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Skochko L.O.*, assistant*
ORCID 0000–0001–7392–814X milabondareva@gmail.com
Kyiv National University of Construction and Architecture

THE REDISTRIBUTION OF THE HEIGHT RETAINING WALLS LEVELS, ITS EFFECT AT THE STRESS-STRAIN STATE OF THE SYSTEM «RETAINING STRUCTURES – SOIL MASS»

The work of multi-level retaining walls in sandy loam soils is investigated. A numerical experiment was conducted for reveal the most rational choice of the level height at a constant total excavation depth. A three-level retaining wall is considered. A number of tasks have been solved. The depend values changing of displacement and internal effort on the redistribution of excavation levels is shown. Values are fixed in the characteristic points of the structural elements of retaining walls each level. Variables are different at level marks of retaining walls. The surfaces were created on bases of the obtained results. These surfaces are used to analyze the relationship between the heights of levels and the values of bending moments. Identified solutions lead to increased displacements in one or another level of retaining walls. The constitutive laws between the geometric parameters of the retaining walls and the stress-strain state of the system «retaining constructions – soil mass» are obtained.

Keywords*: multi-level retaining wall, heights of the level, stress-strain state, horizontal displacements, bending moments.*

Скочко Л.О.*, асистент*
Київський національний університет будівництва та архітектури

ПЕРЕРОЗПОДІЛ ВИСОТ ЯРУСІВ ПІДПІРНИХ СТІН, ЙОГО ВПЛИВ НА НАПРУЖЕНО-ДЕФОРМОВАНИЙ СТАН СИСТЕМИ «УТРИМУЮЧІ КОНСТРУКЦІЇ – ҐРУНТОВИЙ МАСИВ»

Досліджено роботу багатоярусних підпірних стін у супіщаних ґрунтах. Числовий експеримент проведено для виявлення найбільш раціонального вибору висот ярусів при сталому загальному перепаді ґрунту. Розглянуто триярусну підпірну стінку, розв'язано ряд задач, де змінними є позначки окремих ярусів. Показано залежність зміни значень переміщень і внутрішніх зусиль від перерозподілу рівнів розробки ґрунту. Значення зафіксовано у характерних точках конструктивних елементів окремих ярусів підпірних стін. За отриманими результатами побудовано поверхні. За графіками проаналізовано залежності висот ярусів і згинальних моментів у цих ярусах. Визначено рішення, що призводять до збільшення переміщень у тому чи іншому рівні підпірних стін. Отримано закономірності між геометричними параметрами підпірної стіни і напружено-деформованим станом системи «утримуючі конструкції – ґрунтовий масив».

Ключові слова: *багатоярусна підпірна стіна, висота ярусу, напружено-деформований стан, горизонтальні переміщення, згинальний момент.*

Introduction. The planning of areas with complex terrain in a modern city often needs the excavation pits with a depth of about 20 m. The construction of a retaining wall of this height provides for the mandatory use of ground anchors, node-to-node anchor, or any other limiters of horizontal displacements. Such structural elements are usually located in the neighboring territory. These structures can be cut by the following construction. Therefore, one of the solutions for protecting the territory can be the use of several levels of retaining walls.

The latest sources of research and publications analysis. Stability of slopes and methods of numerical modeling of landslide-prone areas were investigated by M. L. Zotsenko and Y. L. Vinnikov [1]. Influence of piles, which are located at the level of soil excavation, on retaining wall is considered in the article of Katzenbach G. [2]. This article presents the results of numerical simulation, which are based on a series of full-scale tests of a reduced model, and the corresponding dependencies are revealed. The methods for determining the parameters of retaining walls was considered in the A. L. Gotman`s paper [3]. Also, the issue of numerical modeling and comparison of the obtained results with geodetic monitoring data was considered by such scientists as I. Skrzypczak, J. Kogut, W. Kokoszka [4], C.V.S. Benjamim, B.S. Bueno, J. G. Zornberg [5] and others.

Distinction of unresolved parts of a common problem. The choice of the planned–high-altitude position of the levels of the retaining walls is an important factor, as well as an understanding of how the change in the position of levels affects to the stress-strain state of the system «retaining structures – soil mass». The results of the numerical experiment on the change in the redistribution of heights of the three-level retaining wall, and the effect of this redistribution on the operation of each of the tiers are described in this paper.

Formulation of the problem. The number of problems is solved to investigate the influence of the distribution of excavating heights of levels of the retaining walls on the stress-strain state of the system «retaining structures – soil mass». The calculations were performed using a model of a physically nonlinear elastic-plastic environment, based on the dilatancy theory of Professor V.M. Nikolaevsky [6]. This soil model is realized in the program complex ASSR «VESNA». Part of the dilatancy theory, which describes the dependence of the critical density level, ρ_{cr} on the hydrostatic pressure, σ_m, was supplemented by Professor I.P. Boyko [7, 8] by the following equations:

$$\begin{aligned}
&\rho_{cr_i} = \rho_{cr_0} \text{ at } \sigma_m > 0 \\
&\rho_{cr_i} = -\frac{2(\rho_{cr_max} - \rho_{cr_0})}{P_0^2}\sigma_m^3 + \frac{3(\rho_{cr_max} - \rho_{cr_0})}{P_0^2}\sigma_m^2 + \rho_{cr_0} \text{ at } P_0 \le \sigma_m \le 0; \qquad (1) \\
&\rho_{cr_i} = \rho_{cr_max} \text{ at } \sigma_m < 0,
\end{aligned}$$

where ρ_{cr_i} – currently critical density;

ρ_{cr_0} – critical density in the absence of all-round compression;

ρ_{cr_max} – the maximum critical density for a given soil;

P_0 – a parameter of the soil that determines the level of hydrostatic pressure at which the transition from the conical surface to the cylindrical surface. Equation (1) shows that the critical density ρ_{cr_i} increases with the hydrostatic pressure σ_m.

The proposed relationships also provide an opportunity for more complete description of soils elastic-plastic deformation processes. Because these relationships allow to consider elastic volume deformations of the soil, while they are in a critical state. The value of the critical density ρ_{cr_i} is variable due to the redistribution of the hydrostatic pressure σ_m in the investigated region.

The purpose of this work is to determine the regularities between the height of the levels of the retaining wall and the components of the retaining structure levels stress-strain state.

The main material and results. A three-level retaining wall with the following input constant geometric parameters for research has been selected. This retaining wall has some geometric parameters: excavation height of the pit, *H;* total distance between levels, *L=2/3H;* distance between each of the levels in the plan*, 1/2L.* Variable for these tasks were height of each level. The calculation scheme for this task set is shown in Fig. 1. The tasks are solved by numerical simulation in a flat formulation.

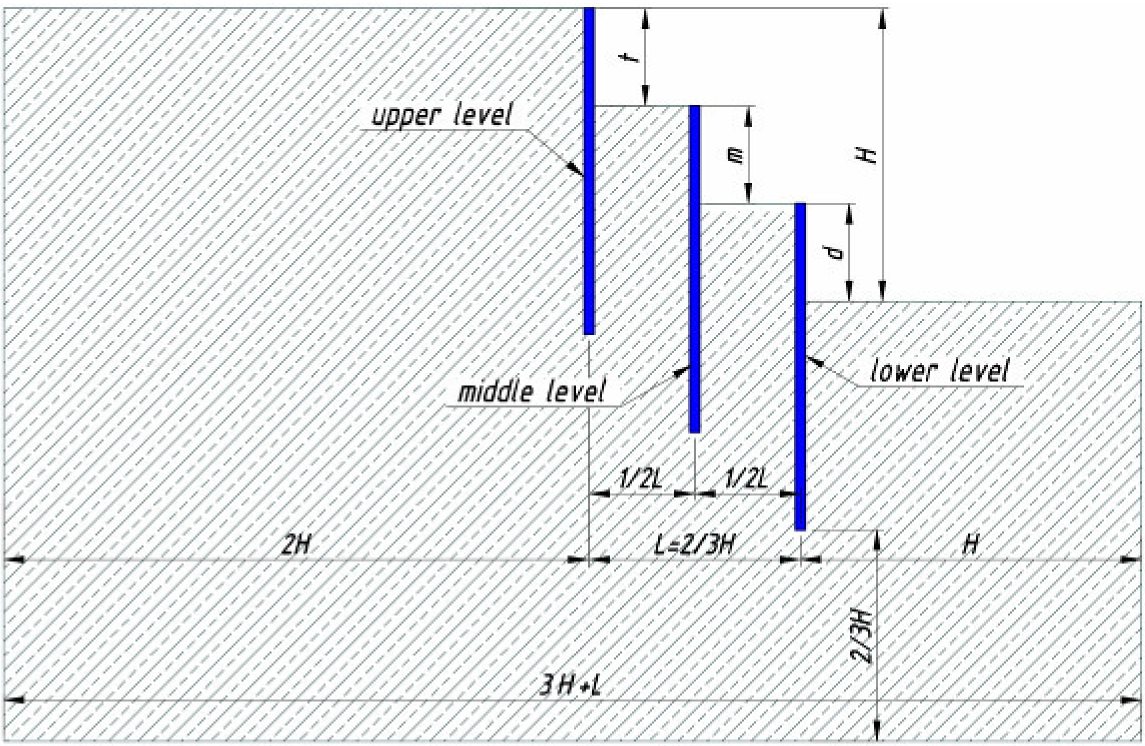


Figure 1 – Calculation scheme for determining the effect of the mutual position of the height of levels of retaining walls on the stress–strain state of the system «retaining structures – soil mass», for sandy loam soils, with the relation L = 2 / 3H

The height of the lower level is *d*, of the middle – *m*, of the upper – *t*. The regularities between these parameters and the components of the stress-strain state are given in the paper.

The calculations are performed for tasks with the following input parameters: *H* = 18 m, respectively *L* = 12 m. The retaining walls are in a homogeneous loam soils to exclude the effect of soil layers on the stress-strain state of the system «retaining structures – soil mass». Sandy loam has the following physical and mechanical characteristics: specific weight, 20,2 kN/m^3; Poisson`s ratio, v = 0,3; cohesion, C = 15 kPa; friction angle, φ = 26; deformation module, E = 38 MPa. The stiffness of the retaining walls, *EI* are the same. All retaining walls are made of bored piles with a diameter of 820 mm, in a 1 m step.

The values of *t*, *m*, *d* are given in Table 1. Also, the results of a numerical experiment, such as the values of maximum bending moments and displacements of the retaining walls top of each level is shown in the table.

The dimensions of the finite element scheme, the sizes of the finite elements, their type and the grid thickening zone are the same for all solved tasks. It allowed to avoid the accumulation of errors in numerical modeling Also, during the modeling of pit excavation, it is important to consider the calculation stages of excavation and the technological sequence of retaining walls levels construction. The results of numerical simulation differ by 15%, when digging out the ground in stages 1 and 2 m. The lack of technological stages of construction in the calculation shows a difference between the results of horizontal deformations of more than 2 and almost 3 times. The results of the soil massif deformation distribution are incorrect without considering the stage of construction. Therefore, the step-by-step calculation and modeling with including phases of retaining walls erection and pit excavation is a necessary component of the numerical modeling of the system «retaining structures – soil mass». The solution of all tasks is performed in 13 stages, and the excavation of the pit is modeled by uniform steps.

Table 1 – Results of numerical modeling of a three-level retaining wall with different distribution of height levels

d, m	m, m	t, m	Displacement the top of piles, mm			Maximum bending moments, kN·m/r.m.		
			Upper level	Middle level	Lower level	Upper level	Middle level	Lower level
4	4	10	39.4	76.4	225	424.7	517	620
4	6	8	41.3	96.8	160.8	432	535	335
4	8	6	45.7	133	151	458.5	613.53	297
6	4	8	55.9	68	122.4	521.3	352	264.6
6	6	6	61.7	94	107	560	371	193
6	8	4	72.5	137.68	125	648	358	237
8	4	6	84.06	80.3	94	649	333.4	156
8	6	4	96.8	115.7	108.5	734	320	195.7
8	8	2	121.6	185.6	124	931.2	390.1	204

The obtained data must be visualized in the form of graphs surfaces. For convenience, it was denoted any investigated component of the stress-strain state *S*. The main task is to associate 4 parameters: *d, m, t*, and *S* in one scheme (one of the obtained data components: displacement the top of piles or maximum bending moments of the levels). This dependence requires the construction of a 4-dimensional surface. It is associated the variation parameters by the following logical equation (2) in order to go to three-dimensional space and visualize the results in the form of iso poles

$$d + m + t = H\,, \tag{2}$$

where H – excavation height of the pit.

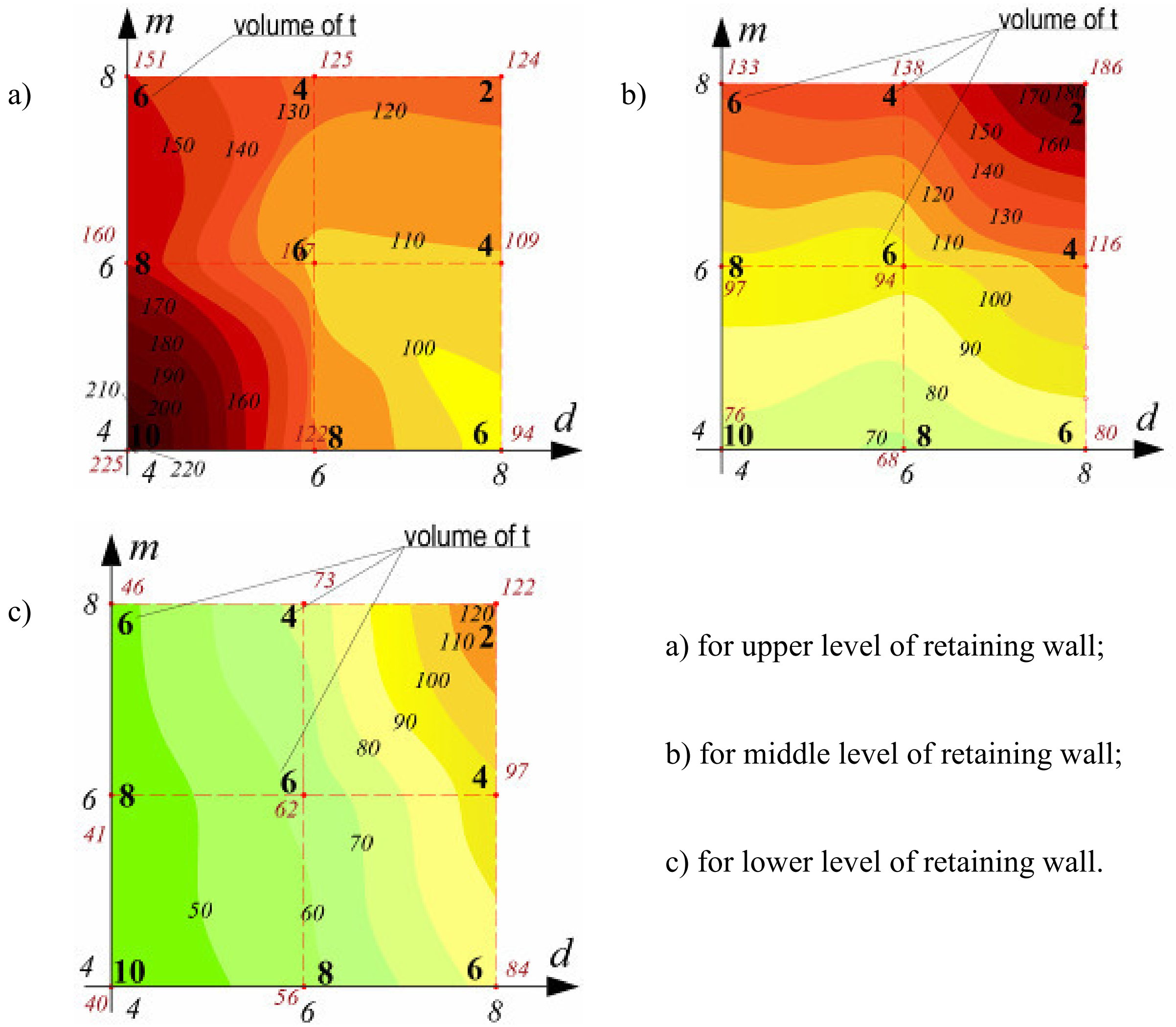
Using equation (2), it can always be expressed the height of the upper level, *t*, presetting the heights *d* and *m*:

$$t(d,m) = H - d - m\,. \tag{3}$$

Now, any physical quantity *S* can be found as a function of only two variation parameters (*d* and *m*):

$$S = S(d,m) = f(d,m). \tag{4}$$

Thus, it is got themethod for constructing dependencies between the components of the stress-strain state of the system «restraining structures – a soil mass» and the geometric parameters of a three-level retaining wall. The projections of the surfaces for horizontal displacements of retaining walls each level are shown in Fig. 2. The values of *t* are shown in the control points on the projections, for convenience of use.



a) for upper level of retaining wall;

b) for middle level of retaining wall;

c) for lower level of retaining wall.

Figure 2 – Horizontal displacements of the top of the retaining walls

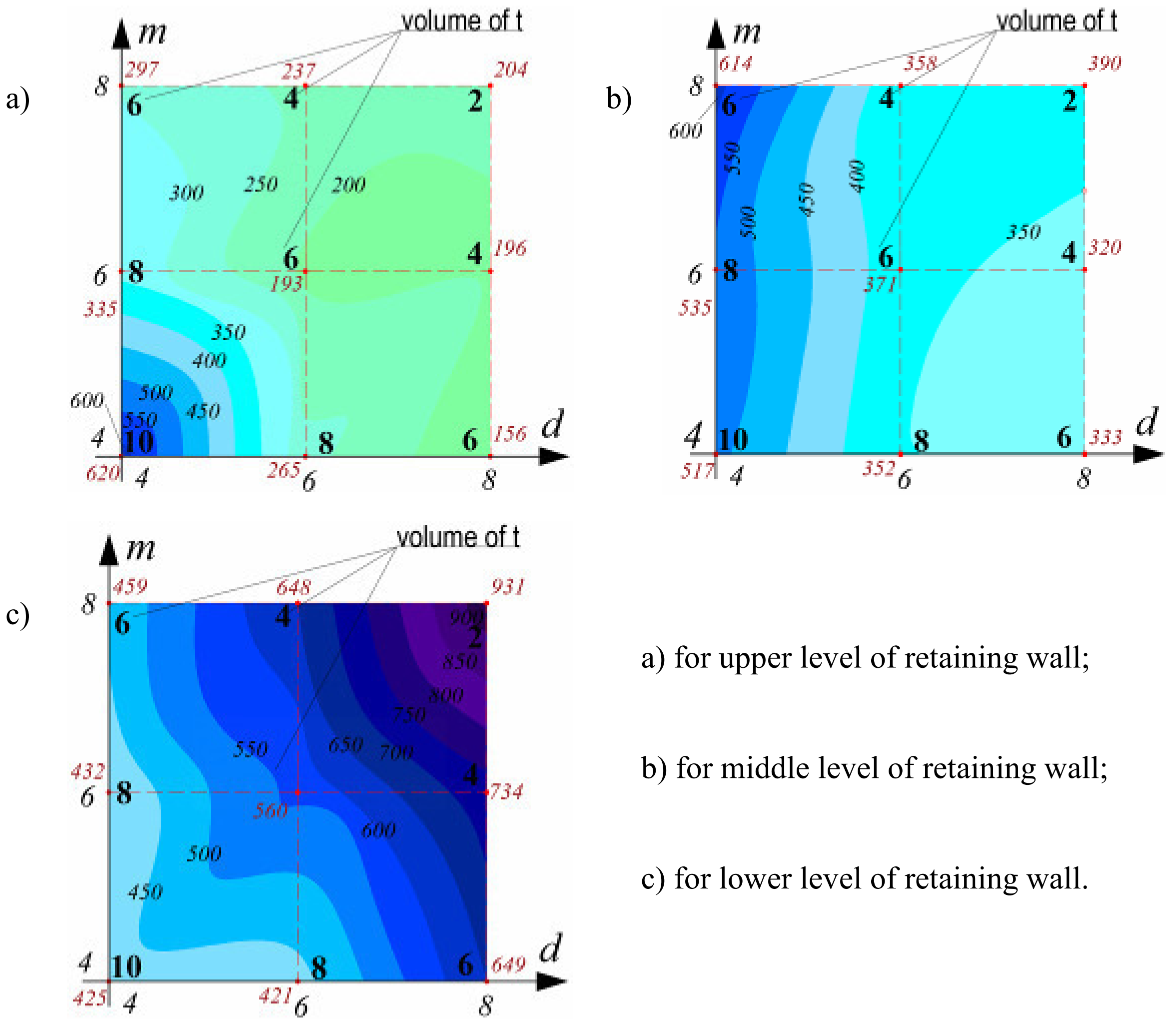
The height of the upper and horizontal displacements of the upper level is increased and level of excavation of the lower level decreases respectively. In addition, the minimum values of horizontal displacements correspond to the values $d = 8$ m, $m = 4$ m, $t = 6$ m, thus, the height of the middle level should be less than all others.

It is expected that an increase in the middle level height of the retaining walls causes an increase in the horizontal displacements of this level (Figure 2, b), but at the same time, an increase in the lower level from 6 to 8 meters also shows a significant increase in the deformations of the middle retaining wall. The minimum values of the horizontal displacements of the retaining walls middle level correspond to the values of the heights $d = 6$ m, $m = 4$ m, $t = 8$ m, the maximum displacements correspond to – $d = 8$ m, $m = 8$ m, $t = 2$ m. That is, increasing the height of the lower level more significantly affects the displacements of the middle retaining wall than the increase in the upper one. This is explained by the fact that the volume of soil, which retains the middle retaining wall, decreases with increasing height of the lower level.

The lower level of the retaining walls has received the smallest absolute horizontal displacements for almost all the considered variants of levels heights distribution. The horizontal displacements of the lower tier had only 4% higher values than for the middle tier only for the altitude relation $d = 6$ m, $m = 4$ m, $t = 8$ m. The obtained isopoles of horizontal displacements of the lower level (Fig. 2, c) showed that the increase in the deformations of this level is due to increase in its height in a greater degree. The increase in the heights of the middle and upper levels showed the least influence on the displacements of the lower level. It can be explained by the fact that the redistribution of the loads level to the lower tier in a lesser way affects the deformations of the retaining wall than the volume of the soil mass that retained this level.

Analysis of the calculations results was limited to tasks with the values d, m and $t = 4...8$ m. It was done to compare the effect of mutual redistribution of the levels heights on the each horizontal displacements. Studies have shown that the difference between the smallest and the largest values of horizontal displacements in the given range of levels heights is 57 % for the lower level; 50,6 % for the middle level; 41 % for the upper level.

The next investigated component of the stress-strain state of the system «retaining structures – soil mass» is the maximum values of the bending moments in the piles of the retaining walls of retaining structure each level. The values of the bending moments are determined at the last stage of modeling pit excavation. The results obtained in the form of a surface projection are shown in Fig. 3.



a) for upper level of retaining wall;

b) for middle level of retaining wall;

c) for lower level of retaining wall.

Figure 3 – Maximum bending moments in the piles of retaining walls each tier

The minimum values of the bending moments in the piles of the upper retaining wall correspond to the values d = 6 m, m = 4 m, t = 8 m. For the upper level, such a position of the retaining walls, also corresponds to the lowest value of the horizontal displacements of this level within the studied values of heights redistribution. The maximum values of the bending moments of retaining walls upper level correspond to the values d=4 m, m = 4 m, t = 10 m and exceed the values of the bending moments for d = 8 m, m = 4 m, t = 6 m by almost 4 times. Our research is limited by the number of solved problems. Range of the solutions (Figure 3a) shows that the position of the middle level influences to the forces in the upper retaining wall in a large way than the position of the lower one. It is analyzed the solutions for a constant value of t = 6 m, in order to investigate the influence of the height of the lower levels on the bending moments of the upper one. It was found that the change in the heights of tiers d and m in the range from 4 to 8 m in different ratios showed the difference between the values of the bending moments of the upper level to 47 %, that is, almost 2 times.

The maximum values of the bending moments in the middle level of the retaining walls correspond to the maximum value of this level height and the minimum possible value of d in the given range of input data. The distribution of the heights d = 4 m, m = 8 m, t = 6 m corresponds to the maximum value of the bending moments in the piles of the middle level, which is almost 3 times greater than the value of the bending moments for d = 8 m, m = 6 m, t = 4 m. This redistribution of the levels heights corresponds to the minimum value of efforts in the constructions of the middle level. Analysis of the graphs showed that the values of the bending moments of the middle tier are significantly influenced by the geometric dimensions of the other tiers, since the minimum bending moments of this tier do not correspond to its minimum height. It is analyzed the value of the bending moments of the middle retaining wall at a constant of its own height, m = 6 m, and the values of d and t in the range 4...8 m, as well as for the upper level. The difference between the smallest and largest values of the bending moments is 40 %.

Most of the researched redistribution variants showed that the greatest bending moments occur in the lower retaining wall. The moments in the piles of lower retaining wall are not the largest among all the levels only when d = 4 m. It can be explained by the fact that the pressure on the lower retaining wall is always greater than on the middle or upper, but the volume of the retaining soil mass depends only on the soils own height and does not change in any way regardless of the other levels heights. The maximum values of the bending moments of the lower levels of the retaining walls correspond to the values d = 8 m, m = 8 m and t = 2 m; the minimum values of the bending moments arise at d = 4 m, m = 4 m and t = 10 m. The difference between the minimum and maximum values of bending moments within the range of values is 54%, that is, more than twice. However, it is important to consider that the researched range of changes in the heights of soil mass for each levels is different. It is limited the comparison of data as follows: d = 6 m; m and t can be variable in the range from 4 to 8 m, as well as for the upper two levels. The difference between the maximum and minimum values of the bending moments with a constant value of the height of the lower level is 24 %.

The maximum bending moments that appear in one or another level of retaining wall in all the researched cases correspond to such a mutual height arrangement of other levels where the own height of the wall level is greatest. The minimum bending moments of each levels do not always correspond to its lowest height. The dependence, at which the minimum own height corresponds to the minimum moment, is valid only for the lower level. For upper level, the redistribution of neighboring levels heights has a greater influence on the values of the bending moments than the own heights.

Conclusions. The construction of multi-level retaining walls allows retaining significant changes in the ground without horizontal limiters use, and at the same time, using the area of the construction site for building, by integrating the retaining structures in the architectural solutions of the new building.

It has been established that the maximum movements of the levels piles top depend largely on their own heights. The change in the height of the level leads to loads redistribution throughout the structure. The upper level is the most sensitive to the change in the geometric parameters of the retaining walls in percentage terms. Thus, the differences between the smallest and largest values of horizontal displacements are: 57 % – for the lower level; 50,6 % – for the middle level; 41 % – for the top level.

The researching of soil mass influence redistribution between levels showed that neighboring levels heights influences on the value of the bending moments are: for the lower level – 24 %, for the average level – 40 %, for the upper level – 47 %.

The visualization of the obtained results in the form of isofields makes it possible to evaluate the influence of the level heights on the components of the stress-strain state of the system «soil massif – retaining structures», which in turn allows to justify the rational dimensions of the retaining structures in each specific case.

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