BASIC ASPECTS OF DESIGN AND OPERATION OF HIGH HYDRAULIC FILL STORAGE FACILITIES IN RUSSIA. ORGANIZATION OF MONITORING, STATE ASSESSMENT, ANALYSIS AND FAILURE RISK ASSESSMENT OF DAMS (*)

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RUSSIAN FEDERATION

1. INTRODUCTION

Russian specialists are now very experienced in the issues of design and operation of tailings and ash storage facilities' (ASF and TSF) dams, which are filled hydraulically from wastes and capping soils.

ASF and TSF dams are the most significant hydraulic structures. They must satisfy a number of regulations on stability, seepage strength and deformations according to their class and also the requirements of environmental protection. Leakage of waste water from the storage facility, as long as its discharge beyond the boundaries of the reservoir is unacceptable without proper mechanical, chemical and biological purification.

* Particularités de conception et d’exploitation des grands remblais hydrauliques en Russie, organisation de la surveillance, de l’analyse et de l’évaluation de l’état et des risques d’accidents des barrages
In Russia all existing storage facilities can be divided into the following groups, according to the method of construction:

- water retention tailings dams, which are built to their full height prior to the beginning of milling and processing operations;
- raised embankment, when a low starter dyke is constructed first; this dyke is needed to organize discharge process; later the embankment is raised by the construction of a number of stages (lifts); in case the dam is assumed to be constructed in stages, this process must be properly designed;
- storage facilities without starter dyke and subsequent lifts.

2. THE FEATURES OF DESIGN

The design of industrial waste storage facility includes technical decisions of the principle issues of the structure's construction and operation, the composition of structures, location, method of waste discharge, influence of seepage and polluted water discharge on the quality of ground waters of the region, circulating water supply, clarification and discharge of water and substantiation of feasibility and financial viability of the considered variant of the structure's design and operation. General description of the site and its detailed plan should be also included.

The technological part of the design includes information on the method of tailings or ash deposition and on the organization of this process, defines the necessity and possibility to use clarified water for circulating water supply, choses basic equipment of the enterprise, forms the data sheet needed to be ordered, assesses the amount of power, water, fuel and personnel needs. Cross-sections of the storage facilities are designed within this part, with locations of basic equipment being marked.

The constructional part of the design according to the active codes and regulations includes information on the location of the storage facility, building materials and facilities needed to construct basic structures. The building description of the storage facility is provided, including schematic plans and cross-sections of buildings and structures with structural volumes and areas being shown. Water sources and waste water discharge points are determined; water supply, sewage, heating and air conditioning schemes are designed with needed equipment being chosen.

The organizational part of the design includes information on the volume of construction works and methods of their fulfilment, needed resources (electro power, water, building machines, materials and labor forces) and approaches
towards satisfaction of these needs. The time schedule is formed, which indicates the construction terms and commissioning of the storage facility and separate structures corresponding to the definite height of the embankment dam.

When choosing the location of the storage facility, the developer fulfils the following work package:

- financial calculations and engineering survey;
- feasibility study and comparison of a number of sites;
- coordination with corresponding bodies in the issues of the design, boundaries of the site, service lines, waste water discharge points, measures to prevent the submergence and impounding of areas in the region of the proposed storage facility location.

The class of responsibility of a TSF or an ASF is determined according to the performance of the enterprise, dam height, type of foundation soils and possible consequences of its failure.

The increase of the class by one is allowable when:

- the failure of especially responsible structures of a TSF can have a disastrous effect on local communities and enterprises;
- the storage facility is used for circulating water supply of a responsible enterprise.

During justification of the design of the embankment height increase, its technological feasibility should be taken into account. The full set of analyses is to be fulfilled, including analyses of stability, seepage strength and deformation of the structure. All active loads and impacts should also be applied. During the process of justification, the segregation of tailings is considered. The distribution of particles varies depending on deposition methods, but in any case the coarser particles settle closer to the discharge point and the finer in the settling pond. The presence of ice in frozen deposits influences their rheological behavior and also defines their behavior under loads and changes of temperatures below zero. That is why the strength properties of wastes depend on their water content.

The design of a TSF or an ASF also depends on the specificity of the foundation of the structure, features of works to be done, class of responsibility, geological and hydrological conditions and economic feasibility. On the design and construction stages such issues as foundation preparation and embankment construction methods (hydraulic fill, damping of sand on dry foundation or into water, filling of capping soils, etc.) are also taken into account.

Special attention is paid to foundation preparation, especially to weak clayey, peat and other soils, which can cause excessive deformations.
Special design of hydraulic structures and foundation preparation methods should be used in case of cold climate conditions and presence of frozen ground (especially on peat swamps).

In case of presence of weak silty loams in the foundation of embankment dams, special attention should be paid to its drainage and development of excessive pore pressures, which considerably reduce the shear strength of soils, should be also considered in slope stability analysis.

In case of presence of permafrost in the foundation of the storage facility, the structure should be designed with regard to thermal and mechanical effect of waste on foundation soils and the features of the embankment.

In every individual case the design should include measures to provide uniform deformations of the dyke.

The storage facility should be designed in such a way as to prevent seepage of water from the settling pond, ground and surface water pollution, the bed and abutments of the TSF should be virtually impermeable. These prevention measures should be considered for the whole period of operation. It is compulsory to create a network of inspection holes designed to monitor phreatic surface levels and chemical composition of water within the adjoining area.

In seismic regions (with seismicity more than 7-point according to MSK-64 scale) or in locations close to industrial dynamic impact sources it is necessary to consider possibility of liquefaction of saturated tailings.

The storage facilities, which can be the source of dusting or objectionable odor, should be separated from residential, public and medical buildings and structures and recreation zones by buffer areas, which should be not less than 300 meters wide (from design boundary of the storage facility to a public or residential building).

As a dusting-prevention measure, wastes should be deposited in uniform layers, so as to provide permanent wetting of the whole area of deposition.

Wind erosion protection measures are developed for every storage facility individually. The upstream slope can be protected in different ways: by maintaining maximum allowable elevation in the settling pond with beach width being supported at the design level, by wetting of the beach using irrigation methods; by chemical grouting of wastes, by casting of ice 3-6 centimeters thick or using snow-keeping techniques.

Downstream slope can be protected from erosion using one of the following methods: covering the surface of the slope with a layer of gravel and sand or slag or with vegetation layer not less than 0.10 meters thick.
The type of covering should be chosen with respect to the features of the structure (climate of its location, chemical and mineralogical makeup of slurry). The surface of the slope should be covered with different chemical compounds, such as bitumen emulsions, synthetic polymers, silica composites and membranes).

Main factors which determine the safety level of the TSF includes its operating (technical) state, correspondence of its operation with the design and active regulations, timely conduction of measures aimed to provide normal safety level. Organization and conduction of state monitoring on the stage of operation is one of the fundamental aspects in the issues of reliability assessment and safety management of high hydraulic fill storage facilities.

Monitoring of TSF and ASF dams is conducted from the very beginning of their construction, throughout the full period of operation and on the stage of reclamation. Storage facilities, which are filled using upstream method, have equal construction and operation periods.

State monitoring and inspection of a TSF or ASF should be conducted according to the designed schedule.

Field observation of TSF and ASFs includes:

- visual inspection;
- geodesic supervision of the structures’ deformation;
- seepage monitoring;
- deposition technology maintenance supervision;
- geotechnical supervision of the quality of tailings, which are used to construct embankment dams;
- filling elevation supervision;
- settling pond water quality control.

The results of seepage regime and pore pressures monitoring help to determine, according to the design:

- phreatic surface location in the structure itself, its foundation and abutments;
- pressure heads in the foundation and interfaces with abutments and embedded structures;
- seepage fluxes within drainage lines, drainage outflows and collectors;
- chemical composition and opacity of seepage waters;
- seepage outflows location on the slopes and abutments, presence of pumping;
- elevation and chemical composition of ground water within adjacent areas;
pore pressures in impervious elements of structures, their foundations and other elements.

The thermal regime of structures and their foundations, which are located in Cold Regions, should be monitored.

During the construction of the TSF geotechnical supervision is conducted, which implies monitoring of the filling process.

For every lift of the dam special executive documentation should be drawn up, including:

- topographic map and typical cross-sections of the dam with design and actual outlines of its elements and elevations being shown;
- the results of geotechnical supervision during the filling process;
- statements for covered-up works.

In the issue of safety management special attention is paid to the procedure of safety assessment. According to the results of this procedure and using safety criteria, the type of technical state of the structure is determined and a number of measures to provide normal safety level are developed. The results of state assessment help to develop all possible failure modes.

State assessment of the structures being in operation is conducted using the results of visual inspection, analysis of monitoring data and numerical analysis.

3. CASE STUDY

The solution of the problem of environmental reliability and safety of hydraulic fill storage facilities using the "structure-foundation system" approach and failure risk assessment procedures is further shown by the example of the TSF of the Achinsk Aluminous Plant (AAP).

The storage facility consists of two cells and a settling pond. The maximum dams' height is about 95.0 meters. The dams are of the 1st class of responsibility (Fig. 1). The structure has the following features:

- the hydraulic fill material is cohesive and its parameters change with time;
- as the construction of the structure progresses and loads increase, a number of cracks of different size and origin can take place in the hydraulic fill mass;
- the physical and mechanical properties of the hydraulic fill are non-uniform horizontally depending on the distance between spigots and vertically with
the formation of layered structure (lower layers are harder due to cementation as compared with upper layers);

- presence of thick layers of weak loamy, clay sandy and sandy soils in the foundation.

During the construction and operation of the dam, the seepage scheme through it became complicated by the presence of cracks of different size and direction in the body of the TSF and layers of sandy and gravel soils in the foundation, through which major part of the flux passes.

The criterial (with respect to slope stability and seepage strength) location of phreatic surface is shown on the cross-section of the dam (Fig. 2).

To determine the technical state of the dam the phreatic surface location (i.e. water levels in piezometers) is compared with criteria values. Deformations are monitored by determination of settlements of the dam within control points.

The procedure of failure risk assessment and analysis is the same both for water retention structures and tailings storage facilities.

One of the first steps in the failure risk assessment implies identification of dangers and possible failure mode list formation.
The block scheme of the Achinsk TSF dam failure process development is shown on Figure 3. Red arrows show the failure mode with the most severe consequences, while blue ones — the most possible.

![Diagram](image-url)

**Fig. 2**
An example of determination of quantitative criteria values

*Exemple de définition des critères quantitatifs de sécurité des barrages du dépôt de boue*

- $r$ — slip surface radius
- $k_s$ — stability factor

**Fig. 3**
The block scheme of the Achinsk TSF dam failure process development

*Diagramme de blocs de l’évolution des accidents de barrages autour de l’installation de stockage des résidus miniers de l’usine d’alumine Atchinski*
The results of preliminary analysis of dangers (PAD) for the "A" failure mode (embankment dam failure) are shown in the Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Structure, element</th>
<th>Undesirable effects, processes, occurrences, which can initiate failure</th>
<th>Expected consequences for the staff, property, local residents and environment</th>
<th>Results of preliminary risk assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Embankment section on the border with cell №2 (near shaft wells)</td>
<td>Dam's slopes instability</td>
<td>Embankment dam failure and impoundment of pool #2. Severity of consequences is classified as average</td>
<td>Possible</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crest overflow</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loss of seepage strength of soils of the dam and its foundation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Embankment section near the supernatant pond area</td>
<td>Dam's slopes instability</td>
<td>Embankment dam failure and impoundment of territory. Severity of consequences is classified as considerable</td>
<td>Possible</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loss of seepage strength of soils of the dam and its foundation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crest overflow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Embankment section at the north</td>
<td>Dam's slopes instability</td>
<td>Embankment dam failure and impoundment of territory. Severity of consequences is classified as considerable</td>
<td>Unlikely</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crest overflow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Embankment section on the border with cell №3</td>
<td>Dam's slopes instability</td>
<td>Embankment dam failure and impoundment of settling pond and territory. Severity of consequences is classified as average</td>
<td>Unlikely</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loss of seepage strength of soils of the dam and its foundation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crest overflow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Discharge and water circulation system</td>
<td>Spillway pits failure, failure of collectors, drainage system and clarified water circulation system</td>
<td>Embankment dam failure and subsequent impoundment of territory is possible. Possible suspension of the plant due to interruption of clarified water supply. Severity of consequences is classified as considerable</td>
<td>Unlikely</td>
</tr>
</tbody>
</table>

The detailed failure risk assessment of the cell #2 embankment dam was conducted using graphical-analytical approach. Fragments of "failure trees" of the embankment dam for A1 scenario are shown on Figure 4. The resulting value of
the annual average failure risk was determined as \( PA1 = 1.5 \times 10^{-4} \) /year. It is lower in Russia the maximum allowable failure risk is set depending on the class of the structure.

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**Fig. 4**

Achinsk TSF’s cell #1 failure tree (A1 failure scenario)

« Arbre de défauts » du barrage en remblai du plan n°1
du dépôt de boue (scénario A1)

The issue of environmental safety provision is illustrated by the following example.

During the operation of cells #1 and #2 of the TSF, a number of seepage outflows were mentioned in the toe of the downstream shoulders of embankment dams (Fig. 5, marked red), which could cause the pollution of the environment and reduce slope stability. The dam has been inspected.

Seepage outflows are shown on Figure 6. Inspection results and field data analysis confirmed the loss of membrane’s integrity within cell #2. This loss can be caused by mechanical damages of the membrane, non-uniform settlements of the foundation, poor quality of preparation of foundation for the membrane and thermal coupling between its parts.
Seepage outflows location (marked red) in the toe of embankment dams
*Sorties de percolation de l’eau (en rouge) près du socle des barrages en remblai*

1. Highway
2. Concrete inverted siphons
3. Overfall basin K-1
4. Overfall basin K-2
5. Embankment dam
6. Drainage zone of the cell No. 2
7. Drainage channel
8. Pump station for underslime water No. 1
9. Pump station for underslime water No. 2
10. Underslime water pipes
11. Retaining reservoir
12. Pump assembly
13. Slime pump station
14. Slime pipelines
15. Settling pond border

Q. 98 – R. 23
Temperature of seepage water has been measured in a number of distinguished points of the dam:

- on the downstream slope of the embankment dam of the drainage channel water temperature was about 38 degrees centigrade.
- in the drainage channel near the piezometer post No. 5 water temperature was about 27 degrees centigrade.
- in the place of the membrane's rupture gushing water temperature was about 42 degrees centigrade.

It was found that hydraulic conductivities of foundation soils should be specified, as discrete values of hydraulic conductivities of loams, sands, pebble and gravel are different by a factor of ten and even more.

The problem was solved using complex approach, i.e. using data about settling pond temperatures and the temperatures of water seeping out of the toe of the dams.

The results of field data analysis made it possible to develop and verify numerical models of heat transfer inside the cell and its foundation. Using numerical analysis the hydraulic conductivities of soils were estimated, which agree with measured temperatures and water levels in piezometers.

Further using numerical modelling the optimal variant of the drainage system was selected, which eliminated pollution of the environment by underslime waters. Here two variants of the drainage system will be shown.

The estimation of seepage parameters of dam's soils within cell No. 2 was conducted for three cross-sections. For all of them seepage outflow temperatures were available 31-32 degrees centigrade. These temperatures together with settling pond water temperature (50 degrees centigrade) were used as boundary conditions for the numerical model. The results of this modelling is presented on Fig. 7.
The hydraulic conductivity of soils and effective length (in cross section) of the impervious membrane are presented on Fig. 8 and in Table 2. The membrane is the least effective within piezometric post #4. In this place outflow water temperature found out to be 47 degrees centigrade (116.6 degrees Fahrenheit) — just a few degrees lower than the temperature of the slimes being discharged. Parameters of soils and membranes sizes estimated during heat transfer modelling in the VS2DHJ software were used as input parameters for the seepage model of the PlaxFlow software. This software was used to develop the variants of interception of seepage flow in the foundation of the cell #2.

Further using numerical modelling the optimal variant of the drainage system was selected, which eliminated pollution of the environment by underslime waters. Here two variants of the drainage system will be shown.

In the first variant the axis of the drainage channel was located 60 m away from the axis of the embankment dam, from the piezometric post #5 to the retaining reservoir near the boundaries of cells #1 and 2. The results of numerical modelling of this drainage system are shown on Fig. 9.
In the first variant the ratio between the Chulym river inflow and the drainage water unit flux was about 50%. That is why the perimeter drainage was modelled, which axis was located 31 m closer to the axis of the embankment dam. The drainage channel is 3 m wide (bottom size) with slope ratio being 2.5. The results of numerical modelling for both variants are shown in the Table 3. Unit flux and seepage velocity values for the second variant are marked red.

As the result the drainage channel was chosen to be 30 m away from the axis of the embankment dam with bottom width being 3 m, as this variant found out to be optimal (Fig. 10). Seepage flux from the cell # 2 was totally intercepted being not more than 10 cubic m/day/m.

<table>
<thead>
<tr>
<th>Color</th>
<th>Name</th>
<th>$K_{zz}/K_{hh}$</th>
<th>Sat. $K_{in}$</th>
<th>$S_t$</th>
<th>Porosity</th>
<th>RMC</th>
<th>alpha</th>
<th>beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inactive</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>Slime</td>
<td>1</td>
<td>0.5</td>
<td>0</td>
<td>0.46</td>
<td>0.46</td>
<td>0.20</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>Loam</td>
<td>1</td>
<td>0.01</td>
<td>0</td>
<td>0.35</td>
<td>0.35</td>
<td>0.23</td>
<td>7.0</td>
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</tr>
<tr>
<td>Gravel</td>
<td>1</td>
<td>100</td>
<td>0</td>
<td>0.36</td>
<td>0.36</td>
<td>3.00</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>1</td>
<td>68</td>
<td>0</td>
<td>0.35</td>
<td>0.35</td>
<td>2.30</td>
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<tr>
<td>Siltstone</td>
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<td>0.01</td>
<td>0</td>
<td>0.36</td>
<td>0.36</td>
<td>0.20</td>
<td>7.0</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 9

Variant #1, cell #2. Phreatic line location before (a) and after (b) excavation of the drainage channel

Variante n°1, plan n°2. Courbe de saturation avant et après la mise en marche du fossé de drainage
Table 3
The results of numerical modelling for the variants 1 and 2

<table>
<thead>
<tr>
<th>Piezometric post #</th>
<th>Unit flux q (cub. m/day/m)</th>
<th>Maximum seepage velocity (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>On the slope of the starter dam</td>
<td>From the side of the cell</td>
</tr>
<tr>
<td>2-2 (6-6)</td>
<td>7.61; 3.31</td>
<td>7.35; 2.71</td>
</tr>
<tr>
<td>4-4 (8-8)</td>
<td>11.83; 7.49</td>
<td>10.03; 6.99</td>
</tr>
<tr>
<td>5-5 (9-9)</td>
<td>7.96; 9.25</td>
<td>7.37; 7.17</td>
</tr>
</tbody>
</table>

Fig. 10
Phreatic line location (variant #2)
*Position de la surface de saturation (variante n°2)*

4. CONCLUSION

Russian specialists are now very experienced in the issues of design and operation of tailings and ash storage facilities' (ASF and TSF) dams, which are filled hydraulically from wastes and capping soils.

The design of a TSF or an ASF depends on the specificity of the foundation of the structure, features of works to be done, class of responsibility, geological, hydrological and climate conditions and economic feasibility.

In the issue of safety management special attention is paid to the procedure of safety assessment.

State assessment of the structures being in operation is conducted using the results of visual inspection, analysis of monitoring data and numerical analysis.
SUMMARY

The report contains information concerning basic principles of design of high hydraulic fill storage facilities' dams (ash, tailings, and industrial wastes storage facilities). On the design stage the structure of embankment dams is chosen according to the codes and regulations being active in Russia. Additionally a number of studies and analyses are conducted, which take into account the features of such structures as ash (ASF) and tailings (TSF) storage facilities' dams as compared to high reservoir dams.

Special attention is paid to the aspects of design, construction and operation of high hydraulic fill storage facilities located in Cold Regions, on weak foundations and seismic regions.

It is mentioned in the report that basic factors, which determine safety level of high hydraulic fill storage facilities' dams, include their technical (operational) state, compliance of dam's operation with active codes and regulations, and timely conduction of measures aimed to maintain normal safety level. Organization and state monitoring of structures being in operation is the fundamental principle in the issue of reliability assessment and safety management of high hydraulic fill storage facilities' dams.

The issues of environmental monitoring organization and the assessment and inspection of environment pollution caused by operation of storage facilities are especially mentioned in the report.

Basic principles and stages of monitoring and state assessment of high hydraulic fill storage facilities are illustrated with a number of case studies for different 'life-stages' of structures: design, construction and operation. Special attention is paid to the setting of dams' safety criteria. It is mentioned that safety criteria pay a special role in the issues of state assessment and monitoring.
Namely the ability to detect, assess and monitor (before measures are taken) the development of any destructive processes, which are capable to cause structure's failure.

The report includes the analysis of principle causes of failures of tailings and ash storage facilities being in operation in Russia.

RÉSUMÉ

Ce rapport présente principes de base de la conception des grands barrages en remblais pour les installations de stockage (cendres, stériles et déchets industriels). Lors des études, la structure du barrage est choisie conformément aux codes et réglementations en vigueur en Russie. En outre, des études et analyses sont effectuées pour prendre en compte les caractéristiques spécifiques des ouvrages de type stockage de cendres (ASF) et de stériles (TSF), comparés à des grands barrages de retenue.

Une attention particulière est accordée aux études, à la construction et à l’exploitation de grandes installations de stockage hydraulique situées dans des régions froides, sur des fondations fragiles et dans des zones sismiques.

Le rapport mentionne que les facteurs principaux déterminant le niveau de sécurité de ces barrages comprennent leur état technique fonctionnel, la conformité de l’exploitation avec les codes et réglementations en vigueur, et la mise en œuvre en temps utile de mesures destinées à maintenir le niveau normal de sécurité. La surveillance de l’état des ouvrages en exploitation est un principe fondamental de l’évaluation de fiabilité de la gestion de sécurité de ce type de barrages.

Les aspects de surveillance environnementale et de l’évaluation et de l’examen des pollutions causées par l’exploitation des installations de stockage sont tout particulièrement abordés dans ce rapport.

Les principes de bases et les étapes de surveillance et d’évaluation de l’état des grands barrages de stockage sont illustrés par un certain nombre d’études de cas pour différentes phases de la vie des ouvrages : études, construction et exploitation. Une attention particulière est accordée à la définition des critères de sécurité. Ceux-ci jouent un rôle spécifique pour l’évaluation et le suivi, notamment pour la capacité à détecter, évaluer et surveiller avant la prise de mesures le développement de tout processus destructif capable de provoquer la rupture de l’ouvrage.

Le rapport comprend l’analyse des principales causes de rupture de barrages de stériles et de cendres exploités en Russie.