Quality analysis of the Earth remote sensing data in the surface runoff modeling for failure prediction at the tailing dumps

Petr Rybnikov[1,2*], and *Alexander* Smirnov[1,2]

[1]Ural State Mining University, 620144, Kuibyshev Str., 30, Ekaterinburg, Russia
[2]Institute of Mining, Ural Branch of the Russian Academy of Sciences, 620075, Mamin-Sibiryak Str., 58, Ekaterinburg, Russia

Abstract. The tailing dump operation periodically leads to the failures. A number of failures that have occurred is related to the underestimation of the exposure to atmospheric precipitations (heavy rains, heavy snowmelt, etc.) on the tailings dams. The studies performed during the previous 50 years indicate the need to consider the climate change when calculating both the long-term average and storm runoff and substantiating the engineering solutions in the tailing dump design. The digital elevation models (DEMs) can be used as a basis for solving the problems of hydrological and hydrogeological modeling. Due to the diversity of such models, it is necessary to develop a methodology for its preparation, evaluate the necessary degree of the material post-processing, and determine the time frame for research.

1 Introduction

The great demand for mineral resources in recent decades is associated with the significant economic growth and an increase in consumption. Satisfaction of the market needs for the minerals has led to an increase in production volumes and, as a result, to the accumulation of more waste from the mining and metallurgical production (sludges, scums, ash dumps, overburden dumps, etc.) that have a negative impact on the environment. Part of the waste is transported through the pipelines in the form of effluents (a blend of solid mineral particles mixed with water in a ratio of 1:15 - 1:30) to the special ponds, namely the tailing dumps. The main purpose of the tailings is to establish conditions for suspended mixture sedimentation under action of gravity, as well as the safe storage of tailings to protect the environment from its impacts [1, 2].

In the Urals (and in particular, in the Sverdlovsk region), as a region with the developed mining and metallurgical production, there is a great number of large tailing dumps. The largest of them are located in Kachkanar, Krasnoturinsk, Kamensk-Uralskiy and Nizhniy Tagil (Table 1).

[*] Corresponding author: ribnikoff@yandex.ru, alexsm94@gmail.com

Table 1. Main tailing dumps of the Sverdlovsk region.

Entity	Dam height (m)	Total area of the tailing damps (ha)	Production	Sludge type
Kachkanar				
Kachkanar Ore Dressing and Processing Enterprise	45	1 500	Iron ore	Ferriferrous sludge
Krasnoturinsk				
Bogoslovsk Aluminum Smelter	-	460	Alumina	Red mud
Kamensk-Uralskiy				
Ural Aluminum Smelter	10	470	Alumina	Red mud
Sinarskiy Pipe Works	10	10	Aluminum	Neutralization sludge
Nizhniy Tagil				
Vysokogorskiy Ore Dressing and Processing Enterprise	-	250	Iron ore	Ferriferrous sludge

In order to reduce the costs of ore dressing and metallurgical enterprises, the banquettes are often constructed using a coarse fraction directly from the tailings material. When topping the dam, a steep slope is formed (Fig. 1) that also causes the vulnerability of strength properties [3]. The probability of tailing destruction is several times higher than that of other hydraulic engineering structures, for example, hydroelectric engineering facilities [4]. Since the tailing dumps are the high-risk locations, the dam condition monitoring should be performed even upon completion of its operation. In the case of overdrying at the post-operational stage, the tailing dumps are also a source of aero-technogenic pollution due to the wind-blown spread of dust containing a large amount of high-hazard pollutants.

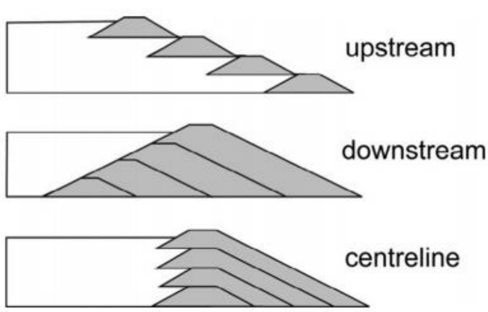

Fig. 1. Schematic diagram of the tailings dam topping by type.

The tailing failures occur annually that has a serious negative impact on the environment, human health and life, and sometimes on the economy of entire countries. The failure consequences include the human casualties, loss of livestock, destruction of buildings and structures, flooding of the river valleys and depressed land areas, pollution of the groundwaters and surface waters, formation of the pollution areas along the spill site, etc. The systematization of such failures is extremely challenging due to the lack of comprehensive data necessary for the analysis of causes and the destruction scenario modeling. Thus, there was enough information for a complete analysis by the scientific community in relation to only 147 of 198 failures at the dams of the mining and metallurgical enterprises in the 20th century [5].

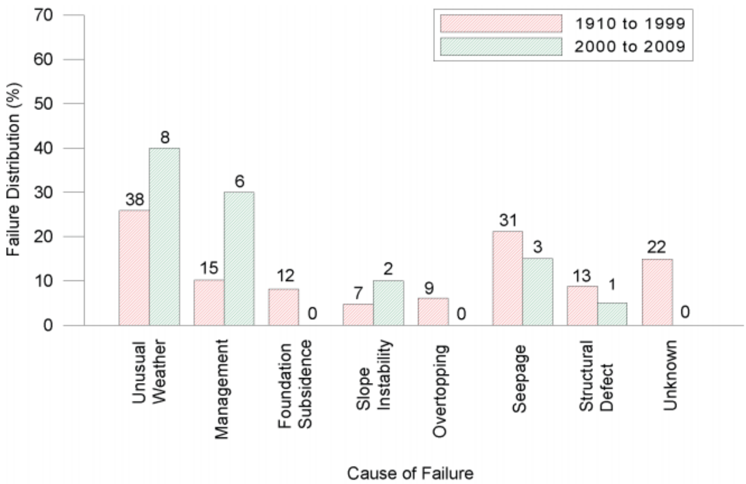

Fig. 2. Failure distribution in relation to the tailings dams by reasons (Shahid Azam, 2010) [5].

The flood waters can destroy the dam body due to the reservoir overfilling, subsequent overflowing and dam edge erosion. In this case, the stress fields in the dam body are changed that leads to instability of the slope angle of the tailing dump, instability of the foundation and further collapse. In the case of heavy rains, a powerful water current occurs, capturing the humus and soil as it goes. It forms the mud stream developing a significant destructive force. Apart from the above, deformation may occur inside the tailing dump due to the pipeline effect caused by osmosis. It leads to an increase in the permeability of deposits, strength reduction and loss of elasticity modulus [6].

According to the statistical data (Fig.2), one of the main causes of tailings spills is atmospheric precipitations: long-duration rains, heavy snowmelt, hurricanes, etc. The share of failures due to the atmospheric precipitations from the total number of all emergency situations, compared with the last century, increased from 20% to 40% [5]. This may be due to accelerating processes of climate changes. Modern design of hydraulic facilities should consider these factors.

It is important to note that major accidents due to the atmospheric precipitations occur regularly and, unfortunately, with an increase in scale and damage to the environment (Table 2). Thus, in 1985, near Stava (Italy), as a result of the water level rise, the banquette of the upper tailing dump was partially damaged that led to the collapse of the lower tailing dump and the acidic sludge spill 4.2 km downstream [7]. In 1986, near Huangmeishan (China), the failure occurred at the tailing dump due to the persistent heavy rains that continued for several days [8]. The main reason included the heavy rains and heavy snowmelt. In 1994, the Merriespruit tailing dam (South Africa) was destroyed due to the rainfall that lasted for several hours [9]. In 2000, over 100,000 m^3 of mud and cyanide-containing water fell into the Somes, Tisza and Danube rivers from the tailing dump in Baia Mare (Romania) as a result of a dam failure [10]. In 2009, there was a spill of cyanide-containing sludge near the Karamken village (Russia). In 2010, the Zijin tailings dam (China) collapsed due to the heavy rains, caused in turn by the Fanapi typhoon. That same year there was a spill of 1.1 million cubic meters at the tailing dump near Ajka (Hungary).

In 2015, 50 million m^3 of ferriferreous sludge poured into the Doce River, and then into the Atlantic Ocean from the dam near Mariana (Brazil) [11]. The reasons included the issues with the drainage system and the developed erosion of the dam edge under due to exposure to the atmospheric precipitations.

Table 2. Basic information in relation to the tailing dump failures.

Year	Description (place of location)	Dam height (m)	Dam type	Spill volume (m^3)	Tailing composition	Fatality rate
1985	Stava (Italy)	29.5	Upstream	240 thousand	Acid sludge	268
1986	Huangmeishan (China)	UN	Upstream	UN	Ferriferrous sludge	19
1994	Merriespruit (South Africa)	31	Upstream	690 thousand	Acid sludge	17
1999	Kachkanar (Russia)	UN	UN	12 mln	Clarified water	UN
2000	Baia Mare and Baia Borsa (Romania)	7	Downstream	100 thousand	Cyanide-containing sludge	UN
2009	Karamken tailing plant (Russia)	20	UN	UN	Cyanide-containing sludge	1
2010	Zijin (China)	UN	UN	UN	Red mud	22
2010	Ajka (Hungary)	22	Downstream	1.1 mln	Red mud	10
2015	Fundão (Brazil)	90	Upstream	50 mln	Ferriferrous sludge	19
2020	Achinsk (Russia)	UN	UN	UN	Red mud	UN

Note: UN - unknown

The total amount of precipitations cannot be predicted at a particular moment of the tailing damp operation. At first glance, the tailings may seem like the drainless water bodies. However, from the point of view of the water balance it is often possible to observe overdrying (evaporation, filtering through the dam body, flowing into the underlying water-bearing beds). All these things make the tailing damp a complex object for the hydrological and hydrogeological modeling. A traditional solution is to design the dam with a margin of strength properties, considering the storm rainfall and rapid snow melting. In order to assess the maximum inflow rates, the hydrological computational models are used that allow to consider not only the amount of precipitations that have fell on the tailing damp area, but also from the adjacent drainage area.

In order to assess the tailing damp effect on the groundwater filtration mode and its pollution, the numerical geofiltration and hydrogeomigration models are used. Solving the geofiltration problems allows to estimate the leak volume from the tailings and to determine the water balance elements of the territory (for example, the elements affecting the tailing damp overdrying in dry years). Solving the geomigration problems allows to outline the polluted area from leakages, to predict the contamination propagation rate. The joint use of numerical hydrological and hydrogeological models can significantly improve the quality of design solutions.

For the modeling purposes, information is often required in relation to the relief surface not only of the hydraulic facility, but also of the drainage area around the tailing dump. The topographic survey performance on such an area is unreasonably expensive, therefore, the Earth's remote sensing materials (ERS) are used for this purpose.

2 Methods and types of the Earth's remote sensing

The Earth's remote sensing (ERS) is the process of data collection about the Earth's surface without direct contact with it. The ERS is performed using unmanned aircraft systems (UASs), aviation assets and aerospace systems (aircrafts, helicopters, space ships, satellites, etc.), ships and submarines, and earth-based stations.

The remote sensing is based on the principle of using electromagnetic radiation as a carrier signal that is reflected from the object (or emitted by the object), returned back and recorded at some space point by the receiver, and then, is interpreted in one way or another. The ERS methods can be either active (laser, radar, etc.) or passive (reflected solar energy, intrinsic electromagnetic radiation of the Earth's surface, etc.).

Since the main specifications of electromagnetic radiation include the wavelength λ and frequency ν, all ERS types can be divided into groups depending on the electromagnetic spectrum interval (from 0.25 μm to 1 m) [12]. The surveys are performed in the ultraviolet (UV), visible, near infrared (IR), middle IR, thermal IR and radio-wave bands. In this case, the atmosphere (molecules of oxygen, ozone, carbon dioxide, water vapor) absorbs the radiation of one or another electromagnetic spectrum range in different ways. When using the ERS data of different spectra, it is also necessary to remember the different spectral reflectivity of the vegetation cover, soils and denudations, water surfaces and snow deposits that requires appropriate skills of the performer.

The ERS results include a two-dimensional metric image of specific areas and objects in the form of a photograph. Depending on the type of the wave signal receiver and emitter, the value of the reflected signal in the image can be expressed, for example, by the color saturation of the resolution cell. Based on such images, it becomes possible to study the features of landscapes and topographical forms from the local to global scales, the hydrosphere, biosphere, and lithosphere of the earth.

It is worth noting that in recent decades, the share of the Earth space survey materials has significantly prevailed over the aerial photographic materials due to the economic costs, greater spatial reach and the imaging technology development. The Earth's remote sensing has contributed to the emergence of new research areas, such as the satellite meteorology, satellite hydrophysics, space oceanology, space mapping, space geodesy, etc. In this case, the ERS use for daily geo-ecological monitoring holds a specific place.

The remote sensing data in hydrology is used for interpretation of the linear and areal water bodies, catchment area identification, estimation of evaporation from the earth's surface and amount of precipitations, monitoring of the high waters and floods, hydrological process modeling, including for observation of the snow melting processes in order to predict the runoff volume [12].

For the drainage basins, the main component that determines its configuration is the terrain. The Earth surface relief data can be represented in the form of a digital elevation model (DEM). Based on the DEM, it is possible to obtain the drainage lines, water course length, position of watersheds, slope angles, etc. The specifications and properties of the hydrological model directly depend on the quality of terrain models; therefore, it becomes extremely important to select the optimal source of the ERS data for subsequent use [6].

3 Analysis of the main ERS data sources for the DEM development

The modern elevation models are obtained using the radarometry technology, InSAR, LiDAR, etc. These technologies have their own specifications, advantages and disadvantages. For example, InSAR technology has the advantage over the optical image interpretation in the absence of cloud coverage and weather conditions. However, a sharp terrain variation (in the mountainous areas, in the areas with complex dissected terrain, etc.) critically affects quality due to the radar shadows.

Table 3. Specifications of the most famous digital elevation models.

Elevation model	Entity	Method of preparation	Coverage	Grid step
SRTM (C-band)	NGA and NASA	InSAR shuttle	56° S – 60° N	3 degree seconds
SRTM (X-band)	DLR	InSAR shuttle (X-band)	56° S – 60° N	1 degree second
ACE2	ESA ESRIN	SRTM + ICESat	60° S – 60° N	3 degree seconds
ASTER GDEM2	METI and NASA	ASTER satellite	83° S – 83° N	1 degree second
AW3D30	EORC and JAXA	ALOS PRISM satellite	82° S – 82° N	1 degree second
ArcticDEM	University of Minnesota	WorldView-1/3 and GeoEye-1	To the North from 60° N	2 m
TanDEM-X	Airbus DS	TanDEM-X InSAR	Global	3 degree seconds
WorldDEM	Airbus DS and DLR	TanDEM-X InSAR	Global	12 m

Despite the high cost and time expenditures for the DEM data obtaining based on the ERS results, the demand for them is considerable. Often, the entities that have initiated this survey provide the open-source DEM with a lower resolution compared to the commercial version. However, after some time, many of them distribute the open-source DEMs of high accuracy, as was the case with the 1-second accuracy SRTM.

A comparative DEM analysis (Table 3) was performed by many researchers in various fields of Earth sciences. It is necessary to understand whether the quality of a particular model meets the project requirements for relative and absolute accuracy, the accuracy dependence on the surface slope, etc. The selection of a global digital elevation model is based on the goals and objectives of the study, and the main factor is not always the degree of details [13, 14].

The most famous and frequently used data source is SRTM (Shuttle Radar Topographic Mission), produced by radar interferometry using the SIR-C and X-SAR sensors, located on board a space shuttle. The survey was conducted in February, 2000. It covers 85% of the Earth’s surface from 54° S up to 60° N. Data are available in several versions: version 1 - preliminary, version 2 - final, versions 3 and 4 - processed. The latest versions were prepared by CGIAR (Consultative Group for International Agriculture Research) using the post-processing algorithms that correct the data artifacts (radar shadows), as mentioned above. The initial data are presented in the options with a grid step of 1 and 3 angular seconds.

The ACE2 digital elevation model is a global digital elevation model obtained by combination of the SRTM initial data with the satellite radar altimetry data as a result of the several missions. Moreover, the areas that are not covered in the SRTM were completed with the GLOBE and ERS-1 data. A number of authors indicate that the areas of disagreement contain no less valuable information than the areas of agreement between SRTM and ACE2. Thus, for example, by subtracting the surfaces, it is possible to obtain information about the top soil, since the altimeter signal easily passes through the vegetation to the earth's surface [15]. The initial data of the latest ACE2 version were released in 2005. Such data are presented in versions with a grid step of 3, 9, 30 angular seconds and 4 angular minutes. The survey covers the Earth's surface from 60° S up to 60° N.

The ASTER GDEM2 digital elevation model was completed in 1999. In 2011, the survey was supplemented by inclusion of about 260 thousand additional scenes. Since April, 2016, data are available for free download. The ASTER sensor consists of three separate subsystems that capture different ranges of the signal spectrum. The stereo effect was achieved by surveying from two satellites, the telescope of one of which was in the nadir, and the other was directed at an angle of 27.7° to the survey point. New data are specified by higher accuracy and improved algorithm for the water surface determination. The survey covers the Earth's surface from 83° S up to 83° N that is 99% of the land mass area.

The ALOS World 3D - 30m global digital surface model (AW3D30) was obtained using the panchromatic cartographic ERS sensor (PRISM) from the ALOS satellite during the period from 2006 to 2011. New model versions are released on average every two years. Moreover, in recent years special attention has been paid to the extreme northern and southern sections, improvement of the coastline interpretation, and filling of voids. The latest version 3.1 was released in 2020. The survey covers the Earth's surface from 82° S up to 82° N with a step of 1 angular second.

For the countries with territories within the Polar Circle, it is extremely important to cover these areas. As has been noted above, these latitudes have been either not considered by other missions, or their quality is significantly worse than the central parts of the digital surface models [13-15]. In order to solve this problem, the University of Minnesota is working to support and update ArcticDEM. The DEM is formed as a result of a combination of asynchronical panchromatic optical images of the WorldView-1, WorldView-2, WorldView-3, and GeoEye-1 satellites by autocorrelation of the high-resolution stereo images. The project traces its roots to the Alaska relief interpretation. In its last 7th version it covers the entire territory within the Polar Circle. This DEM is highly accurate: the grid step is 2 meters [16].

If we consider the global digital surface models created within the framework of the European Community, it is important to mention TanDEM-X, the preparation of which is performed by the German branch of Airbus Defense and Space [13]. The first data were obtained as the results of the TerraSAR-X mission using the SOT interferometer of the SPOT 5 and HRS satellites. They were used in a close formation at a distance of about 200-400 m. The collection of primary data was commenced in 2007, while the entire Earth's surface was covered at least twice from the descent and ascent orbits. The complex sections of the coastal and mountain areas were covered several times from different directions to reduce the shadow effects. The paid version of the data models for this mission is WorldDEM, obtained due to the data collection during the period from 2013 to 2016. This model has a grid step of 12 meters, and the claimed vertical accuracy corresponds to 2 m. The WorldDEM version with a grid step of 3 degree seconds (TDM90) is free.

4 Conclusions

1. An analysis of the main tailing damp failures indicates that in 70% of cases the dams were of the upstream type [6], since topping the dam of this type is the least expensive. The main sludge poured into the environment included the waste of the iron and aluminum production. An in-depth analysis of these incidents is especially relevant for the ore mining and smelting regions with a large number of tailing damps.

2. The main causes of the tailing damp failures include the processes of overfilling, seepage, earthquakes, structural errors, etc. Moreover, the share of failures due to an abnormal amount of atmospheric precipitations in recent years has been increasing [5].

3. With allowance for the catastrophic consequences of such failures, it is necessary to provide forecasting of the spill scenarios and a qualitative assessment of the environmental impact. In order to implement this goal, it is critically important to use the methods of hydrological and hydrogeological modeling, including the numerical geofiltration and hydrogeomigration models.

4. The digital elevation models (DEM) make it possible to obtain information about the Earth's surface over a large territory that significantly reduces the economic costs of modeling. In turn, it contributes to the modeling implementation at all stages (prior to construction, during operation, at the stages of conservation and restoration). A wide range of available models allows to get an accurate terrain model if the appropriate skill level of the performer is available.

5. The trends analysis in the DEM market and introduction of new technologies in the Earth's remote sensing (ERS) make it possible to evaluate the resolving power and accuracy improvement of such models in the future. The DEM data quality enhancement directly affects the quality and accuracy of forecasting solutions in relation to the hydrological and hydrogeological models. The widespread use of the DEM data in solving the scientific and applied problems is an important signal for the countries related to the need for further development of this industry.

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