of the application of an algorithm we developed for the Ukrainian State Building Code (DSTU XXXX:202X "Earth Dams. General Requirements") to calculate settlement profiles of railway, highway, and other embankments, as well as earth dams and levees [6]. The theoretical background of the settlement calculation algorithm presented in [6] is described in detail in works [7] and [8].

Methods.

Theoretical investigation of geomechanical processes using analytical and numerical mathematical methods. Analysis and generalization of the results of theoretical studies.

Results.

A simple algorithm has been developed to determine the required volume of material for the construction of embankments (dams and levees) made of earth materials when founded on weak soils. The algorithm is based on a simple iterative process.

Scientific novelty.

It has been shown that a simple iterative process can be applied to determine the theoretical volume of material required for the construction of embankments (dams and levees) made of earth materials.

Practical significance.

The main practical outcome of this study is the development of a method for calculating the volume of material required to achieve the design profile of an embankment (dam or levee) built on weak soils.

Review of achievements in this field.

To determine the settlements of dams (including those constructed from earth materials), the current building codes in force in Ukraine use either the graphical-analytical method (which provides only approximate results), or a tabular method (in which settlements can be calculated only along a vertical line passing either through the center or the corner of a rectangular area loaded with uniformly distributed pressure) [1, 2, 3, 4, 5]. These data are clearly insufficient for constructing the settlement profile of the base of an embankment (dam or levee). Therefore, the algorithm proposed in [6] for calculating the settlements of embankments and earth dams or levees is considered in more detail.

The settlement of the foundation of an earth embankment (dam or levee) along a computational vertical line S_j, which passes through a point x_j (see Fig. 1), should be calculated using the formulas proposed in [6]:

$$\left.\begin{aligned} S_j &= 0,8\cdot\sum\nolimits_{(i=1)}^{n} S_i(x_j);\\ S_i(x_j) &= \frac{W(x_j,z_{i+1})-W(x_j,z_i)}{E_i}\end{aligned}\right\}, \qquad (1)$$

where: S_j − is the settlement of the embankment (dam or levee) base along the computational vertical located at a horizontal distance x_j from the left edge of the structure (i.e., the origin of coordinates; see Fig. 1); $\beta = 0,8$; $S_i(x_j)$ − is the settlement of the i-th layer of the foundation with thickness $h_i = z_{i+1} - z_i$, whose top is at depth z_i and bottom at depth z_{i+1}; $W(x,z)$ − is the vertical displacement of the foundation at point with coordinates x (horizontal) and z (vertical); $W(x_j,z_i)\, ma\, W(x_j,z_{i+1})$ − are, respectively, the displacements at the top and bottom of the i-th soil layer in the foundation with deformation modulus E_i.

The displacement of the foundation $W(x,z)$ at the calculation depth z should be determined using formulas specified in Eq. 1.

$$\left.\begin{aligned}
&W(x,z) = k_1\cdot(\xi_1+\xi_2+\xi_3+\xi_4+\xi_5+\xi_6+\xi_7+\xi_8+\xi_9+\xi_{10}+\xi_{11}+\xi_{12})\\
&k_1 = \frac{\gamma_г\cdot h}{2\pi\cdot L_1\cdot y_4};\;\; y_1 = -L_1 - b_1 + x_j;\;\; y_2 = -L_1 + x_j;\;\; y_3 = b + x_j;\;\; y_4 = b - L_1 - b_1;\\
&\xi_1 = -L_1\cdot y_1^2\cdot\ln(y_1^2+z^2);\quad \xi_2 = -y_2^2\cdot y_4\cdot\ln(y_2^2+z^2);\quad \xi_3 = L_1\cdot y_3^2\cdot\ln(y_3^2+z^2);\\
&\xi_4 = -2\cdot z\cdot L_1\cdot y_1\cdot arctg\left(\frac{y_1}{z}\right);\quad \xi_5 = -2\cdot z\cdot y_2\cdot y_4\cdot arctg\left(\frac{y_4}{z}\right);\quad \xi_6 = 2\cdot z\cdot L_1\cdot y_3\cdot arctg\left(\frac{y_3}{z}\right);\\
&\xi_7 = x_j^2\cdot y_4\cdot\ln(x_j^2+z^2);\quad \xi_8 = 2\cdot x_j\cdot z\cdot y_4\cdot arctg\left(\frac{x_j}{z}\right);\quad \xi_9 = 2\cdot L_1\cdot y_1^2\cdot\ln(-y_1);\\
&\xi_{10} = 2\cdot y_2^2\cdot y_4\cdot\ln(-y_2);\qquad \xi_{11} = 2\cdot L_1\cdot y_3^2\cdot\ln(y_3);\qquad \xi_{12} = 2\cdot x_j^2\cdot y_4\cdot\ln(x_j).
\end{aligned}\right\} \qquad (2)$$

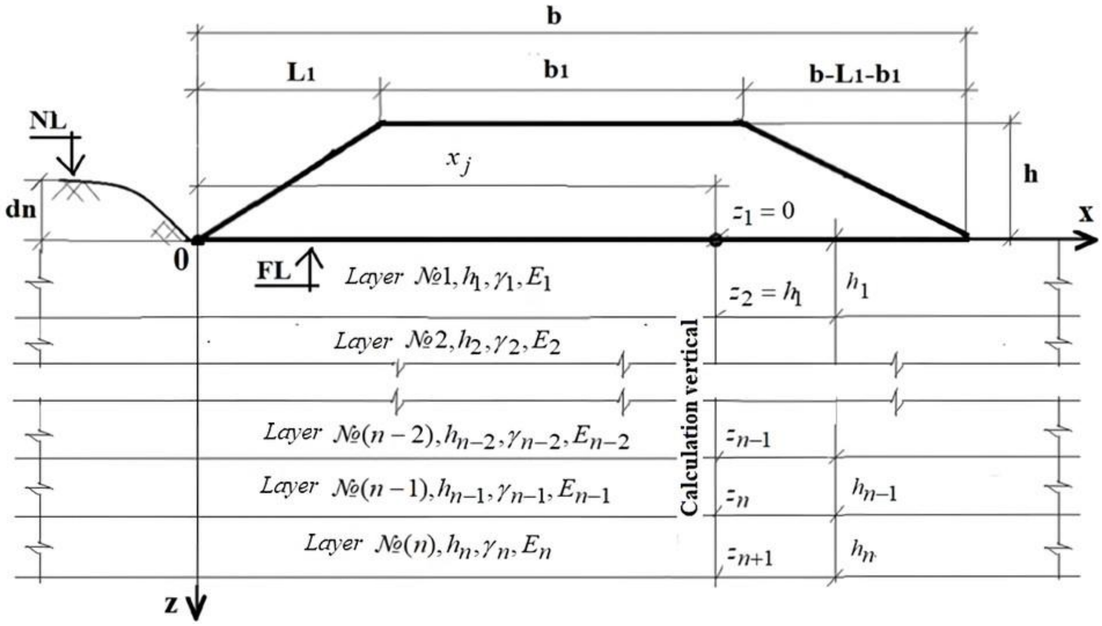

Figure 1 – Scheme for Determining the Settlements of the Foundation of an Earth Dam (Embankment or Dike): if the distance $x_j < 0$ or $x_j > b$, then the calculated vertical lies outside the base of the dam (embankment or dike); $E_{1 \ldots n}$; $\gamma_{1 \ldots n}$ – deformation moduli and densities of the 1 to n soil layers, respectively.

The additional vertical stresses at the foundation from the dam (embankment or dike) weight $\sigma_{zp}(z)$, required to determine the lower boundary of the compressible stratum along the calculated vertical at position x_j , should be determined using the following expression:

$$\sigma_{zr}(z) = \frac{2 \cdot \gamma_e \cdot h}{\pi(b - b_1)} \times \times \left[b \cdot arctan\left(\frac{b}{2z}\right) - b_1 \cdot arctan\left(\frac{b_1}{2z}\right) \right], \tag{3}$$

where: d_n, h, b, b_1 and L_1 are the geometric parameters of the dam (embankment or dike) as shown in Figure 1; γ_e is the unit weight of the dam (embankment or dike) material; if the calculated depth z=0, then in formulas (2) and (3), use z=0.0001 m.

Eqs. (1), (2) and (3) allow determining settlements of the foundation both within and beyond the base of a homogeneous dam (embankment or dike, see Figure 1).

Settlement Calculation Procedure

1. Determine the Design Location of the Calculation Vertical Line – usually specified in the design brief. The calculation vertical can be located either within or beyond the dam base.
2. Calculate the Foundation Settlement S_j at the vertical position x_j using Eqs. (1) and (2).
3. Determine the Depth of the Compressible Layer H_{st}, which satisfies the condition:

$$\sigma_{zr}(0, H_{st}) = k \cdot \sigma_{zq}(x_j, H_{st}), \tag{4}$$

where: k=0.2 for b≤5 m; k=0.5 for b>20 m; for 5<b≤20 m, use linear interpolation. $\sigma_{zp}(0, H_{st})$ – the additional vertical stress from the dam weight (use Eq. 3); $\sigma_{zq}(0, H_{st})$ – the vertical stress from soil weight, calculated as:

$$\left.\begin{aligned} \sigma_{zq}(0, H_{st}) &= \gamma' \cdot d_n + \sum\nolimits_{i=1}^{n} \gamma_i \cdot h_i; \\ H_{st} &= d_n + \sum\nolimits_{i=1}^{n} h_i \end{aligned}\right\} \tag{5}$$

where: γ' denotes the density of the soil located above the base of the dam (embankment or levee); γ_i and h_i represent, respectively, the density and thickness of the i-th soil layer; d_n – see explanation in Figure 1.

4. If the point at which the stresses from the self-weight of the soil are calculated is located below the groundwater level, then instead of γ_i, the density of the soil in a submerged state should be adopted. This density is determined according to the expression:

$$\gamma_{sb,\,i} = \frac{\gamma_{s,i} - \gamma_w}{1 + e_i} \tag{6}$$

where: $\gamma_{s,i}$ is the density of soil particles; γ_w is the density of water; e_i is the soil porosity ratio; i – denotes the number of the elementary soil layer.

Features of Settlement Calculation for Dike Foundations Composed of Weak Soils

1. When calculating settlements of foundations composed of weak soils, it is recommended to take into account the fact that the settlements may be of the same order of magnitude as the dimensions of the dike. In addition, it is necessary to consider the significant nonlinearity of the deformation and strength properties of the foundation under external loading.

2. The task of the calculation is to determine such a filling contour that, when settlements of the foundation are considered, the dike contour coincides with the design one.

3. For calculation purposes, it is recommended to adopt the standard values of the deformation properties of the foundation soil.

4. The computational domain should be defined as follows: vertically, down to the lower boundary of the compressed stratum, which should be determined either according to the requirements of the recommended Annex D of DBN V.2.1-10, or to the upper boundary of the rigid underlying soil (e.g., rock or coarse-grained deposits); horizontally −5-b, where b is the dike width.

The calculation is recommended to be performed using the method of successive approximations (iterations) in the following sequence:

5.1. First, the load on the foundation from the dike with design dimensions is determined.

5.2. Then, using formulas (1)…(5), the settlements of the foundation are calculated.

5.3. If the settlements exceed the design value, the calculated settlement values are added to the coordinates of the design contour.

5.4. The load on the foundation from the dike with the contour established according to Step 3 is determined, and settlements are recalculated in the second approximation.

5.5. The process is repeated until the filling contour, adjusted for foundation settlements, does not differ from the design contour by more than a predetermined value (this parameter should be specified in the project technical assignment).

To illustrate the application of the proposed settlement calculation algorithm, the filling contour for the dike shown in Fig. 2 was determined with consideration of soil foundation settlements. The properties of the soil layers underlying the dam are presented in Table 1. The groundwater level is located at a depth of 2 m. The unit weight of the dam body is $\gamma = 18$ kN/m³. The soil foundation consists of weak soil underlain by bedrock. All further calculations were performed using the “MAPLE-2021” software package, which is freely available.

An identical example was also considered by the authors of study [9].

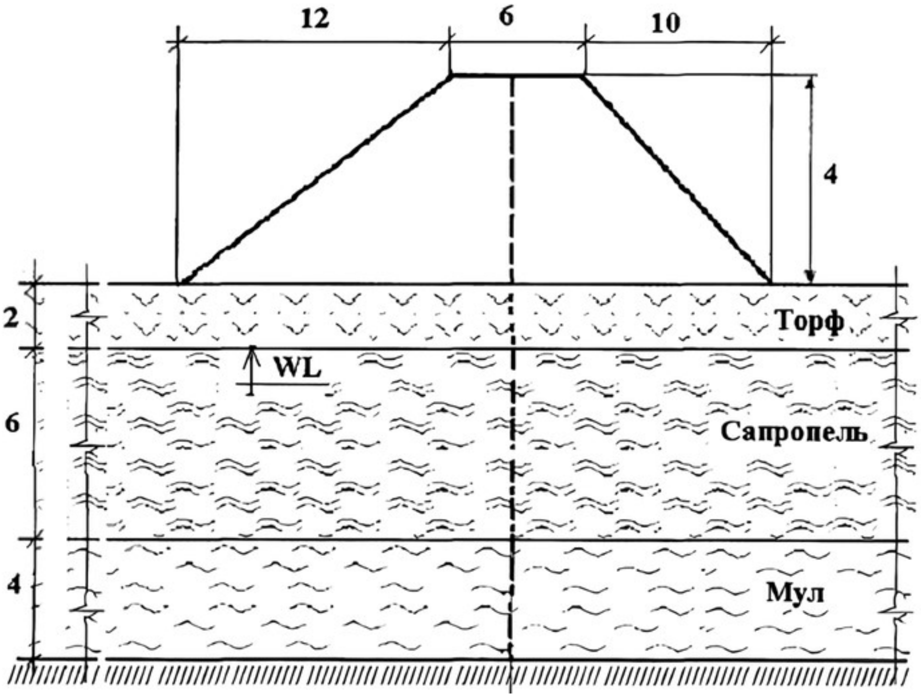

Figure 2 – Computational scheme of the dam

In the first approximation, the load on the foundation was assumed to correspond to row 1 in Fig. 3. This load results in settlements (Fig. 4, row 1) and the dam profile shown in Fig. 5 (row 1). The volume of material required for the construction of 1 linear meter of the embankment amounts: $\frac{6+28}{2}\cdot 4\cdot 1 = 60 м^3$..

In the second approximation, the load on the foundation was assumed to correspond to row 2 in Figure 3. This load results in settlements (Fig. 4, row 2) and the dam profile shown in Figure 5 (row 2). The volume of material required for the construction of 1 linear meter of the embankment amounts: $\frac{6+28}{2}\cdot 4,85\cdot 1 = 72,75 м^3$.

Table 1 – Properties of soil layers of the dam base

№	Soil name	Distance from the surface, m	Soil moisture, %	Density of soil particles, kN/m^3	Soil density, kN/m^3	Density of dry soil, kN/m^3	Porosity coefficient, p.u.	Modulus of total deformation, kPa
1	Low-moisture peat	0-2	55	16,30	8,57	13,29	0,901	330
2	Organomineral sapropel	2-6	62	15,5	7,95	12,87	0,951	500
3	Clay silt	6-10	57	2,55	16,01	25,13	0,593	3600
4	Rock	Unlimited	0-2	-	27,2	-	-	78·10^6

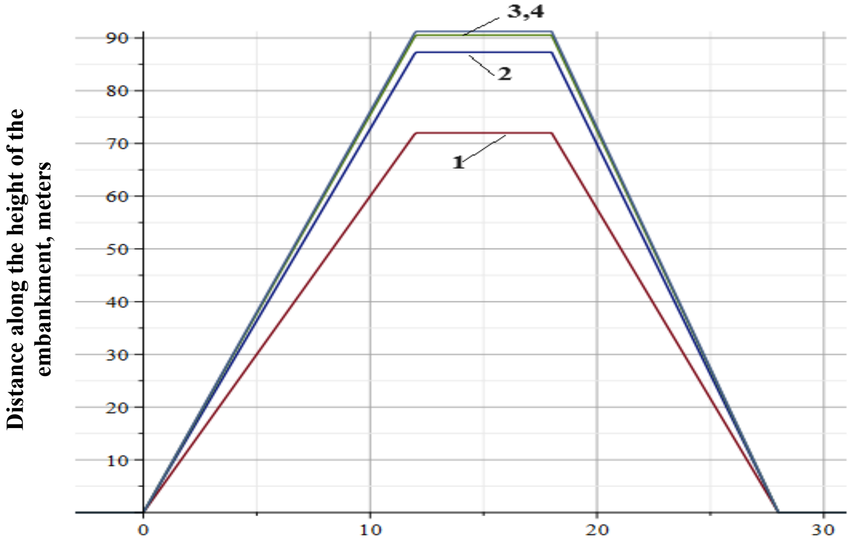

Figure 3 – Loading on the dam foundation.
Row 1 – load assumed in the first approximation; Row 2 – the same, in the second approximation;
Row 3 – the same, in the third approximation; Row 4 – the same, in the fourth approximation.
Note: rows 3 and 4 coincide.

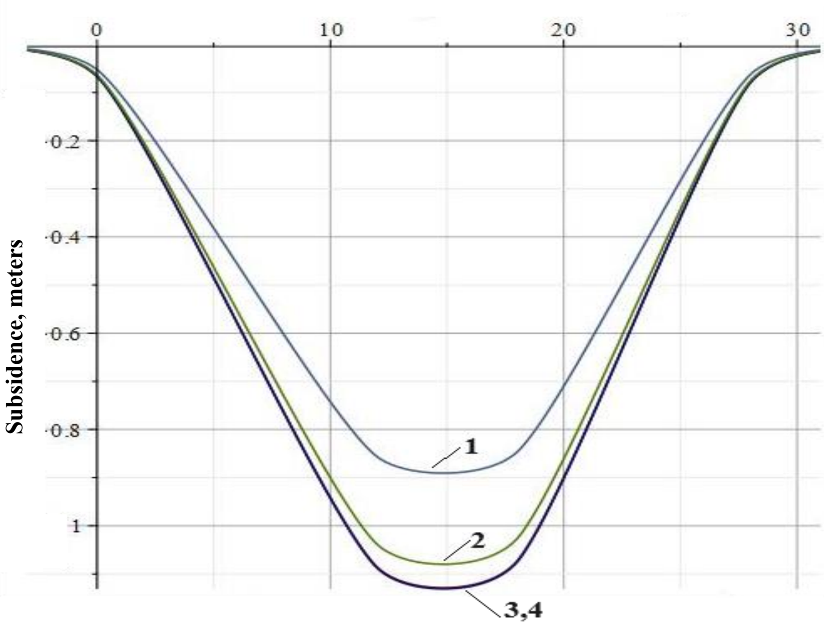

Figure 4 – Settlements of the dam foundation:
Row 1 – settlement calculated in the first approximation; Row 2 – the same, in the second approximation;
Row 3 – the same, in the third approximation; Row 4 – the same, in the fourth approximation.
Note: rows 3 and 4 coincide.

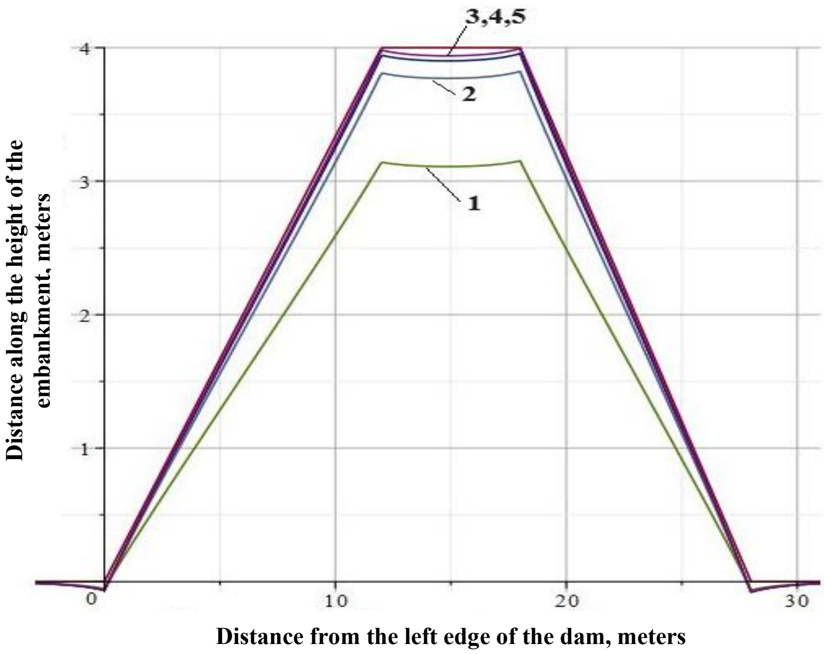

Figure 5 – Settlements of the dam foundation:
Row 1 – settlement calculated in the first approximation; Row 2 – the same, in the second approximation;
Row 3 – the same, in the third approximation; Row 4 – the same, in the fourth approximation.
Note: rows 3 and 4 coincide.

In the third approximation, the foundation loading corresponding to row 3 in Figure 3 was adopted. This loading corresponds to the settlements (Fig. 4, row 3) and the dam contour shown in Fig. 5 (row 3). The volume of material required for the construction of 1 linear meter of the dam is equal to 76.05 m³.

In the fourth approximation, the foundation loading corresponding to row 4 in Figure 3 was adopted. This loading corresponds to the settlements (Fig. 4, row 4) and the dam contour presented in Fig. 5 (row 4). The volume of material required for the construction of 1 linear meter of the dam is equal to 76.20 m³.

Thus, the volumes of material required for the construction of one linear meter of the dam, calculated in the third and fourth approximations, differ by only 0.2%. This result should be considered satisfactory and entirely acceptable for further development of the technical part of the dam construction project.

Moreover, according to the obtained calculation results, in order to ensure the design profile of the dam, it is necessary to use 76.20 m³ of soil instead of 60 m³ (the latter figure was obtained without accounting for foundation settlements). The difference between these values is 27%. This result is fully suitable for further development of the organizational-technological, economic, and cost-estimation parts of the dam construction project.

Conclusions

The research results presented in this paper allow us to draw the following conclusions:

1. Using a specific example, it has been demonstrated that the proposed algorithm for calculating the settlement profiles of railway, highway, and other embankments, as well as earth dams with a trapezoidal cross-section, is sufficiently simple and convenient to apply. Therefore, it can undoubtedly be incorporated into the Ukrainian State Standards (DSTU XXXX:202X "Earth Dams. General Requirements").
2. It has been shown that the proposed algorithm for calculating dam and embankment settlements on weak soil foundations, which is based on an iterative process, is both straightforward to use and exhibits rapid convergence.
3. The obtained results show good agreement with the data presented in [9], which were derived when solving an identical problem using the finite element method [10]. However, the data obtained by the authors of [9] compared to those in the present study have the following drawbacks:

3.1. The calculated settlement profiles, load distributions, and dam profiles appear not as continuous but as broken lines (a drawback inherently associated with the finite element method).

3.2. The current regulatory documents in force in Ukraine provide no answers to several critical questions arising when applying the finite element method to the calculation of settlements of earth dams and embankments [10]:

3.2.1. What should be the dimensions of the computational foundation domain?

3.2.2. What should be the boundary conditions for the computational foundation domain?

3.2.3. What should be the dimensions and configuration of the finite elements?

All of the above allows us to conclude that the algorithms for determining settlements of embankments and dams made of soil materials proposed in this study can be widely applied in the design of embankments and dams with trapezoidal cross-sections.

References

1.ДБН В.2.4-20:2014. (2014). *Греблі з грунтових матеріалів. Основні положення*.

2.Кирієнко, І. І., & Хімерік, Ю. А. (1987). *Гідротехнічні споруди. Проектування та розрахунок: навчальний посібник.* Київ: Вища школа.

3.ДБН В.2.1-10:2009. (2009). *Основи та фундаменти споруд. Основні положення проектування*.

*4.*ДБН В.2.1-10:2019. (2019). *Основи та фундаменти споруд. Основні положення проектування.*

5.ДСТУ-Н Б В.1.1-38:2016. (2016). *Настанова щодо інженерного захисту територій, будівель і споруд від підтоплення та затоплення.*

6.Шаповал, В. Г., Шумінський, В. Д., Скобенко, О. В., & Кулівар, В. В. (2024). *Розрахунок осідань основ гребель із грунтових матеріалів.* У *Матеріали регіональної науково-практичної конференції до Всесвітнього дня води* (с. 101–103). Дніпро: ДДАЕУ.

7.Шаповал, В., Шашенко, О., Скобенко, О., Гапєєв, С., & Коновал, В. (2022). *Напружено-деформований стан основ гребель із грунтового матеріалу з трапецеїдальним поперечним профілем.* У *Scientific foundations for research in engineering: collective monograph* (с. 646–660). Boston: Primedia eLaunch.

8.Shapoval, V. H., Pavluchenko, A. V., Shuminskys, V. D., Skobenko, O. V., & Barsukova, S. O. (2023*). Stressed-deformed state of dam foundation made of soil material with a trapezoidal transverse profile*. In *Scientific research in engineering: collective monograph* (pp. 212–227). Petrosani, Romania: UNIVERSITAS Publishing.

9.ДСТУ-Н Б В.1.1-38:2016. (2016). *Настанова щодо інженерного захисту територій, будівель і споруд від підтоплення та затоплення*

10. Shapoval, V., Shashenko, O., Skobenko, O., Konoval, V., & Shuminskyi, V. (2024). *Technical, agricultural and physical sciences as the main human sciences*. In *Collective monograph.* Boston: Primedia eLaunch, International Science Group (pp. 91–107)

1. DBN V.2.4-20:2014. (2014). *Earth dams. Main provisions*

2. Kirienko, I. I., & Khimerik, Yu. A. (1987). *Hydraulic structures: Design and calculation: Textbook*. Kyiv: Vyscha Shkola.

3. DBN V.2.1-10:2009. (2009). *Bases and foundations of structures. Design provisions.*

4. DBN V.2.1-10:2019. (2019). *Bases and foundations of structures. Design provisions.*

5. DSTU-N B V.1.1-38:2016. (2016). *Guideline for engineering protection of territories, buildings, and structures against flooding.*

6. Shapoval, V. H., Shuminskyi, V. D., Skobenko, O. V., & Kulivar, V. V. (2024). *Settlement calculation of earth dam foundations.* In *Materials of regional scientific-practical conference dedicated to World Water Day* (pp. 101–103). Dnipro: DDAEU.

7. Shapoval, V., Shashenko, O., Skobenko, O., Gapeev, S., & Konoval, V. (2022*). Stressed-deformed state of dam foundations made of soil material with trapezoidal transverse profile*. In *Scientific foundations for research in engineering: Collective monograph* (pp. 646–660). Boston: Primedia eLaunch.

8. Shapoval, V. H., Pavluchenko, A. V., Shuminskys, V. D., Skobenko, O. V., & Barsukova, S. O. (2023). *Stressed-deformed state of dam foundation made of soil material with a trapezoidal transverse profile*. In *Scientific research in engineering: Collective monograph* (pp. 212–227). Petrosani, Romania: UNIVERSITAS Publishing.

9. DSTU-N B V.1.1-38:2016. (2016). *Guideline for engineering protection of territories, buildings, and structures against flooding*.

10. Shapoval, V., Shashenko, O., Skobenko, O., Konoval, V., & Shuminskyi, V. (2024). *Technical, agricultural and physical sciences as the main human sciences.* In *Collective monograph* (pp. 91–107). Boston: Primedia eLaunch, International Science Group.

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Визначення профілів осідань складених слабкими ґрунтами основ залізничних та автодорожніх насипів, гребель і дамб із ґрунтових матеріалів

Стаття присвячена проблемі визначення осідань основи залізничних, автодорожніх та інших насипів, а також гребель і дамб із ґрунтових матеріалів, особливо при будівництві на слабких ґрунтах. У таких випадках осідання можуть бути співмірними з висотою насипу, що потребує не лише оцінки середнього осідання, а й побудови повного профілю осідання у межах споруди та за її межами. У роботі проаналізовано обмеження традиційних методів, передбачених чинними будівельними нормами, зокрема графоаналітичного й табличного, які не забезпечують достатньої точності. Для усунення цих недоліків запропоновано простий ітераційний алгоритм розрахунку профілів осідань. Алгоритм базується на поетапному наближенні та дає змогу розраховувати осідання основ під насипами з трапецеїдальним перерізом. Запропонований підхід демонструє добру збіжність результатів з розрахунками, виконаними методом скінченних елементів, але при цьому не має його недоліків — таких як ламаність профілю та потреба в деталізованих граничних умовах. У статті також обґрунтовано доцільність включення цього алгоритму до проєкту нових ДСТУ щодо проектування гребель з ґрунтових матеріалів. Отримані результати можуть бути використані в інженерній практиці для підвищення точності розрахунків об'ємів матеріалу та формування проектного профілю насипів і гребель на слабких ґрунтах.

Ключові слова: ґрунтові греблі, дамби, осідання основи, довгий насип, трапецієподібна форма насипу, слабкі ґрунти, плоска деформація, глибина стиснення ґрунту, профіль осідання, обсяг матеріалу для насипу на слабких ґрунтах.

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