The red mud pond dam failure at Ajka (Hungary) and subsequent developments

György (George) Bánvölgyi
Senior Process Consultant, Alumina
Bán-Völgy Limited Partnership, Budapest, Hungary
E-mail: gbanvolgyi@gmail.com

Abstract

In November 2010 a keynote lecture was presented by the author on the failure of the dam of the red mud reservoir No. 10 of the Ajka Alumina Refinery in the course of the XVIIIth Symposium of ICSOBA in Zhengzhou, China. Based on this lecture a paper was published.

Since that time further relevant information have been made public by scientific studies, on the legal circumstances, the industrial, governmental and other actions, or their lack, which probably played role in the changes which eventually led to the dam failure. The scientific study results, the industrial and governmental actions, the activities of civil organizations, the report of a parliamentary committee, a study report of the "green party" of Hungary and a leading civil engineer' expert opinion will be summarized in this paper.

The paper challenges the method of the classification of the solid materials whether they are considered to be hazardous or not, a new approach has been proposed.

Though a better understanding on the probable reasons of the tragic failure of the dam has been achieved than was available a year ago, further relevant information may come up in the future.

Keywords: bauxite residue, red mud, storage, embankment, failure

Introduction

The NW corner of the embankment of the reservoir No. 10 of the red mud storage area of the Ajka Alumina Refinery of MAL Zrt (Hungarian Aluminium Production and Trade Company Limited by Shares) failured on October 4, 2010, shortly after noon. The facts, explanations and some lessons which could have been collected by the end of November 2010 were presented as a keynote lecture of the XVIIIth Symposium of ICSOBA in Zhengzhou, China and as a paper in the ICSOBA Newsletter[1]. The objective of the present paper to present a summary overview on investigations which have been revealed over the last year.

Ten residents lost their life due to the sudden release of the large amount of slurry containing bauxite residue. 286 people were given medical care, out of them 120 were hospitalized or treated for a longer period of time. The slurry inundated 1017ha agricultural land and 367 properties (houses and other buildings). Most of the houses and other properties were demolished, the rest was renovated. A number of new houses were built in Kolontár and Devecser, the two most effected places.

Significant efforts have been made to get answers to the basic question: "What happened and why?" Much more are known about the tragic event, though no consent has been arrived at a comprehensive explanation so far with proper and supportive public evidences.

Composition of the bauxite residue

Chemical composition

The chemical composition of the red mud as it was revealed by MAL shortly after the dam failure[2]:

Fe_2O_3 40-45%
Al_2O_3 10-15%
SiO_2 10-15%
CaO 6-10%
TiO_2 4-5%
Na_2O (bound) 5-6%

Mineralogical composition

An XRD pattern and the quantitative mineralogical composition of a characteristic bauxite residue of the Ajka refinery as determined by István Sajó[3] are shown on Figure 1 and in Table 1.

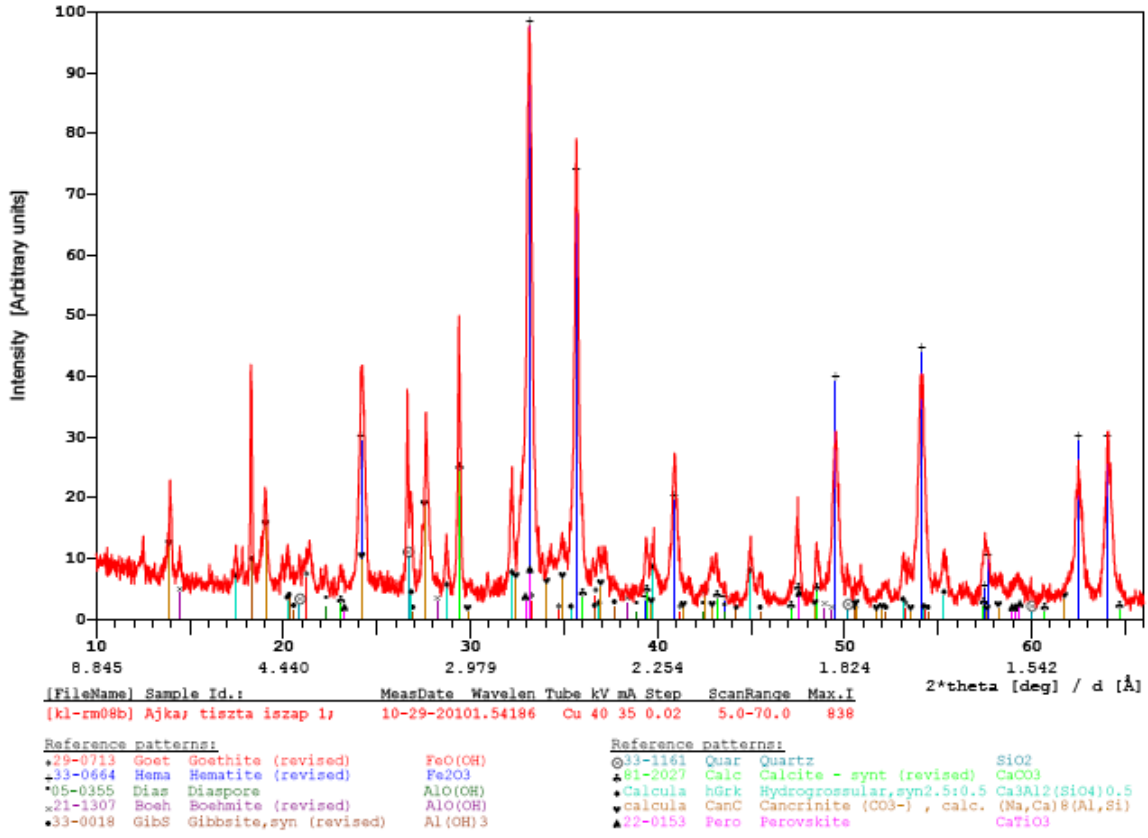

Fig. 1. XRD Pattern of a characteristic bauxite residue of the Ajka alumina refinery

Table 1. Quantitative mineralogical composition of a bauxite residue of the Ajka alumina refinery

[KL-RM08B] Ajka; tiszta iszap 1;

	SUM	Goet	Hema	Dias	Boeh	GibS	Quar	Calc	hGrk	CanC	Pero
Phase%	**98.00**	**5.00**	**40.00**	**2.00**	**3.00**	**6.00**	**3.00**	**8.00**	**8.00**	**20.00**	**3.00**
Fe_2O_3%	44.49	4.49	40.00								
TiO_2%	1.76										1.76
CaO%	10.26							4.48	3.45	1.09	1.24
SiO_2%	10.65						3.00		0.62	7.04	
Al_2O_3%	16.23			1.70	2.55	3.92			2.09	5.97	
Na_2O%	3.63									3.63	
CO_2%	4.38							3.52		0.86	
H_2O%	6.59	0.51		0.30	0.45	2.08			1.85	1.41	
LOI %	10.97	0.51	0.00	0.30	0.45	2.08	0.00	3.52	1.85	2.27	0.00

where: Goet – goethite, Hema – hematite, Dias – diaspore, Boeh – boehmite, GibS – gibbsite, Quar – quartz, Calc – calcite, hGrk – hidrogrossular, CanC – cancrinite, Pero – perovskite.

The supernatant liquor

The composition of the supernatant liquor has not been made public as yet. The data of the liquid phase accompanying the bauxite residue in my earlier paper (4.6 g/l Na_2O_{total}, 3.7 g/l Na_2O_{caust}, 1 g/l Al_2O_3, pH 13) are estimated values on earlier experiences. This solution is equivalent with a NaOH solution of about 0.4w%. It should be noted that over time significant part of the caustic content of the liquid phase transforms to sodium carbonate due to the CO_2 content of the air.

The Pannon University monitored the quality of the released liquid phase beginning of the day of the dam failure. The highest measured pH value was 12.87 in a sample taken on that day[4].

Health effects

Studies on the toxicity of bauxite residue (red mud)

The potential health effects of the fugitive red mud dust is summarized in the paper of A. Gelencsér et al.[5] of Pannon University.

Extensive investigations have been carried out in Hungary to confirm or reject if there is any toxic effect of the bauxite residue. During these investigations the following aspects were tested, as it was summarized by Prof. Dr Schaff[6]:

- Cd, Ni, As, Co, V, Cr concentration of urine in 10 adults and 10 children
- extensive screening tests of several adults and children who lived in the affected area (1220 tests until March 1, 2011),
- chromosoma aberration tests on people who were exposed to red mud (52 people) and same number of people who were not,
- effect of red mud dust on the immune system, the lung and the digestive system,
- carcinogenic and toxic effects of red mud dust on stripe danio (Danio rerio) fishes as model species.

During these studies, for practical reasons “red mud” as discharged having a moisture content of about 50w% was used for the tests as starting material. In this case the caustic soda content of the adhesive moisture of the wet material may have affected the results.

It has been confirmed that the caustic content of the released liquor causes health hazards of various kind. The fine particulate material of the bauxite residue **as any other dust of similar size** may also cause health hazard. **Any health risk which is associated with the bauxite residue (understood as washed dry material) has not been identified.**

Chemical burns due to the caustic content of the liquor released

The huge amount of supernatant liquor that was abruptly discharged, like a tsunami (in the Kolontár village the caustic liquor waves were as high as 2m) caused the majority of the fatalities. The OH^- ion exposure caused the chemical burns of the injured people.

The caustic soda concentration of the discharged supernatant liquor being equivalent of a NaOH solution of 0.4w% or less, which **itself** is not considered to be high. Nevertheless, some injured people spent 2-3 hours in this liquid for various reasons. The OH^- ion exposure is understood as the OH^- ion concentration multiplied with the time of exposure. The unfortunate severe injuries of some people is well explained by the high OH^- ion exposure of those affected.

Composition and mechanical integrity of the dam

Fügedi and his co-workers of the Geological Institute of Hungary investigated the material of the dam at the crack [7].

Chemical composition of dam material samples

Table 2. Chemical composition of the dam material and sand

Samples	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	Na_2O	K_2O	$-H_2O$	$+H_2O$	CO_2	SO_3
Western wall (Ny-5)	9.48	0.27	7.93	2.06	0.26	26.1	1.70	1.65	<0,2	18.9	22.4	3.05	6.13
Western wall (Ny-7)	9.81	0.22	6.59	2.29	0.14	35.5	1.89	1.01	<0,2	15.4	13.8	5.82	7.38
Western wall (Ny-11)	8.78	0.22	4.36	1.83	0.13	39.4	2.12	0.31	0.40	16.4	14.4	6.88	4.54
Sand (HU07)	76.9	0.59	8.01	1.41	1.54	1.06	0.61	0.81	1.16	1.38	6.31	<0,02	<0,15
Sand (HU11)	69.5	0.66	11.2	2.47	1.50	1.16	1.16	1.70	1.31	2.53	6.18	0.26	0.20

Remarks:

-H_2O: adhesive moisture content up to 105°C

+H_2O: chemically combined water between 105 and 1050°C

Mineralogical composition of dam material samples

Table 3: Mineralogical composition of the dam material and sand

Samples	Quartz	Calcite	Ettringite	Magnetite	$(Na,K)_2CO_3$	clay	felspar
Western wall (Ny-5)	0	0.2	95.5	1.1	3.2	0	0
Western wall (Ny-7)	0	20.0	77.4	0.7	1.8	0	0
Western wall (Ny-11)	0	42.0	56.4	0.7	0.9	0	0
Sand (HU07)	56	1	0	1	0	25	8
Sand (HU11)							

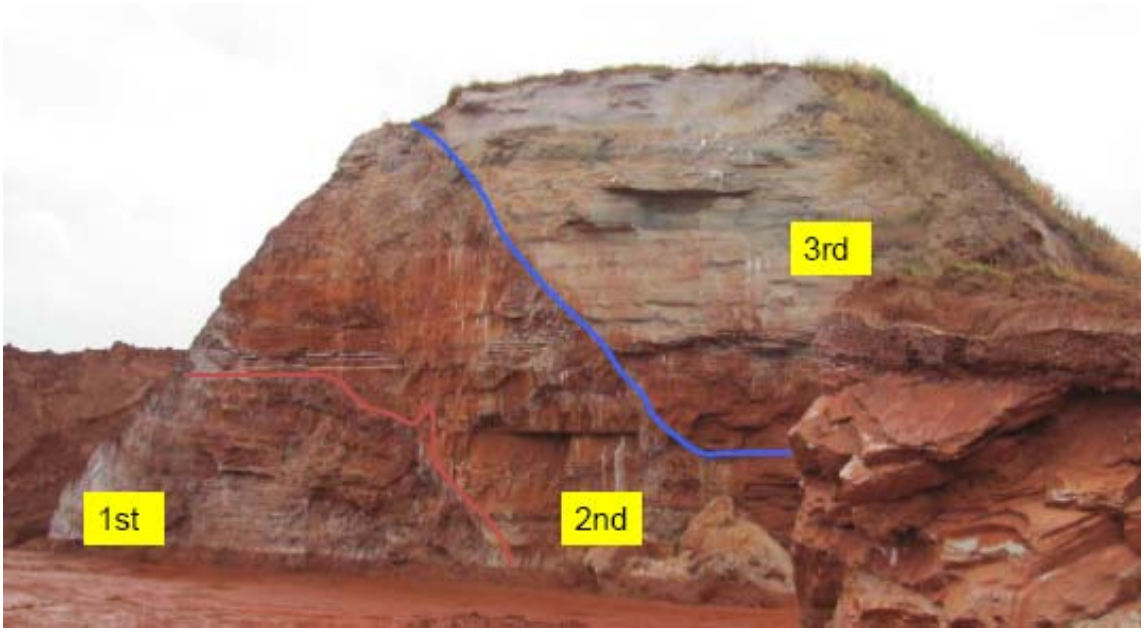

Fig. 4 Stages of building of the dam[8]

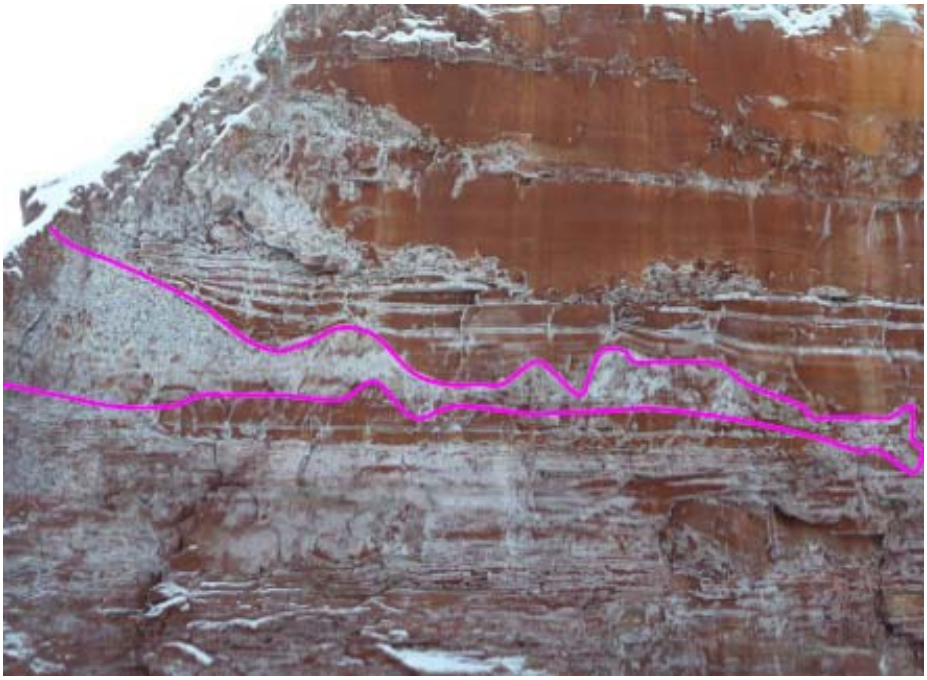

Fig. 5 Caustic corrosion sack in the dam. The caustic containing supernatant liquor seem to have penetrated into and through the sand layer.[9]

Fig. 6 Western wall having removed the fresh surface of the break. Open fissures with dislocations of a size of dm[10]

It can be concluded that the material of the dam is highly variable, with sacks of sand and clay. The clay can react with the caustic content of the liquid phase being stored in the red mud pond, however this reaction is slow[11]. Debris from an earlier construction stage can also be detected. All of these negatively affect the integrity of the dam material.

Metal content of the bauxite residue and its mobility

Bartha and his co-authors [12], Geological Institute of Hungary, studied the minor metals content of the red mud released and their mobility in different reagents.

Table 4. Minor metal content in red mud released

Samples		As	Cd	Cr	Ni	Pb	Zn	Cu	Mo	Co	Hg	pH
		mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	-
		aqua regia	aqua regia	aqua regia	aqua regia	aqua regia	aqua regia	aqua regia	aqua regia	aqua regia	aqua regia	
Red mud1 Kolontár	1	88.0	0.83	450	210	116	114	54.4	17.2	50.5	1.84	12.4
Red mud2 Kolontár	2	70.7	0.585	332	127	87.6	88.1	38.3	8.44	37.1	0.737	12.6
Red mud3 Kolontár	3	78.5	0.87	487	210	117	118	52	8.24	53.3	1.62	12.2
Red mud4-Kol	4	100	0.81	570	268	147	128	61.6	14.5	63.7	2.73	12.1
Red mud5-Kol	5	114	0.94	611	276	154	129	63.5	5.17	68.1	2.96	12.2
Red mud6-Kol	6	90.8	0.92	488	227	130	115	49.3	5.21	53.8	3.59	12.1
Red mud7-Kol	7	104	0.96	514	220	128	121	51.3	8.97	59.8	1.69	12.3
Red mud8-Dev	8	101	1.02	492	220	129	125	45.6	4.97	57.8	1.73	12
Red mud9-Dev	9	85.6	0.803	363	162	93	104	39.9	10.9	44.9	1.06	12.1
Red mud10-Dev	10	97.5	0.96	485	211	119	126	46.9	6.56	56.2	1.57	12.1
	Average	**93.1**	**0.87**	**479**	**213**	**122**	**117**	**50.3**	**9.02**	**54.5**	**1.95**	**12.2**
	SD	12.9	0.1	83.7	43.8	20.8	12.7	8.2	4.1	9.0	0.9	0.18
Maximum contaminant levels for sewage sludge for agricultural use		75	10	1000	200	750	2500	1000	20	50	10	
Contaminant limits for soils		15	1	75	40	100	200	75	7	30	0.5	

Remarks:

a. Maximum allowed minor metal content levels for sewage sludge for agricultural use[13]
b. Contaminant limits (B) for soils[14]

The bauxite residue which was incidentally discharged is certainly not a soil for general purpose, therefore nothing to do with their tolerated very low contaminant levels. In the lack of specific rules for the bauxite residue, as a rule of thumb, the classification of sewage sludge for agricultural use can rather be used to assess the hazard, since the sewage sludge layer used as fertilizer is worked into the bulk of soil by plowing and other agricultural means.

Table 5. Mobility of heavy metals by different solvents

	Aqua regia	Deionised Water pH =10	Ammonium acetate pH=8	AcH pH=8	AcH pH=5	AcH pH=3	Total decomposition
	Average	Average	Average	Average	Average	Average	
	Rel. %	Rel. %	Rel. %	Rel. %	Rel. %	Rel. %	Rel. %
As	86,9	2,48	0,053	0,144	0,245	10,6	100
Cd	99,1	0,627	0,687	0,586	7,76	55,5	100
Co	90,1	0,036	0,018	0,028	0,366	8,21	100
Cr	96,0	0,024	0,005	0,012	0,065	8,23	100
Cu	99,8	1,78	0,518	0,313	0,564	42,9	100
Mo	87,8	53,7	31,6	39,8	1,64	<0,5	100
Ni	97,9	0,026	0,008	0,012	0,403	7,36	100
Pb	98,8	0,025	<0,03	<0,03	0,072	0,66	100
Zn	98,7	0,008	0,059	0,068	0,475	17,5	100

Remarks:
AcH- acetic acid. Different pH values were obtained at different acetic acid dosages mainly due to the caustic content of the adherent liquor.

It should be pointed out that in the important range from practical point of view, let' say pH 5-9 only Mo showed significant mobility. Though As, Ni and Co content exceeded the limits for sewage sludge to some extent (Table 4), however, their mobility was found to be negligible.

Investigations on contaminated soils

Investigations were carried out with soils which were covered by discharged red mud by Anton et al.[15], Institute of Soil Sciences of Hungarian Academy of Sciences (HAS). The As, Cr, Cr_{VI}, Pb, Se and Ni contents were measured on samples taken from different depths of the contaminated gardens and fields. The mobility of these metals was studied using distilled water, ammonium acetate and Lakanen Erviö solution. Less than 1% of the total metal content could have been mobilized by these agents, which is in good agreement with the results of Bartha et al. The conclusions of these investigations were as follow:

- toxic metals penetrated into the soils not deeper than 10 cm, their environmental risk is minimal
- the effect of NaOH can be detected in the upper 30 cm of the soils
- the primary environmental risk is caused by the sodium hydroxide content of the adherent liquor.

Proposed remediation (full revitalization)

- removal of red mud having a height of more than 5 cm
- disking/plowing, using supplementary material (humus containing soil conditioners, manures, bacteria manures)
- plantation as early as possible.

“I would be ready to consume such a bread or alike which is made out of wheat grown on a land which had been inundated by red mud and was rehabilitated according to the suggestions of Institute of Soil Sciences” claimed Prof. Dr Tamás Németh soil scientist, General Secretary of HAS [16].

Risk assessment, classification of materials

The attention should be called that the tolerated minor metal levels **relate to the total metal contents** (except Cr_{VI}), however the studied metal constituents are in such forms in the bauxite residue which are virtually not mobile within the important pH range from the practical point of view. (The Mo is the single exception, though its level is negligable.) It is believed that **the classification of materials whether they are hazardous or not based on their total metal contents can be misleading and the regulations should be revised/modified. The classification should be based on the amount and the mobility of the toxic constituents in the relevant pH range from practical point of view.**

Comprehensive studies

Study Report of LMP

A comprehensive Report[17] was initiated and organized by the parliamentary party LMP (Politics Can Be Different). The party LMP commits itself as the “green party” of Hungary.

The Report revealed that the relevant European Union legislation had not been fully applied in Hungary and there were „holes” in the procedures of issuing permits, checking and supervising of the dam integrity. Beside the parts dealing with the legislation aspects the Executive Summary is probably the best part of the Report. Author of this paper provided inputs to the technical part of the Report.

When Author objected the statement of the Executive Summary "The relatively high concentration of metals (arsenic, mercury, etc.) in the pollutant mix has also presented further health and environmental problems." at one of the editors, he confirmed "this statement was probably exaggerated"[18].

Report of the Parliamentary Committee

The Parliament of Hungary established a committee to reveal the responsibility for the environmental catastrophe and prevention of similar ones in the future. After 10 months of investigation the Report[19] concluded:

- there were deficiencies during the design the storage facility, such as site selection and soil mechanics below the foundation of the dam, the collection of the supernatant liquor was placed at the perimeter instead of a central position of the pond, the tensions arising in the dam having a height of 20-25m and their consequences were not considered,
- there were deficiencies during the permitting process. The red mud waste was improperly classified as non-hazardous waste, the local notary issued the permit for construction and the relevant mining authority had not been consulted beforehand, the Directorate for Disaster Management did not classify the facility under the effect of the Directive 96/82/EU (SEVESO II), therefore it did not control the operation, the environmental permit did not clarify if the facility was a waste disposal facility or a process facility, the cooperation among the various authorities was not seamless,
- the principal cause of the disaster was the large amount of caustic liquor stored having high pH, the height of the supernatant liquor might have been 1m as average and 1.5m as maximum as per

the permit, the fact was 4.45m as average, in the middle of the pond 8m, this caused high load to the dams, the monitoring and checking of the operation of the reservoir was not satisfactory, there were no instruments installed to monitor the micro-motions of the dam, the yearly environmental checkings by the authorities were formal, they did not go into the details of the facility and its operation,

- the responsibility is very complex, though the disaster can not be considered as a consequence of the nature, it is rather the consequence of the industrial activity,
- responsibility for the deficiencies of the designers and constructors during the design and construction and can also be claimed,
- the Environmental Authority made substantial mistakes in the course of the classification of the waste and the checking of the construction of the dam and its operation,
- MAL has serious responsibility for the deficiencies during the operation,
- there have been deficiencies in the legislation which constitute the rules of the permitting, design and operation
- the statements above may not replace the legal procedures.

The MAL stressed some 300,000m^3 process media, containing bauxite residue which is a non-hazardous material was released due to the breach of the dam. A soil failure which was caused by the excessive amount of rain in 2010 and the reaction of montmorillonite of the clayey soil below the dam with the caustic content of the process liquor being stored caused the breach of the dam.

A measurement of later date by the Environmental Authority concluded that the red mud sludge released might have been 1,644,000 m^3, and one third of which was bauxite residue.

There are discrepancies in the pH of the released liquor. Zoltán Illés Environmental Secretary claimed the pH of the red mud slurry was 12.5-13[20]. The Environmental Authority claimed the pH in the failure reservoir was likely 13.7. The highest field test results of Pannon University was pH 12.87. This latter value meets with the earlier process data of the Ajka Alumina Refinery.

Civil engineer' expert opinion

Dr István Kertai is a hydraulician (civil engineer), having enormous expertise in the design of dams and assessment of their operation, including their failure in extreme circumstances. As per the unanimous recommendation of the professionals and the responsible people, on 3rd November 2010 he was assigned with the steering of the Complex Assessment and Design Program[21].

Based on hundreds of meters of drilling program, geotechnical and building material expert assessments by various institutions, companies, professionals of Geological Institute of Hungary, Eötvös Loránd Geophysical Institute of Hungary and the Technical University of Budapest, Dr Kertai prepared a Summary Memorandum[22], which have been made public in parts. The following of this paragraph is based on the Summary Memorandum of Dr Kertai.

The soil failure of the fat clay soil being found at the surface of the original soil just below the basement of the dam almost exclusively at the affected section is claimed to be the primary reason of the dam failure. The fat clay became saturated with water, was submitted to the chemical effect of the caustic content of the liquor accompanying the bauxite residue over years and lost most of its strength. The lower section of the dam which was built out of fly ash weakened due to the permanent load of water. Due to these effects the soil below the failured corner of the dam lost much of its strength, to the own

weight of the quasi rigid dam and also to the load of the stored red mud slurry of low solids content, the affected corner mosaically fissured and bursted. The plastic behavior of the soil below the dam changed and it sank a few decimeters over the rigid break of the affected corner.

The hydraulic modeling suggest that about 1.2 million m^3 thin red mud slurry may have discharged when the dam ruptured.

The serious mistakes of the site selection, design, construction and the supervision by the authorities resulted in the failure of the dam as they follow:

- The foundation of the dam was inappropriate. The soil below the dam was highly heterogeneous and a rigid dam was constructed.
- The design calculations did not take into account the loosing of the strength of the clay due to the caustic content of the liquid phase nor the loosing of strength of the lower third of the dam being constructed out of fly ash due to the permanent load of water.
- The cross section of the dam was not satisfactory, bank slopes were steep, the tension of the dam toe was high.
- The design did not cover the effects of the uneven saggings.
- The material of the dam is largely heterogeneous both in horizontal and vertical directions and this facilitated the formation of fractures.
- The dam was not properly sealed, an inner water sealing wall[23] was not applied
- The filling of the red mud slurry was not consistent, the red mud was randomly distributed at certain places. The safety of a dam having a height of 25m should not have been based on such a process technology.
- The dam integrity checkings were substantially defective.

Recent changes, rehabilitation

Filter presses were implemented in the Ajka refinery early 2011. The moisture content of the bauxite residue filter cake thereby is believed to be 30-35%. Some gypsum is added to the washed press-filtered bauxite residue to adjust its pH between 10 and 11. New phenomena is the dusting of the dry mud stacking during windy weather, this has not been kept under control as yet[24].

Some pictures are below to demonstrate the changes and remediation successfully achieved in the course of the year has passed subsequent to the accident.

Fig. 9 Arial photo of the Resevoir No. 10 after the dam failure in October 2010[25]

Fig. 10 One year later. Dry mud stacking of press filtered bauxite residue.

Fig. 13 New houses in the most affected village, Kolontár[26]

Concluding remarks

a) **Factors which may have played role in the dam failure, among others:**

- **No sealing at the bottom of the reservoir or an inner sealing wall below the dam was applied.**
- **The material of the dam is highly variable, with sacks of sand and clay. This negatively affected the integrity of the dam material. The dam was a rigid construction. The strength of the clayey soil below the dam decreased over the years at the critical corner.**
- **„Holes" were in the design procedures, in the procedures of issuing permits and in the checking and supervising of the dam integrity during the construction and afterward.**
- **The water sealing wall around the storage area was successful in preventing the caustic contamination of the surrounding subsoil water, meanwhile it retarded the rainfall and caustic containing seepage liquor and weekened the clayey subsoil.**

b) Events and other conclusions

- **No toxic effect of the bauxite residue *itself* on human being has been identified though extensive investigations have been carried out. No question about the toxicity of the caustic content of the adherent and seepage liquor.**
- **The classification of materials whether they are hazardous or not based on their total metal contents and the regulations should be revised and modification is proposed where the mobilised metal content in the relevant pH range will be considered instead.**
- **Dry mud stacking has been introduced (pH of bauxite residue disposed of: 10-11).**
- **The contaminated land has been rehabilitated.**
- **The people who lost their homes got new homes, their houses have been renovated or they were relocated to other places.**
- **The cost of dislocation of people and land rehabilitation has reached million USD of 135.**

- **MAL has been fined by the Environmental Authorities to more than million USD 600. MAL appealed, the court suspended the execution of the fine.**
- **30 affected individuals sued MAL and the Environmental Authorities.**
- **15 present and former employees of MAL have been put to trial being accused of professional misconduct of causing deaths , impair of the environment and other issues.**
- **The design, permitting, construction and supervisory faults were made before the mother company of MAL acquired the Ajka Alumina Refinery in 1997, or were beyond the control of MAL.**
- **The investigations of the chemical reaction of the clay minerals and sodium hydroxide have started after the construction of the failured dam[27].**

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