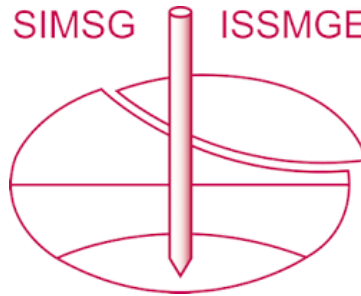


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Methods to estimate and reduce negative impacts of tailing dams on the environment

Méthodes pour l'estimation et la réduction des conséquences négatives des barrages de déchets sur l'environnement

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SYNOPSIS: The paper deals with the analysis of main causes of tailing dam failures. The results of the large-scale studies of silt flow generations during tailing dam failures and of flow movements under plain country and bed conditions are presented. An approximate estimation of principal mud flow parameters is suggested. Measures to prevent failure possibility for tailing dams and to reduce damage caused by silt flows are briefly considered. Based on field and laboratory studies of physico-mechanical characteristics of tailing dam deposits, calculations of the consolidation process with allowance for a substantial non-linearity of these characteristics are shown to be of necessity. It is proposed to make calculations of slope stability and seepage losses on the basis of the consolidation estimation. Measures to prevent environmental contaminations by toxic waters of tailing dams are considered and the reduction of the efficiency of drainage arrangements made in a tailing dam body is shown. As to clay screens, it is suggested that permeability should be determined due to field data, obtained in the tests using specific percolating fluids.

In recent decades quantities of annual ore outputs and ore reprocessing at mine concentration mills have substantially increased. The increase of dressing waste storage sizes as well as the trend toward the reduction of wasted areas have resulted in the increase of tailing dam heights which at present often amount 100-150 meters.

Along with tailing dam height increases one can observe a constant regular tendency toward a significant decrease of strength characteristics of stored materials that is connected with a decrease of ground ore particle sizes. As a result, there rises a danger of environmental contamination due to seeping waters, containing toxic reagents used in the process of ore concentration as well as due to tailing dam failures resulting both in a sudden discharge of polluted waters on the adjacent country and, in some catastrophic cases, in the generation of silt flows of high destructive effects.

The analysis of more than one hundred tailing dam failures made it possible to bring out some principal reasons of these failures (Trunkov, et al. 1980).

More often failures were due to mud settling pond overfilling and to water flowing over dam crests (25%); faults in operation of discharge structures as well as pulp conduit breaking (41%). A number of failures were caused by improper techniques for foundation soil preparations (6%), faults in the construction of pioneer structures and in aggradation techniques (26%).

Some failures (2%) occurred as a result of an inadmissible increase of slope steepness during tailing dam operations.

It is to be noted, while summarizing, that about 50% of tailing dam failures resulted from breaking service instructions. Approximately 28% of all the failures were due to substandard construction of primary structures, primary dams, for example, and some 23% of them resulted from design errors. Moreover, some peculiar changes

in tailing dam failure intensity as compared to conventional hydraulic fill dams can be observed (Figure 1). A higher intensity of tailing dam failures and their faster progress in time may largely be explained by the fact that tailing dams unlike hydraulic fill dams, have been practically constructed and operated at the same time during the whole period of their existence, that is for 20-25 years.

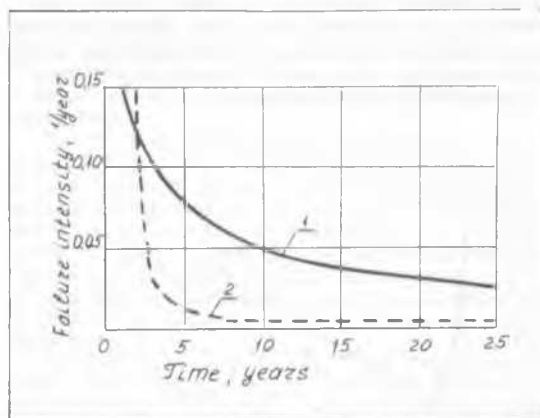


Figure 1. Failure developments in time from the beginning of the structure erection:
 1 - tailing dams; 2 - hydraulic fill dams.

The most hazardous type of failures is a seepage failure or slope scouring of tailing dams resulting in flowing of water and portions of unconsolidated tails out of pond zones on the adjacent regions. The estimation of tailing dam failure impacts, boundaries of mud flow motions and flow parameters in particular (discharge, velocity, depth and pressures exerted on impedi-

ments) enables to design special engineering measures to protect villages and structures getting into a zone of a feasible flow movement.

The generation of silt flows starts with a beach zone scouring, thus, water and pond sediments flow through a breach developed in the dam body.

Mud flows are formed by upper soil strata of a pond zone which have a low density of a soil skeleton ($0.2-0.4 \text{ t/m}^3$) and a moisture content as high as 80-100%. It is characteristic that for pond zone soils ultimate shear stresses determined by means of a viscometer, abruptly decrease at the moisture content more than 100%. Depending on soil grain-size distribution and on the intensity of the tailing dam growth, the capacity of such a movable layer can vary from 2 to 10-20 meters.

In order to study the process of silt flow movement, a number of field experiments were carried out on special test sites built near the operating tailing dams, which simulated two limit cases for flow movements both across a plain country which makes it possible for a free flow expanding and along the bed that has areas with different bottom slopes.

On each test site there were constructed reservoirs formed by dams, with the capacity up to 2000 m^3 for storing and aggradation of pond zone fine tails. Vertical 4 x 6 m panels-gates were installed in concrete bulkheads, a sudden opening (falling) of which simulated a tailing dam failure and a formation of a breach. On the way of a silt flow movement some sensors were installed to measure the velocity of the flow front movements, its width, maximum depth and dynamic pressures. Initial flow depths varied from 1m to 4 m, and initial density variations were in the range of $1.2-1.5 \text{ t/m}^3$. A number of trials were made using water discharge (1 t/m^3). It is to be noted that density variations of the flowing soil-water mixture did not affect the parameters of the spreading flow. Based on the test data, main parameters of the mud flow both on a plain country (Figure 2) and in a given bed could be defined (Figure 3).

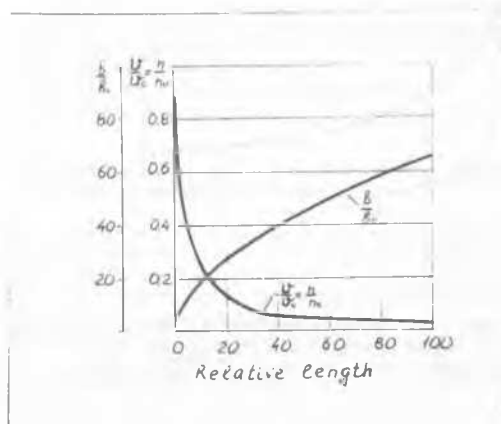


Figure 2. Variations of movement velocity V ; depth h and width b for a mud flow over the length x of a diffusion zone; V_0 , b_0 , h_0 - initial velocity, width and depth.

There are different types of protection structures reducing tailing dam failure consequences,

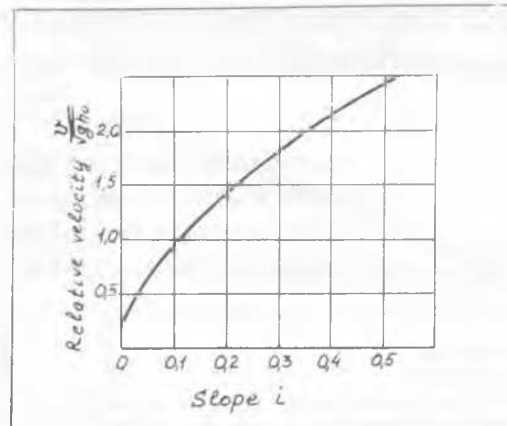


Figure 3. Movement velocity V of a mud flow along the bottom having various slopes i .

namely: barrier dams and wing dams, flumes, tail races as well as dams creating reservoirs for mud flow accumulations. The arrangement at one of the tailing dams on a plane country of a small 3 km dam (its height was 3-1.5m) could prevent the protected settlement from flooding and diverted the mud flow from agricultural lands during the tailing dam failure.

Measures that would completely prevent possible disturbances in the stability of tailing dams that is largely determined by structural characteristics of tailing dam soils should be considered to be the most effective.

As field and laboratory investigations showed three peculiar deposit zones in a tailing dam body could be distinguished: a beach zone mainly represented by sands; a pond zone composed of heavy loams and clays and a transitional zone, grain-size distribution of which corresponds to that of sandy soils and light loams.

Due to a low initial density, tailing dam soils are characterized by essential non-linear relations of deformation, strength and seepage characteristics to a stressed state and also by a great variability of these characteristics both within one and the same zone and in a transition to another zone (Figure 4). For example, an internal friction angle varies from 20° in a pond zone up to $32-35^\circ$ in sand soils of a beach zone. Permeability and consolidation coefficients of pond zone deposits vary in the process of a tailing dam construction over tens or hundreds of times. The soil skeleton density of pond deposits during their compaction varies in the widest ranges, from 0.3 to $1.8-2 \text{ t/m}^3$, for example, as the structure grows in height.

In this connection, the solutions for plane and spatial problems of the consolidation theory in Florin's formulation were applied to estimate the processes developing in tailing dams, with allowance for considerable variability and non-linearity of soil characteristics in space and time and for a gradual structure height increase, incomplete water saturation of soils as well as for a number of other factors (Ivanov 1983).

Based on pressure or head values in pore water for the whole tailing dam, obtained from consolidation computations one could estimate the tailing dam stability using the method of the given slip planes and, what is more essential, for the problems of impurity evaluations it has

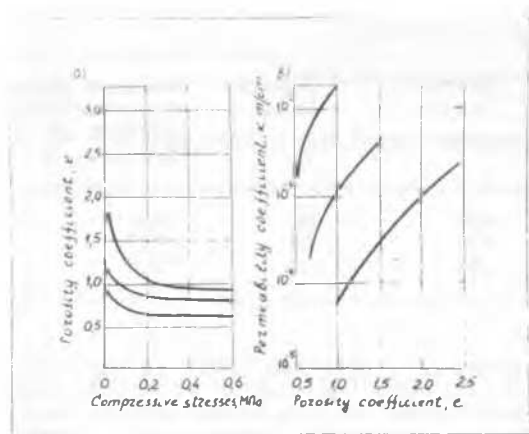


Figure 4. Compressibility and watertightness for soils of tailing dam specific zones: 1 - heavy loams and clay of a pond zone; 2 - light loams of a transition zone; 3 - sands and sandy soils of a beach zone.

become feasible to determine percolation losses of tailing dams on the basis of boundary head gradient and permeability values.

It has been shown that the efficiency of such measures as draining of a tailing dam foundation and body abruptly decreases in time. A substantial reduction of drainage effects on the consolidation process acceleration due to the fast and appreciable permeability decrease of the soils available on the boundary with draining layers was observed. In one of the tailing dams, for example, (Figure 5) the discharge of waters seeping into a draining foundation reduced eight fold, while the structure height increased by 30 m.

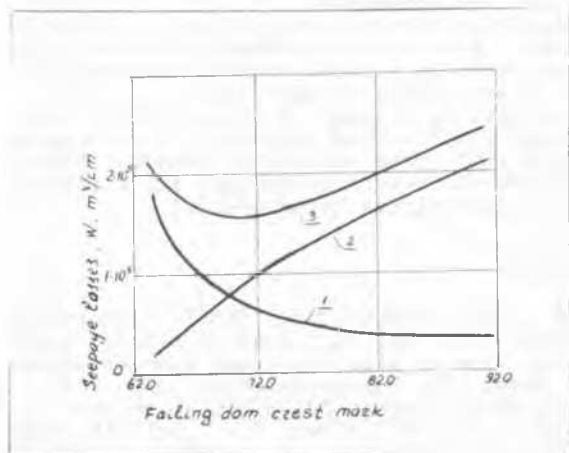


Figure 5. Volumes of water seeping out of tailing dams: 1 - through foundation soils; 2 - into tailing dam slopes and boards; 3 - summary.

In order to decrease and even completely prevent environmental contamination by sewage waters various screening drainage devices may be applied, the most effective of these being

screens made of compacted clay soils, polymer film materials and asphalt-concrete (Nedriga, et al. 1972). The screens are classified into one-layer screens and two-layer screens. If one-layer screens made of polymer films and asphalt-concrete are applied, it is necessary to reduce to allowable limits the quantity of sewage flowing from storage reservoirs.

Since clay soils possess sorption characteristics the application of one-layer screens made of these soils enables not only to reduce seepage, but also to make sewage seeping through soils less detrimental. When two-layer screens are used, it becomes feasible not only to reduce abruptly but also fully prevent, if necessary, seepage from storage reservoirs. Sewage fluids percolated through the upper less pervious screen layer get into the drainage layer and is drained out of the screen by weepers. Since the fluid layer in the drainage layer is small in height, the seepage flow discharge through the lower layer of the screen essentially decreases, and it is this fact by which high anti-seeping characteristics of this type of screens may be explained. Creating vacuum in a drainage layer fully prevents fluid percolations through the lower layer.

Screen operation conditions for river hydroengineering structures and for industrial storage reservoirs greatly differ. Fresh water in the first case and an aggressive sewage fluid in the second case percolate through the screen, the latter situation requires that calculations be made for a screen resistance to stored sewage fluid impacts.

Studies of clay screens have been carried out for several years at the research institute "VODGEO". Data concerning permeability variations for clay soil fragments obtained as a result of a long term exposure to sewage fluids, acids, alkalies, salts were published elsewhere (Pavilonsky 1985). It should be reminded that depending on the soil type and characteristics of a seeping fluid, permeability increased 1.1-1000 times, but in some cases a certain decrease of the permeability coefficient could be observed.

One of the most important and less studied is the problem concerning permeability of clayey soils through which organic fluids and petroleum refining products percolate. In connection with an extensive development of chemical factories there arises the necessity of making calculations for migration of different substances including organic fluids in structure foundations, when solving the problem of environmental protection.

The values of permeability determined in the tests with water being applied which is considered to be incorrect, are commonly employed. The experiments carried out at the "VODGEO" institute enabled to state that soil permeability is largely dependent of the fluid that percolates through the soil. The tests were performed on the samples made of three types of clay (see Table 1), using a glass device or a column type. The volume of the fluid percolated was determined due to reduction of the fluid level in the device over certain time intervals.

At the first stage of the tests permeability was determined by using organic fluids, but at the second stage water was employed. At each test stage about 16-35 permeability values were obtained, the results of their statistical treatment being given in Table 2.

Table 1. Properties of the soils.

Soil	Density of solid particles, g/cm ³	Particle-size distribution, %			Liquid limit	Plastic limit	Maximum molecular moisture content by Lebedev, %
		0.25-0.05mm	0.05-0.005mm	0.005mm			
Clay 9	2.74	6.7	35.6	58.3	45	28	19.0
Clay 15	2.78	40.8	46.5	12.7	47	28	19.7
Loam	2.76	9.8	32.8	57.4	38	24	16.8

Table 2. Results of permeability calculations.

Soil	Permeability during seepage, cm/s	
	Fluid	Water
Clay 9 [■]	Toluol	(7.2±1.5)10 ⁻⁴
	Acetone	(3.6±1.4)10 ⁻⁴
	Kerosene	(4.6±1.3)10 ⁻⁴
	Carbon tetrachloride	(1.7±0.5)10 ⁻⁴
	Petroleum	(1.3±0.1)10 ⁻³
		(1.2±0.4)10 ⁻⁶
Clay 9	Toluol	(5.5±1.2)10 ⁻⁴
	Acetone	(3.1±1.4)10 ⁻⁴
	Kerosene	(5.0±1.1)10 ⁻⁴
	Carbon tetrachloride	(8.8±3.0)10 ⁻⁴
	Petroleum	(1.6±0.4)10 ⁻³
		(7.4±3.5)10 ⁻⁸
Clay 15	Toluol	(1.4±0.3)10 ⁻³
	Acetone	(5.7±1.5)10 ⁻⁴
	Kerosene	(4.3±1.0)10 ⁻⁴
	Carbon tetrachloride	(2.0±0.6)10 ⁻³
	Petroleum	(1.9±0.5)10 ⁻⁴
		(5.1±0.3)10 ⁻⁷

[■]Without a detainer being applied.

Permeability varied in the limits of 1.7×10^{-4} - 3.92×10^{-3} cm/s, at the first stage of all the tests. When a fluid was replaced by water, permeability reduced, this reduction being different depending on the soil and fluid types applied in the first stage.

The decrease of permeability was more pronounced in the tests carried out on clay 9 without a detainer. After the replacement of toluol, kerosene, petroleum and carbon tetrachloride, permeability decreased by a factor of 5268-7409, and when water was used instead of acetone, it decreased 1144 times.

The following data can illustrate permeability dependence on soil and fluid types. When water was applied instead of petroleum, permeability for clay 9 decreased 7082 fold, for clay 15 it decreased 436 fold and for loam - 2543 fold. After replacing carbon tetrachloride by water, permeability decreased 5268 times for clay 9; 2922 times for clay 15 and 377 times for loam.

The absence of a detainer (that is the possibility of soil swelling) deeply affected permeability variations. In the tests carried out without using a detainer, permeability decreased 322-1848 fold, after replacing a fluid by water. It is characteristic that the availability of a detainer or its absence had weak effects on the permeability determined in the tests using organic fluids, but marked effects when water was used.

At the third stage of the tests using loam, after replacing water by a fluid, permeability rose to the values that differed very little from those obtained at the first stage. The reason for this difference in permeability values for organic fluids and for water lies in the fact, that in the latter case there occurred soil swelling, the formation of hydrate envelopes round the particles and so on.

Thus, the environmental protection from contamination by industrial wastes is a complex problem involving such measures that would provide for: stability of both tailing dams and storage reservoirs; reducing seepage through tailing dam boards and foundations; complete purification of sewage getting into a tailing dam; developments of protection measures in certain cases for objects getting into a zone with possible mud flow movements.

Antiseepage screens employed in the Soviet Union enable to reduce substantially and, if necessary, totally prevent sewage from seeping out of waste storage reservoirs.

In estimating seepage of organic fluids and petroleum distillation products, it is necessary to apply only those values for permeability coefficients which were determined experimentally with the same fluids being applied.

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