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THE ANALYSIS AND PREDICTION OF GEO-PERMEABILITY OF HIGH MAN-MADE DUMPS AT OPENCAST MINES IN KUZBASS

The article reviews some basic methods of permeability analysis in dumps composed of coarse refuse rocks and proposes the authors' procedure of permeability determination on a laboratory scale. With a view to predicting water flow regimes in high waste dumps in Kuzbass, using the authors' procedure, the coefficients of permeability are determined for two main types of coal-hosting rocks under normal loads up to 5.0 MPa which conforms with the dump height of 300 m. The correctness of the results is confirmed by the field investigations of the dumps. The numerical modeling of the test flow regimes using RS2 software allowed obtaining reliable coefficients of permeability of refuse rocks. The validate values of the permeability were used to predict water flow regime and slope stability of dumps in similar geological conditions.

Keywords: *dump, coefficient of permeability, geo-permeability, numerical modeling, high dumps*
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Introduction

The recent trend of increasing height of external dumps has greatly impaired the dumping safety. The proof is the 2015 landslide at an external dump of the Zarechny opencast mine in Kuzbass, which involved 27 million m^3 of rocks into the deformation process [1]. The landslide annihilated the close-spaced infrastructure and blocked off a river, with the threat of flooding of the area at the upper pool because of the resultant 'dam effect'. Such accidents, though on a smaller scale and with weaker after-effects, happen increasingly more often when dumps reach a height of 100 m and more. The analysis of the causes indicates that hydrogeological conditions are one of the key factors affecting stability [2–4]. However, geomechanical engineers, when substantiating dump structure designs, neglected that factor and assumed that a filled-up ground remained 'dry' because of the high permeability, and never retained water. The full-scale observations over coal mine dumps in Kuzbass determined their high-degree watering, sometimes up to 60% of a dump height [5]. Omission of this factor in slope stability design increases the risk of landslides. It is difficult to predict hydrological regimes in waste dumps due to lack of relevant rock permeability parameters obtained under high loading due to compaction. For another thing, there is no series-manufactured equipment for the determination of these parameters on a laboratory scale. The common field methods of hydrogeology also have disadvantages. This research aimed to eliminate the listed problems and to reveal patterns of permeability of waste dumps in the range of compaction loads conditioned by gravity pressure in dump bodies more than 100 m high.

In high waste dumps, the increasing compaction induces crushing of disperse elements (lumps, particles), as well as changes the stacking density changes and, consequently, porosity and permeability [1, 5, 6]. Under certain conditions, permeability of rocks may lower down to such values when atmospheric water is retained in the pore space of rocks. As a result, an induced aquifer with free water flow is originated in the dump body [7]. The rate of watering of a dump, and the position of a depression surface on the dump slopes depend on the water intrusion flow rate and on the rock permeability [4, 8] and have a substantial influence on the stability of such geotechnical structures [4, 9].

Research works on hydrogeology usually prefer full-scale methods of rock mass permeability determination, such as test dewatering, filling of boreholes with water and monitoring investigations. Permeability tests are very seldom undertaken at coarse rock dumps because of high labor content and complex technology. The obtained permeability conforms with the current stresses and strains in the natural-and-technical system of a dump, but it will change later on as the dump height is increased; i.e., no hydrogeological object keeps its design parameters in reality.

It is possible to study permeability of growing rock dumps on a laboratory scale using compression strength testing equipment. However, such tests provide incorrect permeability because of the so-called scale effect. Standards of permeation and compression tests cover samples composed of particles not larger than sand, which disagrees with the grain-size composition of waste dumps [10]. Permeation testing of coarser materials can use test bench sets with large test chambers which shut out creation of stress state conformable with the dump stresses. Therefore, predictions of water levels in rock dumps usually take advantage of reference tables. This reduces reliability of hydrogeological calculations, involves high errors in predicted position of a depression curve in a waste dump body and, finally, results in erroneous dump stability. Backward analyses of field hydrogeological observations provide more reliable permeability of waste rock dumps.

Materials and methods

The most amenable method to determine rock dump permeability on site is filling a borehole with water, which allows sufficiently adequate determination of magnitudes of test rock permeability in the first approximation. The method is advantageous for rapidness and simple interpretation of data while disadvantageous for generation of small-size fluid-dynamic excitation during tests. As a consequence, the tests characterize a limited-range zone encircling a test borehole.

The on-hand experience of permeability tests at waste dumps in Kuzbass is scarce. There are data on permeability of dumps composed of siltstone (≈50%), sandstone (35%), mud stone (5%) and silt loam (to 10%) [11]. The permeability tests were carried out during drilling with periodic filling of boreholes with water. The testing embraced a waste dump 127 m thick. Four selected and tested layers in the dump had different coefficients of permeability K_f, namely, the upper layer 35 m thick had K_f of 30 m/day, the second layer 57 m thick had $K_f \sim 20$ m/day, the third layer 35 m thick had $K_f \sim 8$ m/day, and the bottom sand layer had the permeability of 0.5 m/day. The permeability tests revealed permeation nonuniformity along the depth of the dump, due to the change in grain-size composition and in porosity of rocks as the normal loading increased. The permeability in the tests changed as the normal stresses increased from 0 to 2.5 MPa.

The described on-site investigations reveal specific formation of a nonuniform structure of high waste dumps composed of the Balakhon series coal-hosting rocks (C_2-$_3$–P_1). Kuzbass also hosts the Kolchugin series coal–rock masses (P_2) which have much weaker strength [11] and, consequently, are more susceptive to crushing inside a dump body and, accordingly, to decrease in the permeability.

The lab-scale permeability tests of Kuzbass waste rocks under growing vertical loading used a test chamber manufactured as a thick-wall hollow cylinder with a height of 40 cm and internal diameter of 12.5 cm [12]. At the top of the cylinder, a hermetic piston was arranged. The top and bottom of the cylinder had holes for letting water in and out (**Fig. 1**) [12].

The test dispersion sample with grains 2–5 mm in size and a preset density of 1.85 g/cm^3 was placed in the permeability test chamber. Then, the chamber was set on a hydraulic uniaxial compression machine which ensured the required compaction of the sample during the test. A standard procedure was used to determine initial permeability of rocks at $\sigma = 0$ MPa and, then, the successive values of permeability by stages of loading in the range $\sigma = 0.05$–5.0 MPa. Sensors recorded vertical deformations. After stabilization of vertical deformations, the permeability tests were carried out. The tests involved two types of overburden rocks composed of sandstone and siltstone from the Balakhon and Kolchugin series in Kuzbass. Concurrently, the change in the grain-size composition of rocks under vertical loading in the above-said range was examined.

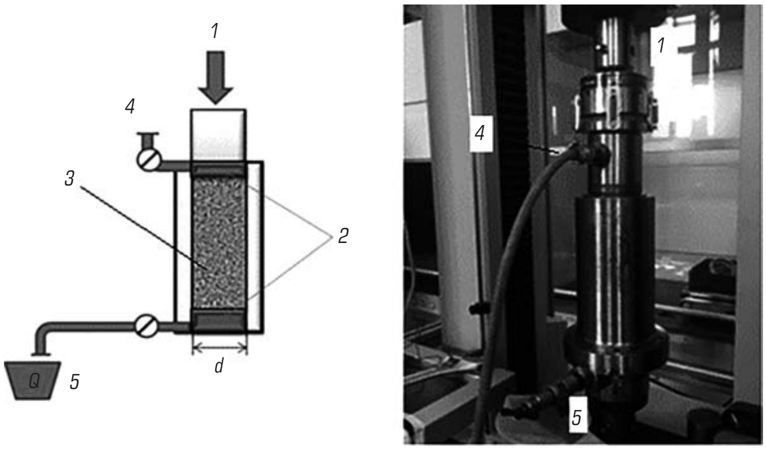

Fig. 1. Permeability testing of coarse rocks:
1 – application of vertical pressure; *2* – filters; *3* – test rock mixture of preset density; *4* – water feed; *5* – water outlet and flow rate metering: *d* – internal diameter of permeability test chamber, m; *Q* – water flow rate, l/s

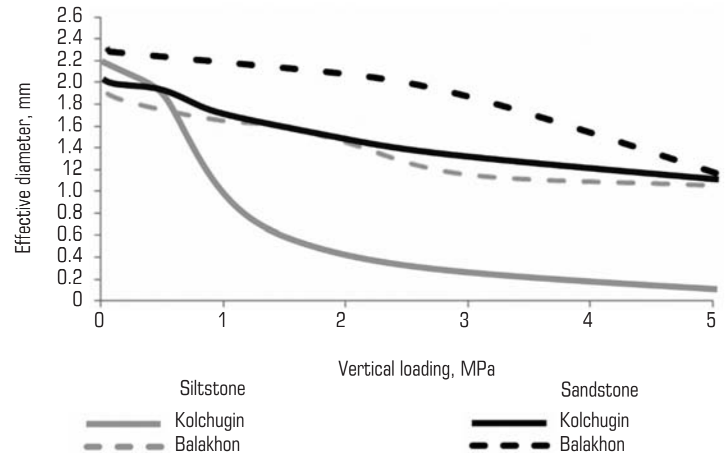

Fig. 2. Change in effective diameter under growing vertical loading for the Balakhon and Kolchugin series rocks

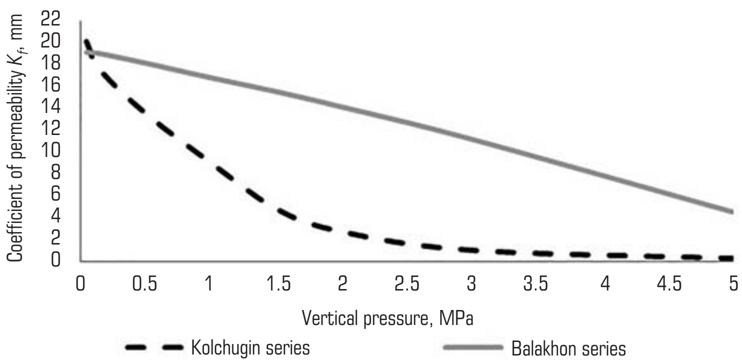

Fig. 3. Permeability versus compaction of waste rocks

Results

The data processing and analysis used the value of the effective diameter understood as a diameter of 10% of all particles in a sample. The resultant curves depict a trend of increase in dispersion ratio of waste rocks as the external loading grows (**Fig. 2**) [12]. In the test stress range (to 5 MPa), the increase in the dispersion ratio of the Kolchugin series rocks takes place at the loads of 0.5 and 1.2 MPa (conforms with the dump heights of 30 and 65 m, respectively), the same takes places in the Balakhon series rocks at 1.5 and 2.7 MPa (dumps 85 and 150 m high, respectively).

The analysis of the lab-scale tests yielded the patterns of variation in the coefficient of permeability of rock dumps (**Fig. 3**) [12]. The Balakhon sandstone–siltstone mixtures with characteristic carbonate cement, metamorphic grade fit with formation of coking and low-caking coal, and uniaxial compression strength to 80 MPa showed a gradual and almost linear decrease in the coefficient of permeability (the upper curve in Fig. 3) from 19 to 4 m/day. This curve may be best approximated by the empirical linear law $y = -2.9351x + 19.61$, where y stands for the value of the coefficient of permeability and x is for the value of the normal load. The Kolchugin series rocks, with clayey cement of particles, metamorphic grade fit with formation of long-flame and gas coal, and uniaxial compression strength to 40 MPa demonstrated a more pronounced exponential decrease (the lower curve in Fig. 3) in the permeability from 30 to 0.2 m/day by the law: $y = 19.827e^{(-0.914x)}$. From the viewpoint of permeability, the first mixture of waste rocks, despite the high compaction loading (agreeable with the dump heights of 250–300 m) remains well-permeable. For this reason, subject to infiltration regime in the test region, such man-made bodies can hardly likely form an aquifer. For the Kolchugin series rocks, the coefficients of permeability under loading higher than 2.5 MPa (conformable with the dump heights of 120–130 m) are 0.25 m/day, which characterizes the test mixture as weakly permeable rocks. Therefore, a free-flow aquifer is quite expectable to appear in such rock dumps. This inference is confirmed by the field observations of dumps at open pit mining of the Kolchugin series seams [13].

In summary of the laboratory permeability tests of refuse rock mixtures, the actual composition of geotechnical structures, especially after elimination of hydraulic stripping in the test region, can greatly differ from the test materials studied by the authors. At some open pit coal mines at the early phase of coal mining, dumping involves much

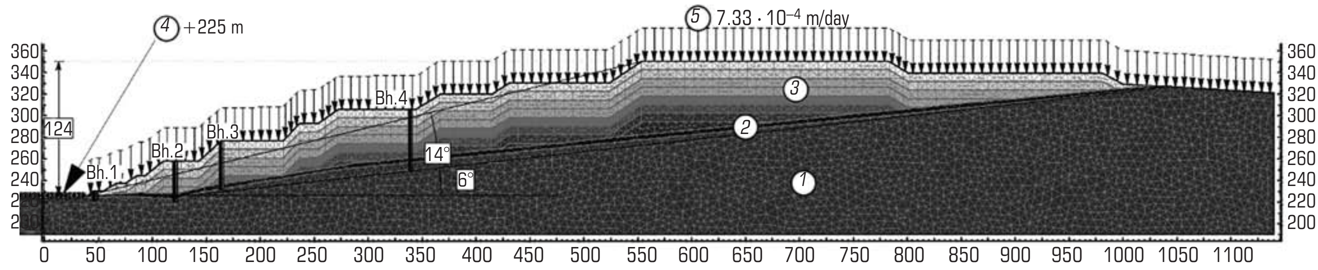

Fig. 4. Analytical model of water flow in dump:
1 – bed rocks; *2* – Neogene–Quaternary rocks; *3* – refuse rocks of various permeability; *4* – constant water head at the level of +225.0; *5* – infiltration flow rate of $7.33 \cdot 10^{-4}$ m/day

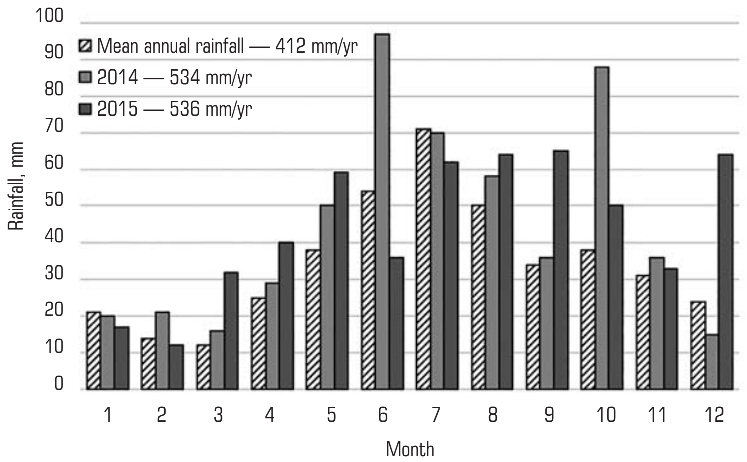

Fig. 5. Rainfall in the test area per months

Neogene–Quaternary clayey rocks (sometimes up to 40%), mostly, light silty loam. This circumstance essentially reduces permeability of waste dumps and conditions formation of induced aquifers even in low dumps. The role of hydrogeology in slope stability increases in proportion to the portion of low-permeable loam placed in the dumps. In this connection, investigations of dumps should first of all address the issues connected with the presence of loam material, its quantity and distribution in a dump. Due to lack of such information, it is impossible to model such dumps and to test them on a laboratory scale. The geo-permeability analysis of specific dumps should use the method of backward hydrological calculations on the basis of stability monitoring investigations of such objects.

Numerical geo-permeability modeling is the favorite method for processing observations over ground water flow in bodies of waste dumps [14–16]. The mathematical model of water flow includes equations, boundary conditions of water heads and initial conditions for nonstationary problems which determine water heads in the test domain at the initial stage of modeling [2, 4]. According to the Darcy law, the main equation is given by:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t},$$

where H is the general head; k_x is the horizontal permeability coefficient; k_y is the vertical permeability coefficient; Q is the boundary flow rate; θ is the volumetric water content; t is the time.

The problems on groundwater head patterns in 2D and 3D formulations are solved either using the analytical relations, or finite or discrete element methods. Practical engineering uses various software systems with mathematical modeling of both stationary and nonstationary flow. In particular, numerous studies addressed prediction of water level in man-made and natural slopes due to rainfall [17–28]. The present research used Rocscience RS program with the finite-element groundwater seepage analysis as the basic functional module.

We report the modeling results as a case-study of an external dump at the Zarechny opencast mine within the limits of the Talda coal field. The external dump is operated since 2004. In the test locality, overburden is composed mostly of siltstone and, to a lesser degree, of sandstone, mudstone and Neogene–Quaternary sediments representing silt loam and clay of various density. The ratio of solid and quaternary rocks in the dump is 60/40%. The dump has a bottom area of 93.6 ha, maximal depth of 1900 m, width of 850 m and an intake capacity of 60 Mm^3. The height of the dump varies laterally from 75 to 140 m, and the net slope angle changes in the range of 10–16°, with the minimal angle recorded at the maximal height of the dump. Geomorphologically, the terrain is sloped at the angles of 4–8° (maximum to 10°). In early April in 2015, during active snow melting, a large landslide occurred on the outward slope and grasped 27 Mm^3 of refuse rock mass of the dump.

For the analysis of the landslide causes, and for the decision-making on recommencement of operation of the emergency facility, a special site survey was carried out, including investigation of the hydrology of the slid and non-slid sites. The scope of hydrogeological analysis included long-term monitoring investigations using a well pattern covering two cross-sections. The wells were equipped with hydrostatic pressure sensors installed in the body and at the bottom of the dump. The measurement analysis definitely revealed the main factor which initiated the deformation process and the change in the water flow regime. Namely, formation of an induced aquifer in the dump body and generation of excessive pore pressure in the natural rock bottom. There were also other causes of landsliding, left beyond the scope of the present research.

The first-stage model of geo-permeability on the non-slid site of the test dump depicts its hydrogeological structure (**Fig. 4**). The permeation properties of the dump from observation drilling to a depth of 10 m are characterized by the coefficient of permeability of 2–10 m/day typical of disintegrated coal–rock mass. For the bottom waste rock layer lying above the natural Neogene–Quaternary clayey rocks, and composed of mostly compact and degraded refuse, the coefficient of permeability is 10^{-3}–10^{-2} m/day. In the central layer between these two distinct layers, the permeability changes according to an exponential distribution law similar to the pattern obtained on a laboratory scale for the Kolchugin series overburden ($K = 7.68\ e^{-0.126h}$, where h is the layer depth).

The second-stage geo-permeability modeling adopted some statements and assumptions:

—2D problem on stationary water flow;

—watering is only due to infiltration flow, additional potential inflow in narrow areas and upward flow from head aquifer in bed rock are discarded from the research;

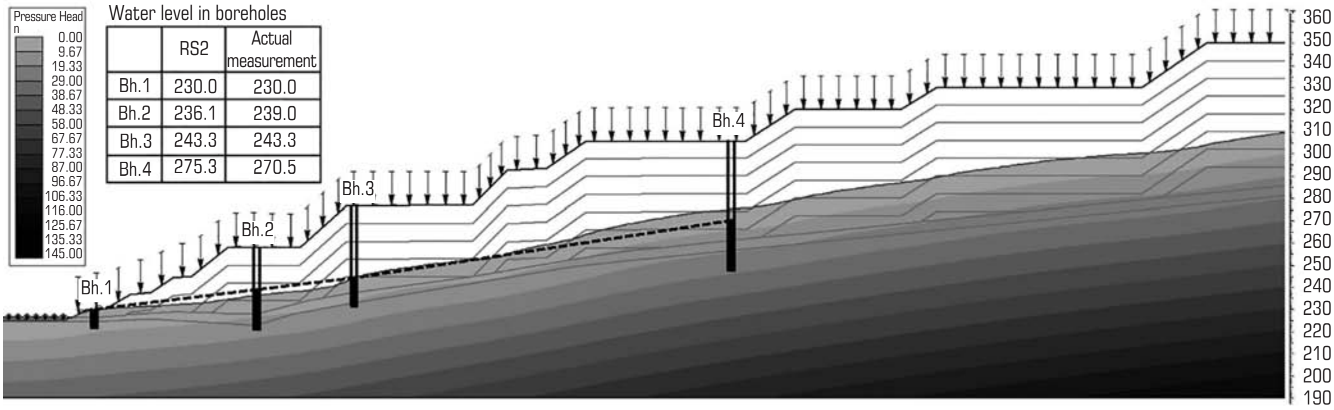

Fig. 6. Geo-permeability modeling

Coefficient of rock permeability from modeling, m/day

Index	Refuse rocks								Neogene–Quaternary loam	Bed rocks
Depth, m	0–8	8–16	16–24	24–32	32–40	40–48	48–56	56–64		
Coefficient of permeability	4.3	2.2	0.69	0.26	0.052	0.026	0.008	0.007	0.005	0.005

—the induced aquifer is water-proof;

—the second-order triangular finite elements have linear size of 4–5 m;

—the clayey bottom and underlying bed rocks have permeability lower than the refuse rocks have;

—the permeability inside each cluster is isotropic;

—for the depth-wise permeability differentiation, the model domain is divided into layers 8 m thick, which is governed by the discrete nature of the model and has no special physical sense.

The geo-permeability modeling included the boundary conditions: at the lower slope edge, a constant head was set in conformity with the elevation (+226.0 m); at the upper boundary, the preset infiltration flow rate was $7.33 \cdot 10^{-4}$ m/day. That value was assumed on the basis of the meteorological observations at the Kiselevsk station, after surface flow and evaporation adjustment [8, 29]. The average annual rainfall in the period of groundwater observations in the dump between 2014 and 215 was 535 mm (**Fig. 5**).

The numerical experiment produced a depression surface very similar to the actual depression surface (**Fig. 6**). The authors verified the model using the water levels determined in the observation boreholes. The model depression surface fitted 1/3 of the dump watering along its height. The modeling results allowed determination of permeability for a specific waste dump (**Table**).

Discussion

The long-term investigations of dumps at coal mines in Kuzbass [1, 30] point at the urgency of adding their slope stability analysis with one of the main factors of hydrogeology—an induced aquifer which forms because of reduction in permeability of waste rocks as the dump height is increased.

The efficient method of studying permeability of waste dumps is filling of boreholes with water as it allows finding permeability of waste rocks at great depths of their occurrence. However, this approach lacks full-scale application because of its high labor content. The analysis of the on-site testing of a dump composed of the Balakhon series overburden shows a gradual decrease in the permeability of rocks from 30 to 8 m/day along the depth of the dump, which agrees with the lab-scale test data of the same types of rocks.

The procedure proposed by the authors for the dump permeability determination on a laboratory scale provided the laws of decrease in the permeability of rocks with the increasing vertical load applied to them to simulate the increasing height of a dump. Moreover, waste rocks of the Balakhon and Kolchugin series were characterized as permeable and impermeable, respectively. These findings explain the specific hydrogeological structure of the dumps composed of 'younger' rocks from the Kolchugin series. Such dumps at the height of more than 100 m contained an induced aquifer. The dumps composed of disintegrated overburden from the Balakhon series remain almost always dry because of their relatively high permeation properties.

In case of the more complex condition of dumping, when it is impossible to predict composition and structure of the man-made objects, or to assess their hydrogeological structure, it is advisable to predict groundwater flow using numerical geo-permeability modeling and the monitoring data of water level measurements. The obtained results are applicable in prediction of watering level in dumps at their design stage and during slope stability estimation to ensure reliable justification of the optimal parameters.

Dumping and dump operation must involve integrated safety monitoring, including, among other things, hydrogeological observations [31–37]. The monitoring data should be used in verification of computer models, which can improve accuracy of prediction of water level changes with the increasing dump height.

Conclusions

The mixtures of refuse disintegrated coal-bearing hard rocks of different material composition, age, metamorphic grade, cement, time and uniaxial compression strength are investigated on a laboratory scale. The permeability coefficients are found for the test rocks of the Balakhon and Kolchugin series from coal deposits in Kuzbass. The Balakhon series overburden rocks feature a linear change in the permeability from 20 to 4 m/day as their compaction pressure grows from 0 to 5 MPa. The second-type rocks have the coefficient of permeability which decreases exponentially from 20 to 0.2 m/day, which is reflective of their low permeability [12].

As a case-study of a waste dump at the Zarechny opencast mine, the experimental numerical prediction of the depression surface is carried out, and the numerical model is verified using the actual water flow monitoring data. Finally, the hydrogeological structure of the test dump is validated, the dump permeation properties are determined, and the dependence of the coefficient permeability on the depth h is found: $K_f = 7.68e^{-0.126h}$.

The developed procedure of the water flow regime analysis and prediction in refuse dumps can facilitate reliable estimation of slope stability and well-justified design of high dumps.

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