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Cut-off wall in foundation of reservoir dam and tailing dam: comparative evaluation

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Abstract. Cut-off wall is used to prevent seepage in foundations of embankment dams of reservoirs and tailing dams. Under the action of external loads, they may be subject to stresses comparable with strength of the wall material. There is a risk of loss of the wall both tensile strength and compressive strength. To decrease stresses, the cut-off wall is made of clay-cement concrete more deformed as compared to material concrete. To compare conditions of operation and strength of the cut-off wall in foundation of the reservoir dam and the cut-off wall in foundation of the tailing dam, there was fulfilled the study of their stress-strain state. Abstract rockfill dam 100 m high with geomembrane face was considered. A 2 m thick cut-off wall is located under the dam upstream slope: it crosses the layer of deformed foundation 15 m thick and is embedded in rock. Mohr–Coulomb model was used for description of behavior. Computations showed that the cut-off wall of the tailing dam performs in less favorable conditions than the cut-off wall of the reservoir dam. It is subject to greater by value vertical and horizontal loads. Due to pressure of slimes, it is subject to several times as much by value vertical compressive stresses. The value of stresses is highly dependent on deformation of the foundation soil. To provide strength, the deformation modulus of the cut-off wall should not exceed the foundation soil deformation modulus by more than 4 times. In spite of the fact that the tailing dam cut-off wall is subject to greater horizontal loads, it has less displacements than the reservoir dam cut-off wall. It was revealed that this is explained by more favorable stress state of soil in foundation of the tailing dam.

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1. *Introduction*

Subject of research. In foundations of dams and dikes composed of soils, the cut-off walls (COW) arranged by one of the methods of slurry trench are frequently used as seepage-control facilities. They may be fulfilled for a considerable depth reaching several dozen meters. The examples of such structures are COWs in embankment dams Xiaolangdi (China, 2000), Karkhe (Iran, 2001), Peribonka (Canada, 2008), Sylvenstein (Germany, 2012) [1–4]. The main seepage-control wall arranged in foundation of Peribonka dam is 116 m deep. The wall up to 80 m deep in the foundation of Karkhe dam is long and the square area of its upstream face is approximately 190000 sq.m.

COW is also used in structural designs of dams of tailings ponds in metal mining industry, namely in Chile and Peru [5]. As an example, we may indicate COW, which was arranged in tailing dam Aznallcolar (1978, Spain) [6, 7].

Literature review

To provide safe operation of COW, proper strength of its material should be provided. Publications [9–20] are dedicated to study of stress-strain state (SSS) of COW in foundation of an embankment dam.

The results of scarce field measurements of displacements and stresses in COW are generalized in [8]. Mainly the study of SSS of COW in foundation of an embankment dam is fulfilled with the aid of numerical modeling.

Publications [9–11, 17, 19] are dedicated to SSS of COW made in foundations under the cores of earth-rockfill dams, [16] – to study of SSS of COW arranged in the dam with asphalt concrete diaphragm. In articles [12–14, 20], there studied SSS of COW made in the foundation of Miaojiaba concrete faced rockfill dam in China.

By the results of studies, there was formulated the theory of forming SSS of COW in the dam foundation. Its main concepts are as follows. COW is subject not only to bend deformations but also to deformations of longitudinal (vertical) compression. Bending moments, longitudinal and transversal forces appear in the wall. Longitudinal compressive force is the results of not only pressure on the upper end (head) of the wall but also of soil friction forces on the wall lateral surface. Pressure on the upper end is determined by dead weight of the dam soil located above the wall and by water pressure.

Under the action of vertical forces, COW may be subject to high compressive stresses comparable with strength of the wall material. This may present a serious danger for COW strength. In order to avoid loss of strength, the wall should be made of material which by its rigidity is close to surrounding soil. By recommendations of ICOLD (International Commission on Large Dams), the ratio between the wall modulus of linear deformation and the soil modulus of linear deformation should not exceed 5.

The results of numerical modeling show that conditions of COW operation also depend on its depth, structural design of an embankment dam and other factors. L. Wen et al. [14] note that conditions of operation, SSS of COW are determined by position of the wall within the embankment dam profile. It is obvious that the wall located at the toe of the embankment dam upstream slope will be subject to less vertical loads than the wall located under the dam central part.

With this regard, it is logical to propose that operation conditions of COW made in foundations of tailing dams should differ from operation conditions of COW arranged in reservoir embankment dam foundation. However, investigations dedicated to studies of SSS of COW in foundations of tailing dams were not found.

Formulation of relevance of research. The urgent issue is evaluation of workability of COW arranged in the layer of soil (deformed) foundation under the tailing dam in comparison with COW in the deformed foundation of the reservoir dam. To fulfill this comparative evaluation, it is necessary to analyze SSS of COW on the example of a certain structure

Aims and tasks of study. Studies of SSS should answer the following questions:

Question no. 1. What is the difference between SSS of COW in foundation of the tailing dam and that of COW made in the reservoir dam foundation? Are operation conditions of COW in foundation of a tailing dam more favorable or unfavorable as compared to those of COW in the reservoir dam foundation?

Question no. 2. Is there the risk of strength loss of COW made in foundation of the tailing dam? In what case the COW strength may not be provided?

2. Materials and Methods

Description of the studied structure

Investigation was conducted on the example of an abstract tailing dam, which is 100 m high. It was assumed that the dam is made of rockfill and grows in several stages towards the downstream side (Fig. 1). Maximum depth of the tailing dam filling is 98 m.

There considered the dam, which is built on 15 m thick layer of cohesionless alluvial soil under which rock is bedded. To provide water tightness of the alluvial layer, a 2 m thick seepage-control wall made of clay-cement concrete is arranged in it.

The dam structural design is assumed to be as follows. The dam seepage-control element is the face made of geomembrane placed along the upstream face. To provide stability of the face, the upstream slope was chosen to be 2.5. The dam downstream slope is 1.6.

The face and the COW are connected with the aid of a concrete apron 2 m long and 0.4 m thick.

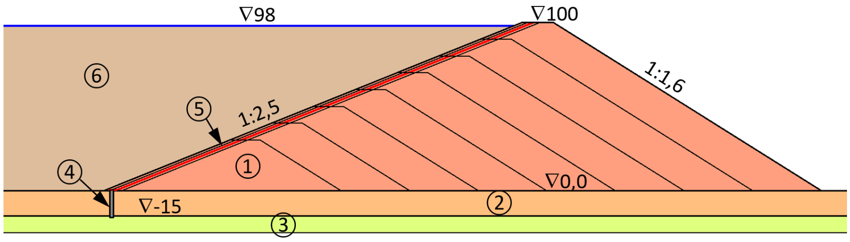

Figure 1. Diagram of the tailing dam structural design: 1 – rockfill; 2 – foundation alluvial layer; 3 – rock foundation; 4 – cut-off wall made of clay-cement concrete; 5 – face made of polymer geomembrane; 6 – slimes.

Description of finite-element model

The structure SSS analysis was conducted by finite-element method with the aid of computer program NDS_N, developed by M.P. Sainov. Analysis was fulfilled in 2D formulation.

The structure computational domain included the dam itself, the layers of soil and rock foundations as well as part of a tailing dam.

The developed finite-element model of the computational domain includes 1273 elements (Fig. 2). The use was made of the elements with square degree of approximation of displacements inside the element. 115 elements out of the total number of elements were Goodman's elements, which are intended for modeling non-linear character of interaction between soils and rigid structures.

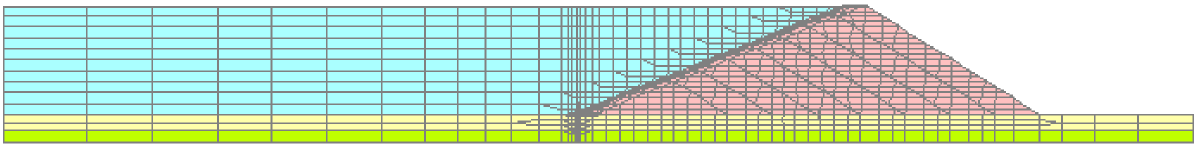

Figure 2. Diagram of dividing the structure into finite elements.

Computations were conducted for loads from the structure dead weight and hydrostatic pressure. Slimes located below the water level were assumed to be in suspended state. Lengthwise distributed load from hydrostatic pressure was applied to upstream faces of seepage-control facilities.

SSS analysis was conducted taking into account the sequence of the dam construction and the tailing dam filling. The dam is constructed in 8 stages. The first stage is 30 m high. Its construction is preceded by arrangement of COW in the layer of the deformed foundation. Each subsequent stage is 10 m higher than the preceding one.

For comparative evaluation, the analysis was also conducted for the reservoir embankment dam with similar structural design. Its only difference is the fact that there are no loads from slimes.

Selection of physical-mechanical properties of medium

Two alternatives of soil deformation of the dam and foundation were considered.

In alternative 1, rockfill modulus of linear deformation was taken equal 75 MPa, and foundation alluvial soil modulus of linear deformation was 40 MPa. They correspond to not high quality of soil compaction. In alternative 2, the moduli of linear deformation of rockfill and foundation soil were two times as much as in alternative 1.

Mohr–Coulomb model was used for description of soil behavior. Tensile strength of soils was assumed to be close to 0.

Rock material was assumed to be elastic and absolutely strong. It was proposed that COW is made of clay-cement concrete. By Russian building code, for clay-cement concrete, the modulus of linear deformation is assumed to be 300–500 MPa, and uniaxial compressive strength is 1–2 MPa.

The most complicated issue is assigning physical-mechanical properties of slimes: strength ρ, modulus of linear deformation E, angle of internal friction φ and cohesion c. With this purpose, the literary sources [21–25] were analyzed.

Publications [21, 22] are dedicated to analysis of tailing dams. In [22], for slimes, the following design characteristics were assumed: ρ = 1.7 kg/cm^3, φ = 40°, c = 10 kPa. In [21], they were assumed as follows: ρ = 2 kg/cm^3, E = 12.1 MPa, φ = 21°, c = 16 kPa.

In [24], by the results of tests in stabilometer, the followings strength indices of slimes were obtained: c = 20 кPa, $\varphi \approx 40°$.

Publications [23, 25] are dedicated to the issue of determining parameters of slimes for Hardening Soil model. In publication [25], the properties of slimes in different zones of Aitik tailing dam (Sweden) were investigated. The following characteristics of slimes were obtained: density in dry state 1.43–1.62 kg/cm^3, averaged modulus of linear deformation E_{50} amounts to 5.5–8.3 MPa, angle of internal friction φ = 38–40°, cohesion c = 0–7 kPa.

In [23], there described the results of investigations of slimes properties in the largest tailing dam of Bulgaria. Soil samples were taken in the interval of depths 12–81 m. There was determined the range of slimes density variation in natural state (1.8–2.2 kg/cm^3) and the range of modulus of linear deformation (6–21 GPa). Processing of the results showed that deformation of slimes decreases with growth of lateral compression.

The indicated effect is explained by the fact that due to pressure of lying above layers, consolidation processes, the density of slimes increases with depth and their deformation decreases. Therefore, in calculation, the tailing dam storage was conditionally divided in two zones by depth. In the lower zone, the slimes were assumed to be denser and less deformed. The depth of the upper zone was taken equal 20 m. As the dam height increased and the tailing dam was filled, the boundary between the zones was also raised.

Parameters of physical-mechanical properties of the structure materials are presented in Table 1.

Table 1. Physical-mechanical properties of materials.

Material	Density, kg/cm^3		E, MPa	ν	φ	c, kPa
	unsaturated	saturated				
Rockfill (alternative 1)	2.00	2.28	75	0.30	45°	–
Rockfill (alternative 2)	2.00	2.28	150	0.30	45°	–
Foundation alluvium (alternative 1)	1.85	2.16	40	0.30	38°	–
Foundation alluvium (alternative 2)	1.85	2.16	80	0.30	38°	–
Slimes (upper zone)	1.64	2.02	10	0.38	35°	1
Clay-cement concrete	1.74	2.10	25	0.38	35°	1
Clay-cement concrete	1.90		300	0.35	strong	
Concrete	2.40		30000	0.20	strong	
Rock	2.55	2.63	5000	0.25	strong	

Note: E – modulus of linear deformation; ν – Poisson's ratio; φ – angle of internal friction; c – specific cohesion.

Shear stiffness of contacts between rock structures and soils was taken equal 500 MPa/m. Preliminary calculations showed that variation of shear stiffness in the interval 500–2500 MPa/m does not greatly affect the results of calculations.

3. Results and Discussion

SSS analysis of the dam and COW was fulfilled for the last construction stage of the tailing dam.

Stress-strain state of the dam

In order to evaluate difference in SSS of a tailing dam and a reservoir dam, Figs. 3, 4 show distribution of displacements, and Figs. 5, 6 – distribution of stresses. They are plotted with consideration of the dam construction sequence.

Values of stresses in the dam body and foundation are mainly determined by acting loads (function of the structure) and are less depended on the variant of deformation properties of soils. The tailing dam is subject to greater by value stresses.

In the reservoir dam, vertical stresses σ_y reach maximum value (1.8 MPa) at the toe, in the internal zone (Fig. 5,b). In COW zone, they amount to approximately 0.7 MPa. In the tailing dam, due to the weight of slimes, the vertical stresses reach 2.1 MPa (Fig. 5,a). In COW zone, they comprise approximately 1.2 MPa.

Horizontal compressive stresses σ_x reach their maximum in the rock foundation layer, as a rule, in the zone from the downstream side from COW. At construction of a tailing dam, they exceed 1.1 MPa (Fig. 6,a), and at creation of an reservoir, they are 1.0 MPa (Fig. 6,b).

Considerable difference is noted in soil stress state from the downstream side of the wall. In case of a reservoir, the zone of soil loosening appears in front of the wall; there the soil loses compressive strength and/or shear strength. In this zone, horizontal stresses σ_x are close to 0 (Fig. 6,b). In case of a tailing dam, from the upstream side of the wall, the soil is subject to compressive stresses σ_x with value at least 0.15 MPa (Fig. 6,a). This compression arises from pressure of slimes lying above.

The tailing dam is characterized by greater by value displacements and settlements than those of the reservoir dam. This is explained by existence of additional loads from the weight and pressure of slimes. However, the difference in displacements is not large. Horizontal displacements of a tailing dam exceed the displacements of a reservoir dam by approximately 15 % (Table 2). The tailing dam displacements reach their maximum at the upstream face (Fig. 3). The tailing dam settlements also reach their maximum near the upstream face and for the reservoir dam they are in its internal part (Fig. 4). But maximum values of settlements differ not greatly.

Table 2. Maximum values of the tailing dam displacements and settlements.

Parameter	Tailing		Reservoir	
	Alternative 1	Alternative 2	Alternative 1	Alternative 2
U_x [cm]	41	21	36	18
U_y [cm]	88	44	85	43

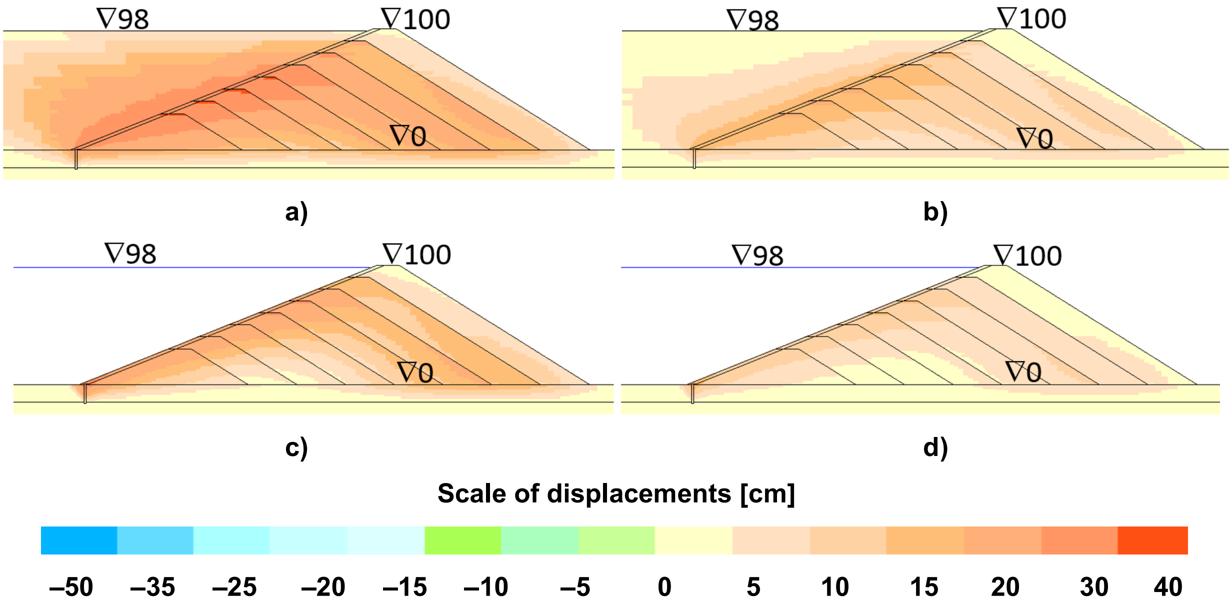

Figure 3. Tailing dam horizontal displacements^
a), b) – tailing dam; c), d) – reservoir dam; a), c) – alternative 2; b), d) – alternative 1.

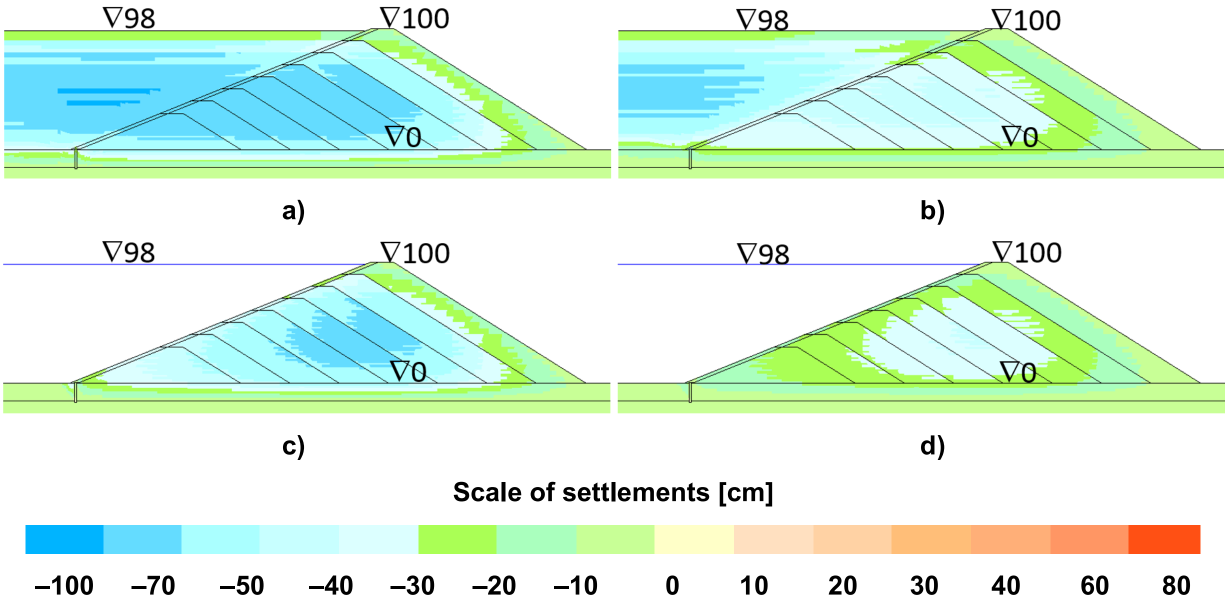

Figure 4. Tailing dam vertical settlements:
a), b) – tailing dam; c), d) – reservoir dam; a), c) – alternative 2; b), d) – alternative 1.

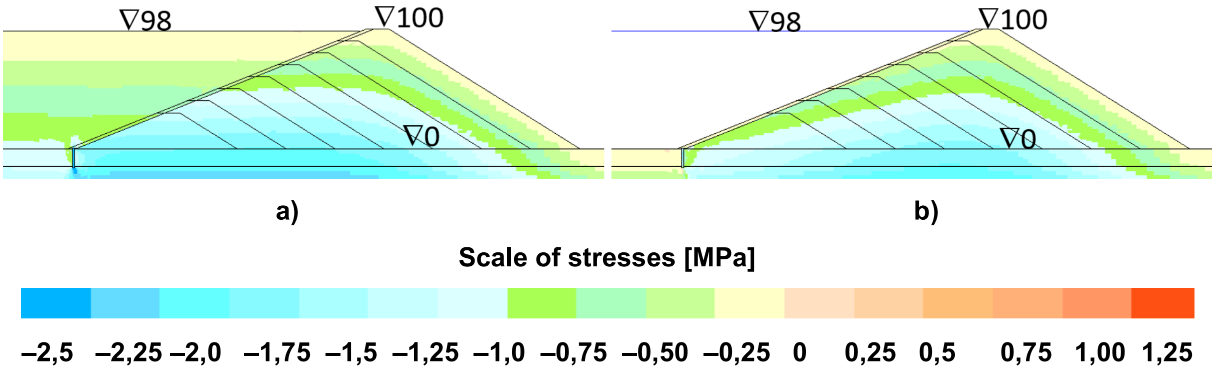

Figure 5. Vertical stresses in a tailing dam foundation and body (alternative 1):
a) – tailing dam; b) – reservoir dam.

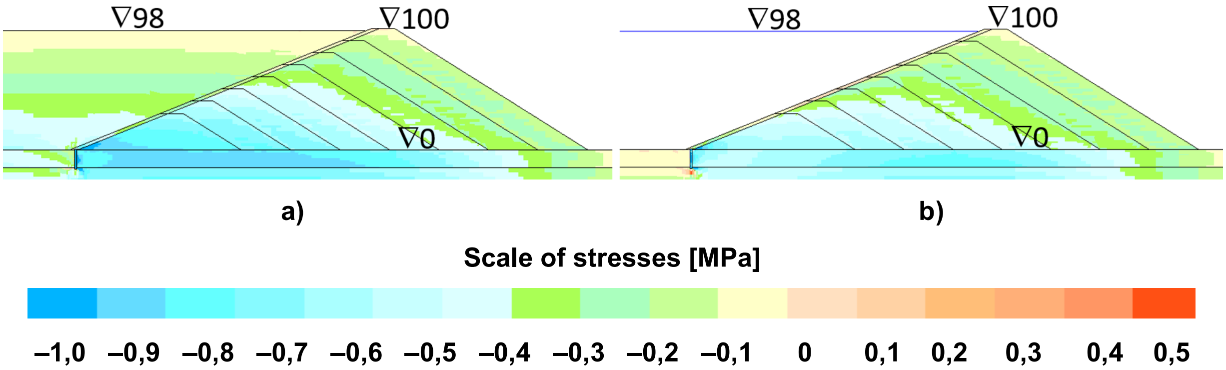

Figure 6. Horizontal stresses in a tailing dam foundation and body (alternative 1):
a) – tailing dam; b) – reservoir dam.

Stress-strain state of a cut-off wall

In SSS of COW in a tailing dam and a reservoir dam, the difference is expressed more vividly.

The first difference refers to the values of COW horizontal displacements.

In all the considered cases, COW is displaced towards the downstream side and displacements reach their maximum in COW upper part. By the results of calculations, it was revealed that a tailing dam COW horizontal displacements are always less than those of a reservoir dam COW (Fig. 7). It seems that it should be vice versa because in a tailing dam the wall is subject to more by value horizontal loads from the upstream side than that in a reservoir. However, it was revealed that such effect is explained by specific feature of soil stress state from the upstream side of the wall.

With the aid of additional calculations, it was shown that a tailing dam COW displacements would be more than a reservoir COW displacements in case if soils were assumed to be strong and able to perceive any by value tensile and shear stresses. However, in real conditions, the soils tensile strength is close to 0 and this results in increase of a reservoir COW displacements. At displacements of a reservoir dam, the soils bedded from the upstream side of the wall turn to be unable to resist shear displacements.

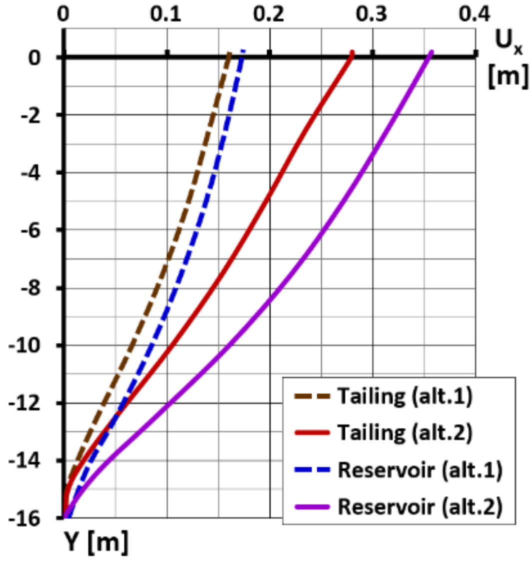

Figure 7. COW horizontal displacements.

The second difference is in the character of COW stress state. In both cases, SSS is formed by two processes.

The first process is the wall bend deformations. At horizontal displacements, COW bends towards the upstream side. In the wall upper part and in the zone of its embedment into rock foundation, the bend occurs towards the upstream side. The highest wall bend deformations are revealed in the zone of embedment. Bend deformations are expressed in non-uniform distribution of vertical stresses σ_y between the wall faces (Fig. 8). In the tailing dam wall, they are revealed to some more extent.

The second process is wall longitudinal compression, which is mainly formed by the forces acting on its upper end. From the point of view of longitudinal forces value, the tailing dam wall principally differs from the reservoir wall. Vertical load on the reservoir wall is mainly formed due to hydrostatic pressure. In a tailing dam COW, it is added by pressure from the weight of slimes. Calculations showed that the tailing dam wall is subject to compressive force approximately 3 times as much as compared to the reservoir wall. This creates danger of loss of compressive strength of clay-cement concrete of which the wall is built.

Calculations showed that in all the considered cases in COW, there are zones where vertical stresses σ_y exceed uniaxial compressive strength of clay-cement concrete (2 MPa). In the reservoir COW, as a rule, this is the downstream face of the wall in the zone of its embedment into rock foundation (Fig. 8). At that, the values of stresses slightly vary depending on deformation of the foundation alluvial soil.

In the tailing dam wall, vertical stresses exceed uniaxial compressive strength of clay-cement concrete actually height-wise. They amount to 4–6 MPa, and in the zone of embedment into rock, they exceed 5 MPa in alternative 2 (Fig. 8,b) and 10 MPa in alternative 1 (Fig. 8,a).

However, as clay-cement concrete is a plastic material, at evaluation of its compressive strength, it is necessary to take into account the effect of strength increase if lateral compression takes place. This effect is known from experimental results of a number of authors [26, 27].

Mohr–Coulomb theory was used to determine compressive strength of clay-cement concrete in conditions of complicated stress state. The value of hydrostatic pressure on the wall was approximately used as compressive stress. At that, it was assumed that the angle of internal friction of clay-cement concrete was equal to φ = 30°.

Analysis showed that with consideration of the indicated effect, the strength of clay-cement concrete in the reservoir wall would be provided in all the considered alternatives. COW strength of the tailing dam will be provided only in case if deformation modulus of foundation soil will not be less than 80 MPa (alternative 2, Fig. 8, b). In alternative 1, when deformation modulus of foundation soil amounts to 40 MPa, the wall strength will not be provided in any sections height-wise (Fig. 8, a); its integrity will be damaged.

Thus, the tailing dam COW operates in more unfavorable conditions than the reservoir COW and not always it may serve as a safe seepage-control facility of the tailing dam.

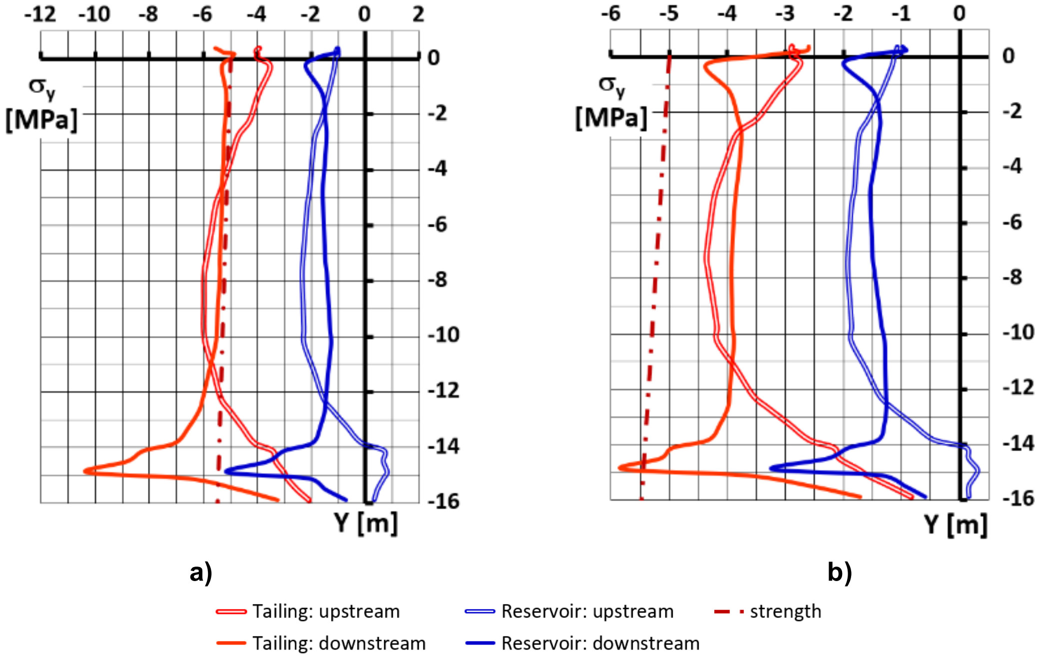

Fig.8. Vertical stresses in в COW: a) – alternative 1; b) – alternative 2.

4. Conclusion

The fulfilled study shows that COW in the foundation of the tailing dam operates in more unfavorable conditions than the COW in the reservoir dam foundation. This is related to existence of additional vertical and horizontal loads.

Pressure from the weight of slimes creates additional vertical force in the wall and increases the risk of compressive strength loss of its material. Selection of mix and properties of clay-cement concrete for COW should be accomplished with consideration of deformation properties of foundation soil. For the considered case of a high tailing dam, the wall strength will not be provided if clay-cement concrete modulus of deformation will be 4 times as much as deformation modulus of foundation soil.

As a result of investigations, an interesting effect was revealed: under other equal conditions, the wall displacements in foundation of a tailing dam may be a little bit less than displacements of the wall in foundation of the reservoir dam. This is related to specific feature of elastic-plastic behavior of soils embedded in the tailing dam foundation.

References

1. Balian, S. Cut-Off Wall Construction at Peribonka dam. International Water Power & Dam Construction. 2007. 59(2). Pp. 42–44.
2. Noll, H., Langhagen, K., Popp, M., Lang, T. Rehabilitation of the Sylvenstein earth-fill dam – Design and Construction of the Cut-Off Wall [Ertüchtigung des Sylvenstein-Staudamms – Planung und Ausführung der Dichtwand]. WasserWirtschaft. 2013. 103(5). Pp. 76–79.
3. Mirghasemi, A.A., Pakzad, M., Shadravan, B. The world's largest cutoff wall at Karkheh dam. The International Journal on Hydropower & Dams. 2005. 2. Pp. 2–6.
4. Faridmehr, I., YazdaniPour, M.R., Jokar, M.J., Ozbakkaloglu, T. Construction and Monitoring of Cement/Bentonite Cutoff Walls: Case Study of Karkheh Dam, Iran. Studia Geotechnica et Mechanica. 2019. 41(4). Pp. 184–199. DOI: 10.2478/sgem-2019-0019
5. Cacciuttolo, C., Pastor, A., Valderrama, P., Atencio, E. Process Water Management and Seepage Control in Tailings Storage Facilities: Engineered Environmental Solutions Applied in Chile and Peru. Water. 2023. 15(1). Article no. 196. DOI: 10.3390/w15010196
6. Alonso, E. The Failure of the Aznalcóllar Tailings Dam in SW Spain. Mine Water and the Environment. 2021. 40. Pp. 209–224. DOI: 10.1007/s10230-021-00751-9
7. Alonso, E., Gens, A. Aznalco´llar dam failure. Part 1: Field observations and material properties. Geotechnique. 2006. 56(3). Pp. 165–183. DOI: 10.1680/geot.2006.56.3.165
8. Wen, L., Chai, J., Xu, Z., Qin, Y., Li, Y. A statistical analysis on concrete cut-off wall behaviour. Proceedings of the Institution of Civil Engineers: Geotechnical Engineering. 2018. 171(2). Pp. 160–173. DOI: 10.1680/jgeen.17.00142
9. Pan, Y., He, Y.-L., Zhou, X.-X., Cao, X.-X. Analysis of effect of canyon terrain on stress and displacement of cutoff wall in dam foundation with deep overburden. Yantu Lixue / Rock and Soil Mechanics. 2013. 34(7). Pp. 2023–2030.

10. Liu, S.-h., Wang, L.-j., Wang, Z.-j., Bauer, E. Numerical stress-deformation analysis of cut-off wall in clay-core rockfill dam on thick overburden. Water Science and Engineering. 2016. 9(3). Pp. 219–226. DOI: 10.1016/j.wse.2016.11.002
11. Pisheh, Y.P., Hosseini, S.M.M.M. Numerical analyses of embankment dams containing plastic concrete cut-off walls using finite difference method (A case study: The Karkheh Embankment Dam). Global Journal of Engineering and Technology Advances. 2021. 9(3). Pp. 143–153. DOI: 10.30574/gjeta.2021.9.3.0176
12. Wen, L., Chai, J., Wang, X., Xu, Z., Qin, Y., Li, Y. Behaviour of concrete-face rockfill dam on sand and gravel foundation. Proceedings of the Institution of Civil Engineers: Geotechnical Engineering. 2015. 168(5). 439–456. DOI: 10.1680/geng.14.00103
13. Wen, L., Chai, J., Xu, Z., Qin, Y., Li, Y. Monitoring and numerical analysis of behaviour of Miaojiaba concrete-face rockfill dam built on river gravel foundation in China. Computers and Geotechnics. 2017. 85. Pp. 230–248. DOI: 10.1016/j.compgeo.2016.12.018
14. Wen, L., Chai, J., Xu, Z., Qin, Y., Li, Y. (2019) Comparative and Numerical Analyses of Response of Concrete Cutoff Walls of Earthen Dams on Alluvium Foundations. Journal of Geotechnical and Geoenvironmental Engineering. 2019. 145(10). Article no. 04019069. DOI: 10.1061/(ASCE)GT.1943-5606.0002132
15. Yu, H., Yu, S., Li, C., Li, W. FEM Analysis of Stress Charecteristics of Cut-off Wall in Rushan River Groundwater Reservoir. IOP Conference Series: Earth and Environmental Science. 2019. 384. Article no. 012171. DOI: 10.1088/1755-1315/384/1/012171
16. Yu, X., Kong, X., Zou, D., Zhou, Y., Hu, Z. Linear elastic and plastic-damage analyses of a concrete cut-off wall constructed in deep overburden. Computers and Geotechnics. 2015. 69. Pp. 462–473. DOI: 10.1016/j.compgeo.2015.05.015
17. Sainov, M.P. 3D performance of a seepage control wall in dam and foundation. Magazine of Civil Engineering. 2015. 57(5). Pp. 20–33. DOI: 10.5862/MCE.57.2
18. Sainov, M.P., Anisimov, O.V. Stress-strain state of seepage-control wall constructed for repairs of earth rock-fill dam. Magazine of Civil Engineering. 2016. (68)8. 3–17. DOI: 10.5862/MCE.68.1
19. Sainov, M.P., Lubyanov, L.V. Stress-strain state of seepage-control walls in foundations of embankment dams. Magazine of Civil Engineering. 2017. 73(5). 96–112. DOI: 10.18720/MCE.73.9
20. Sainov, M., Soroka, V., Gunasekaran, M. Combination of rockfill dam reinforced concrete face and seepage control wall in the foundation: stress-strain state. Construction of Unique Buildings and Structures. 2022. 99(1). Article no. 9902. DOI: 10.4123/CUBS.99.2
21. Li, Q., Ma, G., Li, P., Su, Z. Dynamic characteristics of tailings dam with geotextile tubes under seismic load. Reviews on Advanced Materials Science. 2021. 60(1). Pp. 599–614. DOI: 10.1515/rams-2021-0046
22. Solans, D., Kontoe, S., Zdravković, L. Impact of foundation layer characteristics on the seismic response of a tailings dam. 10th European Conference on Numerical Methods in Geotechnical Engineering (NUMGE 2023). Imperial College. London, 2023. DOI: 10.53243/NUMGE2023-307
23. Kerenchev, N. On the E50 modulus of Tailings dam materials. 19th International Multidisciplinary Scientific GeoConference (SGEM 2019). STEF92 Technology Ltd. Sofia, 2019. DOI: 10.5593/sgem2019/1.2/S02.051
24. Luo, P. Investigation on Shear Wave Velocity and Triaxial Mechanical Performance of Tailings Core from Tailings Dam. Advances in Civil Engineering. 2021. Article no. 5848324. DOI: 10.1155/2021/5848324
25. Bhanbhro, R., Knutsson, R., Auchar Zardari, M., Edeskär, T., Knutsson, S. Mechanical properties of soft tailings from different depths of a Swedish tailings dam: Results from triaxial tests. Scientia Iranica. 2020. 27(3). Pp. 1066–1074. DOI: 10.24200/sci.2018.20418
26. Rasskazov, L.N., Radzinskii, A.V., Sainov, M.P. Strength and Deformability of Clay-Cement Concrete in a Complex Stress State. Power Technology and Engineering. 2015. 48(5). Pp. 361–365. DOI: 10.1007/s10749-015-0534-1
27. Razavi, S.-K., Hajialilue-Bonab, M., Pak, A. Design of a Plastic Concrete Cutoff Wall as a Remediation Plan for an Earth-Fill Dam Subjected to an Internal Erosion. International Journal of Geomechanics. 2021. 21(5). Article no. 04021061. DOI: 10.1061/(ASCE)GM.1943-5622.0001991

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