Causes and Circumstances of Red Mud Reservoir Dam Failure In 2010 at MAL Zrt Factory Site in Ajka, Hungary

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ABSTRACT

The red mud reservoir failure in Ajka, Hungary has claimed 10 lives and cost millions of dollars in damages. Immediately after emergency measures investigations started to shed light on causes and circumstances. The authors performed an extensive desktop study of about 20 thousand pages reaching back to the 1970s, when the facility has been designed.
Beside this study the dam and its area have gone through series of site investigations, from drilling to CPTu testing and laboratory testing. The information so collected resulted in the following conclusion.
Contributing factors to this substantial dam failure included poor siting of the facility, partly on top of a diverted creek bed and marshy area; design faults when calculating safety reserves, as well as basic stability at designed maximum reservoir load. Construction technology has not been controlled; its foundation was built unprofessionally. The negligence of regulators at licensing, at commissioning, as well as at the periodic safety reviews. There was no geotechnical monitoring plan, it was considered to be unnecessary. External negative factors further converged with these deficiencies. The frequency of smaller earthquakes was significantly higher in the accident-preceding year than during the previous ten years. Precipitation was unusual, its level during the accident-preceding half year reached an incidence frequency of 3000 years! Heightened groundwater level saturated the clay base surface of the reservoir already weakened by cat-ion exchanges due to high alkalinity of red mud – on sloping surface. The slurry walls built around the reservoir, from environmental protection purpose, have intensified this process. Strong wind gusts shifting direction pressured the dam walls during the day of accident.

INTRODUCTION

On October 4th, 2010, at 12:14, near Kolontár, Hungary, the worst industrial accident happened in the country's history. The north-western corner of the No. 10 red mud reservoir, operated by the Hungarian Aluminium Production and Trading Company (MAL Zrt), broke, with tragic consequences.
As a result of the dam rapture, hundreds of thousand cubic meters highly alkaline (around 13 pH) red mud and technological water flooded the surroundings: various parts of the municipalities of Kolontár, Devecser, and Somlóvásárhely along the Torna creek valley (see Figure 1.). The catastrophe resulted in 10 casualties, while 286 persons had to be treated by medical personnel, damaged 367 properties, and covered 1017 hectares land.
Based on existing information, there was no sing of the rapture before the even occurred. There was no premonitory requiring action (e.g. seepage of red mud, cracks in the dam structure, scaling slope) noticed during the daily and other regular expert walkouts and other checks, therefore the event occurred unexpectedly.

Fig. 1. satellite image of the flooded are by NASA October 9, 2010

It is also important to note that never during the operation of reservoir No. 10 its designed and permitted maximum storage level of red mud and water has been exceeded.

Data used for analyses

The management of MAL zrt has contracted our company to study all available documentation relevant to this event, going back to three decades (approximately consisting of 20 thousand pages) and all the information collected after the accident by various experts and institutes, via geotechnical investigations (117 boreholes and CPTu with the total length of 2006 m), and processing of laboratory test results. This manuscript is based on all these information.

Short history of MAL Zrt

Through the privatisation process along the socio-economic changes in Central and East Europe, the privy of the Hungarian Aluminium Trust, the National Privatization and Trustee Co. and its 100% owned Hungalu Co. has privatized the Ajka Aluminium Industry Ltd, which was, in those times, one of the frontrunners in Hungarian alum earth (aluminium oxide) production. Since the privatization the company has got transformed a number of times until it became MAL Zrt, establish in 1995 by private investors.
Utilizing the vast amount of economically producible bauxite the company has grown to become one of the biggest industrial complexes, employing 6000 workers. 70-75% od the company's products are sold for West European export.

OUTLINE OF THE SITE

The Ajka Alum Earth Factory has got built in 1942-1943, based on the bauxite and coal deposits found in the area. The facility is situated in Veszprém County, Hungary, in the south-west suburb of Ajka municipality, next to the Budapest-Szombathely railway corridor. There is railway line north of the factory, and behind it stands the slag and ash repository of the Bakony Power Plant, plus some houses. To the east there is the power plant, to the south there are agricultural lands and to the west there are the red mud reservoirs of the MAL Zrt (see Figure 2).

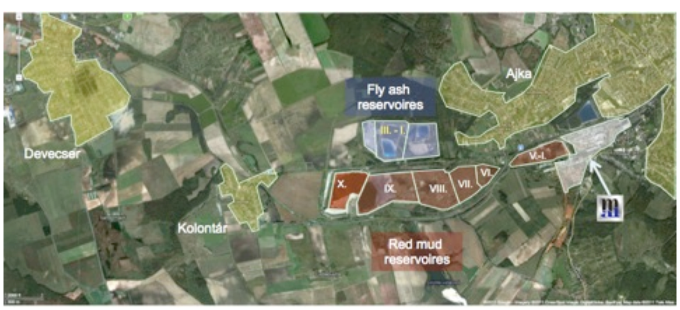

Fig 2. MAL Zrt. and its surroundings (Google)

There has been 11 red mud reservoirs (I—X and X/A) built up till now on this industrial site of which I-V are situated inside Ajka, in the factory site, while reservoirs VI-X/A lay between Ajka and Kolontár on the right side the the road to Kolontár. Reservoirs VI-VIII have got recultivated already, while this process is still on at reservoir IX. On the recultivated surface of reservoir VIII, MAL Zrt plans to deposit more red mud resulted from dry technology processing. Figure 3. shows the layout of red mud reservoirs VI-X/A.

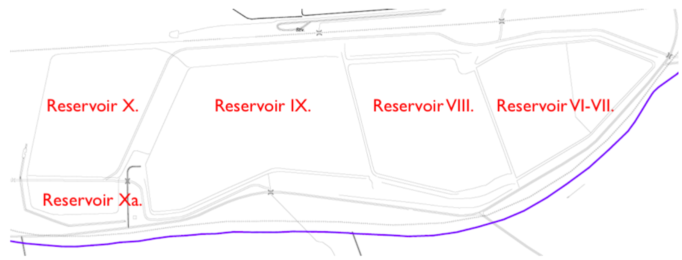

Fig. 3. Layout of the reservoirs

0,8 - 1,5 km to the north of the reservoirs Kolontár and 2,5 - 3,0 km to the southeast Padragkút municipalities can be found. Torna creek is situated on the south side of the reservoirs, into which Csinger creek flows. The original, natural path of Torna creek has run on the north side of the reservoirs.
The entire industrial site of MAL Zrt is over 250 hectares (ha), of which 62 ha is factory and 174 ha is red mud reservoir. The damaged Reservoir X. is over 19 ha, with 18-25,68 m dam height.

HISTORY OF RESERVOIR X

In Hungary aluminium oxide production is based on the Bauer technology, resulting in up till now non-reusable high volume, highly alkaline red mud „waste". Its volume is twice as large as the aluminium oxide produced, therefor required huge landfill sites. This red mud has special physical properties, similar to clay, binding caustic soda, iron and water. Along geotechnical soil characterization (particle distribution for grainy, plasticity index for more bind soils) it can be considered for both grainy (mud or powdery sand) and bind (clay). Its water content remains relatively stabile for a long time, so in the deeper layers even years later it is between 30 to 40 per cent. The top layer, after extended dry period, starts to heavily crack.
Production capacity has been increased in the 1970s. During those times reservoir VIII has been filled up till 1981. After that reservoir IX has got operated till 2000. Still during its operation as a government organization the company has got the design study for its red mud deposition prepared by a design firm (designer) in 1980.
All together ten sites have been considered (from „A" to „J"), from which site „I" has been assigned, as the result of a tedious regulatory process, to establish future reservoir X. This siting process was disputed from the 1980s amongst the political leaders of those times, the company and the communities of the surroundings (1). The interests of local people have got ignored, superseded by economic and political interests. The company has been one of the major economic

players in the country. Therefore the selection process of its waste site has been based mostly of its perceived economic and technical benefits in the communist state. Considerations of potential human casualties in an industrial accident have not been high on the list of decision-makers.

The groundwater pollution resulting from reservoirs VI-IX has become known during those times, as the reservoirs have not got sealed. The regulator ordered to stop further pollution, so the company has contracted designer to prepare a study for suitable intervention. Based on due engineering geological investigations, limiting further pollution effectively and economically required underground corrective measures. Having considered 8 different alternative measures the choice was to erect diaphragm walls around reservoirs VI-X.

After commissioning reservoir IX the pollution became so severe that it has started to endanger the local drinking water base. Various interventions have been made:

- Diaphragm walls for vertical seal
- Water level observation wells
- Trench system inside the diaphragm walls
- Trench system outside the diaphragm walls

Elements of the environmental protection system:

(a) Vertical closures (diaphragm wall)
(b) Collection system for polluted waters
(c) Collection system for clean water
(d) Monitoring systems

(a) Vertical closures

Retaining walls have been constructed in a number of phases, in all together 7.400 m length, between 1987 and 2001, and the walls were totally closed the reservoir area.

(b) Collection system for polluted waters:

- Trenches (leachate trenches)
- Collection basins

(c) Collection system for clean water:

- Tósoki basin
- Northern seepage system

(d) Monitoring systems:

- Observation wells
- Dug wells
- Surface sampling points
- Leachate sampling points
- Waste sinking level measurement points

Parallel to the environmental protection retaining walls, was the design of reservoir X. In its theoretical licensing plan (April 1984) the height of the continuously hydraulically constructed dams, from the slag and ash of the local power plant, would have reached 41,5 - 43,5 m with 1:1 slope incline. Thus the maximum height of the 10 m wide dam crest would reach 235,5 m.a.s.l (meter above the Baltic sea). The maximum allowed level for red mud fill would have been 234,5 m.a.s.l, resulting in 13M m^3 red mud storage capacity. The close to flat terrain slanted towards the west. The average slant in the valley was 5-8 per cent. The highest point at the nothestern corner was about 197,5 m.a.s.l and the lowest at the western wall was 191,0 m.a.s.l.

Dam construction was planned in two phases:

Phase I: to level 216,00 m.a.s.l (with level 215,0 m.a.s.l red mud fill),

Phase II: to level 235,50 m.a.s.l (with level 234, 5 m.a.s.l red mud fill).

Later, fortunately, these planned heights have been rejected, and in the Detailed geotechnical expert report of January 1990 „only" 216,50 m.a.s.l dam crown height has been noted, meaning a maximum of 25 m dam height, with 1:1 slope incline on the northern and southern walls and 1:2 slope incline on the external side of the western wall.

First licencing for constructing reservoir X was awarded in 1993, which was started in the same year with the technology used at reservoir IX. Phese I was concluded in 1995 reaching 205,00 m.a.s.l dam crown level with 1:1 slope incline. The slag and ash tailing conductor has been built, as well as slanted water sinks on both the eastern and southern sides. Then phase II was started buildin up the dam to level 216,5 m.a.s.l, and widening the western walls due to recultivation prescriptions with 1:2 slope incline and a 5 m wide berm. The bottom width of the so built dam system varied between 50 and 80 m, depending on terrain conditions. The designed height of the dams varied between 21 and 25 m. The are of the reservoir is approximately 19 ha, its final capacity at **216,00 m.a.s.l** filling level was circa 4,2-4,5M m^3.

The lengths of reservoir X are 657 m on north, 581 m on west, 269 m on south, and 405 m on east.

In 1998 the filling of reservoir X has started. Red mud, diluted with process water in 1:5 ratio has been transported to the reservoir via pipe system from the factory site. The red mud has been blown circularly to the inner slopes of the reservoir for slushing the surface. This increases water retaining properties. Ideally the water depth increases from the edges to the centre inside the reservoir. Till the end of 2009 3.405.000 m^3 materia has got deposited.

As the factory has used up all its reservoir capacities during years of operation, it had no space for further expansion, except to increase the dam crown to an even height across the existing reservoir walls. The construction of reservoir X has started with the power plant ash fill up through a pipe between two smaller dams. The so created dam crown has not been on even level. The northern side has been lower from the start of construction. As the red mud level increased this uneven hight became prevalent. Therefore the hightening of the norhtern wall became necessary in order to use the maximum designed and licenced capacity of the reservoir. This work has been completed in July 2010 with the use of materials from nearby ash storage. The once deposited and since cemented ash was broken by bulldozer clam-shell and put on top of the dam's nortehrn wall. The broken cemented ash parts have been broken into smaller particles by the dozer blade, smoothened,

and then compressed by roller. This method produced 0.25-0.30 m even layers. To increase compression efficiency, water has been sprinkled on the layers. This way a relatively even and homogenious crown has been formed. These have been performed in approximately 400 m length on the northern wall. The sodden and humusy parts have been removed and corrected. The entire work has been completed in about two weeks, using 5277 m^3 materials. The added layers' thickness varied between 0.3 and 1.4 m.
The red mud reservoir, the condition of the dams have been monitored by eye daily. The dams vave been driven around by 4 x 4, looking for signs of wetting. On each Mondays the level of liquid in the reservoir has been measured by the pump operators and data recorded. There was never any sign recorded of a problem. The appropriate flushing of red mud, and the condition of the pipe system has been checked upon twice daily.
According to the records, on October 4th, 2010, at the time of the dam rapture, the level of tailings in the reservoir was at **215,88 m.a.s.l**, thus 0.12 m lower than its maxmum allowed level of **216,00 m.a.s.l**. The catastrophy occurred at 12:10 according to the work logbook, and caused complete electricity failure.

CONSTRUCTION OF RESERVOIR X

According to design, at the bottom of the dams, on both sides, an earthwork of 1,0 - 1,5 - 1,8 m height, 2,5 – 4,0 m crown width, and 1:1 and 1:1.5 m slope inclines had to be built. This was necessary because the stabilization of slag-ash structure required some days and ill that these earth structures supported the tailing. These earthworks have been prepared by dozer extracting and building up materials to the its left and right and thus taking off top soils to about 1 m depth. The technology of this embankment construction is shown on Figure 4.

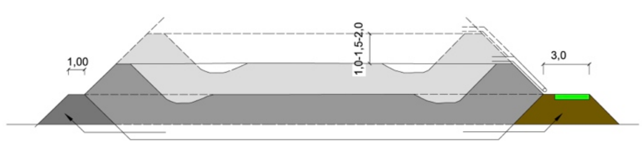

Fig. 4. Dam building technology

The Ø350 mud circular pipe was laid on the external dam side. According to the timing, the filling pipes branch off upward by extension. The dams were built of the slag-ash mud by hydromechanization.
Upon the phase I. (phase between the earth dams) on the two brims of the dam by the use of a bulldozer, the dams of the next phases were constructed of its own material. In the same way were built the dams of the dam's own material also in transversal direction, as sealing of the construction joints. As a consequence of the dam's inclined surface, the superfluous water flew on the embankment into the provisional mud reservoir, at the sole of the western dam. Along the dam's longitudinal side the heaped embankment material was loose. In the course of the construction the voids of this embankment were filled up with diluted mud. The outer, loose parts dropped down to the sole of the dam, or had been eroded during the years. When building the embankment, construction of a seepage collecting ditch system became also necessary, for collecting and returning the effluent water, which left the area and to introduce it into the secondary settling tank.
Construction of the north dam started at its eastern end and proceeded toward the western dam. Before the pumping station, on the deepest point of the area, a reservoir was to be built for the returning mud water. It was pumped back with a pump into the factory. On the east dam of about 4 places took place, where the cross section changed. In the vicinity of the injection points the bigger grains of the mud, the slag settled down, the diluted ash material flew away, therefore the material of the dam is not of the same quality and homogenous at every place.
The thickness of the dam's cross section is not equal because near to the filling openings the mud, ejected at high pressure, spread out wider and extruded also laterally. At the meeting point of the dams IX. and X. started the construction of the dam on the circular pipe, therefore the highest pressure on the northern side was the highest. Consequently the northern dam is "undulating".
Depending from the weather, the settled slag-ash coagulates in a favourable dam material, its water permeability, by using a correct storage technology, practically ceases.
When planning the eastern dam of the reservoir X. it was taken in consideration, that in the "immediate future" the construction of the next red mud reservoir is to be expected, therefore the north dam was built as an intermediate dam. In this sense its slope was 1 : 1 and the west dam, as the end toward village Kolontár, was built with a slope of 1 : 2. The motive of the omission of this extension, could not be deducted from the disposed documents.
Into the reservoir X. during the construction, the red mud was already introduced. After this, the construction of the dam continued until the end of 2001. Due to alignment of the north dam's crest, every dam of the reservoir X. reached the permitted level of 216,50 m.a.s.l.

DESCRIPTION OF THE DAM RAPTURE

In the area of the reservoir from the morning of 4th October 2010 a continuously increasing wind was blowing from southeast toward northwest. According to the testimonies, the water of the reservoir rippled, undulated, but did not hit the walls of the dam. According to the direction of wind, the waves travelled toward the corner, which broke later away.
In the 6-month period before the wall failure, excessive volume of precipitation fell in this area. This heightened the ground water level and a significant amount of rainwater got in the area within the curtain walls. Consequently the water balance of the reservoir X. toppled in an unfavourable way. The water level, what became swollen by the curtain wall, and

the exceptional volume of the rainwater and seepage water, collecting in the seepage ditches were pumped regularly into the reservoir X. Such a big water quantity could not be used by the technology, therefore it was accumulated in the reservoir. During the big August rains the water had to be pumped from the reservoir X. into the neighbouring southward reservoir X/A.

It could be achieved so, that in the reservoir X. the storage level does not reach before time the permitted storage level (216,0 m.a.s.l). This was a technological and economical step, because it could be reached so, that beside the maintaining the continuous operation the permitted storage levels do not exceed in the active reservoirs the permitted storage levels.

The height of the water head above the red mud was due to a sonar measurement, carried out in a boat at 30th September 2010 was 0,4 - 0,6 m near to the place of the wall failure (it was necessary for preventing the dust due to the employed technology and with regard to the natural water evaporation).

At the down of the catastrophe the pumps regulating the seepage water were in operation, because the volume of the seepage water increased. However in the days before the catastrophe it did not rained, but due to the big precipitation which fell on the by the curtain walls enclosed area of 274 hectares (of which the total area of the reservoirs is 174 ha) and as consequence of the precipitation at this time the seepage water seeped through the reservoirs in the underground and filtered into the “reservoir” encircled by the curtain walls and indirectly also into the seepage ditches.

No groundwater seepage, no jets, no water eruption (i.e. on the ground level) were observed neither in the vicinity of the soles of the dams, nor on higher places, like on the dams.

The catastrophe occurred on a level, being 0.12 m deeper than the storage level, on 215,88 m.a.s.l. This is proved by the operational log of the reservoir, what was kept due to the prescriptions by the factory. The last entry into the diary was written at about 8 hour at Monday: the water level on the “water absorbing pipe” is 215,88 m.a.s.l.

Owing to the site diaries, from 13th September 2010 to 4th October the mud injector on the southern side operated. During the wall failure the injector Nr. 2. operated on the same, southern side. Prior to this, from 24 August until 12 September injection took place on the north side.

When the dam breach before the area of the X. reservoir’s north side sole, and on the area at on the lower transport road at about 12 hour, the water “billowed”. Workers of the Sédex Kft., who were working beside the northwest corner of the reservoir IX., noticed, that on the shrubby area before the northern dam of the reservoir X. the water is streaming and the “straw bales are floating on the liquid’s top”

Two eye witnesses, who stayed in the vicinity, narrated, that beside the north-western corner of the reservoir X. – where the dam was the highest – in the arched section, and on its northern wall, a sparkling pink liquid began to flow out and down through a crack which arose on the upper part of the dam crest (due to one of the eye-witnesses through a “washed out groove”) “which was still not dense”. The developing nearly vertical upper crack, a groove subsequent to this, extended downward to the sole. Workers, who worked beside the reservoir IX., heard a cascade-like voice. The out-flowing mud inundated quickly the area near to the corner. The mud flowed out at first only through the crack (“through the groove”) and dripped down. The high velocity effluent disrupted the dam material already cracked due to the loads and 5—6 minutes after the discharge, the dam, containing rigid, and stiff material suddenly burst, accompanied by a strong hubbub. One of the huge ash blocks, flying out in northern direction hit and broke the pole of he electricity wires in the near. The wires sparked and later got torn. The effluent mud broke to huge pieces and swept away the dam materials, sweeping it onto the arable land. After the flowing out the water level began to sink in the reservoir, therefore it is not probable, that the liquid “several minutes long” would sweep over the dam, as one of the eyewitnesses believed. As we mentioned before, the bigger chunks of the (ash) dam material flew more toward north and the most part of the liquid flew also in this direction.

Due to the data so far, the dam breach occurred at 12 hour 14 min. According the eyewitnesses the “red liquid” reached Kolontár within about 10 minutes.

The northern dam section broke to pieces, beginning from the western corner at a length of about 300 m. In the mid of this section the outer slope “broke out”, the dam got punctured and the red mud flew out through this opening.

Workers, along the northern section of the junction of the reservoirs IX. and X. heard a “hubbub” and the “dam trembled” One of the workers, as he said, heard a thump, then a strong “explosion”, and saw at a distance that the red mud is flowing. When the dam corner collapsed, at first a 20 – 25 m wide ”V” shaped gap was formed above (and significantly water flew out here), then it grew continuously, got deeper and more red mud flew out through it together with the water. The flowing out became increasingly louder. After some minutes the proximal section of the dam “collapsed” and the muddy water flew out of the reservoir beside a strong turbulence. Due to one eyewitness at “12 hour 12 minute a 40 m wide rupture was visible” and later a further, about 10 m wide section disconnected and fell into the mud. Finally the entire, 60 m wide dam section broke to pieces. During 15 – 20 minutes flew out the red mud from the reservoir and at 12 hours 30 minutes almost no water was left in the reservoir. The “substantial” material flow blow over in a time of 25 – 30 minutes – according to the eyewitnesses. The water drained nearly completely from the reservoir. The remained stumps of the western dam wall displayed a breaking surface, which was perpendicular to the western axe of the dam, its upper third tilted slightly toward the breach. The surface of the northern dam’s broken stump had a curious, “L”-shaped breaking picture, it was nearly vertical.

Upon the mud flow, the internal part of the northern dam’s damaged section settled. Characteristic, mainly with the dam axe parallel cracks were formed. The dam crest level tilted inward, beside the outer dam sole longitudinal and diagonal cracks were formed, hinting of the dam’s heave.

The state of the section, remained after the breach of the northern dam’s western section deteriorated continuously. The cracks of the dam widened, the movements along the nearly vertical cracks increased, the significant crack at the junction of the moving and of the not moving northern dam section increased, along the outer side repeated ash blocks peeled.

GEOTECHNICS

In April, 1981, 128 borings were carried out as part of the Soil Mechanical Data Supply presented by the designer. The final design plans of the reservoir X were based on these explorations among others. Average depths of the borings were between 5-7 m.

As the next design phase, the designer composed an expert opinion on preventing the soil-pollution spread caused by the reservoir. Additional 25 borings were carried out with an average depth of 6-8 m, also used at the design of reservoir X.

The Data Supply does not contain the coordinates of the explorations therefore the accurate positions are unknown. Laboratory test reports are also missing. Soil mechanical properties can only be gathered from borehole logs.

The area of the total reservoir is approximately 150 ha emerging from the valley between Ajka and Kolontár, 10-22 metres above these villages. The following general description is based on the explorations: the site is covered by an anthropogenic fill, which is 1-2 m thick and has varying horizontal and vertical extent. The fill's state and strength parameters differ excessively. Mostly, it contains gravelly sand and clay. Typical surface layer is the organic, silty fine sand, sandy silt from Holocene epoch. It is thicker (4-6 m) on the eastern side and gets thinner (0.5-3 m) around reservoir X on the western side. The young surface layer is followed by coarse grained measure from Quaternary Period. It consists of finer grains close to the surface (sandy gravel) and gets coarse with depth even containing boulder sized (0.1-0.15 m) particles. The bedrock of the area is the so-called Pannonian clay. This high-plasticity clay was formed during the filling of the Pannonian Sea in the Carpathian Basin. The clay's thickness goes from hundreds of metres as far as few kilometres. The dam walls were designed and built from the by-product of the power plant: slag and ash. This material has considerable hydraulic binding power and has the grain size distribution of a silty fine sand. If deposited it becomes hard and obtains medium permeability. The designer considered the slag and ash homogeneous with an average strength of 453 kN/m^2 after 28 days. Referring to previous tests, the angle of friction was considered constant 40°, the value of cohesion was derived from unconfined compression tests.

FUGRO Consult Ltd. carried out 7 borings with continuous core sampling near the failure with 10 CPTu soundings after the catastrophe (see Figure 5.). Our aim was to obtain trustworthy information on the strength parameters of the subsoil around the failure and particularly of the deposited red mud.

According top our site investigations and surveying datas under the critical NW dam corner the ground surface and also the pannonian clay surface gradient is much bigger than any other part of the area (see Figure 6.)

Although red mud cannot be considered as soil it is necessary to determine soil mechanical parameters in order to perform a stability analyses.

Previous laboratory tests show high standard deviation. Friction ratio varies between 0.4-17.0° and cohesion varies between 1.5-22.2 kPa, which were depends on the water content of the red mud.

Since red mud is a highly alkaline material reacting, for instance, with aluminium, therefore it was not heavily used in valuable laboratory equipment, so only a few such tests could be performed.

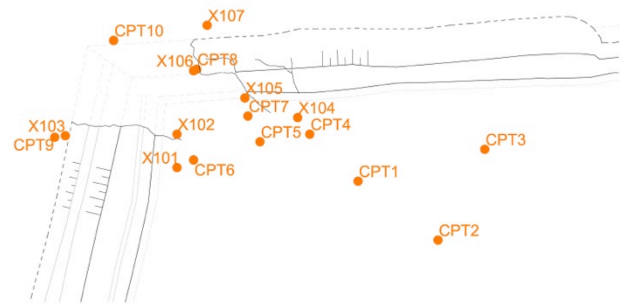

Fig. 5. Site investigations after the catastrophe

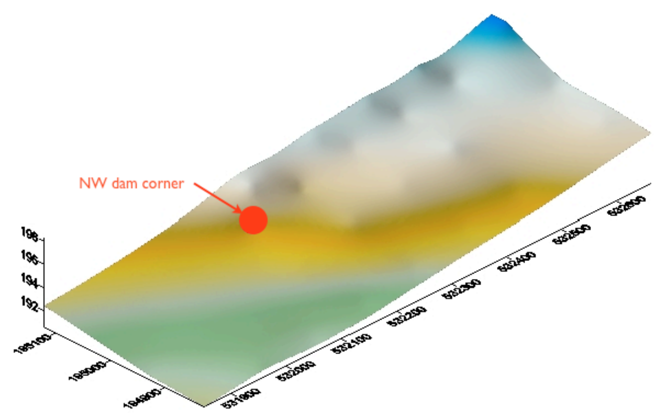

Fig. 6. Gradient of the surface level by the NW dam corner

The triaxial tests carried out after the catastrophe defined the shear strength parameters as $\varphi=2.13°$; $c=14.8$ kPa. Nevertheless, it is essential to mention that red mud is highly sensitive to changes in moisture content.

To verify the friction ratio of red mud we also used the hydrometric measures performed in the reservoir. Based on the measures the angle of spread was around 1.2-2.8°, which correlated well with the triaxial test results.

Defining the strength parameters of the dam was also vital and was absolutely unknown before. Our site surveys showed that dams built with the hydro-mechanization technology and are utterly inhomogeneous, and thus the structure became stratified. The layers can be observed on Figure 7.

Fig. 7. Dam section by the rapture

To determine the dam's strength properties we performed the so called Schmidt hammer tests (widely used for testing structural strength of concrete structures), an in-situ non-destructive test. The correlation between the dam's strength properties and the measured Schmidt rebound numbers has been established according to EN 13791:2007 referring to concrete structures. The applied relation, and the matching strength parameters and rebound numbers of the tested dam elements is shown on Figure 8, where the red dots are the calibration values, and the blue dots are the measured values of the dam.

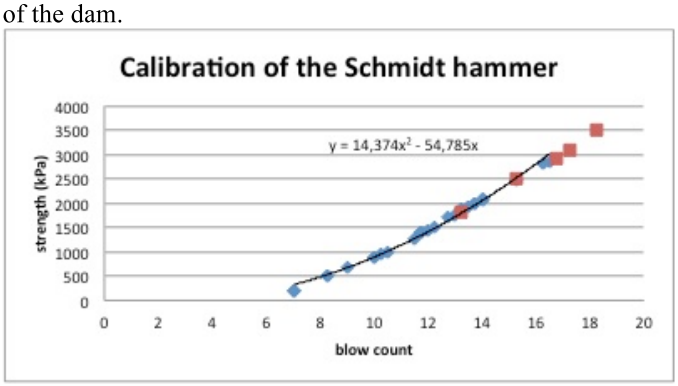

Fig. 8. Strength of the dam

There is a wide range of differences in the strength parameters of the intact northern dam wall (б=200-3500 kPa). Based on the measurements and results the average strength of the collapsed western wall was no more than б=200-600 kPa. Figure 9. demonstrates the sensitivity to moisture content change in the dam. The core of the boring near the failure contains slag and ash losing its strength due to alkaline water, and thus becoming soft and degrading.

Fig. 9. Completely soft dam part

Laboratory tests have also been performed, complementing the in-situ measurements. It was possible to obtain solid blocks of slag and ash from the failure surroundings. The following conclusions were made based on the performed unconfined compression tests. The samples gained from the borings were loaded perpendicular to the stratigraphy. After the first cracks the sample could not bear more load and brittle fracture happened, as shown in Figure 10.
Samples of the blocks were also loaded parallel to the stratigraphy. After the first vertical cracks appeared the samples could still bear load (see Figure 11). Failure only occurred after the fracture of the strongest plate or layer, usually with brittle fracture.

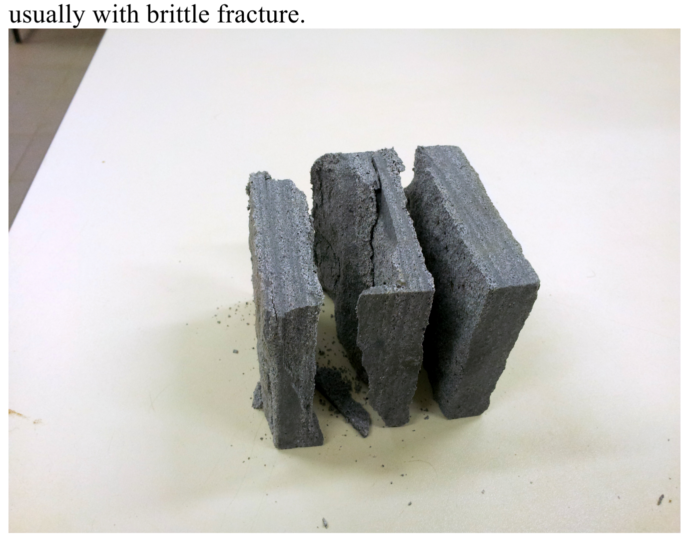

Fig. 10. Cracked dam sample

Fig. 11. Unconfined compression test

Based on the in situ and laboratory tests the slag and ash dam proved to be a rigid structure due to hydro-mechanization. Small deformations are followed by an abrupt brittle failure without any warning sign.

It became vital to find relationship between the strength and deformation parameters of the dam and the clay deposit laying and supporting underneath. Figure 12. shows connection between the strength and moisture content of the clay subsoil, pointing out how strength reduces while moisture content rises, regardless of the plasticity. The average values of the tests are б=213 kPa; w=30%. On a sample from the 80 cm thick layer of clay under the failure, these parameters are б=174.6 kPa; w=54% (see red dots on Fig. 12.), meaning the strength of the soaked clay is significantly lower.

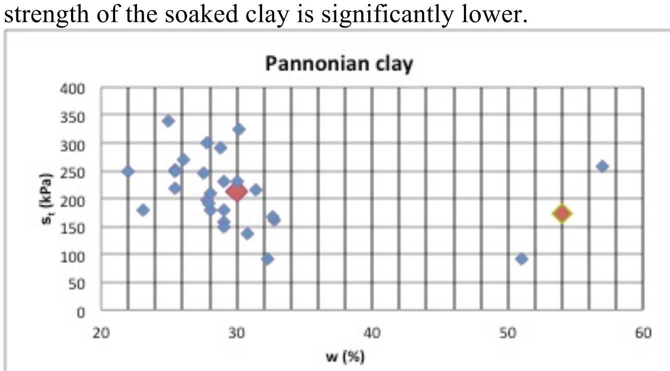

Fig. 12. Strength properties of the clay

It is essential to be familiar with the deformations in order to understand the brittle fracture mechanism. Figure 13. shows the unconfined compression test results both on slag and clay samples. While the dam's strength ends around ε=1-4% by an abrupt brittle fracture, clays' strength ceases after a slow creeping phenomenon after ε=10-25% vertical deformation.

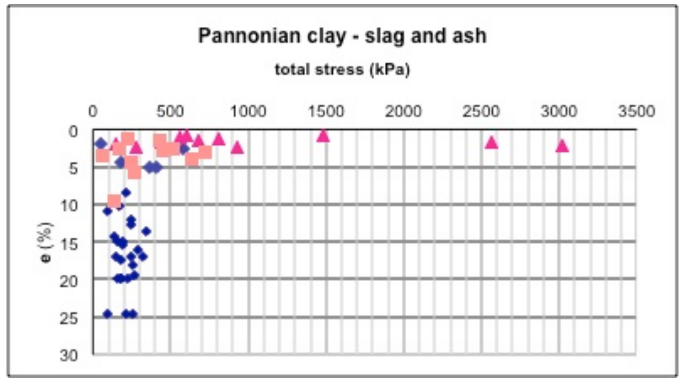

Fig. 13. Strain values of the clay and the dam

On the grounds of our tests, measurements and in-situ observations, the probable boundaries of the dam strength can be defined as follows.

From the crest near the flooded (inner) part to the toe of dam on the protected (external) part the dam's strength varies between 1000-3000 kPa. This consists of approximately one-third of the dam's section, and is likely to be mainly unsaturated (see on Figure 14. Zone 1). The strength of the remaining two-third part is around 100-500 kPa. From the crest to level 202.0 mBf the strength of the saturated part is around 300-500 kPa (Zone 2.), and underneath that level, until the bottom, it is even lower, at around 0-500 kPa (Zone 3.). It is understood that these estimated strength values do not have a uniform distribution, but appear highly varying throughout the dam structure. Since the dam structure is highly inhomogeneous, the strength values differ by at least 1 but rather 2 orders of magnitude.

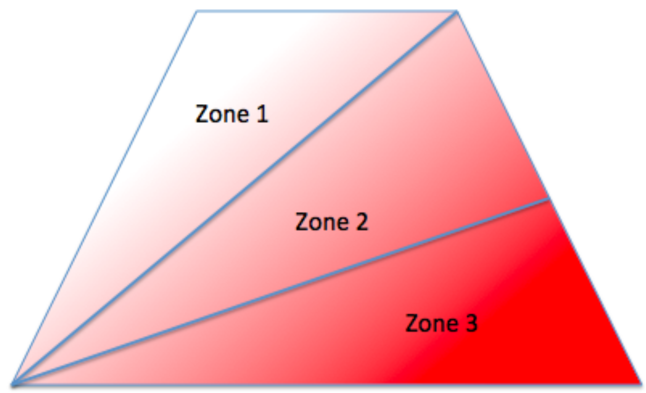

Fig. 14. Strength distribution in the dam

GROUNDWATER DATA

The area is situated in the valley of Torna creek with Csinger creek and Padragi stream running into it. Groundwater flows west from northest in the valley that tends to east - west. The bases of the creeks' erosion are Torna talus and Torna bed cited on the deepest zones of the area resulting in an eastern flow direction.

Regime of the area is highly affected by precipitation, its infiltration and the surface water's flow towards the deepest

point, thus by the water of Torna.
The creek was diverted from its original path in 1990 to south of the reservoirs, parallel with the relocated railway line. It reaches the area from northeast and flows towards Kolontár. Figure 15. shows the groundwater flow directions of the area based on 2010's first half-year data.

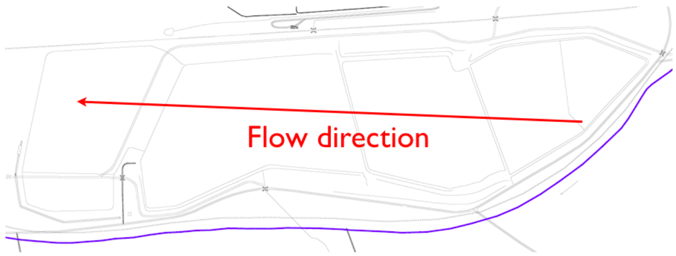

Fig. 15. Groundwater flow direction

ENVIRONMENTAL EFFECTS

Rainwater

According to standards the precipitation of the area sealed by the diaphragm wall must have been collected and lifted up to the surface of reservoir X. Therefore it is crucial to know the exact amount of precipitation. A precipitation measurement station, called Ajka 135, monitored this. After January 1, 2006, the precipitation was registered by the factory's measurement station. Based on the data collected, the total amount's annual average between 1965 and 2009 was 714mm, the maximum was 958 mm (2007) and the minimum was 495 mm (2000). The data collected by the Hungarian Central Institute of Meteorology (OMSZ) between October 1997 and October 2010 are shown on Figure 16., broken down by 6 month long periods.

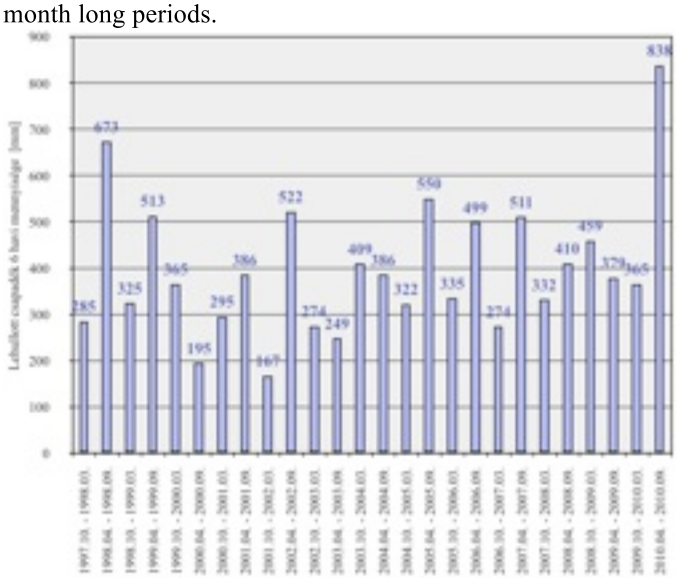

Fig. 16. Distribution of rainwater in 6 months periods

It is clear that before the catastrophe the precipitation was higher than the annual average for years retrospectively.

Wind

Average wind speed and maximum wind gusts were registered on the day of the catastrophe. In the 4th of October after a calm night the wind started to blow and the wind force reached its maximum exactly when the dam wall collapsed. At that time the average of the wind speed was 28,8 km/h, while the maximum wind gust was 48,3 km/h. The wind was blowing towards the north-western dam corner.

Seismicity

Ajka lies on an area of Hungary considered seismically calm. The nearest area, which has been active before, is in 45-50 km distance, called Berhida, or further areas of Bérbaltavár and Várpalota. Notably, low activity has been registered in this area during the observed period of January 1, 2000 and October 4, 2010 at Pápa, Csót, and Pápasalamon.
Locations of the activities within 50 km diameter of the area (47° 05' 20.19" N; 17° 29' 43.76" E) can be seen on Figure 17. in the above mentioned time period.

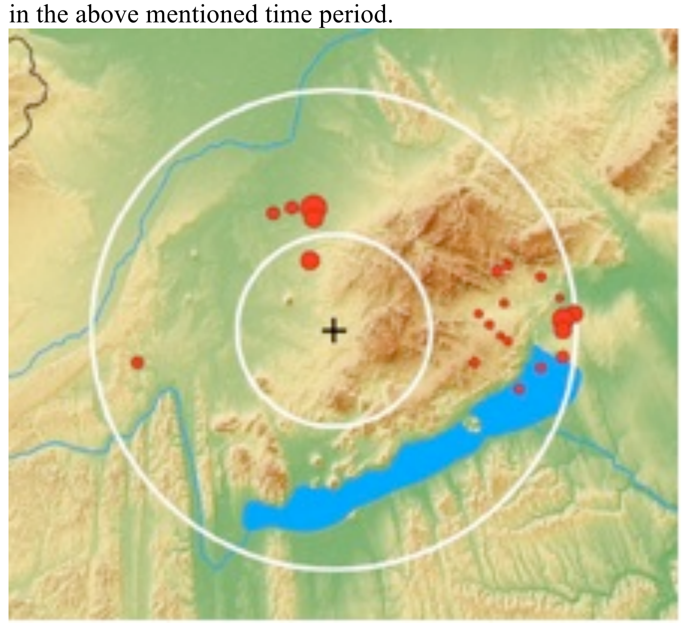

Fig. 17. Earthquakes in the region

The Hungarian earthquake observation system has registered 115 earthquakes in the first 8 months of 2010, 72 of them within 100 km of the dam's area. A map of these locations is shown on Figure 18. The lowest magnitude was ML=0.5, while the highest was ML=2.7 (ML: local Richter magnitude). Most of them were micro quakes centred in the area of Móri Trench.

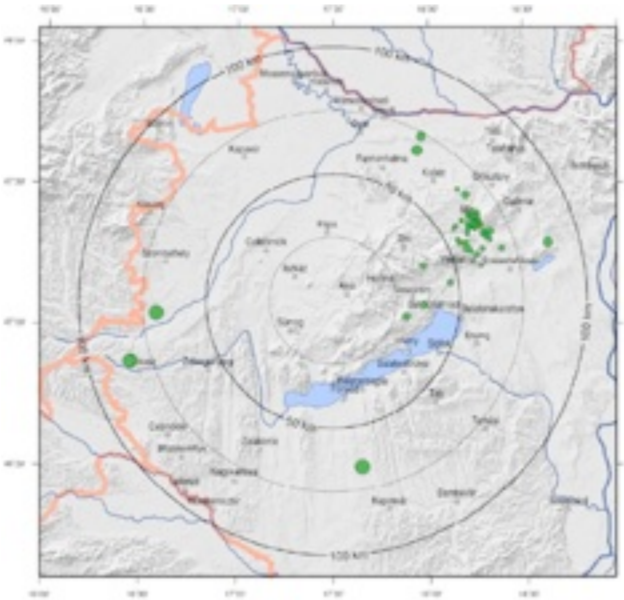

Fig. 18. Earthquakes in the bigger region

Based on approximations the maximum horizontal seismic soil velocity caused by these activities was 0.0327 m/s^2 assuming loose surface deposits.

Water level and quantity on the Reservoir X.

According to the licenses all of the leaking water must be pumped back to the area of reservoir X. It was required that on the area of reservoir X must be min. 0.5 m water over the red mud.

Red mud has been transported to the reservoir via pipe system from the factory site. The red mud has been blown circularly to the inner slopes of the reservoir for slushing the surface. Ideally the water depth increases from the edges to the centre inside the reservoir. In the middle of the reservoir the water depth was more than 8 meter, but by the dam crest only 0.5 m (see Figure 19.)! We made a few 3D calculations, to determine the total stored water quantity. Considering the regualtions it must be stored min. 850.000 m3 of water in the reservoir X. From the site measurements the angle of friction of the wet red mud were 1,5-2,5°, which correlated well with the triaxial test results.

Leachate alkalinity

The caustic, highly alkaline red mud is the by-product of hydrate production. Figure 20. shows the annual distribution of alkaline concentration based on available information.

There is a close to linear increase starting from 2000, which reached 4g/l $Na_2O_ö$ in 2002. It is equivalent with pH value 13, and the increase continued.

It is important to note that diaphragm walls were erected in order to seal the area of the reservoirs. The walls were finished in 2000 and, as the diagram shows, the alkaline concentration began to increase afterwards, up to 100 per cent. The bottom of the reservoirs were not lined thus the NaOH could continuously dissolve from the red mud.

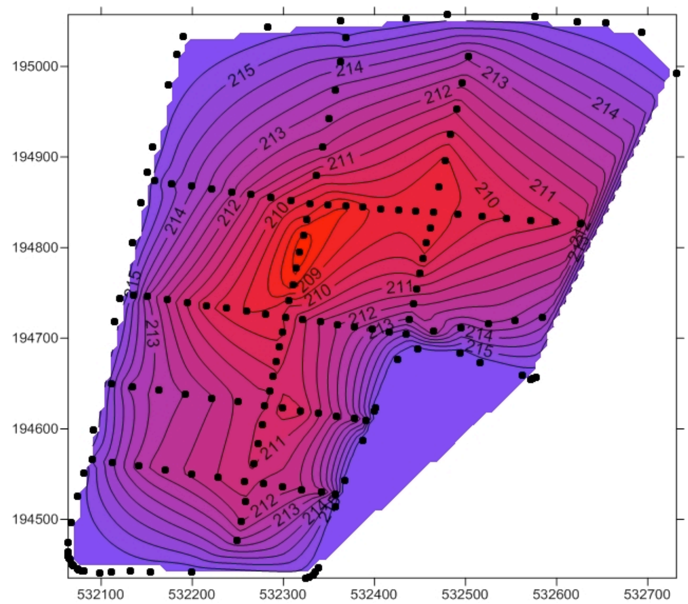

Fig. 19. Depth of the water over the reservoir X.

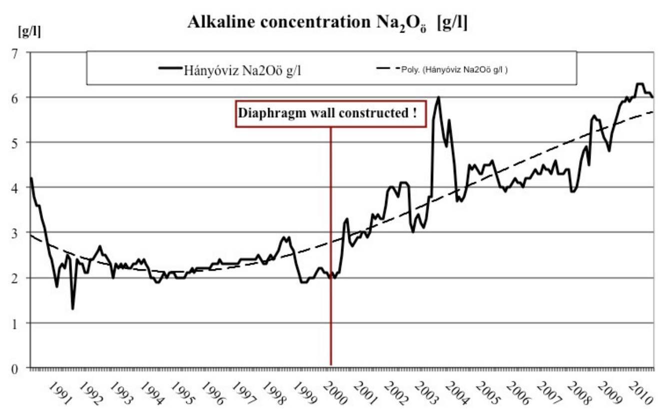

Fig. 20. pH increase from the year 2000.

Mineralogical analysis of clay

Mineralogical analyses were also performed on the clay subsoil after the catastrophe. The question was if the highly alkaline leachate affected the properties of the clay layers underneath the dam. On the upper zone of the clay layers, tests showed a considerable amount of salt soluble in water. Most of these salts were sodium salts due to constant effect of caustic soda. Increasing sodium hydroxide concentration makes cation exchange more active. When calcium exchanges to sodium, the ratio of adsorbed sodium-cation increases, which leads to reduction in the mechanical properties of clay, specifically of its cohesion. X-ray diffraction and derivatograph tests drew our attention to the fact, that the main mineral of the critical high plasticity clay layer is sodiummontmorillonite, probably caused by the leachate.

As is commonly known, clays containing sodium have low shear strength and high compressibility. In other words, after the facility began to operate, the clay layer's strength underneath the dam has got constantly reduced by sodium salts.

STABILITY ANALYSIS, 3D FEM MODEL

The goal of this investigation was to complete stability analysis using the original data and the new data gained after the accident. We controlled the designer's original analysis with finite element method (Plaxis 2D) and with classical methods as well. Four sections' stability has been checked by the designer, two of them from the northern wall (I-I, III-III), one from the western (IX-IX) and one from the southern (VI-VI) wall. In case the dam wall is considered impermeable – as the designer assumed - the safety factor is at least 1.5, which is required by Hungarian regulations regarding stability. But since the dam wall is inhomogeneous and permeable, the safety factor reduces dramatically (see Figure 21.), which was confirmed by both FEM and classical analyses.

Section	Flow through the dam	Earth pressure	Factor of Safety (FoS)		
			Manual calculation	FEM calculation	Designer
I. - I.	yes	Active	1,17	**0,97**	**1,67**
	yes	In rest	1,02		
	no	Active	1,72	1,55	
	no	In rest	1,50		
III. - III.	yes	Active	1,59	1,31	**1,81**
	yes	In rest	1,41		
	no	Active	2,14	1,75	
	no	In rest	1,90		
VI. - VI.	yes	Active	**0,99**	**0,82**	**1,51**
	yes	In rest	**0,89**		
	no	Active	1,53	1,45	
	no	In rest	1,37		
IX. - IX.	yes	Active	1,26	**0,99**	**1,62**
	yes	In rest	1,14		
	no	Active	2,04	1,85	
	no	In rest	1,83		

Fig. 21. Safety factors

This could bring forth the question: why was the dam stable for many years? A logical explanation is that the corner of the dam was acting like a rigid spatial structure able to bear high specific tension, unlike soils. We run the 3D calculation both with the original and the new data. Assuming the reservoir is filled up until level 215.88 mBf, the result with the original parameters was n=1.02. The maximum allowed level was 216.00 mBf. Using the new parameters, according to our calculations the dam corner cannot resist the load from the 215.88 level fill, and collapses (see Figure 22.).

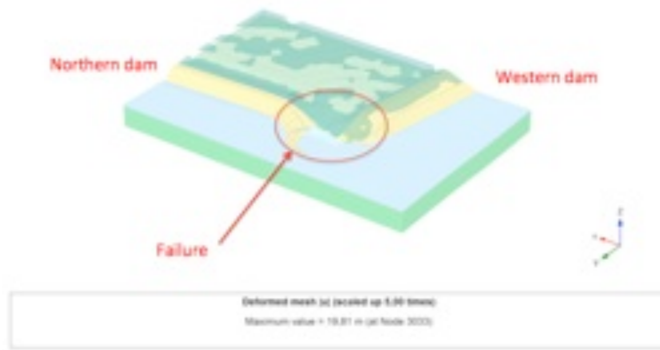

Fig. 22. 3D FEM Analysis

The comparison of the failure mode from our calculation and the actual pictures taken after the catastrophe confirms our calculation method (see Fig. 23).

Fig.23. The cracked dam corner

CONCLUSION

In order to provide profound answers for the causes of the October 4, 2010 dam rapture of red mud reservoir X, it is imperative to specify all factors by topic and process that contributed to the accident. These factors, in chronological order, were the followings:

- Original siting of facility
- Design of facility
- Licensing
- Construction
- Commissioning
- Operation
- Periodic review of license (monitoring, license renewal by responsible authorities/regulators)
- External causes (e.g. natural events, previously unknown factors)

Siting

One of the primer investments in Hungarian industry during the late 1970s has been the Ajka Alumina Factory and the extension of its operational capacities. It was one of the major sources of hard currency generation for the Socialist Economic Machinery. In light of this it is easy to imagine how the highest levels of political and economic decision-making and their mechanisms pressed these investments.

During capacity extension the correct risk assessment, in relation to building reservoir X, the characterisation of these risks by the size of potential effects and the probability of failures have not been professionally performed. Specific attention should have been given to the so-called external risk factors, such as the various environmental effects to the structure(s), as well as due considerations to population exposures to potential pollution and/or catastrophic events. To our knowledge there is no written information that has systematically assessed this vital subject of any large-scale developmental program.

On the other hand there were prevention plans prepared for catastrophic flood event at the two closest municipalities to the factory, Devecser and Kolontár, assuming the risk arising from reservoir X. In the Northern section of Kolontár, which has been hardest hit during the actual catastrophe, there was an evacuation plan. Nevertheless, during the decades, several homes were allowed to get built on the very area known to have exposed to flood in a catastrophic event.

The fact that reservoir X was built on a site already 10 meters above Kolontár situated only 1 kilometre away and the enormous quantity of red mud is going to be raised by over another 20 meters was known. Therefore is was clear that in case of an accident that material had to flow towards the low area, thus risk to human life was considerable.

Further it is important to note that reservoir X has been designed to an area with varied geological and soil mechanical conditions, where groundwater is at around ground level, Torna creek had to be diverted from its original path, and there was a marshy area just where the critical Northern wall of the reservoir has got built.

The only reasonable standpoint on which this siting could be based on was that it was a logical continuation next to the already existing reservoir(s) toward the West side. Without a doubt, the decision for this siting was strongly motivated by micro-economic and financial considerations.

It can be reasonably stated that risks to human population has been gravely underestimated during siting of this large project. The decision-making process, driven purely by perceived economic benefit, has been settled till the late 1980s and got never questioned since; until the catastrophe has happened.

Design

Assessment from the point of view of standards Construction design documentation satisfies respective geotechnical investigation standards as to the frequency of measurement points; however, their required depth has not been met. Moreover, verification testing has not been correctly performed. The design documents submitted to the authorities for commissioning the new facility lacked structural stability assessment and its verification prescribed by the valid standards of the 1980s (let alone today's standards).

Assessment by content Based on review of various design documents a number of contradictions have been found. One of the mistakes found was that stability assessments have been performed for an area 32-48 m East of actual construction of the reservoir. Actual altitude of the critical Northwest wall section is also off by the order of magnitude of a meter compared to the design documents.

As prescribed in the design document the analyses of power plant ashes for their suitability as construction materials have been conducted only in laboratory conditions, and there was no in situ verification of expected performance, regardless of the fact that the walls were built from inhomogeneous materials.

Foundation design was clearly insufficient. In fact no foundation has been designed and built, except the removal of topsoil to 0.30 m (for a structure tens of meters high!) and its refill and compression after the extraction of humus. Therefore, as due assessment of geometries and subsoil conditions have been performed, it became clear that reservoir X has not satisfied the standard for structural endurance and safety (1.50), or even for basic stability (1.00) at designed maximum reservoir load. Moreover, after planned recultivation, the load level would have reached an extra 1 meter – accounting for extra about 100 kN/m further load on the instable structure.

As the designer has not recognised the inherent risk of his work the reservoir has had only minor safety reserves (1.02 - 1.08, thus 2 - 8 %) for its structural integrity. Even this slight reserve was not designed deliberately but was the result of naturally occurring spatial framing effect of the built structure.

Licensing

Authorities commissioned the reservoir X without seeing the necessary fully-fledged stability and safety assessments prescribed by geotechnical standard.

Construction

Besides or rather arising from the deficiencies in the design, construction technology has not been controlled correctly. It can be stated that the foundation of the dam has been performed unprofessionally.

Foundation depth should have been adjusted to the heterogeneous soil properties indicated by geotechnical investigations. Beside the upper humus layer, all poor shear strength materials should have been removed, and water permeable layers should have been sealed, all seepages blocked.

Commissioning

In this phase regulators have known not only the design documentation but the realisation records during construction. Regulators could have intervened at several times and provided additional guidelines and orders for strengthening built in and operational safety, for instance via advanced monitoring systems. Nevertheless, we could recover no sign of such construction time or ex-post intervention. Meanwhile the factory has maintained its production and received its temporary licences till final commissioning of reservoir X.

Operation

Based on the information we have got access to we can state that the operation of reservoir X has met the prescribed and licensed/commissioned operating parameters and pertaining standard(s).
There was no designer prescription or regulatory obligation found for the maximum allowed water level for reservoir X.
The stored quantity of water, according to our calculations based on actual measurements (according to workbook logs), was 853.000 m3. Its height reached 215.88 mBf, 0.12 m below the allowed maximum level.
This water volume at the time of accident corresponded to technologies to be followed according to design parameters and regulatory obligation.

Maintenance of leachate trench According to available information the maintenance of leachate trench has been correctly managed. Its smooth operation was proven by the continuous working of the pumps. While preceeding the catasrophe the two pump pairs operated over their normal operating conditions, however, this has happened before without any problem, thus were considered an acceptable state. Therefore this increased pump activity cannot be considered as an uneqvivocal precursor of the catastrophe.

Operation of the red mud intake pipe network Red mud was transported in liquid state through the pipes. Congestion phenomena is out of question under the temperature conditions of Hungary's climatic zone (between -20 C° and +40 C°. There was no congestion recorded in the past 10 years.
Two or three times a year, from technological reasons, the factory has stopped its production. In these occasions the materials inside the pipe system have been high pressure air blowed towards the reservoir. As the factory has been in normal production during the catastrophy, it is even theoretically impossible that any congestion occured in the system.

The role of dam crest level adjustments in July 2010, as part of the reservoir X's normal operation This dam crown level increase was in line with the orginal design and regulatory licence, therefore it cannot be thought of as te application of extra weight to the structure.
This levelling has started 50-100 m away from the northwestern corner on the norht wall. It was not due to uneaven settlement in the dam wall, but to the original construction level anomaly compared to other sections of the walls. As the red mud and water level increased, this adjustment became necessary for utlizing maximum allowed and licenced reservoir storage capacity.
If the reservoir has the required overall structural safety level, this levelling can have no negative influence on its integrity.
In case the red mud reservoir was at or below its designed safety level (equillibrium limit), it could still not fail due to this additional levelling, as them hightened dam structure has tood strong months after this corrective measure.

Periodic license reviews

There has been no new regulatory requirement, order, or changing respective standard till the fault occurred at reservoir X, so the operator has not had to overview the original plans for its activities.

Monitoring We are not aware of any geotechnical monitoring plan that would have addressed deformations in the body of the dam system, prescribed by any designer, expert consultant, or regulatory body up till October 4, 2010.
According to the documents we got access to, the competent water authority has not thought such a monitoring system would be necessary to maintain technical safety, or at least has not requested it from the factory.
It was likely due to policy deficiency that the designer in the 1990s has not included monitoring systems in his design and that regulator(s) have not requested it later for safe operating conditions.
Regarding the necessity of monitoring it is important to mention that making a decision on whether geotechnical monitoring is needed or not, and if needed, what type of method(s) and system(s) to use, requires geotechnical expertise. In order to make an educated decision the dam's physical properties have to be understood and thus what kind of failure(s) may be faced (e.g., rigid or creeping). This requires competence and substantiation from the designer, involved experts, regulators, as well as from standardization. Creating the necessary framework conditions is not the responsibility of the plant operators. As the regulatory and legal framework for monitoring has been deficient, neither the designer nor the regulator have enforced further preventive measures to the operation of the reservoir, most likely because nobody presumed the facility having not sufficient safety level. It is rather unfortunate that only after the accident – along tedious and profound geotechnical investigations – was realized that this sufficient level of safety was not present.
The results of our investigations have pointed to the recognition that the dam's material exerts rigid failure behaviour, and thus the hazard signalling potential of a monitoring system is rather low. The changes to sense would be so sudden that there would be no realistic chance to effectively intervene before rapture occurs.

Renewal of licenses According to available information the factory has been operating with valid licenses, with the necessary periodic (annual) license renewals. Therefore regulators had the opportunity to review the safety of these operations and request, in light of reported data and assessed processes and tendencies, further investigations, testing, and the introduction of safety improvements from the operator.

Potential external causes

Effect of slurry wall to increasing alkali concentration and ensuing changes in the consistency of clay base Slurry walls have been completed in 2000 due to environmental considerations (on the order of the regulator). Since this a linear function in alkalinity growth can be traced in the concentrations of heap and leachate waters. In 2004 the concentration reached pH 13. This has interfered – through cation exchange – with the shear strength, important from the point of view of structural integrity, of the surfacing clay base containing Na-montmorillonite below the Northwest corner of reservoir X. And thus a soapy slide has been formed just below the Northwest corner of the reservoir dam.

While the slurry wall frame has been prescribed by the environmental regulator, in order to avoid groundwater and then soil pollution of surrounding agricultural land, to our knowledge, nobody has researched the potential effect of such a structure on the structural integrity of the dam. It seems – from retrospect - that with this decision a non-deliberate trade off happened between environmental and geotechnical safety criteria. It can be stated that the slurry walls acted as catalyser of the cation exchange and degradation of soil physical conditions.

It is also a fact that this reservoir has been designed to store alkali.

Role of seismicity There was no seismic event recorded on the day of accident at the Ajka area.

However, it is a fact that during the year before the dam failure there have been 17 small events recorded of 0.7-2.7 magnitude (ML) in a 100 km diameter circle, of which 5 have been 1.7-2.7 ML in the few months preceding the accident. In contrast, there have been only 22 such events recorded in a 50 km diameter circle around the factory during the preceding 10 years.

This dam was built of inhomogeneous materials, framed in several sequences, with minimum safety reserves, behaving as a rigid spatial structure that has been subjected to 5 considerable quakes in 5 months. Due to this, at its weak points, e.g. at its sequential construction joints, cracks (not necessarily detectible externally by eye) might have generated and or existing cracks might have become more significant.

While these relatively small earthquakes cannot be made responsible directly for the dam failure, it is logical to suspect that they have contributed to the break of this rigid, inhomogeneous structure.

Role of precipitation According to calibrated measurements, during the catastrophe preceding 6 months, from 838 mm (according to the National Meteorological Service, 5 km away from the site) to 908 mm (according to the factory's own meteorological system) precipitation occurred on the site of 214 acres framed by slurry walls built on the request of the environmental regulator, of which 174 acres are the total size of red mud reservoirs. The average precipitation of the preceding 44 years has been 714 mm. This precipitation level fallen during the 6 months pre-accident equals to an expected (and thus designed) incidence frequency of 3000 years!

This extraordinary quantity of water, naturally, has been influencing the water balance and hydraulics of the area, including raising groundwater, reservoir stored water and leachate levels. It has significantly changed the hydraulics inside the slurry wall frame.

It is a fact that even this unusual precipitation has not in itself caused problem for reservoir operation, as the allowed maximum storing capacity has never been exceeded. On the other hand it is also a fact that groundwater was very close to ground level at the critical north-western corner of reservoir X. This is important as this heightened groundwater level has further saturated the clay base surface already weakened by cat-ion exchanges due to high alkalinity of red mud, on a sloping surface.

Role of wind Assessing wind data during the day of dam failure (October 4, 2010) from 00:00 to 13:00 wind blew from Southeast to Northwest direction towards the breakage. This isn't the prevailing wind direction of this area but in the exact opposing direction, which has turned so in the accident preceding days.

Wind pressure has continuously increased and wind gusts reached their peaks of 13,4 m/s (48,24 km/h) at around 12:00, just when the dam failure occurred.

It is clear that wind pressure influences negatively structural safety. While we talk about a relatively small factor here, it has clearly been one of the converging risk factors in the event.

In fact, this wind gust was the only factor in complete synchrony with the occurrence of the dam rapture. While in itself may be a small factor, it has likely caused a butterfly effect in the already seriously challenged structure

CLOSING

Thus the failure of this reservoir structure was due to the converging factors of poor siting, design, construction, as well as regulatory deficiencies, and unfavourable environmental conditions.

"The stability of reservoir X was provided by nature, and taken away by nature."