STABILITY ANALYSIS OF DAM FAILURES.
APPLICATION TO AURUL TAILING POND IN BAIA MARE (ROMANIA)
Autorizo la presentación del proyecto

STABILITY ANALYSIS OF DAM FAILURES.
APPLICATION TO AURUL TAILING POND IN BAIA MARE
(ROMANIA)

Realizado por
Natalia Pérez del Postigo Prieto

Dirigido por
Prof. Francisco Javier Elorza Tenreiro

Prof. Francisco Javier Elorza Tenreiro
Firmado: ..................................
Fecha: .................................
A mi familia y amigos, en especial a Miky por siempre estar ahí. Gracias.


# LIST OF CONTENTS

RESUMEN ........................................................................................................ VI
ABSTRACT ....................................................................................................... VI

**DOCUMENT Nº1: REPORT**

1. OBJECTIVES AND SCOPE ................................................................. 2
2. PROBLEM STATEMENT ................................................................. 3
3. BACKGROUND .................................................................................. 4
   3.1. Case study location and features .................................................. 4
   3.2. Baia Mare mining facilities ......................................................... 6
   3.3. The disaster .............................................................................. 9
   3.4. Environmental, economical and social impacts ....................... 10
4. METHODOLOGY ........................................................................... 14
5. PROJECT DEVELOPMENT ......................................................... 15
   5.1. Geological context ................................................................. 15
   5.2. Risk management in tailings dams design ............................... 24
   5.3. Aurul tailing pond ................................................................. 40
   5.4. Stability analysis of Aurul tailing pond dam ......................... 50
6. CONCLUSIONS AND PROPOSALS ........................................... 59
7. REFERENCES .................................................................................. 62
   7.1. Bibliographic references ......................................................... 62
   7.2. Legislative references ............................................................. 63
   7.3. Online references ................................................................. 63
## DOCUMENT Nº2: ECONOMICAL STUDY

1. **INTRODUCTION** .......................................................................................... 1  
2. **PROJECT COSTS** .................................................................................... 1  
3. **PERSONAL COSTS** .............................................................................. 1  
4. **MATERIAL RESOURCES** ..................................................................... 2  
5. **TOTAL COSTS** .................................................................................... 3  

## DOCUMENT Nº3: ANNEXES
LIST OF FIGURES

DOCUMENT Nº1: REPORT

Figure 1 Location of Baia Mare and Maramures County ........................................ 4
Figure 2 Baia Sprie's mine ................................................................. 7
Figure 3 Aurul S.A.'s processing plant ..................................................... 8
Figure 4 Rupture of tailing dam (Bozanta Mare, 30th January 2000) .............. 9
Figure 5 Spread of the cyanide spill .................................................. 10
Figure 6 Contaminated rivers and streams ........................................ 11
Figure 7 Dead fishes consequence of Baia Mare's spill ......................... 11
Figure 8 Red line encircling the Transylvanian Basin Province ............... 15
Figure 9 Location and structural features of the Carpathian Mountains region in Eastern Europe ................................................................. 16
Figure 10 Stratigraphic column for the Transylvanian Basin, Central Romania, Eastern Europe ................................................................. 18
Figure 11 Map of study area and its tailing ponds facilities ................. 21
Figure 12 Sequence of the life cycle of a Tailings Deposit Facility .......... 26
Figure 13 Dam construction types (I) ............................................... 30
Figure 14 Dams construction types (II) ............................................... 31
Figure 16 Proper internal permeability configuration .............................. 33
Figure 17 Seepage blocked effect ....................................................... 33
Figure 18 Seepage restricted effect ....................................................... 33
Figure 19 Upstream embankment drain .......................................... 35
Figure 20 Downstream embankment drain ...................................... 35
Figure 21 Centreline embankment drain .......................................... 35
Figure 22 Filter example ................................................................. 36
Figure 24 Slope failure ................................................................. 37
Figure 23 Over-topping failure ......................................................... 37
Figure 25 Foundation failure .......................................................... 38
Figure 26 Dike configuration .......................................................... 38
Figure 27 Cracks resulted from internal erosion .................................. 39
Figure 28 Over-steepened slopes cracks ........................................... 39
Figure 29 Variable thickness could cause cracks.......................... 39
Figure 30 Plan of Baia Mare and Aurul plant and ponds.............. 40
Figure 31 Hydrocyclone and beach formation................................. 43
Figure 32 (A) Upstream beach formation method. (B) Downstream beach formation method.......................................................... 43
Figure 33 Aurul's new pond dimensions........................................ 45
Figure 34 Former plan of Aurul new pond in Bozanta Mare............ 46
Figure 35 Cshematic drawing of the pond operation......................... 47
Figure 36 Longitudinal section of the pond (schematic, scale of heights >> scale of lengths) .......................................................... 49
Figure 37 Outline of the resultant forces acting on a sliding mass...... 52
Figure 38 System of forces acting on a slice .................................. 53
Figure 39 Bishop Method ............................................................... 53
Figure 40 Saturada 1 stability model output................................... 55
Figure 41 Saturada 1 stability model without load output................. 55
Figure 42 Saturada 1 stability model output................................... 56
Figure 43 Saturada 1 stability model without load output................. 56
Figure 44 Húmeda 1 stability model for 25% output......................... 57
Figure 45 Húmeda 1 stability model for 100% output....................... 58
Figure 46 Proposal 1 with 5kPa load and top water level............... 60
Figure 47 Proposal 1 with 5kPa load and water level ok................. 60
Figure 48 Proposal 2 with 5kPa load and water level ok............... 61
Figure 49 Proposal 2 with 5kPa load and top water level............... 61
LIST OF TABLES

DOCUMENT Nº1: REPORT

Table 1 Tourism damage costs up to September 2000 ........................................ 12
Table 2 Historical water chemical data of the River Sasar, Lapus, Somes and Tisza in September 1992 ........................................................................................................... 22
Table 3 Water quality criteria for the River Rhine as established by the European Commission ........................................................................................................ 23
Table 4 Description of the phases concerning actions monitored by external experts ........................................................................................................ 27
Table 5 Advantages & disadvantages of construction methods ........................ 28
Table 6 Upstream, Downstream & Centreline methods. Advantages & Disadvantages ........................................................................................................ 29
Table 7 General requirements for different construction methods ............... 32
Table 8 Permeability values of different types of soil ........................................ 34

DOCUMENT Nº2: ECONOMICAL STUDY

Table 1 Estimated cost by steps ........................................................................ 1
Table 2 Salaries ................................................................................................ 2
Table 3 Field costs ........................................................................................... 2
Table 4 Total costs ........................................................................................... 3
RESUMEN

La gestión de estériles de una explotación minera es un punto clave en el desarrollo económico de una actividad extractiva, y en especial, del entorno natural y social en el que se emplaza dicho proyecto.

La minería de metales preciosos lleva asociada la construcción de balsas de residuos muy peligrosos, fruto de su proceso extractivo, como por ejemplo la cianuración en el caso del oro.

Para un correcto funcionamiento de dichos emplazamientos es necesario escoger correctamente el método constructivo a partir de estudios de reconocimiento previos, como estudios de estabilidad geotécnica, contexto geológico de la zona, sismicidad, hidrología, etc. Así mismo, han de llevarse a cabo unas exhaustivas medidas de control y vigilancia para asegurar las condiciones de seguridad exigidas.

La ruptura de la balsa de decantación de Aurul S.A. en Baia Mare (Rumania) el 30 de Enero del año 2000 ha sido escogido como caso de estudio de estabilidad de diques.

ABSTRACT

Tailing's management of a mining exploitation is a key point in the economical development of the extractive activity and, especially, of the natural and social environment of the site.

Precious metals mining has high hazardous embankment construction associated, product of its extractive process, i.e. gold cyanidation.

A correct operation of those sites makes necessary to choose a suitable construction method, based on previous studies as geotechnical stability studies, geological context of the area, seismicity, hydrology, etc. At the same time, exhaustive control and monitoring must be carried out in order to assure the required safety conditions.

Aurul's decantation pond failure in Baia Mare (Romania), on 30th January 2000, has been chosen as a stability analysis case-study.
STABILITY ANALYSIS OF DAM FAILURES.
APPLICATION TO AURUL TAILING POND IN BAIA MARE (ROMANIA)

DOCUMENT Nº1: REPORT

Natalia Pérez del Postigo Prieto  octubre de 2014
1. OBJECTIVES AND SCOPE

Main Objective

In this Diploma Thesis have been studied the different factors involved in the stability of tailings dams. For this aim geological and hydrogeological context, construction method and geotechnical aspects has been taken into account. Drainage systems and meteorological conditions are relevant as well according to the scope of this thesis.

All these factors have been considered for a detailed simulation in order to conclude failure causes and propose alternatives and solutions.

Report Scope

The events occurred in Baia Mare (Romania) on 30th January 2000 have been selected to be studied. A breach in the tailing decantation pond of 20 m wide, resulted in a pollution of the nearby river system which crossed three countries ending in the Black Sea.

After further studies, it has been concluded that weather conditions and failures in design were the main reasons of the accident. These conditions have been simulated in Slide software over AutoCAD draft designs of the pond. Once critical points are identified, different alternatives in design and construction are simulated too.
2. PROBLEM STATEMENT

According to the environmental impact caused by the accident at the treatment facilities of Aurul S.A. in Baia Mare (Romania), this thesis scope propose different alternatives that might had avoided the accident, and which could help in future similar situations.

For this aim, a detailed study of the accident has been done in order to compare the given situation to every condition that may be in relation with design and requirements of tailings dam construction.

Once all information has been collected, several AutoCAD designs will be simulated attending to the geotechnical and stability conditions of every possible scenario.
3. BACKGROUND

3.1. Case study location and features

The Maramures County, situated at the northern border of Romania with Ukraine, consists of the old "lands" of Maramures-Chioarul, Lapus and Baia Mare Depressions.

![Figure 1 Location of Baia Mare and Maramures County](source: Wikipedia [15])

This area is rich in gold, silver, lead, copper and salt and there is a long history of mining in the region. There are seven key mining sites in the county. The facilities produce:

- Gold (Au)
- Manganese (Mn)
- Silver (Ag)
- Lead (Pb)
- Zinc (Zn)

Waste water and materials from these facilities are stored in flotation ponds and tailing dams. However, the design, quality, and protection applied to such dams can vary depending on the previous studies (geological mapping, geotechnical and geophysical surveys) done, or not, to settle its placement.
For example, there are nineteen flotation ponds identified by the local Environmental Protection Agency (EPA) in Maramures County. Twelve of these have been abandoned due to several incidents, and seven are still active sites.

The most significant incident related with these tailing dams happened in Baia Mare. It was rated as the biggest freshwater disaster in Central and Eastern Europe.

Baia Mare is a municipality located along the Săsar River, in the northwestern area of Romania; it is the capital of said Maramureș County. The city is situated about 600 km from Bucharest, 70 km from the border with Hungary, and 50 km from the border with Ukraine.

As of 2011 census data, Baia Mare has a population of 123,738, a decrease from the figure recorded at the 2002 census (137,976).

Baia Mare is placed in the western part of Maramureș County, the city occupying partially some of the depression area, also the mountainous northern part. So, Baia Mare is situated at the contact zone between the Baia Mare depression and the IgnisMasive, at an altitude of 194 m above sea level. Baia Mare County is based on a rather wavy geomorphology, made from a complex of hills (with altitudes) between 450-800 m (height), separated by the tributaries of the Somes, Lapus and Sasar rivers. The entire area has a kind of amphitheater aspect, with a large opening towards the west, while on the northern side the Ignis and Gutai mountains lay.
3.2. **Baia Mare mining facilities**

Baia Mare has a growing population and urban development with expansion restricted in some areas by the presence of old tailing ponds. In the early 1990s it was agreed that three such ponds should be cleaned and recovered to allow development to proceed. Residents are living within 50 m of highly toxic, potentially chronically leaking, waste sites that cause concern, especially in the dry months. There would be a clear environmental improvement from removing such waste sites.

Aurul was set up as a joint venture with Australian and Romanian partners following an international tender to clean up the sites. The design concept was that the waste would be transported away from the city (at least for two dams) where the remaining gold and silver in the tailings waste could be recovered using efficient modern technology that was not available when the original ponds were established.

The company described the process as follows (UNEP/OCHA, 2000) [1]:

“after removal of the precious metals, the tailings will be re-deposited in a plastic lined dam which will provide a totally closed water circuit with zero discharge to the surrounding environment”.

As per intention, the dam was therefore the most modern in the region, designed to be a major environmental improvement to the existing chronic polluting ponds. It was intended to be a safe and efficient method of meeting the requirements of the Romanian authorities and the Australian investors.

3.2.1. **Company activity**

AURUL S.A. was a company jointly owned by the Australian “Esmeralda Ltd.” and the Romanian “REMIN S.A.” (“Romanian Compania Nationala a Metalelor Pretiosasi si Neferoase”). Over a seven-year period, Aurul obtained all of the necessary environmental permits required under Romanian law for its plant in Baia Mare, before beginning operations in May 1999 by processing an existing 30 year-old tailing dam (Meda dam) located near Baia Mare city, to the west, close to the residential area. Nowadays, the treatment plant and restoration plan are develop by Romaltyn S.A.
The source of the raw materials utilized by the Aurul company is of mining residues accumulated in the Meda tailing dam. These solid wastes resulted from former gold and silver extraction. The technology introduced by Aurul utilizes high concentrations of free cyanide in the process waters for the extraction of the precious metals. The whole process is designed to operate in closed circuit with the cyanide containing waters being re-used, after solids sedimentation in the Aurul pond.

![Figure 2 Baia Sprie's mine](source)


The carbon-in-pulp (Clearing in Place) technology was used for the first time in Romania for precious metals recovery. This technology is capable of recovering gold and silver from tailings containing low contents of precious metals originated from previous production processes of ores. The major tailing dams planned to be mined were:

- Sasar (Meda dam): 4.43 Mt with a recoverable gold grade of 0.60 g gold per t
- Central Flotation: 10.05 Mt with a recoverable gold grade of 0.48 g gold per t
- Old Bozanta: 8.5 Mt with a recoverable gold grade around 0.30 g gold per t

The precious metal treatment plant of Aurul was designed with a throughput capacity of 2.5 Mt per year. Gold extraction in the Aurul plant was expected to be approximately 700 mg/l of slurry. The whole project would produce approximately 1.6 t of gold and 9 t of silver per year.
In the case of Baia Mare, the tailings from the old Meda ponds, used for gold extraction are combined with water to form slurry that was pumped to a processing plant where more CN is added if needed.

As part of the process slurry is pumped 6.5 km westbound from Baia Mare to a new dam near Bozanta Mare village, which is in the southwest direction from Baia Mare. The process was designed to release no waste to the surrounding environment.

The processing plant was in charge of receiving the slurry from the chronically leaking Meda ponds, assessing the level of cyanide in the slurry and adding more if needed.

Cyanide levels were monitored and if needed brought to an acceptable range of 0.015 – 0.035% NaCN within the slurry and then pumped into the new tailing dams. (see Table 3 "Water quality criteria for the River Rhine as established by the European Commission" to have an idea of the limit values accepted by the European Commission)

To maximize gold extraction, tailings from the new dam were pumped back to the plant for further extraction of extremely low levels of gold and were then pumped back to the tailing dam. (Close circuit process)

The Baia Mare plant was designed to process 2.5 Mt of tailings per year — to recover about 1.6 t of gold and 9 t of silver per year. The project was to last 10 to 12 years, although this may increase due to recent business deals made with Romanian companies.
3.3. The disaster

On January 30th at 10pm, there was a break in a dam encircling a tailings pond at a facility operated by Aurul SA in Baia Mare. The result was a spill of about 100,000 m³ of liquid and suspended waste containing about 50 to 100 t of cyanide, as well as copper and other heavy metals (Baia Mare Task Force, 2000) [2].

The break was probably caused by a combination of design defects in the facilities set up by Aurul, unexpected operating conditions and unusual weather conditions. Due to the precipitation in the area and the rapidly snow melting, the dam crest was flooded and over 25 m of the dam wall was washed away.

The Baia Mare area received approximately 120 mm of snowfall and 40 mm of rain from mid-December until the end of January. There was reportedly: between 60 and 70 cm accumulated snow in the pond; 30 l/m² precipitation (solid and liquid); and a temperature which rose above 0 °C, whereas on 22nd of January the temperature was of -10°C.

The dam was only able to accommodate storm run-off up to 118 mm.

Figure 4 Rupture of tailing dam (Bozanta Mare, 30th January 2000)


The contaminated spill travelled through Lapus stream, reaching the Szamos, Tisza, and finally Danube rivers affecting the environment of the surrounding areas. It finally reached the Black Sea four weeks later.
3.4. **Environmental, economical and social impacts**

As a consequence of the incident, all the environment of the region was seriously damaged, as well as the social and economic life of the inhabitant of the region. Next sub-sections enclose the main aspects of those consequences.

3.4.1. **Environmental consequences: changes in water and soil composition**

Very high concentrations of heavy metals were detected:

- Copper (total concentration 412.3 mg/l)
- Iron (total concentration 31.3 mg/l)
- Manganese (total concentration 18 mg/l)
- Zinc (total concentration 14.5 mg/l)

The rivers that fed or were fed into the Tisza river, have very high heavy metal concentrations, and the concentration is increasing over time.

The plume traveled down the length of the river, into the Danube river and then into the Black Sea by which time it had significantly diluted.

The waters pH would have changed from the chemical reactions taking place within.
3.4.2. Effect on social and economical life: future projects, fishing and tourism

It was estimated that 80% of all fish in the Tisza River died. We are talking of thousands of tons of specimens. Some of them were found to contain 2.6 mg of cyanide per kg of weight.

Moreover, 30%-60% plankton was killed.

An extensive damage was done to the river’s ecosystems and its fauna, affecting birds, and carnivores also.

The Cyanide plume that traveled through the rivers was 100 times more concentrated than the limit value for drinking water in the region.
Hence, the cyanide spill had - and still has - a considerable effect on the local fishing economies of municipalities along the Tisza region.

The estimated total loss to the fishing and angling sectors (i.e. including direct and indirect damage) is estimated at **USD 5,839,000** (4,330,606.20 EUR). This sum includes the market value of 1,241 t of poisoned, deceased fish, plus only two fishermen' and one angler's association's damage.

Heavy metals persist in the environment and as a bioaccumulation in living organisms.

Since the incident, the heavy metals accumulated in the sediments are being collected 6-10 km downstream of Baia Mare. They will continue to be washed downstream and spread throughout the river system (see Figure 6).

**Table 1 Tourism damage costs up to September 2000**

<table>
<thead>
<tr>
<th>TYPE OF DAMAGE</th>
<th>REVENUE LOSS IN USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild-watercanoeing</td>
<td>800,000-1,300,000</td>
</tr>
<tr>
<td>Szabolcs-Szatmár-Bereg county accommodation revenue losses</td>
<td>185,000</td>
</tr>
<tr>
<td>Szabolcs-Szatmár-Bereg county additional revenue losses</td>
<td>92,000-240,000</td>
</tr>
<tr>
<td>Revenue losses in Tokaj</td>
<td>345,000</td>
</tr>
<tr>
<td>Accommodation revenue losses in the Lake Tisza region</td>
<td>430,000</td>
</tr>
<tr>
<td>Other revenue losses in the Lake Tisza region</td>
<td>658,000-1,600,000</td>
</tr>
<tr>
<td>Accommodation losses in Jász-Nagy kun-Szolnok County</td>
<td>104,000</td>
</tr>
<tr>
<td>Accommodation losses in Csongrád County</td>
<td>120,000</td>
</tr>
<tr>
<td>Other revenue losses in the lower section of the Tisza River</td>
<td>208,000-540,000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>2,942,000-4,864,000</strong></td>
</tr>
</tbody>
</table>

Baia Mare accident that happened in northwest Romania on January 30, 2000 is often mentioned in relation to the planned project in Rosia Montana and significantly influences the public opinion about the use of cyanide in gold production despite RMGC plans to use different method when working with cyanide. It can be inferred that due to this reason Rosia Montana project deserves more attention from non-Romanian NGOs.

In case a serious accident happens in the mine, the spill may reach Romanian-Hungarian border. Hungarian NGOs and governmental institutions expressed concerns about the development of Rosia Montana Project, however Espoo Convention on Environmental Impact Assessment in a Transboundary Context was not yet initiated.
4. METHODOLOGY

According to the problem statement described above, the methodology followed in this thesis involves the study of this areas:

- Geological context
  
  Refers to the regional (Maramures County) and local (Baia Mare region) geology features, dealing with stratigraphy and soil characteristics.

- Hydrogeology
  
  Analyze the regional and local hydrology and river systems, and also review the effects of the mining activity in the area.

- Tailings dam design
  
  Method of construction, materials disposal, tailings composition, drainage, control and monitoring, and failure mechanisms.

- Case study
  
  Aurul Tailings Pond features.

- Stability analysis:
  
  Methods of stability analysis, dam design and simulations on SLIDE.

- Conclusion and proposals
  
  A detailed study of the accident has been done in order to compare the given situation to every condition that may be in relation with design and requirements of tailings dam construction. This thesis scope propose different alternatives that might had avoided the accident, and which could help in future similar situations.
5. PROJECT DEVELOPMENT

5.1. Geological context

5.1.1. Regional geology: Transylvanian Basin Province

Baia Mare is placed in the western part of Maramureș County, the city occupying partially some of the depression area, also the mountainous northern part. So, Baia Mare is situated at the contact zone between the Baia Mare depression and the Ignis Masive, at an altitude of 194 m above sea level. It belongs to the Transylvanian Basin province.

![Map of Europe with the Transylvanian Basin Province highlighted.](image)

**Figure 8 Red line encircling the Transylvanian Basin Province**


The Transylvanian Basin lies entirely within the country of Romania in Eastern Europe (Figure 8) The basin is a middle Miocene to Pliocene sag basin that covers an area of about 20,000 km² in the central part of the Transylvanian intra-Carpathian depression. Surrounding the basin are the Carpathian Mountains on the north, east, and south and the Apuseni Mountains on the west.
Geophysical data show that an estimated 7.5 to 8 km of sediments accumulated in the two deepest parts of the basin, one near the geographical center and the other near the northeast margin. The structure of the sedimentary-rock terrain was strongly influenced by salt tectonics, which created salt domes 10–15 km in diameter in the central part of the basin and diapiric folds with a north-south orientation along the basin perimeter (Mark Pawlewicz, 2005) [3].

5.1.2. Stratigraphy

The Transylvanian basement consists of two distinct sequences:

1) A lower sequence of folded and thrustsed crystalline rocks, Triassic to Lower Cretaceous sedimentary strata, and pre-Upper Cretaceous volcanic rocks, all of which represent an extension of Carpathian flysch stacked in nappes emplaced during Late Cretaceous compression.
2) An upper sequence forming the post-tectonic basin fill composed of Upper Cretaceous to Tertiary formations, with thicknesses as much as 8 km (see Figure 10). Paleogene to lower Miocene deposits are mostly confined to the northwestern part of the Transylvanian Basin and an area just to the north-northwest. Middle Miocene–Pliocene strata are restricted to the central and southern parts of the basin, and middle to upper Miocene volcanic rock overlies the Paleogene to lower Miocene strata in the eastern and northern parts.
Sediments in the northwestern part of the Transylvanian Basin, where we can situate Baia Mare, can be separated into three depositional cycles:

- Eocene continental, brackish, evaporitic, and shallow-marine sequences;
• Lower Oligocene continental brackish-water deposits and marine deposits;
• Lower Miocene siliciclastic deposits. During these depositional intervals, the direction of transgression shifted clockwise from northwest to south-southeast.

Volcanism occurred during Late Cretaceous–Paleocene time on the west side of the basin, whereas within the basin proper, volcanic activity started during the Badenian. Volcanic activity, represented primarily by calc-alkaline tuffs, reached a peak in the Pliocene, and the final episode of volcanism was in the form of basaltic eruptions in the late Pliocene and Pleistocene.

Sedimentary strata in the Transylvanian Basin were strongly affected by salt tectonics, which created domes 10–15 km in diameter in the central part of the basin and diapiric folds with a north-south orientation in the marginal areas.

5.1.3. Local geology: Maramures County, Baia Mare region

The Maramureş depression, situated in the northern part of the Eastern Carpathians is the first from the series of depressions that make up the big groove. Most of the authors admit the origin of volcanic barrier of the Maramureş depression because, without the westwards volcanic chain, its depression character would not have manifested itself. Geologically, the Maramureş depression includes the Transcarpathian zone of the flysch, over which the Miocene and Quaternary formations are disposed.

The oldest sedimentary formations belong to the Eocene, the Strâmtura and Voroniciu sandstone which crops out in the average course of Iza and in its affluents from this zone. The Oligocene deposits represent the biggest part from the Transcarpathian zone from Maramureş area. In the facies of the Borşa sandstone, the Oligocene deposits include: the Caselor Valley formation; the marl-sandstone formation; the Borşa sandstone formation and the superior marl-sandstone formation.

The Badenian is disposed discordantly over the Paleogene deposits. The deposits are tightly folded and have in their structure an alternation of marls and sandstone and intercalations of dacitic tuffs finer in the upper part and coarser at the lower part.

The deposits attributed to the Sarmatian are disposed in continuity of sedimentation over the Badenian ones, forming, usually, the filling of some synclinals. The Pannonian deposits, which finish the Miocene sedimentary cycle, are disposed discordantly over the Sarmatian formations. These deposits of variable thickness
include mainly grey marls, and subordinately thin intercalations of sandstone with bivalve’s remains and intercalations of sands with cross stratification.

Baia Mare region, which belongs to the Maramures County mentioned above, is based on a rather wavy geomorphology, made from a complex of hills with altitudes between 450-800m, separated by the tributaries of the Somes, Lapus and Sasar rivers. The entire area has a kind of amphitheater aspect, with a large opening towards the west, while on the northern side the Ignis and Gutai mountains lay.

In the Baia Mare Basin, there is a hydrothermal characterization:

- Gold and silver: Sasar, Valea Roșie and Dealul Crucii mines.
- Zinc and lead: Ilba, Nistru, Herja, Baia Sprie, Suior, Cavnic, Baiuț, Turț, Borșa mines.
- Copper: Ilba, Nistru, Herja, Baia Sprie, Cavnic, Baiuț, Turț, Borșa mines.

The two main deposits which "fed" the Old Meda tailings deposit in Baia Mare are: Cavnic and V_ratec- Baiut.

Cavnic, located along this main tectonic line, is the host area of one of the most important epithermal gold-base polymetallic ore deposit in NW Romania. Other epithermal polymetallic ore deposits in the area are: Ilba, Nistru, Sasar, Herja, Baia Sprie, and Suior.

The V_ratec ore deposit consists of 18 veins. The Pb-Zn-Cu>Au-Ag veins are hosted by 65 Tertiary sedimentary and igneous rocks. Three groups can be defined: north-western (Trans- Livia, Livia, V_ratec, Radu-Vasile, Gheorghe, Ramur_ Livia and Maria veins), central (Ioan Vechi, Ioan Nou, Tereza, Alexandru and 200 veins), and south-eastern (350, Botiza II, Botiza I, Botiza III, Botiza IV and Borcut veins) ones.

The veins belong to three fracture systems: NE-SW, ENE-WSW and NNE-SSW. Their length varies between 0.2 and 5.9 km, with an average of 0.9 to 1.5 km. The vein thickness varies between 0.2-0.3 to more than 5.5 m. The current height of the mineralized level is variable, from tens of meters in the case of less-developed veins, up to about 500 m.

The veins show diverse textures, most frequently being present the banded, brecciated, massive, cockade and geode ones; impregnations are subordinate.

A more detailed description of both deposits can be found in Annex 1 and Annex 2.
5.1.4. Hydrogeology of Maramures county

Rivers and lakes: dense river system totalling over 3,000 km. There are natural and artificial lakes, including two reservoirs: Stramtori-Firiza (18 Mm$^3$) and Runcu-Brazi-Firiza (30 Mm$^3$) used primarily for water supply and also for flood mitigation and hydro-power production.

5.1.4.1. Baia Mare hydrogeological features

Three rivers essentially play roles of natural boundaries of the investigated area. Lăpuș River flows from SE to NW, and receives Săsar River that flows on a NE-SW direction, in the southern part of the area. Băița River, a tributary of Lăpuș River flowing south-westward, is a smaller water course in the NW of the investigated area. The three TMFs, Aurul, Săsar, and Flotaţia Centrală, are located on the lowest alluvial terrace of Lăpuș and Săsar Rivers (see Figure 11).

Figure 11 Map of study area and its tailing ponds facilities

SOURCE: E. S. Gurzau, C. Baciu, A. E. Gurzau, S. Surdu, G. Damian, Impact of the tailings in Impoundments on the Groundwater Quality Bozanta Area (Baia Mare-NW Romania) and Human Exposure (2012) [4]

The hydrogeological context is mainly controlled by the shallow geological structure. The general structure of the shallow sediments is the following (E. S. Gurzau, C. Baciu, A. E. Gurzau, S. Surdu, G. Damian, 2012) [4]:

21
• A layer of soil rich in organic matter, generally more than 1 m thick;
• Fine-grained sediments (mixture of clay, silt and sand) about 1.5 – 3 m thick. This layer has low permeability, $K \approx 5 \times 10^{-3}$ m/day;
• Coarse alluvial sediments, 3 to 4 m thick, consisting of sands and gravels, with boulders locally, with high permeability, $K \approx 5$ m/day;
• Miocene compact marls, representing the impermeable bed of the shallow aquifer. The shallow aquifer is contained in the coarse alluvial deposits and it is hydraulically connected to the rivers that border the area, being influenced by them in terms of hydrodynamics and chemical status. The watertable depth varies between 0.5 and 3 m.

The quality of the river system varies considerably with respect to the concentrations of heavy metals. There is historic chronic pollution, which inevitably affects the quality along stretches of the river. Inputs include point source industrial effluents, sewage effluents and agricultural runoff. The background data for heavy metals are summarized in Table 2.

**Table 2 Historical water chemical data of the River Sasar, Lapus, Somes and Tisza in September 1992**

<table>
<thead>
<tr>
<th>River</th>
<th>Sampling site</th>
<th>rkm</th>
<th>As</th>
<th>Zn</th>
<th>Cu</th>
<th>Pb</th>
<th>Cd</th>
<th>Fe</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sasar</td>
<td>Baias Mare</td>
<td>0.40</td>
<td>2.8</td>
<td>1.7</td>
<td>0.92</td>
<td>0.02</td>
<td>14.8</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Lapus</td>
<td>Busag</td>
<td>0.42</td>
<td>3.4</td>
<td>2.2</td>
<td>0.38</td>
<td>0.02</td>
<td>14.0</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Somes</td>
<td>Ulmeni</td>
<td>163</td>
<td>0.00</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
<td>1.10</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>Somes</td>
<td>Cicearlu</td>
<td>123</td>
<td>0.36</td>
<td>1.5</td>
<td>1.6</td>
<td>0.32</td>
<td>7.3</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Somes</td>
<td>Satu Mare</td>
<td>68</td>
<td>0.13</td>
<td>1.0</td>
<td>0.56</td>
<td>0.12</td>
<td>6.03</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Somes</td>
<td>Cisenger</td>
<td>48</td>
<td>0.01</td>
<td>0.25</td>
<td>0.06</td>
<td>0.01</td>
<td>1.6</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>Somes</td>
<td>Tunuyognoales</td>
<td>3</td>
<td>0.01</td>
<td>0.26</td>
<td>0.017</td>
<td>0.02</td>
<td>2.3</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>Tisza</td>
<td>Borzhava</td>
<td>725</td>
<td>0.00</td>
<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
<td>0.38</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Tisza</td>
<td>Aranyakapatı</td>
<td>669</td>
<td>0.01</td>
<td>0.28</td>
<td>0.06</td>
<td>0.02</td>
<td>2.7</td>
<td>0.51</td>
<td></td>
</tr>
</tbody>
</table>

**SOURCE: UNEP/OCHA, Spill of liquid and suspended waste at the Aurul S.A. retreatment plant in Baia Mare (2000) [1]**

These numbers can be compared with water quality criteria for the river Rhine, established by the European Commission. The limit concentrations are as shown in Table 3:
From comparing the values in Table 1 with the quality goals in Table 2 it can be concluded that historically (reference year = 1992), at all locations in the rivers Sasar, Lapus, Somes and Tisza, the limit values are exceeded for arsenic (As; range: 0.01-0.42 mg/l) and for lead (Pb, range: 0.01-2.2 mg/l). The reported concentrations for these two heavy metals are 100- to 1,000-fold, respectively, above the quality goal concentrations of the river Rhine. For cadmium (Cd, range 0.00-0.02 mg/l), in the Lapus and Sasar rivers, the concentrations measured in 1992 are almost 10-fold above the Rhine quality criteria level.

The data in Table 2 also show that in the Baia Mare mining area, the concentrations for all heavy metals measured are higher than further downstream the river system. Nevertheless, overall the water data show that these rivers have been highly impacted with heavy metals for many years.
5.2. Risk management in tailings dams design

In this chapter is explained every step to follow during the planning, design, construction, operation and decommissioning of a Tailings Storage Facility.

5.2.1. Glossary

There are a few concepts that should be taken on account a few concepts:

- **Tailings (or Tailing or Tail)**: a waste product or residue from a process.
- **Tailings Storage**: a site where waste, from a process is temporarily or permanently stored, not necessarily formed by a dam structure.
- **Tailings Storage Facility (TSF)**: includes the tailings storage and associated infrastructure.
- **Tailings Management Facility (TMF)**: includes the tailings management and associated infrastructure.
- **Tailings Dam**: a structure or embankment that is built to retain tailings and/or to manage, water associated with the tailings storage.
- **Freeboard**: the vertical distance between the operating or predicted water level in storage and the crest level where water would overflow the dam.
- **Probable Maximum Precipitation (PMP)**: the theoretical greatest depth of precipitation for a given duration that is physically possible over a particular catchment.
- **Probable Maximum Flood (PMF)**: the flood hydrograph resulting from PMP and, where applicable, snowmelt, coupled with the worst flood-producing catchment conditions that can be realistically expected in the prevailing meteorological conditions.
- **Annual Exceedance Flood (PMF)**: the probability that a particular storm or event will be exceeded in any year.
- **Solids content**: mass of solid as a percentage of the combined mass of solids plus liquids.
- **Water Content**: mass of water as a percentage of the combined mass of solids plus liquids (process engineering definition)
- **Moisture Content**: mass of evaporable water as a percentage of the mass of solids (geotechnical definition)
- **Slimes**: silt or clay size material, usually with high water content.
- **Specific Gravity (or Soil Particle Density)**: mass per unit of solid volume of the solids particles in the tailings.
- **Density**: mass of the wet or dry (as defined in each case) tailings per unit of total volume of the solids plus liquids plus air voids.
5.2.2. General tasks for design and construction of tailing dams

Tailings dams are convenient structures to aid the main purpose of storing unwanted waste from a mineral or manufacturing process. This gives rise to the following particular features which differ from conventional dams (Dr. G. Ward Wilson, 2012) [5].

- The embankments must store solids as slurry as well as any free water.
- Their working life may be relatively short.
- They are often built in stages over a number of years.
- The construction, particularly any subsequent raising, may be undertaken by mine personnel without the same level of civil engineering input or control.
- Water management is crucial, particularly if harmful materials are contained.
- Seepage may have a major impact on the environment.
- Daily operations such as placement of tailings and recovery of water are critical to the safety of the storage.
- The filling rate, the ultimate height and even the overall storage configuration may well change in unforeseeable ways.
- The storage must be designed with mine closure in mind, so as to create a permanent maintenance free deposit.

For these reasons, the term "Tailings Storage Facility" is used in this text instead of dam.

The parts that can be usually distinguished in a tailing pond are:

- External dam which acts as barrier for the tailings.
- The beach consisting on sand or coarse tailings deposited nearby the dumping point.
- Decantation pond.
- Tailings sedimentary pond.

In the following diagram (Figure 12) it is shown the life cycle of a Tailings Deposit Facility.
Figure 12 Sequence of the life cycle of a Tailings Deposit Facility

In Table 4 appears a short summary of the phases concerning a project of a Tailing Storage Facility. Whilst, it's going to be analyzed in detailed in this chapter.

Table 4 Description of the phases concerning actions monitored by external experts

<table>
<thead>
<tr>
<th>Phases</th>
<th>Groundwork</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>- probable tailings volume&lt;br&gt;- site investigation&lt;br&gt;- morphology and infrastructure of the area&lt;br&gt;- type and behaviour of tailings&lt;br&gt;- geological and hydro-geological situation</td>
<td>- design of the safety systems&lt;br&gt;- design of a monitoring&lt;br&gt;- definition of an accident plan</td>
</tr>
<tr>
<td>Installation</td>
<td>- protection of built components&lt;br&gt;- necessary minimal dimensions&lt;br&gt;- simple and proof constructions&lt;br&gt;- climatic conditions&lt;br&gt;- availability of used construction material</td>
<td>- installation of sealing control systems&lt;br&gt;- building of basis dam&lt;br&gt;- installation of a monitoring&lt;br&gt;- installation of an accident plan</td>
</tr>
<tr>
<td>Use</td>
<td>- continuous evaluation of measurements (monitoring) &lt;br&gt;- comparison: prognosticated tailings volume vs. actual tailings volume</td>
<td>- estimate of dam stability&lt;br&gt;- adaptation of the monitoring&lt;br&gt;- adaptation of the accident plan&lt;br&gt;- decision: achieving of maximum dump capacity</td>
</tr>
<tr>
<td>Closure-Rehabilitation</td>
<td>- description: current state of surrounding dam and pond&lt;br&gt;- results of measurements: definition of contaminants eroding from the dump (air, water)</td>
<td>- design of a rehabilitation plan&lt;br&gt;- design and construction of safety systems (include existing systems)&lt;br&gt;- adaptation of the monitoring relating to long term phase</td>
</tr>
<tr>
<td>Long term</td>
<td>- continuous evaluation of measurements (monitoring)</td>
<td>- provide accident plan</td>
</tr>
</tbody>
</table>

As the aim of this report is to purpose a solution for dam failures, taking as an example Baia Mare incident, I am going to focus in the dam design and construction, and its main aspects to be aware of.

### 5.2.3. Design and construction

Construction staged over the life of the mine. Usually begins with a starter dike constructed of natural soils and sized to contain initial 1 - 3 years of tailings plus flood inflows. Subsequent lifts made as more tailings produced. This method is known as “construction by operation”. The advantages and disadvantages of applying it are:

**Table 5 Advantages & disadvantages of construction methods**

<table>
<thead>
<tr>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Construction costs occur over life of mine - lower discounted cash flow, lower cash requirements at startup of mine</td>
<td>• Responsibility of mine operator.</td>
</tr>
<tr>
<td>• More flexibility in material selection - could use waste rock</td>
<td>• Planning and scheduling of construction required</td>
</tr>
</tbody>
</table>

*SOURCE: Dr. G. Ward Wilson, Tailings Stability (2012) [5]*

There are several types of tailing ponds referring to the dam construction, but the main ones are listed below: (see Figures 13 and 14)

1. **Upstream embankment.** Lifts over starter dike are constructed of cycloned sand. Tailings are spigotted from topmost lift. Some work has been done on drainage techniques to remove water from slimes, eg. Wicks, geotextiles filter cloth. It leads to ‘modified upstream construction’.

2. **Downstream embankment.** Shells of cycloned sand deposited over starter dike in a downstream direction. A drainage layer should be installed to lower the phreatic surface.

3. **Centerline embankment.** The top of the lifts is centered over the top of the starter dike.
### Table 6 Upstream, Downstream & Centreline methods. Advantages & Disadvantages

<table>
<thead>
<tr>
<th></th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Upstream</td>
<td>• Cheap, requires little construction control</td>
<td>• Foundation of later lifts is on unconsolidated tailings slimes - not stable - not used in earthquake zones as a result</td>
</tr>
<tr>
<td></td>
<td>• Small material requirement</td>
<td>• High phreatic surface due to presence of impermeable fines - leads to further instability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High level of monitoring using instrumentation required during operation</td>
</tr>
<tr>
<td>2. Downstream</td>
<td>• Low phreatic surface resulting stability</td>
<td>• Large material requirements.</td>
</tr>
<tr>
<td>3. Centreline</td>
<td>• Material requirements are midway between those of upstream and downstream embankments</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Phreatic surface tends to be low depending on materials - requires monitoring.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Embankment is stable</td>
<td></td>
</tr>
</tbody>
</table>

*SOURCE: Dr. G. Ward Wilson, Tailings Stability (2012) [5]*
1. Upstream Construction

2. Downstream Construction

3. Centerline Construction

4. Improved Upstream Construction

Figure 13 Dam construction types (I)

5. Waste Rock Downstream Construction

6. Rockfill Modified Centerline Construction

Figure 14 Dams construction types (II)

### Table 7 General requirements for different construction methods

<table>
<thead>
<tr>
<th>Embankment Type</th>
<th>Tailing Requirements</th>
<th>Discharge requirements</th>
<th>Water Storage Suitability</th>
<th>Seismic Resistance</th>
<th>Raising rate restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Upstream</td>
<td>Preferably sand in tailings. Low pulp density will promote sand segregation</td>
<td>Peripheral discharge and well controlled beach</td>
<td>Not suitable for significant water storage</td>
<td>High risk of failure</td>
<td>No more than 5m/year. Less preferably.</td>
</tr>
<tr>
<td>B. Downstream</td>
<td>Suitable for any type of tailings</td>
<td>Varies according to design details</td>
<td>Good</td>
<td>Good</td>
<td>None</td>
</tr>
<tr>
<td>C. Centreline</td>
<td>Sand or low plasticity slimes</td>
<td>Peripheral discharge to create beach</td>
<td>Not recommended for permanent storage. Temporary flood storage possible</td>
<td>Acceptable</td>
<td>Height restrictions for individual raises may apply</td>
</tr>
</tbody>
</table>

*SOURCE: Dr. G. Ward Wilson, Tailings Stability (2012) [5]*

In our case, the construction method is downstream, and its calculations are in section 6 named Stability Analysis of Aurul Tailing Pond, where it is described and designed with Autocad.
5.2.4. Control of the phreatic surface

Control of water levels is of fundamental importance to the stability of dams and embankments.

The water level in embankments or retention dams must be monitored throughout the operational life of the tailing pond.

The objective is to keep the phreatic surface as low as possible. This is done by controlling of permeability of materials within the embankment or dam.

The possible effects of the internal zoning on phreatic surface are:

- Proper internal permeability configuration for control of phreatic surface. (Arrows indicate flow direction)

![Figure 15 Proper internal permeability configuration](SOURCE: Dr. G. Ward Wilson, Tailings Stability (2012) [5])

- Seepage blocked by low-permeability material at embankment face, producing high phreatic surface.

![Figure 16 Seepage blocked effect](SOURCE: Dr. G. Ward Wilson, Tailings Stability (2012) [5])

- Seepage restricted by upstream core and drained by downstream pervious zone to produce good phreatic surface control.

![Figure 17 Seepage restricted effect](SOURCE: Dr. G. Ward Wilson, Tailings Stability (2012) [5])
5.2.4.1. Permeability

Water flows through a fully saturated soil (permeable medium) in accordance with Darcy’s law:

\[ Q = Aki \]

Where:

- \( Q \): the volume of water flowing per unit time (m³/s),
- \( A \): the cross-sectional area of soil through which flow is occurring (m²),
- \( k \): the coefficient of permeability, and
- \( i \): the hydraulic gradient (change in water level divided by the distance over which the change occurs). The units of \( k \) are m/s, i.e., velocity units.

Permeability depends on average size of pores which, in turn, is related to distribution of particle sizes (gradation). Permeability is related to porosity, the ratio of void volume to total volume, the void ratio, and the ratio of void volume to solid volume. However, permeability and porosity should not be confused.

The presence of a small amount of fines in coarse-grained soil can decrease permeability by several orders of magnitude. If the soil is stratified, permeability (and flow) parallel to the stratification is higher than that perpendicular to the direction of stratification.

Values of \( k \) for different types of soil are shown below.

**Table 8 Permeability values of different types of soil**

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>10⁻¹</th>
<th>10⁻²</th>
<th>10⁻³</th>
<th>10⁻⁴</th>
<th>10⁻⁵</th>
<th>10⁻⁶</th>
<th>10⁻⁷</th>
<th>10⁻⁸</th>
<th>10⁻⁹</th>
<th>10⁻¹⁰ m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean gravel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean sands</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>and sand-gravel mixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very fine sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sands, silts and clay-silt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>laminate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unfissured</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>clays and clay-silts (&gt; 20% clay)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*SOURCE: Dr. G. Ward Wilson, Tailings Stability (2012) [5]*
5.2.4.2. Methods of control

Use of internal drainage zones in raised embankments, depending on the raising method applied.

1. Upstream embankment using pervious starter dike with upstream blanket drain.

2. Downstream embankment using inclined chimney drain and blanket drain.

3. Centreline embankment with vertical chimney drain and blanket drain.

The control of the phreatic surface does not depend on absolute value of permeability – depends on relative values. Thus relative increase in permeability can be achieved by either: construction of lower permeability zones in upstream section

- Construction of higher permeability zones in downstream section.
- Construction of higher permeability zones in downstream section.

The principle for controlling the drainage consists of:

- In general, increase the relative permeability between materials in the direction of seepage either by construction of impervious cores upstream or pervious drainage zones downstream.
- If cores or drainage zones are used, the dam can be designed to operate essentially independently of the tailings or retained water.
There are several ways of drainage:

- Chimney drains: intercept lateral seepage.
- Blanket drains: use at base of the embankment.
- Finger or strip drains: variation of blanket drains, forms discontinuous drain along the dam centerline.

5.2.4.3. Filters

Filters are used as buffers between zones of differing permeability to prevent migration of fines such as tailings or dam cores into coarser drainage zones of the embankment or dam.

This is sometimes referred to as **piping** or **internal erosion**.

The principle of filter design is that any change from fine to coarse material must be made as a gradual change from the protected soil (the soil that must be protected from piping) to a drain.

\[
\text{protected soil} \rightarrow \text{transition} \rightarrow \text{filters} \rightarrow \text{drain}
\]

Filters must be sufficiently fine to prevent migration of the protected soil, but permeable enough to discharge seepage. The following criteria have been established:

1. Buffers between soils of different permeability.
   - Prevent migration of fines into coarse-grained zones
   - Allow free drainage of water.

\[\text{Figure 21 Filter example}\]


The fundamental idea is:

\[
\text{protected soil (s)} \rightarrow \text{transition/filters (f)} \rightarrow \text{drain}
\]

Graded filters comprising two or more layers with different gradings can be used.
5.2.5. Failure mechanisms

A. Over-topping of the dam:
   - Resulting from inadequate discharge and hydraulic structure capacity.
   - Underestimate design flood - hydrology.
   - Caused by erosion due to freeboard waves.

   Vaient dam - Arch dam:

   [Diagram showing over-topping]

   Vaient dam is the classical dam failure due to over-topping.

   Figure 22 Over-topping failure
   SOURCE: Dr. G. Ward Wilson, Tailings Stability (2012)

B. Slope failure:

   [Diagram showing slope failure stages]

   Figure 23 Slope failure
   SOURCE: Dr. G. Ward Wilson, Tailings Stability (2012)

   The dam needs strength and pore water pressures, that give the stability of the structure.

   The first filling of a reservoir is always nerve-racking and it exists the possibility of a slope failure.
C. Foundation failure:

The placement of tailings waste is not as well controlled as water filled dams, therefore, more tailings dam failures occur.

Possibility of a weak foundation layer (may have to flatten downstream slope or have drainage).

Need Strength and Pore water Pressures of Foundation Soils.

D. Erosion failure. There are two possibilities:

i. External:
   - Wave attack on upstream.
   - Rain-wash on downstream.
   - Wind erosion on downstream.

ii. Internal:
   - Fine sands and silts erode easily as well as dispersive clays (do not have cohesion)
   - May also occur at the contact with rock abutments or concrete structures.

iii. Control of seepage forces:

Figure 24 Foundation failure


Figure 25 Dike configuration


- Need special treatment at the contact between the rock foundation and internal core
• Good filters are paramount
• Grout curtain or cutoff and drains may also be used
• May encounter cracking of the core
• Self-healing core has been proposed with the use of well graded materials for the construction of the core. Therefore, cracks that develop may heal with coarser material that drops into crack.

E. Cracking
• Differential movements commonly lead to cracking
• Results shown in internal erosion

Figure 26 Cracks resulted from internal erosion


![Section A](image)

Figure 27 Over-steepened slopes cracks


• Caused by over-steepened slopes.
• Tensile zones must be identified.

• Caused by variable thickness of fill.
• Consider re-grading of abutment slopes.
• Evaluate with stress-deformation analysis.

Figure 28 Variable thickness could cause cracks

F. Earthquake
- Lateral forces due to shaking
- Generation of excess pore water pressure
- Liquefaction

5.3. Aurul tailing pond

5.3.1. Introduction

Aurul extracts precious metals from the Old Meda Pond tailings, located in Baia Mare, close to the processing plant.

Old Meda pond contained 4.43 Mt of flotation solid wastes which had 30 years old. A pipeline carried the solid wastes as slurry to the processing plant, where Aurul extracts gold by cyanidation (see Annex 3). The tailings fluid, after gold extraction, was pumped through a pipeline 6.5 km away to the Aurul new pond, a sedimentation pond located in the surroundings of Bozanta Mare.

All the process consists of a close circuit in order to recover and reuse the cyanide. To get an idea of the approximated amount of cyanide in circulation during the whole process, those are the quantities:

- Cyanide after gold extraction: 700 mg/l.
- Cyanide pumped to the new pond: 400 mg/l

Figure 29 Plan of Baia Mare and Aurul plant and ponds

SOURCE: UNEP/OCHA, Spill of liquid and suspended waste at the Aurul S.A. retreatment plant in Baia Mare (2000) [1]
5.3.2. Brief description of Old Meda Pond

At the end of October 1999, S.C. Aurul received "green wave" for running at the entire capacity. Old "Meda" tailings deposit (see Figure 30), which is located in the Baia Mare administrative territory - west side, on Sasar River left bank, immediate vicinity with Decebal ward.

The deposit surface is over 21 ha and its volume to 4.5 Mt. The old pond was built directly on the soil without using land impermeable materials.

The tailing deposit represents an indubitable pollution source for the neighbouring soils, due to the stream waters and winds. The result is soil accident increasing and the non-ferrous minerals movement. The studies undertaken in this area regarding the underground water reveal that its quality is hardly affected. (See Hydrogeology of Maramures Region, Table 2)

The tailing exploitation is made by dislocation using strong water-jet hydro monitors at 30 atm. pressure resulting slurry, with 40% solid material (800 t/h discharge), which contain ionic-cyanide.

5.3.3. Description of Aurul new pond at Bozanta Mare

The Aurul new pond at Bozanta Mare has an approx. surface of 94 ha. The maximum lend quota is 171 masl and the minimum quota of 163 masl.

The construction method chosen was “construction by operation”. The start dam was built from tailing resulted through hydro-cyclone. An access leading was built with borrowed material from the neighbouring closed old Bozanta dam towards the evacuation system, which is connected to a pumping station placed on the pond outline.

5.3.3.1. Tailings beaches formation by hydrocyclones

Disposal of slurry from a pipeline will cause the slurry to run down slope and concentrate in the lowest point. The erosive effect of this need to be considered, particularly where there are underlying drainage systems or liners. Droppers or spreaders consisting of smaller diameter distribution pipes or nozzles can alleviate this problem (ANCOLD, 1999) [6].

Upon reaching level ground or existing stored tailings, the tailings will spread out to form a beach in the shape of a cone or fan with its focus at the drainage line or discharge pipe. The cone is not necessarily uniform and may have major erosion.
channels caused by change in fluid density, flushing discharge or runoff from storms. Such erosion will carry material from upper beaches into the lower beach area.

The angle of the beach depends on the solids content of the tailings, the nature of tailings including the tendency to segregate at low beach velocities, and the distance to the decant pond. Steeper beaches can accommodate significant volumes in the cone and can thereby minimize the size of the containing storage. However, allowance must be made for potential slumping in earthquake or storm, for storm freeboard around the base of the cone and for sediment from erosion channels as described above.

Beaches angles can be approximated from laboratory trials but are neither reliable nor consistent with actual beach behaviour. Theoretical calculations based on rheology or shear strength may be imprecise due to material variability and the difficulty in determining the low shear strength of recently settled material. If there are existing or nearby tailings beaches of similar material, grading and process then these will be a useful guide.

Beaches angles are also function of the method of operation of storage. Beaches angles below water are complex due to various influences that can occur, but are generally steeper where the beach enters the water.

Hydrocyclones have been mainly used for the construction of tailings embankments where the tailings contains a high fraction of coarse material or where a clean separation can be achieved. This is the case of the beach formation, where dried material is needed.
Figure 30 Hydrocyclone and beach formation


Figure 31 (A) Upstream beach formation method. (B) Downstream beach formation method

5.3.3.2. Waterproofing

The construction of Aurul TMF includes an isolating system at the bottom of the deposit, consisting of a geomembrane able to protect of pollution the groundwater and soil beneath the pond. The geomembrane is made of high density polyethylene (HDPE) (see Annex 4), with a general thickness of 0.5 mm, and 1 mm under the marginal dams respectively. The aim of the geomembrane is to prevent seepage of cyanide contaminated water into shallow ground water body.

Generally, the geomembranes have extremely low permeability; however they are not fully impermeable. For the moment the mechanism by which the water may cross the membrane is not completely clear. It is very likely that the water flow occurs at a molecular level. The hydraulic conductivity $K$ is about 10-12 cm/s. For such low values, Darcy’s law is not valid anymore, and the hydrogeological modeling that is based on Darcy’s law, should consider this peculiarity (E. S. Gurzau, C. Baciu, A. E. Gurzau, S. Surdu, G. Damian, 2012) [4].

Usually, this micro-permeability generates negligible flow through the membrane. Sometimes, the membrane may have manufacturing defects, as microscopic perforations, with the diameter smaller than the thickness of the membrane, called pinholes (Weber, 2008) [7].

The water flow through the membrane is negligible even in this case. If the welding of the sheets has not been well performed, or if the membrane was accidentally punctured during the installment, bigger holes may occur, that will allow the flow of certain water quantities through the membrane. In the case of Aurul TMF, there are no arguments for presuming that the membrane would be broken, or that it would have any defects allowing important water flow through it. However, it is very likely to have percolation of very low amounts of water due to the intrinsic permeability of the membrane or to the pinholes. The tailings have low permeability; consequently the amount of water that may be transferred to the soil and shallow aquifer would be low.
The main features of this sedimentation pond are (Montreal, 2003) [8]:

- Flat land pond.
- 89 ha approx.
- Volume: 15 Mm$^3$.
- Maximum height of the contour dike: 17-18 m.

In its future final stage it was expected to be nearly 20 m high. It was constructed on gently sloping terrain by forming a surrounding dam and a decant well in the pond centre to allow decanted liquid to be re-circulated to the plant. As it is mentioned above the entire pond was lined with a plastic membrane to prevent loss to the ground and drains were fitted in the dam wall to collect any seepage which was included in the decant water fed back to the processing plant.

Thus, the system would be completely contained, with no loss to the surrounding environment as per the permit requirements. Observation wells were installed along the perimeter to monitor the success of the operation with regard to groundwater pollution.
5.3.3.3. Transport of tailings

The most common method of transport is as a slurry, generally with 20% to 65% solids content.

In some cases the initial settled density of tailings is a function of the density at discharge i.e. higher density slurries generally give higher density of settled tailings.

Selection of transport system and the use of any aids such as thickeners, fluidizer, etc. is generally based on economic considerations of both capital and operating costs. However, these should also be considered in light of related costs such as return water costs, environmental control of spillages, ponds, etc.

All transport systems should be fail safe. Any spillages or breakages should be confined or directed to areas where recovery/rehabilitation is possible. Monitoring of pipeline pressures or flow rates at each end of pipelines will assist the minimization of any spillage.

Attending to those comments, if it would have exist a good monitoring system in the Aurul installations, it may have been avoided or stop the spill.
At the Aurul scheme, decant water from the Aurul new pond was re-used in the remaining of the old Meda deposits. This return water still had high cyanide levels, thus reducing the need for fresh cyanide addition at the processing plant.

![Cshematic drawing of the pond operation](SOURCE: UNEP/OCHA, Spill of liquid and suspended waste at the Aurul S.A. retreatment plant in Baia Mare (2000) [1])

5.3.3.4. Problems encountered

There were some critical points in this approach and problems were encountered in the operation of the system (UNEP/OCHA, 2000) [1]:

I. The old Meda pond has no liner, yet decants water with elevated levels of cyanide was pumped back from the new pond to the old, potentially adding to the toxic seepage near a residential area (losses of cyanide to air and groundwater).

II. Large quantities of toxic slurry and water were pumped through an extensive network of unprotected pipelines.

III. When the toxic slurry reached the new pond, tailings were removed by hydrocyclones onto the surface of the dam and beach and a large volume of toxic water was continuously stored in the pond as well as in the settling slimes.

IV. The lining membrane is 1mm thick under the dam and 0.5mm thick in the pond floor area. There was no further protection provided in the event of a puncture.

V. The solids in the slurry must have both sufficient coarse materials to add to the dam and enough fine material to create a dry beach within the dam. Site visits on
26-27 February, 2000 showed that the quantity of coarse material may have been insufficient to build the dam as per the design specification.

VI. For proper dam formation, the hydrocyclones must be able to operate at all times with only short interruptions allowed. However, hydrocyclone operation is difficult at very low temperatures due to freezing of the underflow, and appropriate dam reinforcement can no longer be achieved. Temperatures went below zero on 21 December, 1999, and stayed low for five weeks. Temperatures below -10 °C were recorded from 22 January, 2000, onwards. Under these conditions, hydrocyclone operation would have to be halted, and the tailings fluid would have been discharged directly into the pond without dam formation, instead operation of the processing was shut down.

VII. Except for the case of the storm run-off event, a sound volume balance taking into account realistic (known) values of precipitation and of evaporation seemed to be missing. Local precipitation regularly exceeds evaporation by nearly 300 mm (on average) per year. Distribution of evaporation over the year is extremely uneven with zero values in the cold season. Relief through evaporation since the start of operation in April 1999 was reduced because the rainfall collected at the lower end of the pond (built on inclined ground), thus substantially reducing the surface for evaporation. Precipitation in the area of the Meda pond (remined tailings) further added to the inflow into the system. These factors led to considerable collection of surplus water in the pond during 1999 so that the rise of the water level was quicker than possible formation of the dam, as no mechanism for relief of the toxic water was provided. A closed circuit operation with “no discharges into the environment” as per the original plans is thus not possible under such conditions.
VIII. The above situation made it difficult for the plant to deal with the period of severe weather at the end of the year. The imbalance between water burden and safe storage volume in the period December 1999/January 2000 was substantially aggravated by the specific climatic conditions of that time. Early in December, 26 mm of rain fell in the entire pond area and assembled in its lower portion, raising the water level there. From mid-December 1999 until end of January 2000, about 120 mm of precipitation fell in the area in the form of snow. On 27January, nearly 40 mm of rain fell on the snow cover after a sudden temperature rise (above zero), making part of the snow cover melt, adding to the water burden.

IX. As can be shown by quantitative analysis on the basis of available date, the actual capacity of the pond at that stage was insufficient to safely store the slimes (already fed in) and the unexpected quantities of water. The dam crest in its poor condition was flooded and washed away in a critical area over a length of 25 m down to the crest of the original starter dam, resulting in the spill. The water stored in the reservoir above that level escaped.
5.4. Stability analysis of Aurul tailing pond dam

In this section deals with the dimensions of the Aurul Tailing Pond (see Figures 33 and 34). A general design in AutoCAD shows how the beach formation behaves with a downstream method. Furthermore, many cross-sections has also been done with AutoCAD in order to simulate the slope failure occurred, and purpose solutions to that kind of problems. (See Annex 5)

Taking on account every existing data about litology, cyanidation process, rock mechanics and climatology, and having the cross-sections, SLIDE software (Rockscience, Inc) simulates the possible failure and its security range.

5.4.1. Software used for stability analysis. Slide 5.0, Rocscience Inc.

In this study SLIDE 5.0 version has been used, created by the Civil Engineering Department of Toronto University. This software calculates the plastic balance that happens in a fracture surface.

First of all, a geometric model has to be done, like the one designed by AutoCAD, in which limits for the different zones can be introduced. the properties that this software requires are:

- Cohesion (kN/m²)
- Friction angle (°)
- Specific weight (kN/m³)

Once you import the model, phreatic level and distributed loads can be added, depending on gravity.

By creating a grid, in this case I have chosen 50x50, SLIDE calculates the safety value of the possible circles of failure in the dam slope.

Making the interpretation of these results, it is possible to get the safest outskirts by plotting the maximum and minimum circles of failure. This is shown by a color range which means the safety range.
5.4.2. Stability analysis

Stability analysis done with SLIDE has been developed using Bishop Simplified Method for every calculation.

Mohr-Coulomb Method has been used in order to consider the global slope stability (a detailed explanation of this method can be found in Annex 6).

Below it is explained the methodology and the fundamentals applied to the calculations for the stability study, as well as the assumed hypothesis to simplify.

Analyses done refer to the possibility that the overall slope break occurs spherically.

The conditions under which breakage typically is spherical are those in which the particle size of the ground is treated as a continuous medium, is very small compared to the dimensions of the slope. This happens in soils or highly fractured and/or altered rock masses.

To analyze the stability of a given slope excavated material with known resistant features, it is necessary to determine the position of the center and the diameter of the circle where it will produce the glide. This circle, known as critical circle, must satisfy the condition that the ratio of the shear strength of the soil or equivalent material along the sliding surface, and the hoop stresses that tend to produce it, result in a minimum.

Except in simple cases, in which the critic circle can be determined by analytical methods, generally the position is obtained by trial and error.

As shown below in Figure 37, the forces acting on a sliding mass are its weight \( W \), the resultant of the external forces which bear upon it, \( A \), the resultant of the normal effective forces to the tear line, \( \bar{N} \), the resultant of the tangential along the tear line, \( T \), and the resulting pore pressure on said line, \( U \).
There are a number of general methods for studying this type of slope failure. One is the method of the slices based on the assumption that the normal stresses are concentrated at a single point arc slide.

In cases where the slope surface is very uneven or broken surfaces intersect geotechnical materials with different characteristics, it is necessary to analyze the slope stability by other methods which are based all in the slices method.

In the method of the slices, the sliding mass is divided into a number of vertical slices and the balance of each is considered. Figure 38 shows a slice with the system of forces acting.
Analysis of the slopes of the slices was made using simplified Bishop method, which is a simplification of the slices method.

According to the Bishop simplified method, the safety factor of the analyzed circle is defined in terms of the moments of resistant and overturning about the center of the circle sliding forces (IGME, 1986) [9].

Figure 38 Bishop Method

SOURCE: Google [16]

Figure 39 shows the breakdown into slices of a slope for analysis by the balance of the breakage limit circle by the method of Bishop simplified.
5.4.3. Results of the dam stability analysis

First of all, case-study dam design was done by AutoCAD, which corresponds with 25% of filling (supposed for simplifying the calculations and because of the lack of data; explanation for choosing 25%: 10-12 project life and only 1 year of exploitation)

My proposal was to do first the simulation of the incident using SLIDE and then try to mitigate the effect in a situation like that, changing the material properties which means drying the tailing more effectively, adding another decantation well or putting another membrane in the outside slope of the dam while forming the beach.

Several trials has been done approximating material properties to the conditions in Baia Mare between 22nd January and 30th January 2000. Those conditions follow a pattern that looks like:

- "Seca":( which means dry) for the medium cohesive materials.
- "Húmeda":(Which means wet) for the most cohesive materials due to possible cementation.
- "Saturada": (which means saturated) for the less cohesive materials due to its high content in water.

A spreadsheet with all this classification and its properties can be found in Annex 7.

To explain the case-study, the following parameters have been chosen:

- The water table level is situated at the same height as the top of the dam because there was overflow on 30th January 2000.
- Piezometric level located in the base of the starter dikes to simulate infiltration until the membrane.

After several trials "Saturada1" was chosen as the ideal material for simulating the incident. "Left to right" direction was chosen for the failure and 5kPa (kN/m²) load was added along the dam crest due to the solid and liquid precipitation fell. Figure 40 shows this result.

Same results were obtained with "Saturada2", "Saturada3", "Saturada4", "Saturada5" and "Saturada6". See Spreadsheet in Annex 7.
If we supposed that there is no effect on the slope because of the solid and liquid precipitation, in meaning of additional weight on the slope, or changes in materials properties (which could vary due to infiltration), the failure is worst (a few more cm deeper). Same results were obtained for the rest "Saturada" as before. Those can be seen in Figure 41:
Another interesting situation is that what would have happened if the dam construction reached the top expected in the last step of the project. (beach formation 100% which corresponds to 20 m approx.) Materials properties and same "modus operandi" as for 25% were supposed and its results are in Figures 42 and 43.

Figure 41 Saturada 1 stability model output
SOURCE: Slide-Rocscience

Figure 42 Saturada 1 stability model without load output
SOURCE: Slide-Rocscience
The next simulations correspond to the situation that could have happened if the pond had been with its correct water level. That means the material properties are not saturated (could de wet with possible cementation) and that there was not infiltration (there is no piezometric level below the starter dikes). The following figures 44 and 45 show that situation in 25% and 100% dam filling. The material properties chosen are "Húmeda#". See Annex 7.

Figure 43 Húmeda I stability model for 25% output

SOURCE: Slide-Rocscience
Same results were obtained with "Húmeda 2", "Húmeda 3", "Húmeda 4", "Húmeda 5" and "Húmeda 6". See spreadsheet in Annex 7.
6. CONCLUSIONS AND PROPOSALS

This project concludes that the stability of the pond was mainly affected by the construction method of the dam reinforced by a deficient drainage. Safety factor went beyond the required (RD 975/2001, modified to RD 777/2012, and 2006/21/CEE) [13] [14].

Regarding the results from last section, two main proposals, which has been simulated on SLIDE, are described below in order to avoid and/or mitigate the problems encountered on 30th January 2000:

1. Instead of "construction by operation" as dam construction method, build the entire pond before operating on it.
2. Waterproofing of the opposite slope of the beach in order to mitigate infiltration.

The first proposal (Proposal 1 in figures) offers the possibility of improving the waterproofing of the dam and its stability. This means adding a waterproof layer named "MARGA" at the top of the dam, between the material used for its construction and the water table level. In addition, a more compacted material could be placed while the dam is being built. Figures 46 and 47 show what would be the behavior of the dam. Properties have been changed to a more cohesive material and the piezometric level has been removed because of the waterproofing level of "MARGA"
The second proposal (Proposal 2 in figures) consists on having the same situation as the incident, with 25% of dam construction as in past section, with 5kPa load reflecting the solid and liquid precipitation, and the water table level at the top of the dam. The solution consists on placing a layer of waterproof material, which could be another level of clay named "MARGAS", at the opposite slope of the beach, and it puts
the piezometric level away from the outer dike and gives more stability to the dam. Figures 48 and 49 show that proposal behavior.

**Figure 47** Proposal 2 with 5kPa load and water level ok  
*SOURCE: Slide-Rocscience*

**Figure 48** Proposal 2 with 5kPa load and top water level  
*SOURCE: Slide-Rocscience*
7. REFERENCES

7.1. Bibliographic references


7.2. Legislative references


[14] 2006/21/CEE

7.3. Online references


[16] www.google.com
STABILITY ANALYSIS OF DAM FAILURES.
APPLICATION TO AURUL TAILING POND IN BAIA MARE (ROMANIA)

DOCUMENT Nº2: ECONOMICAL STUDY

Natalia Pérez del Postigo Prieto
octubre de 2014
1. INTRODUCTION

The aim of this section deals with the global cost of the project described. It is divided into two different sub-sections: project costs and personal costs.

2. PROJECT COSTS

Despite there were two proposals quoted in chapter 6, just costs of proposal 2 are going to be mentioned. Obviously, costs of proposal 1 are much more higher than the ones from proposal 2, and that is the reason of choosing the first.

Focusing on proposal 2, its costs could be divided as it follows:

- Soil preparation where the dike is being built
  - Labor.
  - Equipment.
- Waterproofing. HDPE cost and installation.
  - HDPE membrane acquisition cost.
  - Installation and maintenance.

Estimated cost of the mention steps is:

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Soil preparation</td>
<td>38340 EUR</td>
</tr>
<tr>
<td>2</td>
<td>Waterproofing</td>
<td>1585938,47 EUR</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1624278,47 EUR *</td>
</tr>
</tbody>
</table>

*This cost is estimated along the long life of the project (11 years aprox.)

SOURCE: own

Detailed prices can be found in Annex 8.

3. PERSONAL COSTS

The necessary technical staff to perform this project is formed by:

- Junior engineer (graduate or undergraduate):
- Senior engineer with at least 10 years of experience background:
Price per hour, hours per journey and total cost are shown in the following table:

**Table 2 Salaries**

<table>
<thead>
<tr>
<th>Item</th>
<th>Price (EUR/h)</th>
<th>Time (h)</th>
<th>Cost (EUR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Junior Engineer</td>
<td>20</td>
<td>800</td>
<td>16,000</td>
</tr>
<tr>
<td>Senior Engineer</td>
<td>65</td>
<td>25</td>
<td>1,625</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td><strong>17,625</strong></td>
</tr>
</tbody>
</table>

**SOURCE:** owned

Field work and research performed by the junior engineer have the next cost:

**Table 3 Field costs**

<table>
<thead>
<tr>
<th>Item</th>
<th>Price (EUR/h)</th>
<th>Time (h)</th>
<th>Cost (EUR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Junior Field Engineer</td>
<td>35</td>
<td>20</td>
<td>700</td>
</tr>
<tr>
<td>Travel</td>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>Accommodation</td>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Meals</td>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td><strong>870</strong></td>
</tr>
</tbody>
</table>

**SOURCE:** owned

4. MATERIAL RESOURCES

Material resources used in this project are tangible (physical equipment) or intangible (software):

a) Tangibles:
   - Computer: ASUS Intel(R) Core(TM) i7-3537U CPU@2.00GHz 2.50GHz 8.00 GB (RAM), 800 EUR.
   - Printer and printing costs 200 EUR.

b) Intangibles:
   - Software license: free UPM student license and trial version
5. TOTAL COSTS

In the next table are summed up subtotals and totals from previous chapters giving a total cost of:

*Table 4 Total costs*

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (EUR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salaries</td>
<td>17,625</td>
</tr>
<tr>
<td>Field</td>
<td>870</td>
</tr>
<tr>
<td>Tangibles</td>
<td>1,000</td>
</tr>
<tr>
<td>Intangibles</td>
<td>0</td>
</tr>
<tr>
<td><strong>SUBTOTAL</strong></td>
<td><strong>19,495</strong></td>
</tr>
</tbody>
</table>

*SOURCE: owned*
STABILITY ANALYSIS OF DAM FAILURES.
APPLICATION TO AURUL TAILING POND IN BAIA MARE (ROMANIA)

DOCUMENT Nº3: ANNEXES

Natalia Pérez del Postigo Prieto
octubre de 2014
ANNEX 1
CAVNIC GOLD-BASE METAL VEIN DEPOSIT
(BAIA MARE DISTRICT, EASTERN CARPATHIANS)
Cavnic gold-base metal vein deposit  
(Baia Mare district, Eastern Carpathians)

**Edina VÁGÓ** (Eötvös Loránd University, Budapest)  
**Thierry BINELLY** (University of Geneva)

**Introduction**

Baia Mare district is located in the eastern parts of the Carpathian Mountains in NW Romania, about 100 km N of Cluj Napoca. This area is an important metallogenic province. Mineral deposits (porphyry and epithermal veins) are related to Miocene volcanic and subvolcanic igneous activity. Neogene has been characterised by an overall subduction regime, due to the collision between the European and the African plates giving rise to a subduction-related continental margin arc. The Miocene magmatism and the related mineralization in the area of the Baia Mare district are controlled by a major E-W transform zone, the Dragos-Voda strike-slip fault (Fig. 1; Borcos et al. 1975; Lang 1979).

Figure 1: (A) Schematic map of Baia Mare district showing the position of the major Dragos Voda transform fault system and the boundaries of the underlying Neogene plutons recognized by geophysical studies; (B) Simplified geological map showing the distribution of the major epithermal deposits, modified from Crahmaliuc et al. (1995), Bailly et al. (1998) and Grancea et al. (2002).

Cavnic, located along this main tectonic line, is the host area of one of the most important epithermal gold-base polymetallic ore deposit in NW Romania. Other epithermal polymetallic ore deposits in the area are: Ilba, Nistru, Sasar, Herja, Baia Sprie, and Suior (Fig. 1).

**General geological setting**

Retreating subduction front in the Carpathians and a complex microplate tectonic are the characteristics of this area. The continental collision between the European and African plates resulted from the closure of the Mesozoic Tethys Ocean (Seghedi et al. 1998). The movement of two main continental blocks, Alcapa and Tisza-Dacia, has strongly influenced the geological development of the area. The boundary between these blocks is represented by the Mid-Hungarian line extending eastwards into the Dragos-Voda fault. The Alcapa block showed counter clockwise rotation, the Tisza-Dacia block had clockwise rotation (Fig. 2; Patrascu et al. 1994). The collision was accompanied by calc-alkaline magmatism (Szabo et al. 1992) and the formation of a flysch sediments belt.

Magmatic activity started with deposition of felsic tuffs and ignimbrites (~14 Ma), followed by basaltic andesites, andesites and dacites (13.4-9.0 Ma), and ended by emplacement of small basaltic intrusions (8.0-6.9 Ma). The Miocene predominantly medium-K, calc-alkaline andesitic magmatism shows subduction-related mantle-derived signature with strong crustal contamination. Magmatic rocks have been generated during subduction rollback processes and an almost simultaneous break-off of the descending plate along the entire arc segment (Seghedi et al. 1998). Episodic extrusion of alkaline basaltic lavas was the final stages of the volcanic activity in Plio-Pleistocene. Hydrothermal activity accompanied the orogenic magmatism; the fluid circulation was fault-controlled. Mineralization took place during two main episodes: 11.5-10.0 Ma – in the western part of the district (Ilba, Nistru and Sasar), and 9.4-7.9 Ma – in the eastern part (Herja, Baia Sprie, Suior, Cavnic), following the emplacement of host rocks by 1.5-0.5 Ma (Lang et al., 1994).
Mining and exploration

The Inner Carpathians contain several Neogene Pb-Zn-Cu-Ag-Au ore districts. The Cavnic deposit has a long history of mining, probably beginning in Roman times, but the most intense exploitation has occurred during the last 50 years - mainly as underground mining activity or small open pits. The deposit has current reserves of 20 Mt of ore with grades of 1g/t Au, 30g/t Ag, 1-2% Pb, 1-3% Zn, and 1% Cu.

Alteration and mineralization

Cavnic deposit is a polymetallic deposit with local Au-Ag enrichments generally in the upper part of the system, which was selectively mined out in the past. The deposit is hosted by Neogene volcanic rocks (Fig. 3)

The main ore minerals at Cavnic are sphalerite, galena, chalcopyrite and gold. Minor Sb-, Pb-, and Ag-sulphosalts and tungstates also occur. All deposits of the district have typical features of low sulfidation- or adularia sericite-type epithermal systems. Characteristic alterations are propylitic-, adularia-sericite, phyllic alteration and strong silicification. The mineralization has wide variety of textures: dominated by veins, cavity fillings (bands, druses), minor dissemination, and stockwork structures. Five main alteration and mineralization stages have been distinguished (Fig. 4; Grancea et al. 2002):

1. M0 corresponds to regional propylitic alteration (epidote, andesine, chlorite) which marks the beginning of the hydrothermal activity.
2. M1 is characterized by formation of quartz, pyrite, magnetite, hematite, scheelite and chlorite mineral assemblage. A potassic alteration event is observed at the end of the stage. The transition from stages M1 to M2 is gradual, with some deposition of M1 minerals during M2.
3. M2 corresponds to a copper-rich event with precipitation of chalcopyrite, pyrite, covellite, chlorite and rare occurrences of gold.
4. M3 marks the deposition of sphalerite, galena and sometimes gold in a gangue of quartz, adularia, argillic minerals (illite/smectite) and carbonates (calcite).
5. M4 represents a Pb-, Zn- and Mn-rich stage with deposition of rhodonite, rhodochrosite and adularia. This assemblage is gradually replaced by kutnahorite and antimony-bearing phases such as boumnonite, tetrahedrite and stibnite. Some occurrences of electrum are also observed. The mineral assemblage also includes rare realgar and orpiment.
Fluid-inclusion studies

Fluid inclusions were studied in quartz, sphalerite and carbonate from samples collected from different veins, from different levels of the deposit (Fig. 3; Grancea et al. 2002). Inclusions can be grouped into three types:

- aqueous inclusions with traces of CO₂ in the vapour phase;
- aqueous two-phase liquid-rich inclusions;
- aqueous two-phase vapour-rich inclusions.

The salinity of hydrothermal solutions varies from 1 to 14 wt% NaCl equiv. More saline fluids characterize the early mineralization stages (M1-M2), and lower salinity characterize the later mineralizing events (M3-M4), which was due to a greater involvement of meteoric fluids in the hydrothermal system. The homogenization temperatures indicate also a general cooling trend from the early stage mineralization (M1~315 °C) to the later chalcopyrite-rich stage (M2=260-300 °C), and to the latest base metal event (M3-M4 = 200 °C). Bulk crush-leach analyses were also applied on individual quartz-hosted inclusions from the Cavnic deposit. The Na/K ratio decreases from 19 in M1 (Fe- and W-rich) stage to 3 in M3 (base metal event) stage.

Results from fluid-inclusion and the stable isotope analyses indicate significant contribution of meteoric waters into the ore forming hydrothermal system at Cavnic.

References


ANNEX 2
ORE FORMATION AT VARATEC-BAIUT, BAIA MARE REGION, EAST CARPATHIANS, ROMANIA
Au-Ag-Te-Se deposits
IGCP Project 486, 2005 Field Workshop, Kiten, Bulgaria, 14-19 September 2005

Ore formation at Varatec-Baiut, Baia Mare region, East Carpathians, Romania

Dan Costin¹, Şerban Vlad²

¹Babes-Bolyai University, Faculty of Environmental Science, 1 Kogalniceanu Street, 400084 Cluj-Napoca;
²Ecological University, Faculty of Natural Sciences and Ecology, 22 Franceza Street, Bucuresti 3, Romania

Abstract. The PbZnCu>AuAg ores are located in groups of veins hosted by Tertiary sedimentary and igneous rocks. Sulfides, i.e., pyrite, chalcopyrite, sphalerite and galena, prevail, with subordinate amounts of marcasite, pyrrhotite, arsenopyrite, bornite, chalcocite, and covellite. Sulfosalts, i.e., tetrahedrite-tennantite, bournonite, polybasite-peaceite and especially Bi-sulfosalts such as bismuthinite-aikinite, lillianite-gustavite, matildite, pavonite, berryite, and wittichenite, are characteristic of this field. Gold is associated with Bi-inners, sulfides and gangue minerals. Wolframite, scheelite, hematite and magnetite are also present in the paragenesis. The metallogenesis is polystage, that is Fe±W, Cu Bi±Fe, Pb Zn Cu±Bi, Ba Fe. Metallogenesis of the Varatec-Baiut-Poiana Botizei field is to be assigned to polymetallic > precious metal low sulfur (adularia-sericite) epithermal type / sulfide-rich sub-type.

Key words: Varatec-Baiut, Baia Mare District, Romania, epithermal, sulfides, Bi minerals, gold, fluid evolution, magmatic, meteoric fluid

Introduction

The Varatec ore deposit is part of the Baiut – Varatec – Poiana Botizei metallogenetic field, located in the eastern end of the Neogene Baia Mare Metallogenic Province (East Carpathians, Romania). The orebodies have been mined for centuries, providing one of the main economic activities in the region. Previous geological papers focused mainly on the general geology and less on the mineralized structures themselves.

Geological setting

The geology of the area relates to Jurassic, Cretaceous and Paleogene sedimentary formations included in the Pienid units, posttectonic Neogene and Quaternary sedimentary deposits, as well as explosive, effusive and intrusive volcanic sequences. The magmatism associated with ore formation is subduction-related and consists of a volcano-plutonic edifice of calc-alkaline character, mainly andesitic to dioritic in composition. The complex tectonic pattern resulted from the movements leading to the formation of the Pienid Nappes, followed by reactivation of previously-formed faults and the formation of new ones, synchronous with magmatic activity.

The hydrothermal alteration associated with ore-forming processes is potassic and phyllic, locally also propylitic, siliceous and carbonaceous.

Description of the ore deposit

The Văratec ore deposit consists of 18 veins. The Pb-Zn-Cu>Au-Ag veins are hosted by
Tertiary sedimentary and igneous rocks. Three groups can be defined: north-western (Trans-Livia, Livia, Vâratec, Radu-Vasile, Gheorghe, Ramură Livia and Maria veins), central (Ioan Vechi, Ioan Nou, Tereza, Alexandru and 200 veins), and south-eastern (350, Botiza II, Botiza I, Botiza III, Botiza IV and Borcut veins) ones.

The veins belong to three fracture systems: NE-SW, ENE-WSW and NNE-SSW. Their length varies between 0.2 and 5.9 km, with an average of 0.9 to 1.5 km. The vein thickness varies between 0.2-0.3 to more than 5.5 m. The current height of the mineralized level is variable, from tens of meters in the case of less-developed veins, up to about 500 m.

The veins show diverse textures, most frequently being present the banded, brecciated, massive, cockade and geode ones; impregnations are subordinate.

**Mineralogical composition**

The veins in all the three vein groups of the Vâratec ore deposit are almost identical mineralogically, the differences being related to the ratios between the mineral species. The following mineral classes are represented: native elements, sulfides, sulfosalts, wolframates, oxides and hydroxides, carbonates, sulfates and silicates. Among the native elements, gold shows similar compositions throughout the deposit. It can be divided two types of gold: Ag-rich (16.75-18.49 wt.% Ag) and Ag-poor (12.27-15.25 wt.% Ag). Gold is associated with Bi minerals, sulfides and gangue minerals.

Quantitatively, sulfides are dominant: the most frequent species are pyrite, chalcopyrite, sphalerite, and galena. Marcasite, pyrhotite, arsenopyrite, bornite, chalcocite, and covellite are subordinate. Even if sulfosalts occur in considerably lesser amounts, they nevertheless constitute an essential part of the mineralization. The most frequent sulfosalts are members of the tetrahedrite-tennantite series; bouroninite is subordinate, while members of the polybasite-pearceite series occur sporadically. The presence of Bi- sulfosalts is a characteristic feature of the veins from Vâratec. The chemical data showed the presence of members of the bismuthinite-aikinite series, the lillianite-gustavite series, as well as matildite, pavonite, beryrite and wittichenite.

Bi-minerals, and especially Bi sulfosalts, all contain Se. The content of Se is up to 2.69 wt.%, the Se-richest minerals being lillianite-gustavite series and beryrite.

Another typical mineralogical aspect of Vâratec ore deposit is the presence of wolframates. This class is represented by wolframite – the Fe-rich member (ferberite) and scheelite. Among the oxides, hematite and magnetite have been identified, while hydroxides are represented by lepidocrocite and goethite.

Quartz is the most widespread gangue mineral in the Vâratec veins. It shows various colors: greyish-white, dark grey or smoky, violet-coloured or transparent. Carbonates are mainly represented by siderite and calcite, rarely by malachite and cerussite. Sulfates are scarce, among which gypsum, barite and rarely anglesite were noticed. Clay minerals occur as nests in the central parts of the veins.

**Mineralogenetic succession**

Four distinctive stages may be distinguished within the mineralogenetic processes that led to vein formation. Each is characterized by a specific geochemical assemblage: Fe ± W, Cu – Bi ± Fe, Pb – Zn – Cu ± Bi and Ba – Fe.

The first stage is characterized by the presence of the association quartz – Fe-oxides ± pyrite ± wolframates; it formed close to the wallrock.

For the second stage, the association quartz – chalcopyrite – Bi-minerals – pyrite ± Fe-oxides is typical, including grains of native gold. This association gave birth to the median part of the veins, especially of those belonging to the north-western group.

The third stage represents the main mineralogenetic stage, being characterized by quartz – base metal sulfides ± Bi-minerals. Gold grains are associated with various minerals within this assemblage, which is
located in the central parts of the veins, being more significant in the case of the central and south-eastern groups.

The final stage is characterized by the formation of the quartz-barite-marcasite association, and it formed in the central parts of the veins, especially as geodes.

**Ore forming conditions**

The study of the hydrothermal solutions was based on fluid inclusions in quartz from all four stages of mineralization. The investigated fluid inclusions are primary, two-phase inclusions, with sizes between 2-3 and 50 μm. The temperature of formation was defined by measuring homogenization temperature, and the salinity of the solution was estimated based on the final ice melting temperature (Potter et al., 1978).

The mineralization took place at temperatures between 228.4-356.6°C, and the salinity of the hydrothermal fluids varied between 0.46 and 3.36 NaCl wt.% equiv. The temperature of formation increases from the first stage till the third stage, when the maximum values were recorded; it then drops again during the fourth stage. The salinity increases from the first stage to the second one which is characterized by the maximum values; it then gradually decreases till the fourth stage.

This evolutionary pattern of the hydrothermal solutions was due to dilution of hot, more saline fluids by colder, less saline fluids (first and fourth stages), as well as to a less significant cooling during the third stage. During the third stage, processes of isothermal mixing of fluids with different salinity and slightly different temperatures overlapped with boiling and dilution with surface fluids (Hedenquist and Henley, 1985; Hedenquist et al., 1992). Most of the density values for the hydrothermal solutions fall within the range 0.7-0.8 g.cm³ (Wilkinson, 2001).

**Geochemistry and zoning**

Based on the variation of major element contents with direction, several mineralized columns can be discriminated in the case of large veins, separated by areas depleted in metals, along several horizons. These columns, showing maximum development in the central parts of the veins, usually disappear at deeper levels. In a vertical profile, the following zones can be separated: an upper Pb-Zn zone enriched in precious metals, a clearly poly-metallic, basically Pb-Zn median zone, and a lower, Cu-rich zone. The latter zone also typically shows relatively larger amounts of Au and Ag. The veins in the northwestern group are dominantly Cu-rich, while the veins in the central and south-eastern groups are Pb-Zn-rich.

Based on minor elements, the veins in the north-western and central groups are dominated by W and Bi, while the south-eastern group is characterized by Cd and Sb. Pyrite and marcasite are rich in As, Co, and partly Ni and Ag. Relatively high contents of Ag and Bi were noticed in chalcopyrite, especially in the veins form the north-western group. Galena displays high concentrations of Ag, Bi, and Sb, while sphalerite registers the highest values for Mn and Cd.

**Metallogenesis**

The formation of Váratec deposit was favored by a series of local metallogenetic factors: lithology, tectonics, magmatic features and physical-chemical factors. The specific features of the host rocks influenced the formation and development of the veins, the main role being played by porosity and permeability. The Paleogene deposits and the magmatic rocks represented a favorable geological environment for development of vein fractures, while the volcanoclastic and the Neogene sedimentary deposits were less suitable for this process. The screening effect of Paleogene sedimentary rocks also contributed to the genesis of well-represented mineralized areas.

The tectonic movements affecting the rock sequence in the Váratec Massif led to the formation of fractures that allowed the migration of the hydrothermal solutions. These fractures occurred simultaneously with the
establishment of the regional structural framework, and they were subsequently reactivated during the tectono-magmatic stage. The intersection of several fracture alignments with different orientations represented areas of minimal resistance that favored the emplacement of subvolcanic bodies. Changes of the fractures orientation or dip and their intersection contributed to the enrichment of the mineralizations.

At the initiation of the magmatic activity, the structural framework of Váratec massif was already established, the basement consisting of intensely tectonised Eocene flysch deposits (Fig. 1).

Mineral deposition took place from hydrothermal solutions characterized by a variable thermal regime; the temperature range being over 125°C. The change in the temperatures was connected to the beginning of a new stage. Within the stages rich in metallic minerals (the second and the third stages), several intervals of temperature variation can be noticed during the formation of various mineral associations. The salinity values of the hydrothermal solutions were relatively moderate as compared to the sulfide contents. The high values of salinity are typical for the first three stages, while the deposition of the minerals belonging to the final stage was characterized by lower salinity. The first and the last mineral assemblages were formed from solutions depleted in metallic components. The solutions that led to the formation of the second
Conclusions

The geological, tectonic, mineralogical and geochemical characteristics of the Vărătec ore deposit define its assignment to the low sulfidation (Hedenquist, 1987), or adularia-sericite (Hayba et al., 1985) epithermal type. Based on the type of metals and associated volcanic rocks, the ore deposit may be considered as rich in polymetallic sulfides associated with andesitic-rhyodacitic rocks (Sillitoe, 1993), or as an intermediate-sulfidation deposit (Hedenquist et al., 2000). All the features of the Vărătec ore deposits indicate its best fit with the Creede model (Mosier et al., 1986), while according to the mineralogy, depth and geotectonic setting it belongs to the very low sulfidation subtype (Corbett, 2002). Among the two models previously defined for Baia Mare region (Vlad and Borcos, 1997), the Vărătec ore deposit more closely resembles the Baia Sprie model.

The relatively high temperature of formation is due to the genetic relationship with subvolcanic bodies. The wolframite and Bi-mineral signature marks the role played by the magmatic source during ore formation. Furthermore the low salinity suggests involvement of meteoric water, creating a convective system at the Varatec-Baiut magmatic-hydrothermal center.

Acknowledgment. The authors are deeply indebted to Dr. Richard Herrington, Dr. Chris Stanley and Dr. Robin Armstrong for their help in performing the analysis and for discussions relating to the subject of this paper. The results are part of the research carried out by D. Costin during a five-month Marie Curie fellowship at Natural History Museum London, U.K.

References


ANNEX 3
CYANIDATION
Most the world’s gold supply is found in low concentrations in nature and must be dissolved from ore to be acquired. Less than 10 grams/ton of ore excavated. Gold is readily dissolved by cyanide.

NaCN is typically used as a solvent and diluted to a concentration of 0.015 – 0.035% NaCN.

Most gold mines are often found near water sources since water is used to dilute the NaCN to acceptable levels for mining. Having a readily available supply of water cuts down on transportation and other costs associated with water needs.

Cyanidation

The process of extracting gold from ore with cyanide is called cyanidation. The reaction, known as Elsner's Equation, is:

\[ 4 \text{Au} + 8 \text{CN} + 2\text{H}_2\text{O} = 4 \text{Au(CN)}_2 + 4 \text{OH} \]

Although the affinity of cyanide for gold is such that it is extracted preferentially, cyanide will also form complexes with other metals from the ore, including copper, iron and zinc. The formation of strongly bound complexes such as those with iron and copper will tie up cyanide that would otherwise be available to dissolve gold.
ANNEX 4

HDPE GEOMEMBRANES
GRI-GM13 Specification
High Density Polyethylene Geomembranes

• spec covers smooth and textured HDPE
• thicknesses 0.75-3.00 mm (30-120 mils)
• formulated density ≥ 0.940 g/cc
• silent on flat die or blown film
• lists properties, test methods, test values and test frequencies
• covers eleven (11) properties

Preliminary Comments

• definition of “formulation”
The mixture of a unique combination of ingredients identified by type, properties and quantity. For HDPE geomembranes a formulation is defined as the exact percentages and types of resin(s), additives and carbon black.

• regarding quantities referred to in spec
  90,000 kg = 200,000 lb ~ 1 railcar
  20,000 kg = 45,000 lb ~ 25 rolls of 1.5 mm (60 mil)
  9,000 kg = 20,000 lb ~ 10 rolls of 1.5 mm (60 mil)
**Physical Properties**
1. thickness
2. density

**Mechanical Properties**
3. tensile
4. tear
5. puncture
6. stress crack

**Endurance Properties**
7. CB content
8. CB dispersion
9. OIT
10. oven aging
11. UV resistance

---

### 1. Thickness

(a) smooth sheet

- follows ASTM D5199
- dead weight micrometer with flat tip
- 10-specimens across roll width
- required for each roll
- average must equal nominal
- lowest individual is -10%
(b) textured sheet – core thickness

- follows ASTM D5994
- dead weight micrometer with tapered tip (screw micrometer)
- 10-specimens across roll width
- required for each roll
- average equal nominal -5%
- lowest individual is -15%
Details of Dead Weight Measurement Device for Textured Geomembrane

Core Thickness

Textured Geomembrane Test Specimen

radius of tip = 0.8±0.025mm
angle of tip = 60°±1°
(c) textured sheet – asperity height

- follows ASTM D7466
- uses a stylus to measure height
- 10 specimens across roll width
- required every 2nd roll
- alternate for double sided sheet
- min. ave. $\geq 0.25$ mm (10 mil)
2. Density

- uses ASTM D1505 (gradient column) or ASTM D792 (displacement)
- min. ave. of 3 tests for D1505
- min. ave. of 2 tests for D792
- D1505 is the more accurate test
- value $\geq 0.940$ g/cc (resin is lower)
- each railcar: 90,000 kg or 200,000 lb
3. Tensile Properties

- uses ASTM D6693 Type IV
- min. ave. of 5 MD and 5 XMD
- lower value applies

<table>
<thead>
<tr>
<th>Property</th>
<th>Smooth</th>
<th>Textured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>yield str.</td>
<td>15 MN/m² (2100 lb/in²)</td>
</tr>
<tr>
<td></td>
<td>break str.</td>
<td>27 MN/m² (3800 lb/in²)</td>
</tr>
<tr>
<td></td>
<td>yield elong.</td>
<td>12%</td>
</tr>
<tr>
<td></td>
<td>break elong.</td>
<td>700%</td>
</tr>
</tbody>
</table>

- every 9000 kg (20,000 lb) ~ 10 rolls
ASTM D6693 Type IV Test Specimens

D6693 Type IV “Dogbone” Test in Progress
4. Tear Resistance

- uses ASTM D1004
- called 90 deg. tear test
- min. ave. of 10 MD and 10 XMD
- lesser value $\geq 125$ N/mm (700 lb/in)
- every 20,000 kg (45,000 lb) $\sim 25$ rolls
5. Puncture Resistance

- follows ASTM D4833
- called “pin” puncture
- min. ave. of 15-tests
  smooth $\geq 320$ N/m (1800 lb/in)
  textured $\geq 267$ N/mm (1500 lb/in)
- every 20,000 kg (40,000 lb) $\sim$ 25 rolls
6. Stress Crack Resistance

• follows ASTM D5397 App. A
• called SP-NCTL test (Grace’s Test)
• dogbone specimen (D-1822) in MD
• 20% notch depth in XMD
• loaded at 30% $\sigma_y$ (based on mfgrs. data)
• 10% Igepal in tap water at 50°C
• each railcar: 90,000 kg (200,000 lb)

Pass/Fail Criteria

• follows GRI GM10
• $4/5 \geq 300$ hr; $1/5 \geq 150$ hr.
• if failure, repeat entire process
• if failure again, do entire curve requiring $T_t \geq 100$ hr
• if still failure, reject railcar
NCTL Test Result - Full Curve

SP-NCTL Test Result @ 30% $\sigma_y$

Range of failure times from 9 field failures
7. Carbon Black Content

- follows ASTM D1603 (combustion boat placed in tube furnace)
- muffle furnace (D4218) or microwave okay if correlation is established
- ave. of two tests in 2.0 to 3.0% range
- every 9000 kg (20,000 lb) ~ 10 rolls
8. Carbon Black Dispersion

- follows ASTM D5596
- microtome section (8-15 mm thick)
- view under microscope at 100X
- 10 views are compared to chart
- 9 in Cat. 1 or 2; 1 in Cat. 3
- only considers “near spherial” shapes (this is not CB distribution)
- every 20,000 kg (45,000 lb) ~ 25 rolls
Microtoming Thin Sections per D5596
Commentary

• “dispersion” is concerned over CB agglomerates, i.e., flocs with no resin
• can lead to low tensile values or even stress crack initiation
• “distribution” is concerned with incomplete mixing
• leads to streaking with different shades of darkness but CB is dispersed
• distribution has not been shown to be a problem...

9. Oxidative Induction Time

• OIT is an indirect measurement of the amount of antioxidants

<table>
<thead>
<tr>
<th>Item</th>
<th>Standard</th>
<th>High Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM</td>
<td>D3985</td>
<td>D5885</td>
</tr>
<tr>
<td>Specimen</td>
<td>~ 2 mg</td>
<td>~ 2 mg</td>
</tr>
<tr>
<td>Pressure</td>
<td>35 kPa (5 lb/in²)</td>
<td>3500 kPa (500 lb/in²)</td>
</tr>
<tr>
<td>Temperature</td>
<td>200°C in N₂; 1 min. dwell; switch to O₂</td>
<td>150°C to N₂; 1 min. dwell; switch to O₂</td>
</tr>
<tr>
<td>Spec Value</td>
<td>≥ 100 min.</td>
<td>≥ 400 min.</td>
</tr>
</tbody>
</table>

• Frequency is each railcar: 90,000 kg (200,000 lb)
High Pressure (Left) and Standard (Right) Cells for Measuring OIT
On choice of Std. or HP-OIT

- Std-OIT misrepresents AO packages with thiosynergists and/or hindered amines
- HP-OIT is always applicable (but $10,000 cell and longer test time)

10. Oven Aging

- assessment of thermal stability of antioxidants (AOs)
- follows ASTM D5721
- forced air oven at 85°C
- Std.-OIT $\geq 55\%$ ret. after 90 days exposure
- HP-OIT $\geq 80\%$ ret. after 90 days
- frequency is per formulation
11. Ultraviolet Resistance

- assessment of UV stability of the AOs and CB (there should be synergy)
- uses a laboratory weatherometer
- follows ASTM D7238
- called “ultraviolet fluorescent device”
- 20 hr. UV cycle at 75°C, then 4 hr. condensation at 60°C
- HP-OIT $\geq$ 50% ret. after 1600 hrs.
- frequency is per formulation
Regarding the Warranty

- manufacturers requested so as to avoid 20-year warranties and foolish expenses
- based on GRI Report #16, i.e., if AOs are present lifetime ~ 200 yrs.
- GM13 was crafted to be sure the AOs are present and of proper type, i.e., OIT and oven aging verification
- also, for geomembrane used in exposed conditions a UV exposure is included
- recommended material warranty using GM13 spec is for 5-years (it promises to be 100’s)
- GM13 is silent on any type of installation warranty (this is the major concern)
Concluding Comments

- specification was essential due to NSF dropping its Std. 54 in 1997
- mfgrs. want spec for both covered and exposed GM installations
- this is MQC specification i.e., the manufacturers required tests, minimum values and frequencies
- if MQA project specific spec is more restrictive, manufacturer may ask for additional compensation

The Basic Tables Follow

HDPE – Smooth (SI Units)
HDPE – Smooth (English)
HDPE – Textured (SI Units)
HDPE – Textured (English)

Note: The most recent version of this specification (text and tables) is available on the GSI Web Site <geosynthetic-institute.org>.
### Table 1(a) - High Density Polyethylene (HDPE) Geomembrane - Smooth

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Test Value</th>
<th>Testing Frequency (40°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>30 min.</td>
<td>40 min.</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ENGLISH UNITS**

Table 1(b) - High Density Polyethylene (HDPE) Geomembrane - Smooth

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Test Value</th>
<th>Testing Frequency (40°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.5 mm</td>
<td>1.0 mm</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**METRIC UNITS**
### Table 2(a) - High Density Polyethylene (HDPE) Geomembrane - Textured

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Test Value</th>
<th>Testing Frequency (per side)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile with (max. err.)</td>
<td></td>
<td>D 5038</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for 6 out of 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for any of the 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>Apparent Weight basis (max. err.)</td>
<td></td>
<td>D 1681</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for 6 out of 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for any of the 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>Tensile Properties (max. err. ± %)</td>
<td></td>
<td>D 5038</td>
<td></td>
</tr>
<tr>
<td>- yield stress</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- maximum stress</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- elongation</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- elongation %</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>Tear Properties (max. err. ± %)</td>
<td></td>
<td>D 5038</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for 6 out of 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for any of the 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>Yield Strength (max. err. ± %)</td>
<td></td>
<td>D 5038</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for 6 out of 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for any of the 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
</tbody>
</table>
| *Note:* All values are in ENGLISH UNITS.

---

### Table 2(b) - High Density Polyethylene (HDPE) Geomembrane - Textured

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Test Value</th>
<th>Testing Frequency (per side)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile with (max. err.)</td>
<td></td>
<td>D 5038</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for 6 out of 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for any of the 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>Apparent Weight basis (max. err.)</td>
<td></td>
<td>D 1681</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for 6 out of 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for any of the 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>Tensile Properties (max. err. ± %)</td>
<td></td>
<td>D 5038</td>
<td></td>
</tr>
<tr>
<td>- yield stress</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- maximum stress</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- elongation</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- elongation %</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>Tear Properties (max. err. ± %)</td>
<td></td>
<td>D 5038</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for 6 out of 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for any of the 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>Yield Strength (max. err. ± %)</td>
<td></td>
<td>D 5038</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for 6 out of 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>- lowest individual for any of the 10 values</td>
<td>24 ms/m</td>
<td>-2%</td>
<td></td>
</tr>
</tbody>
</table>
| *Note:* All values are in SI METRIC UNITS.

---

**ENGLISH UNITS**

**SI METRIC UNITS**

---

**GME3-10 of 11**

**Revision 11: 12/3/412**

---

24
ANNEX 5

AUTOCAD DAM SECTION

DESIGNS
1m de altura

2m de altura

TERRENO NATURAL

25%
ANNEX 6
MOHR COULOMB CRITERION
The **Mohr-Coulomb** criterion is the most common failure criterion encountered in geotechnical engineering. Many geotechnical analysis methods and programs require use of this strength model. The Mohr-Coulomb criterion describes a linear relationship between normal and shear stresses (or maximum and minimum principal stresses) at failure.

The Mohr-Coulomb criterion implementation in *RocData* can be used to analyze both direct shear and triaxial test data.

The direct shear formulation of the criterion is given by Eqn.1:

$$
\tau' = c' + \sigma'_{\text{max}} \tan \phi'
$$

Eqn.1

The Mohr-Coulomb criterion for triaxial data is given by Eqn.2:

$$
\sigma_1' = \frac{2c' \cos \phi'}{1 - \sin \phi'} + \frac{1 + \sin \phi'}{1 - \sin \phi'} \sigma_3'
$$

Eqn.2

where \(c\) is the cohesive strength, and \(\phi\) is the friction angle.

**Equivalent Mohr-Coulomb Parameters**

If you are working with one of the non-linear strength criteria in *RocData* (e.g. Generalized Hoek-Brown, Barton-Bandis or Power Curve), then the equivalent Mohr-Coulomb linear failure envelope is automatically computed over a given stress range. See the Equivalent Mohr-Coulomb Parameters topic for more information.
ANNEX 7

MATERIAL PROPERTIES DATA

SPREADSHEET
### VALORES DE CÁLCULO

**Simulaciones sobre balsa sin recrecer, recrecida al 50% y recrecida al 100%**

<table>
<thead>
<tr>
<th></th>
<th>Arena seca</th>
<th>Arena húmeda</th>
<th>Arena saturada</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cohesión inicial (kN/m²)</strong></td>
<td>1</td>
<td>0.6</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>0.6</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Doble cohesión inicial (kN/m²)</strong></td>
<td>2</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Cohesión (doble + 25%) (kN/m²)</strong></td>
<td>2.25</td>
<td>1.35</td>
<td>0.7875</td>
</tr>
<tr>
<td></td>
<td>0.7875</td>
<td>0.675</td>
<td>0.3375</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Arena seca</th>
<th>Arena húmeda</th>
<th>Arena saturada</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peso específico (kN/m³)</strong></td>
<td>15,696</td>
<td>17,658</td>
<td>20,601</td>
</tr>
<tr>
<td><strong>Ángulo rozamiento interno</strong></td>
<td>34</td>
<td>45</td>
<td>15-30</td>
</tr>
</tbody>
</table>

### VALORES DE CÁLCULO

<table>
<thead>
<tr>
<th></th>
<th>Arena seca</th>
<th>Arena húmeda</th>
<th>Arena saturada</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cohesión inicial (kN/m²)</strong></td>
<td>0.35</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.6</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Doble cohesión inicial (kN/m²)</strong></td>
<td>0.7</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Cohesión (doble + 25%) (kN/m²)</strong></td>
<td>0.7875</td>
<td>0.675</td>
<td>0.7875</td>
</tr>
<tr>
<td></td>
<td>0.3375</td>
<td>0.27</td>
<td>0.3375</td>
</tr>
<tr>
<td><strong>Peso especifico (kN/m³)</strong></td>
<td>15,696</td>
<td>17,658</td>
<td>20,601</td>
</tr>
<tr>
<td><strong>Ángulo rozamiento interno</strong></td>
<td>34</td>
<td>45</td>
<td>15-30</td>
</tr>
</tbody>
</table>

### VALORES DE CÁLCULO

<table>
<thead>
<tr>
<th></th>
<th>Arena húmeda</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cohesión inicial (kN/m²)</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>Peso específico (kN/m³)</strong></td>
<td>17,658</td>
</tr>
<tr>
<td><strong>Ángulo rozamiento interno</strong></td>
<td>45</td>
</tr>
</tbody>
</table>

### VALORES DE CÁLCULO

<table>
<thead>
<tr>
<th></th>
<th>Suelo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cohesión inicial (kN/m²)</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>Peso específico (kN/m³)</strong></td>
<td>16.2</td>
</tr>
<tr>
<td><strong>Ángulo rozamiento interno</strong></td>
<td>35</td>
</tr>
</tbody>
</table>

*estimado preparado para balsa (compactado)
**aproximado al valor de arena natural compacta
ANNEX 8
ADDITIONAL INFORMATION
FOR THE ECONOMICAL STUDY
### STEP 1. SOIL PREPARATION

<table>
<thead>
<tr>
<th>Concept</th>
<th>Price (EUR per m²)</th>
<th>Surface (m²)</th>
<th>Cost (EUR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scarifying to prepare the base dam slope</td>
<td>0.142</td>
<td>270,000.00</td>
<td>38,340.00</td>
</tr>
</tbody>
</table>

### STEP 2. WATERPROOFING

- **Contour (m)**: 4,500.00
- **Price (USD per sqm)**: 2.57

<table>
<thead>
<tr>
<th>Dike level</th>
<th>Height</th>
<th>Base lenght (3*Height)</th>
<th>Slope lenght</th>
<th>Surface covered</th>
<th>Net price (USD)</th>
<th>Cost including installation (EUR) (+10%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>5.00</td>
<td>15.00</td>
<td>15.81</td>
<td>71,151.25</td>
<td>182,858.71</td>
<td>158,593.85</td>
</tr>
<tr>
<td>50%</td>
<td>10.00</td>
<td>30.00</td>
<td>31.62</td>
<td>142,302.49</td>
<td>365,717.41</td>
<td>317,187.69</td>
</tr>
<tr>
<td>75%</td>
<td>15.00</td>
<td>45.00</td>
<td>47.43</td>
<td>213,453.74</td>
<td>548,576.12</td>
<td>475,781.54</td>
</tr>
<tr>
<td>100%</td>
<td>20.00</td>
<td>60.00</td>
<td>63.25</td>
<td>284,604.99</td>
<td>731,434.82</td>
<td>634,375.39</td>
</tr>
</tbody>
</table>

**Total**: 1,585,938.47