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Finnish mine waste disposal areas

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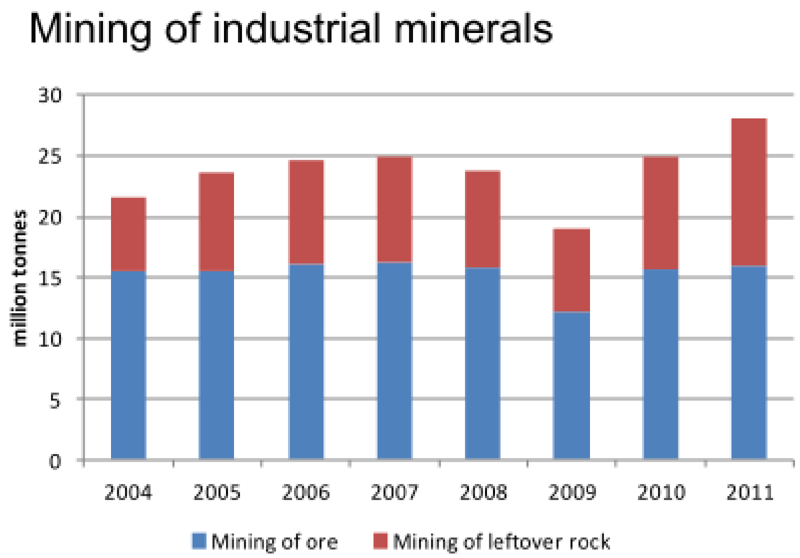
Abstract

In 2013, a total of forty-six mines and quarries were operating in Finland, and several new mining projects were in progress. Both mining and environmental legislation and dam safety regulations have been developed and renewed during recent years, and the mining and permitting authorities have changed. Due to problems at the Talvivaara Mine in 2013, the Finnish government decided to implement a voluntary stress test for Finnish mines. The method was developed based on the stress test designed for nuclear power plants by the European Nuclear Safety Regulators Group (ENSREG). Altogether twenty-one mines or concentrating plants were chosen to be tested, and twenty responded. In the stress test questionnaire there were fifteen questions on seven risk scenarios that the nominated expert group assessed to be both potential and significant.

There are sixty-seven tailings dams in Finland. Nine of them have been classified as Class 1 ("consequence class"), that is, dams which could cause loss of life in the event of dam failure. The study showed that the hydrological design of tailings dams has to be reconsidered. One finding of the stress test was that the dam safety legislation and the guidelines do not define criteria for the closure of tailings dams. Based on the results, mining companies are monitoring their dams quite well and are aware of dam safety risks, probably thanks to the detailed dam safety legislation. However, the base of the waste areas is typically ignored. Old mining waste areas are mainly built on natural soil layer without any liners. New mining waste areas require an environmental permit, which contains requirements for the bottom liners as well.

Introduction

The mining industry has a long history in Finland, thanks to our geological conditions. Nowadays the industrial minerals, such as dolomite, limestone, talc and other minerals, constitute the main part of the Finnish mining industry (Figures 1 and 2). The volume of mining had been decreasing, but at the beginning of the twenty-first century, nearly ten new metal mining projects were launched, while the demand for, and price of, certain metals increased. Meanwhile, the operating environment has changed substantially. The environmental legislation, dam safety regulations, and especially mining legislation and authorities, have been constantly evolving. New mining legislation includes the Mining Act of Finland, the Finnish Government Decree on Mining Activities, and the Government Decree on Mining Waste.



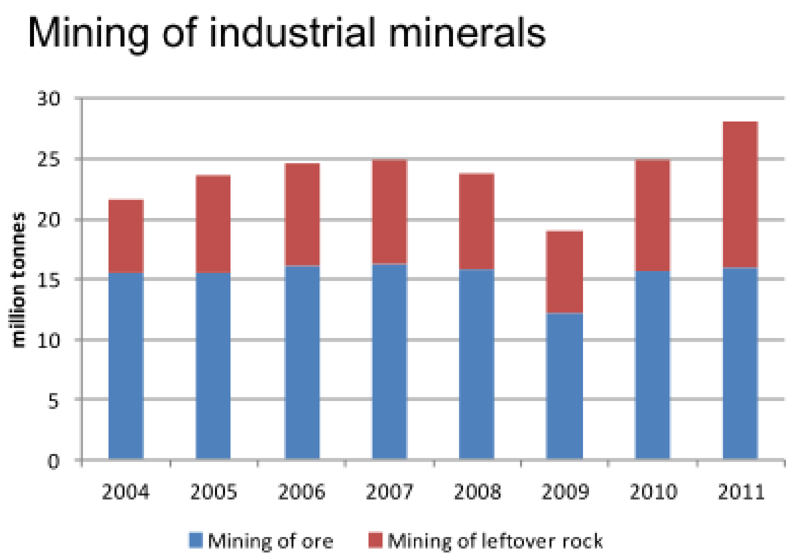


Figure 1: Mining of metallic ore and industrial minerals in Finland, 2004–2011 (Uusisuo, 2013)

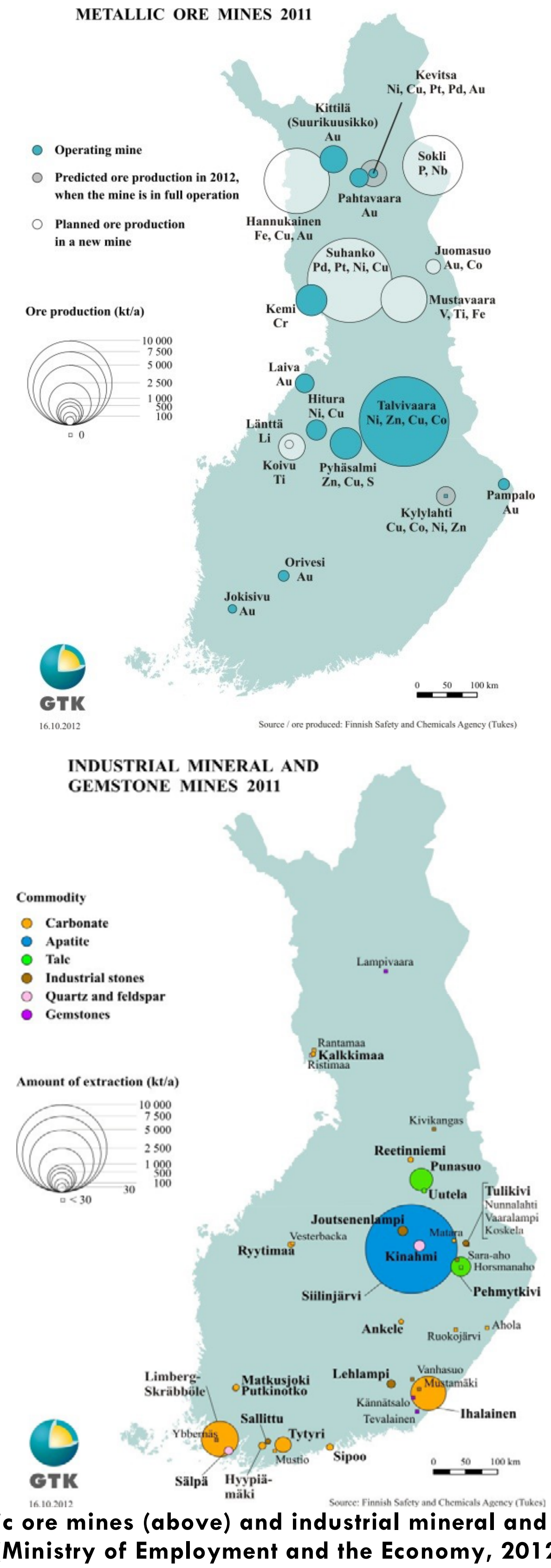


Figure 2: Finnish metallic ore mines (above) and industrial mineral and gemstone mines in 2011 (Ministry of Employment and the Economy, 2012)

After the significant hydrological balance problems and recurring pond failures at the Talvivaara Mine in 2013, the Finnish government decided to implement a stress test for Finnish mines. For the same reason, the Ministry of Environment appointed an authoritative working group to evaluate the tasks, jurisdiction, guidance methods and cooperation of authorities for preventing environmental effects of mining.

A stress test is one tool to evaluate the current state of the mining industry. A stress test differs from a risk analysis. In risk analysis the target is to recognize the possible risks, determine their risk level, that is, their severity and probability, and identify actions to decrease the risk. In a stress test the stress factors have already been identified in a risk analysis, or by an expert group. A stress test is limited to the chosen scenarios, and is not as comprehensive as a risk analysis. In a stress test the focus is on selected questions, and the aim is to determine the state of precautionary measures. The principle of the stress test is to expose the object to stress factors which are clearly beyond normal design limits, identify the consequences caused by the abnormal stress, and determine the state of preparedness of the objects to mitigate the harmful effects.

Stress test for mining

To our knowledge, a stress test has not been applied to the mining industry before. Therefore the model was taken from the stress test applied to nuclear power plants by the European Nuclear Safety Regulators Group (ENSREG) in 2011. The test stress was developed by expert representatives from three guiding ministries (Ministry of the Environment, Ministry of Employment and the Economy, and Ministry of Agriculture and Forestry); research institutes and agencies such as the Finnish Environment Institute, the Technical Research Centre of Finland, the Geological Survey of Finland, Radiation and Nuclear Safety Authority, the Finnish Safety and Chemicals Agency (TUKES), the Centre for Economic Development, Transport and the Environment of Kainuu, and the National Institute for Health and Welfare. Since July 1, 2011, TUKES has been the surveillance and permit consideration authority in Finland, as referred to in the Mining Act (621/2011), and the Centre for Economic Development, Transport and the Environment of Kainuu is the dam safety authority.

The risk account of realized damages or other reported exceptional situations formed the basis for the stress test. The information sources were three administrative databases (namely the VAHTI database of environmental administration, the PRONTO resource and accident statistics from the Ministry of the Interior and VARO damage register of TUKES), and one recently completed project on environmental damage (ONSE-project). Based on the statistics, about half of the exceptional situations involved water, that is, sixty-eight cases out of a total 128 (Figure 3) (Välisalo et al., 2014).

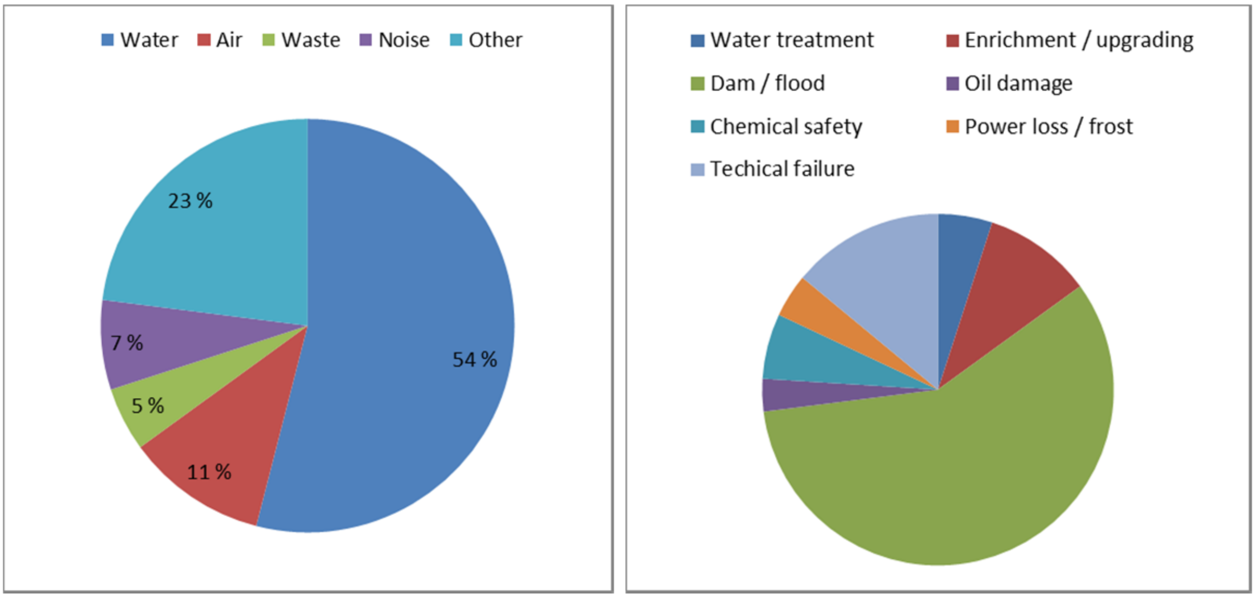


Figure 3: (Left) Distribution of exceptional situations on mines based on type of emission, n = 128. (Right) Exceptional situations related to water, n = 68 (Välisalo et al., 2014)

The multi-stage development process of the stress test started with a free-creation phase based on area of expertise and functional classification, which led to the formulation of stress test questions. A risk scenario and the possible content of answers were considered for each question. Questions were processed in several phases, by elimination and commenting rounds within the expert group. The final set of fifteen questions were developed based on seven environmental risk scenarios related to:

1. exceptionally high precipitation or runoff;
2. dam or pond failure;
3. leaching of contaminating or radioactive elements;
4. power failure;
5. lack of resources in risk assessment;
6. risk communication problems; and
7. vandalism or sabotage.

In their responses the mines describe briefly how they are prepared for each risk scenario, and how probable it is. Most importantly, they make a self-evaluation of how each risk scenario has been taken into account in their monitoring and contingency planning (Välisalo et al., 2014).

Selection of participants

At the time the stress test was developed there were fifty-two active mines and three separate concentrating plants in Finland. The sample of participating mines was made based on the type and functions. All twelve metallic mineral mines were included in the stress test. In addition, mines and concentrating plants that had classified waste or water ponds with dams, and mines doing large-scale treatment of chemicals, were included. Location in the vicinity of an environmental protection area or other sensitive area was an additional factor, as was underground mining (Välisalo et al., 2014).

Eventually, a total of twenty-one mines and concentrating plants were chosen for testing. The questionnaire was sent to all twelve metal ore mines and both metal ore concentrating plants, and to the selected industrial mineral mines and concentrating plants listed in Table 1 (Välisalo et al., 2014).

Table 1: Mines and concentrating plants considered in stress test (Välisalo et al., 2014)

Metallic ore mines	Metallic ore mines and concentrating plants	Metallic ore concentrating plants	Carbonate mines	Other industrial mineral mines and concentrating plants	Industrial mineral concentrating plants
Jokisivu	Suurkuusikko	Luikonlahti	Ihalainen	Siilinjärvi	Vuonos
Orivesi	Hitura	Vammala	Tytyri	Sälpä	
Kylylahti	Pampalo			Kinahmi	
	Kevitsa			Punasuo-Lahnaslampi	
	Pahtavaara				
	Laiva				
	Kemi				
	Pyhäsalmi				
	Talvivaara				

Replies

The Ministry of the Environment sent the stress test questionnaires to the mines and the concentrating plants on May 15, 2013. Three weeks later a training and discussion session was organized by the Finnish Association of Extractive Resources Industry (FinnMin). In addition, during the summer additional support for the mines was available, but was not widely utilized (Välisalo et al., 2014).

Another independent group was formed to evaluate the answers. The group consisted of experts from the same, previously-mentioned governmental agencies, with some external specialists on dam safety and liner structures.

The stress testing was voluntary for the mines and concentrating plants, but the response rate was high: altogether twenty answers were received. One mine had interrupted its activities, so it did not respond to the inquiry. It was not possible to visit every mine, or thoroughly examine the permission documents of mines. (Note: the permission documents are the design plans, calculations and written descriptions of activities, waste, water balance, dam safety, environmental impacts, etc. required for the environmental permit application and mining permit.) Therefore, the evaluation was based on the written responses only. It should be noted that the responses, and especially the self-evaluations, are not comparable, since the mines and plants are not alike, and some respondents were more critical than others (Välisalo et al., 2014).

This paper reviews the results from risk scenario number 2, “The structures of dam ponds (dams, synthetic bottom liners or other bottom structures, edge drop or elevations) or related equipment (such as decantation wells, subsurface drain, pumping stations, pipe lines, collection ditches or radical drainage) cannot tolerate the loading caused by an exceptionally high water amount.” The related four questions in the stress test questionnaire were following (Välisalo et al., 2014):

1. How are the condition of the dam and bottom structures, and waste sludge pumping station, and water management equipment monitored?
2. How are they prepared for the emergency repair of dam or bottom liner failures (including the availability of repairing material)?
3. In case of dam or bottom failure, how is the transmission of waste sludge and water to the environment prevented?
4. What measures are taken to prevent local loading producing erosion (such as flowing tailing sand or water from a broken pipe above the dam) from causing a failure in dam structure?

Tailings dam safety

Finnish dam safety legislation presented in the act, the decree and the guidelines were enacted in 1984. As an exception, the mining law (503/1965) and the safety regulations of mines (921/1975) were applied to tailings dams. Finnish dam safety legislation was renewed in 2009, and since then tailings dams have been included in the Dam Safety Act (429/2009) and in the Government Decree on Dam Safety (319/2010).

The objective of the Dam Safety Act is to ensure safety in the construction, maintenance and operation of dams, and reduce the hazards that may be caused by a dam. The Dam Safety Act comprises seven chapters:

1. General provisions
2. Planning design and construction of dams
3. Classification of dams and dam safety documents
4. Maintenance, operation and monitoring of dams

5. Preparing for accidents and action in the event of accidents
6. Control and coercive measures
7. Miscellaneous provisions (Dam Safety Act, 429/2009)

The consequence classification of dams is based on the damage that would be caused if the dam breached. Based on the hazard, the dam is placed in one of the following classes (Dam Safety Act, 429/2009):

1. Class 1 dam, which in the event of an accident would cause danger to human life and health, or considerable danger to the environment or property.
2. Class 2 dam, which in the event of an accident might cause danger to health, or greater than minor danger to the environment or property.
3. Class 3 dam, which in the event of an accident might cause only minor danger.

For dams classified as Class 1, the owner must prepare a dam-break hazard analysis, which is an analysis of the dam hazard to humans and property as well as the environment. In addition, he must prepare and regularly update an emergency action plan for the dam, that is, a plan of measures to be taken in case of accidents or disturbances (Dam Safety Act, 429/2009).

There are sixty-seven tailings dams in Finland, and nine of them have been classified as consequence Class 1. They were all involved in the stress test. Three participating mines did not have any dams, because they transport their waste elsewhere, or use it to fill old quarries. Four mines had dams belonging to Class 1: Kevitsa (two), Laiva (two), Siilinjärvi (three) and Suurikuusikko in Kittilä (two).

The responses did not contain detailed descriptions of dam structures or decantation systems, thus it is not possible to evaluate the structural risks, but the respondents verbally described dam structure, materials and subsoil conditions, and seven respondents enclosed a typical cross-section plan. One example of plans is presented in Figure 4. Based on the answers, most of the dams are homogenous, earthen dams made from moraine, or zoned-earth dams with low-permeable core built from moraine, designed for seepage. Five new mines have used geomembranes in tailings dams and bottom structures, either together with local low-permeability moraine or geosynthetic clay liner, or both (Table 2). In Talvivaara, geosynthetic structures have been used in all process ponds and water reservoirs.

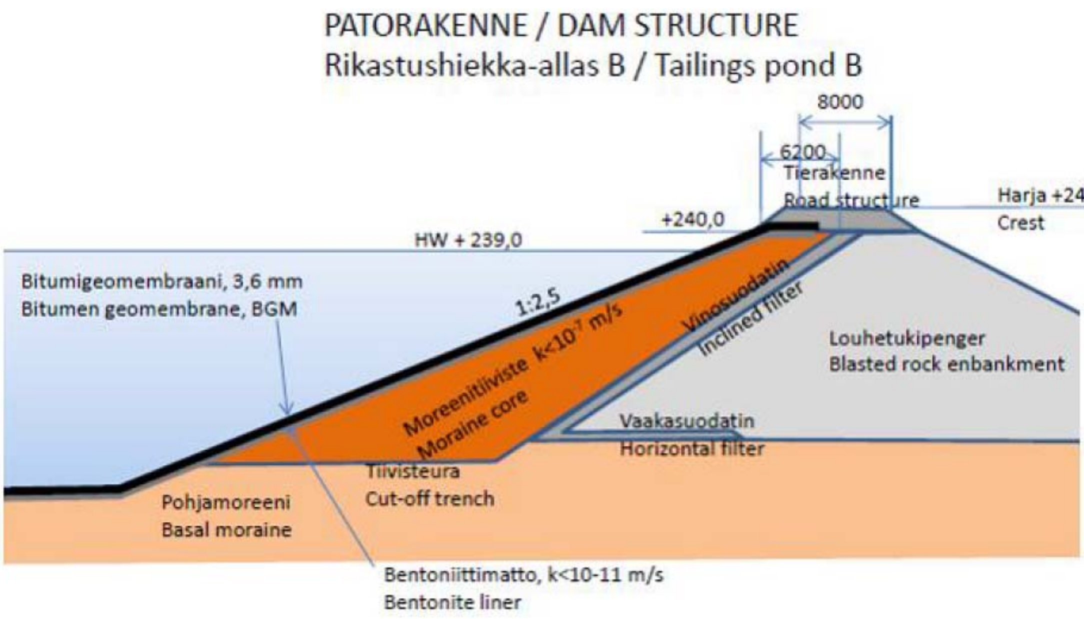


Figure 4: Cross-section of tailings dam B in Kevitsa, Sodankylä (FQM Kevitsa Mining Ltd., 2013)

Table 2: Zoned-earth dams lined with geomembranes (Välisalo et al., 2014)

Mine or concentrating plant	Subsoil	Liner	Filter	Embankment
Luikonlahti	Moraine	LLDPE GM GCL Moraine	300 mm crushed aggregate #0-64mm 700 mm crushed aggregate#0-200 mm filler	blasted rock
Laiva	Moraine Rock	Bituminous GM GCL Moraine	Drainage layer: 300 mm crushed aggregate #8/16mm	
Suurkuusikko	Moraine	Bituminous GM Till	filter geotextile crushed aggregate #0-55 mm small blasted rock D_{max} 300 mm	blasted rock D_{max} 600 mm
Talvivaara	Moraine Rock	HDPE GM GCL / Moraine	50 mm crushed aggregate # 0-16mm 50 mm crushed aggregate # 0-100mm filter geotextile filler	blasted rock
Kevitsa	Moraine	Bituminous GM GCL Moraine	diagonal and horizontal filter	blasted rock

The structural details of dams were observed from a viewpoint of dam safety and long-term behavior. The reviewed details were selected based on surveys of the International Commission on Large Dams (ICOLD), and international dam accident statistics.

The hydrological design with the design flood concept came with the dam safety legislation. The design flood is determined by the frequency analysis, and the return period of 5,000–10,000 years is applied for dams in high consequence Class 1. The responses of the mines on the hydrological risk indicated the whole water balance, but the design flood and corresponding storage capacity at the different stages of the tailings dam construction were not described. The design flood is determined by the runoff of the snow smelting, but it is recommended that it should be checked with flash floods caused by heavy rains.

Only one respondent reported a dam leakage. However, several dam fault situations have been reported in dam safety documents. Typical incidents at Finnish tailings dams during 1982–2013 have been internal erosion (sixteen cases) and change in the seepage / wetting of the slope (fourteen cases). The mines have reported thirty-three tailings dam incidents in 2000–2013.

The tailings dam failures were identified in the answers. However, neither the type of the failure mode nor the failure development were presented. The mines suggested the following mitigation measures to improve incident management: increase the storage volume; improve arrangement of runoff flows; build dikes around tailings dams; improve the monitoring.

According to the stress test answers, the mines are well aware of mining safety risks and are monitoring their dams according to the requirements. All dam owners have suitable material such as rock and moraine, GCL and filter geotextile, and trucks and trucks loaders available for dam or bottom failures. In addition, they are prepared for pumping or other water management methods, such as rerouting or diking the flow in case of leakage.

Five mines have used tailings sand in dam elevations, which may cause slope stability problems and contamination due to the erosion and spreading of tailings sand.

Filter geotextile has been commonly used in filter and drainage structures of tailings dams (Table 2). In waterway dams geotextile is not so commonly used, due to the risk of clogging and doubts about long-term durability. Lacking or malfunctioning filters may cause piping and internal erosion.

One finding of the stress test was that the dam safety legislation and the guidelines do not define criteria for the closure of the tailings dams. Tailings dams should be safe after their closure, as well during their operational phase.

Mining waste disposal areas

There were no direct questions about the bottom structures of waste areas in the stress test, and one third of the respondents ignored them, or their monitoring, in their responses. In general, the performance of the lining structures (or low-permeable subsoil) was monitored indirectly through the effects, such as seeping water amount and quality. The monitoring consists typically of ground-water and surface-water levels observations, and follow-up of the amount of leaching water based on pumping. Quality control of ground and surface water was based on sampling, and was typically done to control the environmental impacts, rather than to monitor the behavior of liners. Electrical continuous measurements for real-time water levels or quality monitoring, or electrical leakage control for liners, were not widely used, but were suggested for quicker reactions (Välisalo et al., 2014).

Old mining waste areas were built according to the previous mining legislation that did not require structural soil and groundwater protection measures. However, the new Finnish environmental legislation, especially the Government Decree on Mining Waste (379/2008, updated version 190/2013) set a goal for protective measures. Nowadays, mining waste areas require an environmental permit.

Waste areas based on natural soil

Old mining waste areas had no structural regulations. Hence, they were primarily based only on local natural subsoil, which in Finland fortunately is mainly low permeable and retentive moraine, silt or peat, yet mostly has only low buffering capacity. In addition, the disposed tailings typically have quite low permeability, 10^{-7} m/s on average (Pyysing, 2012).

The dissemination of water-soluble contaminants depends on the permeability of the subsoil and the current hydraulic gradient. The higher the gradient, the permeability and the cross-section area, the larger the flow. Sorption, cation exchange and complexing reaction are detention processes which may reduce the contamination transportation and the environmental effects.

The permeability of natural peat varies depending on the portion of mineral particles, degree of humification, and especially degree of consolidation. The permeability (k) of untouched peat can vary between 10^{-4} and 10^{-7} m/s, corresponding to sand and silt. The vertical permeability can be significantly lower than horizontal (Kauranne et al., 1972).

However, under loading the peat compacts, which results in decreasing water content, porosity and permeability. Already under a moderate loading, such as a road embankment, the permeability reduces quickly to 10^{-6} to 10^{-8} m/s due to the primary consolidation. If the loading is large and long-lasting, the permeability can reach values as low as 10^{-10} to 10^{-11} m/s, corresponding to the requirements of mineral liners (Uotila, 2014).

Nevertheless, the natural heterogeneity of geological deformations and the initial conditions can cause a risk of subsoil contamination and dissemination of contaminants. In the beginning of the activities, the load to the subsoil is small and the positive effect of consolidation is not activated. Moreover, the consolidation causes settlement, which can be harmful for other structures. In particular, uneven settlement causes detrimental strains in geomembranes. Particularly at the final state the internal water pressure level can be very high, for example 20 m, causing a large hydraulic gradient and further, a large flow through the subsoil. Rain and snowfall will sustain the hydraulic gradient even after closure, especially if the closure structures are permeable or do not exist at all. The hydraulic gradient could be significantly decreased by a drainage layer on top of the liner, or a natural low-permeable soil, which is required in landfill bottom structures as a standard, but is still seldom used in mining waste areas.

Use of geosynthetic liners

As presented in Table 2, five new mines have used geomembranes in their mining waste areas, both at the bottom and on the dam slope. All these waste ponds, with the exception of Talvivaara, are disposal sites for waste classified as hazardous waste, based on the total concentration or leaching amount of contaminants. In Talvivaara, the need for watertightness in process ponds is also economical: the ore diluted by the microbes is in the stored water. In Kevitsa and Luikonlahti the waste produces sulfuric acids and should be stored under the water level (Välisalo et al., 2014).

Bituminous geomembrane has been used in three mines. They were introduced at the Kittilä Gold Mine (Suurikuusikko) in Northen Finland in 2007. The mine is owned and operated by Agnico-Eagle Mines Ltd. A watertight liner was required in the environmental permit, and the original high-density polyethylene (HDPE) geomembrane was replaced at the owner's request.

There was no previous experience of using bituminous geomembranes (BGM) in liners, nor knowledge of their long-term performance in mining areas. According to the producer, the main advantage of BGM is that they are easier to install than HDPE geomembranes. Installation is much less dependent on weather conditions, and BGM can be installed at very low temperatures, such as −30°C. In addition, they are less susceptible to point loading than HDPE geomembranes, and thus do not require a protective layer (Bertrand et al., 2008).

Vital parts of high-quality liner structures are competent design and careful implementation. Quality control of both the products and the execution, plus the competence of the workmen, ensure a good result. Therefore, new guidelines have to be written for new materials, such as bituminous geomembranes (Kortelainen, 2012).

The proper use of geosynthetics requires knowledge of their material properties and their long-term behavior, and of their chemical and physical compatibility with other structural elements. Clearly we need professional education and dialogue on waste mining area design practices, especially due to the new mining legislation and the changes in permitting and supervising authorities.

Conclusion

The goal of the voluntary stress test was to assess the environmental risks posed by mines. The stress test was a one-off review of the present situation, but proved to be a useful tool in a dialogue between mining companies and regulators. There is a clear need for this kind of interdisciplinary interaction and discussion due to the rapid changes in operating environment, especially changes in the legislation and responsible authorities, together with sparse resources in the public sector. The process brought up some problems caused by the changes, such as hydrological design criteria, and the concept of disposal of the dam at closure, where the practice differs in mining and in water bodies.

The self-evaluations are not comparable, because the mines and concentrating plants differ in size, processes, environmental risks and impacts. Also, the breadth and particularity of the responses varied.

Based on the stress risks responses, the risks associated with waste areas (other than dam safety) are not well recognized. Monitoring of dam safety has been well implemented, but the dissemination of the contaminants with leaching water through the dam and bottom is merely observed subsequently in the quality of ground and surface water. Real-time and online monitoring would improve understanding of the transportation processes in soil, and highlight possibilities for preventing and limiting unwanted consequences.

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