CONSTRUCTION, DESIGN AND EVALUATION OF TAILINGS DAMS FOR NEW MINING PROJECTS

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ABSTRACT*: This paper intends to discuss general features of tailings dams and embankments, the most significant factors to be considered while designing and evaluating the construction and methods of analysing the embankments stability.*

KEY WORDS: *construction, mining, tailing dams, stability*

1. INTRODUCTION

Design depends on the quantity and the individual characteristics of the tailings produced by the mining operation, as well as the climatic, topographic, geologic, hydro-geologic and geotechnical characteristics of the disposal site, and on regulatory requirements related to dam safety and to environmental performance.

It is essential that each specific dam has its own design process and one important factor is the estimated quantity of tailings to be disposed.

One significant aspect to be considered while design and construction are done is to minimize adverse effects to the environment.

The stability of the tailings impoundment is also dependent on foundation characteristics, such as shear strength, compressibility, and permeability. Depending on soil characteristics, the layout can be adapted to account for high permeability materials in the design through the use of liners and/or adequate internal drainage.

2. THE NEW MINING PROJECT IN ROMANIA

The Metaliferi Mountains represent an anomaly of the European gold metallogeny and constitute one of the most productive gold areas in Europe and worldwide, especially due to the number of ore deposits, mined and discovered gold reserves *vs.* the surface of the metallogenic province [11]. Along the perimeter of the Golden Quadrilateral, Fig 1, are proposed three new mining projects which will operate gold and silver deposits: Rosia Montana, Rovina and Certej all of them are companies established in Romania, with majority private shareholders. Rosia Montana Gold Cororation, RMGC obtains the concession license for exploitation in 1999, for the exploitation of gold and silver ores in the Roşia Montană area.

The mining perimeter of RMGC has a surface of 21.45 square kilometers and it overlaps the area of Valea Roşia River and its junction with Abrud River. [13]

The project covers 25% of the surface of Roşia Montană Commune, a traditional mining community, located in Apuseni Mountains.

Roşia Montană Mining Project includes the following objectives: the processing plant, Corna Valley Tailing Management Facility TMF, 4 open pits: Cetate, Carnic, Jig and Orlea, the waste dams of Gura Roşiei and Valea Sălıştei. In addition to these main access roads, service roads will be constructed to connect the plant site, open pits (Cetate, Cîrnic, Jig and Orlea), waste rock dumps (Cetate and Cîrnic) and the Corna TMF Dam. [13]

The 4 pits will be mined in two stages: Cetate and Carnic during the first 9 years, whereas the pits from Orlea and Jig will be open after the 9th year, and the mining in Cetate pit will continue. Ore mining in the pits will be carried out until year 14. The closure of the pits and stockpiles will take place gradually, with Cetate stockpile as of year 5, the stockpile and pit of Carnic as of year 9, and Orlea and Jig pits during years 12 – 14. The tailings dams of Gura Roşiei and Valea Sălıştei are located in the Wstern part of the area, on the left bank of Abrud River, the tailings dam of Gura Roşiei, and, respectively, the tailings dam of Valea Sălıştei in the valley of Sălişte Creek. They have a surface exceeding 40 hectares and they store a total volume of waste of 3.4 mil. m^3.

A series of investigations were carried out in view of developing a detailed understanding of the TMF site characteristics which provided information on the geology, hydrogeology and geotechnical conditions of the region and location of TMF dams.

3. BASIC DESIGN CONCEPTS OF THE STABILITY ANALYSIS

In general, tailings impoundments (and the embankments that confine them) are designed using information on tailings characteristics, available construction materials, site specific factors (such as topography, geology, hydrology and seismicity) and costs. [4]

One of the basic principles used in the design of impoundments and their embankments is the maintenance of the phreatic surface within the embankment. The phreatic surface is the level of saturation in the impoundment and embankment (the surface along which pressure in the fluid equals atmospheric pressure. The phreatic surface exerts a large degree of control over the stability of the embankment, under both static and seismic loading conditions. The major design precept is that the phreatic surface should not emerge from the embankment and should be as low as possible near the embankment face. This basically maintains a pore pressure at the face of the embankment lower than atmospheric pressure plus the weight of the embankment particles and maintains the face of the dam. Thus any factors that might affect the phreatic surface in the embankment may also affect stability of the embankment. [8]

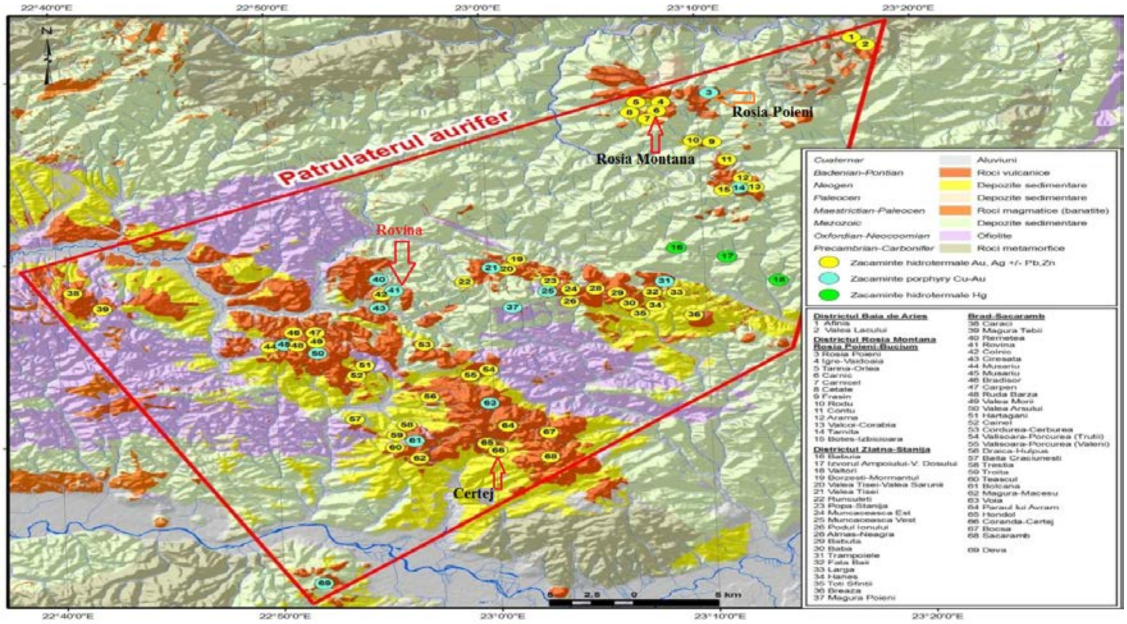

Fig. 1 Ore deposits and occurrences of mineralization in the Golden Quadrilateral, Apuseni Mountains [11]

3.1 Geological and geo-morphological factors

Even if they do not represent a direct cause of the landslides, the geological factor is especially important in their generation; this is why the diagram and methods for forecasting the stability of the tailings dams must be chosen depending on the geological conditions.

3.2 Hydro-geological factor

It plays an important role for generating the slide surface, and the presence of water in the rocks influences the unit stress condition by the following elements [4]:

- the variation of the humidity in unsaturated soil;
- hydrostatic pressure of the water in pores;
- hydrodynamic pressure of the underground water.

When the water level decreases, a load increase may be recorded, due to the cancellation of the water's negative pressure effect, a phenomena manifesting especially in the case of permeable rocks. The water in the pores creates a pressure leading to the decrease of the shearing strength of the rocks as a result of the decrease of the actual pressure on the slide surface. All these enforce the execution of drainage as effective as possible of the base of the tailings dam in order to completely remove the accumulated water to decrease its hydrostatic level, a fact leading to the improvement of this cause's influence and the increase of the overall stability of the rocks from the dam.

If the foundation base on which the dam shall be built is not drained and the water stagnate in its vicinity, the blocks rolling down on the embankment become saturated with water and generates mud, which, soaking the dam's materials, discharges and generates deformations. [3]

3.3 Geo-technical and geo-mechanical factors

Taking in consideration the geo-technical factor always implies the determination of the strength parameters and the weakest surfaces of the foundation base, where the slide forces are concentrated. [1,2]. These surfaces may be considered stratification surfaces, the fracture planes or the contact surfaces of the rocks from the earthworks with the foundation base. In the case of earthworks, it is considered that, during the initial stage, the stored material lacks cohesion. Nevertheless, due to the action of geological load, the earthworks consolidate naturally and attain a certain cohesion that must be taken into consideration in the stability calculations. [5]

3.4 Anthropogenic (technogenic) factors

They refer to the changes of the stress and tensions status in the earthworks due to the engineering action of the human factor. Among these factors are mentioned the overload of the earthworks in the upper part by the technological machines placement and traffic or by storing the rocks, respectively the excavation of the rocks in the lower part of the earthworks. These factors change the relation between the resistance forces and the forces stressing the earthworks generating landslides.

In the same category may also be included the earthworks geometric elements (gradient and elevation) that are set out by geotechnical project and that influence the stability level.

3.5 Hydro-meteorological and seismic factors

The rainfalls increase the humidity of the rocks forming the earthworks and, implicitly, decrease the stability reserves of even generate landslides. As a result of the experimental research in the filed of earthworks construction, it was found that the moistening of the rocks of the foundation base may be detected at various depths ($2 \div 3$) m from the surface. The seismic factor – it is known that, during an earthquake, the seismic action may go in any direction; due to this reason, it is considered to be horizontal in the calculation, this being the worst case condition as regards the effect on the earthworks stability. [6]

4. EMBANKMENT CONSTRUCTION- LINERS USAGE AND DRAINAGE SYSTEMS

Two research directions are followed in the tailings dam stability study: dams' stability and foundation base's stability.[10]

Environmental considerations may create a need for liners since tailings may have a potential to leach toxic or undesirable constituents to underlying strata. Liners may be composed of compacted native soils, compacted tailings slimes. For economic reasons, compaction of native soils or tailings slimes is the preferred methods of reducing the permeability of impoundment bases.

The primary function of drainage systems is the dissipation of pore pressure across the embankment. [10]

5. MATHEMATIC METHODS IN ANALYZING THE STABILITY OF THE MINING CONSTRUCTION

The analysis of the dams' stability is performed based on the calculation of the stability factor F_S, its value indicating if the gradient shall slide or not.

The stability factor can be calculated depending on the shearing strength parameters, in the simplest case of non-cohesive soil, the stability factor being:

$$F_S = \frac{tg\varphi}{tg\beta} \qquad (1)$$

where, φ is the inside friction angle of the embankment and earthworks material, corresponding to the shearing strength, and β is the gradient of the rewired slope.

A more complete definition is given by comparing the stresses on the slide surface plane, respectively:

$$F_S = \frac{\tau_f}{\tau} \qquad (2)$$

where, τ_f represents the shearing strength put into action, and τ is the value of the shear stress generated in the body of the construction.

This definition also involves the concept of action level *m*, being

$$m = \frac{\tau}{\tau_f} = \frac{l}{F_S} \qquad (3)$$

All definitions show that, in order to assure the dams' stability, the F_S must have values greater that one, F_S.> 1.

There are two main categories of stability analyses: balance (static) methods, and, respectively, deformation (hyperstatic) methods, which take into consideration the ratio stress-deformation, as well as certain mixed methods. [9]

The static methods are based on the analysis of the landmarks from massive; they are presently the most used. These methods admit the sliding of a portion of the earth massive, by making up a well defined sliding surface and study the balance of this portion under the action of the external forces at the time of starting up of the movement.

The methods of the ultimate balance use the equations of the static balance for calculating the average value of the tangential shearing effort τ and of the normal effort σ, which satisfy the Coulomb criteria:

$$\tau = \sigma\, tg\varphi + C \qquad (4)$$

Most of the methods divide the free mass, outlined by the sliding surface in *n* vertical strips.

In order that the balance is ensured, the following conditions must be satisfied:

1. the forces acting on each strip should be in balance (the polygon of forces should close up);
2. the vectorial amount of the resultants of the forces that arise on the separation surfaces between each pair of strips must be null ($\sum E_i = 0$, $\sum X_i = 0$);
3. the sum of the moments of all forces in relation to any point of the plan, therefore in relation to the rotation center 0, must be null.

These conditions are materialized through equations of balance of the vertical forces ($\sum X_i$) and of the horizontal forces ($\sum E_i$). The methods of analysis of the stability may be classified according to the way in which they satisfy such equations.

The methods satisfying all the balance equations take into consideration 3 equations on strip, therefore *3n* equations. The unknown are: n values of N (one on a strip), (*n-1*) for *X* (one on the interface), (*n-1*) for *E*, (*n-*

1) for the position of E (noted h_E) and another unknown F_S, totalizing *(4n-2)* unknown. Therefore there are necessary *(n - 2)* additional equations resulted from supplementary hypotheses.

Only the Janbu and Morganstern-Price methods satisfy all balance conditions. In the analysis of the stability of earthworks, the most used methods are, Fellenius, Janbu and Bishop, for which there are presently many calculation programs or dedicated software, developed on these methods.

The recommended values for the safety coefficients are, $Fs > 1.5$. The experience shows that:

- the earthwork remains stable if, Fs > 1, 5;
- the braking risk arises for , 1< Fs< 1,5

The methods of assessment of the stability may be grouped as follows:

- assessment of the possibility that an earthwork may be involved in a sliding phenomenon;
- the assessment of the stability of different types of earthworks in different conditions (for instance, at the completion of their building or after some time);
- the analysis of the stability of the sliding body, in order to understand the mechanisms that determined the breaking of the earthworks;
- economic assessment of the works of restoration over the earthwork stability;
- the assessment of the effects of dynamic loading, such as those induced by earthquakes ;
- understanding the evolution of the natural forms emphasized by the morphological analyses.

Normally, one would rather choose the Janbu methods, as it is a more precise method and allows more ample analyses of the tailings dam stability.

5.1 Fellenius Method

In order to determine the coefficient of stability, the sliding mass, determined by the sliding surface established through the same method is divided into several strips, Fig. 2.

Usually, the width of a strip is $b_i = 0.1R$. If such a ratio is taken into account, it results a too big number of strips (or too small), and consequently it is adopted an average width that should lead to a total number of strips between 5 and 10. In this case, the expression of the coefficient of stability Fs is provided by the ratio between the sum of the moments of the forces opposing M_r to the sliding and the sum of the moments of the forces that converge to put in movement the earthworks M_a.

$$Fs = \frac{\sum M_r}{\sum M_a} \qquad (5)$$

The rock's resistance coefficient, φ and C, are taken as average values along the sliding surface *L*. The authors of the Swedish method outlined that on the two sides of the strip, considered on the sliding direction, another two categories of forces: X_i forces that are vertical shearing forces and the horizontal forces E_i .The X_i forces being very similar as size, and of contrary direction, were neglected in the general balance of the sliding mass. Later on, Bishop took into consideration the X_i forced in the analysis of the stability, and the difference between the two resultants was only 1 %. As concerns the E_i, horizontal forces Fellenius showed that, if they are not taken into account, it is only produced an error of 5 %.

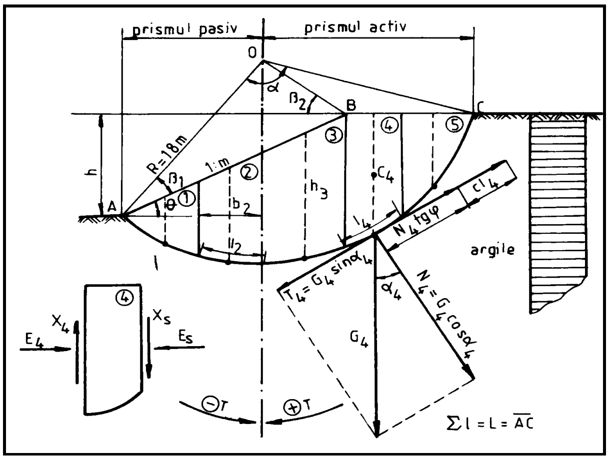

Fig. 2 Method of calculation of the stability coefficient according to Fellenius

So that the earthwork would not slide, the calculated safety coefficient must be improper, meaning *s* >1. For less than a unit values, the massive losses the natural balance and the sliding of the examined earthwork takes place.

5.2 Janbu Method

Janbu Method is a simplified extrapolated version also for the cases when the earthworks is made of many layers with different physical and mechanical properties and is based on the calculation of the shearing effort.

The sliding surface is divided into more strips, like in case of the Fellenius methods.

There are calculated the vertical and horizontal pushing forces for each strip and then the stability coefficient. These are implicit equations and are solved iteratively, making as much iteration as are necessary until obtaining the right solution

5.3 Bishop method

This method is based on the hypothesis that the active side forces for a single strip have null resultant after the vertical direction.

At the Fellenius method, for determining the stability coefficient, the sliding mass, determined by the sliding surface established by this method is divided into more strips.

Janbu method is an extrapolated version also for the situations when the earthworks are made of many layers with different physical and mechanical properties and are based on the calculation of the shearing effort. The sliding surface is divided into more strips, the calculation principle being shown in the figure 2.

6. GEOMECHANICS TESTS IN STUDIED AREAS

All methods for analysing mining construction stability are based on the rocks geomechanical study. Therefore lab tests have been made in the Analysis and Construction Tests Laboratory from Petrosani University on rocks collected from the new mining projects areas. [1, 2] The main physical and mechanical characteristics which are particularly relevant to carry out the stability study are presented next and have been made available to development engineers.

The results are presented in Table 1 and Table 2 which summarise the lab tests.

7. CONCLUSIONS AND REMARKS

The water from pores creates a pressure that leads to reduction of the rocks' shearing resistance as a result of the diminution of the effective pressure on the sliding surface.

Among the anthropogenic factors with influence over the stability of earthworks, we mention the overloading of the earthworks on the upper part by the setting and running of the technological machines, the rocks storage, respectively the excavation of rocks at the lower part of earthworks. These factors modify the ratio between the resistance forces and the forces that stresses over the earthworks for sliding.

The stability degree is influenced also by the geometric elements of the earthworks, the inclination and the height that are established by geotechnical projects. The calculation of the shearing effort is based on physical and mechanical properties.

The seismic factor, the seismic action, may have any direction, but the most dangerous is deemed the horizontal one, as it is the most unfavorable concerning the effect over the stability of earthworks.

The analysis of the stability of earthworks is made though the models: Fellenius, Janbu and Bishop but the Janbu method is preferred, as it is a more precise method and allows more ample analyses of the stability of the tailings dam.

The experience showed that the breaking risk arises for 1< Fs< 1.5 and – the earthworks remain stable if Fs > 1.5;

A review of the practice in tailings dam/impoundment design and construction shows that great technical progress has been made. Better investigation and design tools are available.

New technologies in construction and geo-membrane liners are commonly used where tailings may present a risk of groundwater contamination, and design and construction methods for lined impoundments have been developed. Improvements have been made to the traditional upstream construction method to reduce stability risks.

Environmental considerations have become increasingly more important in tailings dam design and permitting.

Table 1. Physical properties of rocks from mining areas of interest

Mining area	Sample no.	The compre-ssibility module M [KPa]	The bulk density γ_a [kN/m^3]	Porosity n	Limits of plasticity [%]		Plasticity Index I_P	Graininess/ degree of uniformity, Rock type, U	
					Upper W_c	Lower W_f		Screening	Settling
Certej-	1	7981	18.70	30.22	36.15	21.65	14.50	Fine sand Neuniform	U=3.197 Dust,Very uniform
	2	-	23.58	13.53	-	-	-		-
	3	-	17,79	31,50	-	-	-	Large sand Irregularly	U=6.461 Dust, Uniform
Rosia Montana	1	12352	17.24	35.36	-	-	-	Fine sand Irregularly	U=11.205 Dust, Uniform
	2	5924	17.31	34.23	51.32	32.57	18.75	Fine sand Irregularly	U=4.676 Dust, Very uniform
	3	6103	17.26	35.31	-	-	-	Large sand Irregularly	U=6.070 Dust, Uniform
Rovina	1	5178	18.99	21.50	46.25	21.96	24.29	Fine sand Irregularly	U=3.556 Dust, Very uniform
	2	6306	20.76	18.36	-	-	-	Small gravel Irregularly	U=2.526 Dust. Very uniform
	3	4719	18.04	26.52	-	-	-	Large sand Irregularly	U=5.749 Dust, Uniform

Table 2 **Mechanical characteristics of rocks from mining area of interest**

Mining area	Sample no.	UCS [kPa]	Compressive strength triaxial TCS [kPa]				Cohesion/ Friction angle from TCS C/φ [kPa]/[°]		Shear strength [kPa]				Cohesion / Friction angle from Share strength [kPa]/[°]
			Drained		Undrained		Drained	Un-drained	σ	τ	σ	τ	
Certej	1	485.0	1047.9	1236.1	651.1	883.4	313.4/ 17.8	137.4/ 23.5	175	208.3	225	238.1	104.2/30
	2	475.3	1055.3	1232.6	701.0	905.3	312/20	187/22	175	210.5	225	245.6	107.2/31
	3	499.5	1095.2	1247.2	696.3	911.3	315.3/ 21	191/23	175	212.5	225	243.7	110/30.5
Rosia Montana	1	242.5	562.9	795.2	430.7	618.8	108.5/ 23.5	88.4/ 17.8	175	160.7	225	178.6	98.2/19.7
	2	154.3	761.3	949.5	298.4	464.5	208.9/ 17.8	51.3/ 14.4	175	125.0	225	142.9	62.5/19.7
	3	176.3	629.0	971.5	496.8	751.1	77.4/ 33.2	76.0/ 25.8	175	166.7	225	208.3	20.8/39.8
Rovina	1	141.1	496.8	618.8	298.4	486.6	169.6/ 5.7	40.2/ 17.8	175	101.2	225	131.0	23.8/25.5
	2	66.1	342.5	486.6	188.2	310.2	82.6/ 10,4	29.9/ 5,7	175	65.5	225	89.3	35.7/13.4
	3	88.2	364.5	508.6	254.3	420.4	91.8/ 10.4	34.2/ 14.4	175	89.3	225	107.1	26.8/19.7

REFERENCES

[1]. Arad, V**.,** Arad, S., 1995. *The stability and reliability analysis of development openings in the Jiu Valley*, Proceedings of the Fourth International Symposium on Mine Planning and Equipment Selection, Eds. Singhal, Mehrotra, Hadgigeorgiou, Poulin, Balkema Publisher, pp. 825-827, 1117 pg., Calgary, Canada, ISBN 90 54 10 569 0

[2] Arad, V**.,** Arad, S., Nita, A., Baciu, F., Nistor, C., Anca, D., 2011. *Geomechanical characterization of rocks from Sibiu County used in construction*, Proceedings Paper, International Multidisciplinary Scientific Geo Conference, pp. 467-473, DOI: 10.5593/sgem2011, Sofia, Bulgaria ISSN 1314-2704, 2011

[3] Das, B.M., 1990. *Principles of Geotechnical Engineering*, Second Edition. PWS-Kent Publishing Corp., Boston, Massachusetts.

[4] Davies, M.P., T.E. Martin and P.C. Lighthall, 2000. *Tailings dam stability: essential ingredients for success. Chapter 40, Slope Stability in Surface Mining*, SME, pp. 365-377.

[5] Davies, M.P. and S. Rice, 2001. *An alternative to conventional tailings management – "dry stack" filtered tailings. . "Tailings and Mine Waste* 2001," Fort Collins, Colorado, pp. 411- 420.

[6] Dougherty, E.R., 1990. *Probability and Statistics for the Engineering, Computing, and Physical Sciences*. Prentice Hall: New Jersey, 800 pages.

[7] Doyle, F.M. (ed.)., 1990. "Mining and Mineral Processing Wastes: *Proceedings of the Western Regional Symposium on Mining and Mineral Processing Wastes, Berkeley, CA*, May 30 - June 1, 1990." Society for Mining, Metallurgy, and Exploration, Inc. Littleton, Colorado.

[8] Dunne, B. 1997. Managing design and construction of tailings dams. "*Proceedings of the International Workshop on Managing the Risks of Tailings Disposal*". ICME-UNEP, Stockholm, pp. 77-88.

[9] Michael P. Davies, Peter C. Lighthall, Steve Rice and Todd E. Martin Canadian Dam Association (CDA) 1999. "Dam Safety Guidelines".

[10] International Committee on Large Dams (ICOLD) 1994. "*Tailings Dams – Design of Drainage – Review and Recommendations*", Bulletin 97.

[11] Popescu Gh. C., 1986. *Applied metallogeny and geological prognosis"* (in Romanian), Part 1. Ed. Univ. of Bucharest.

[12] Popescu Gh. C., Neacsu, A., 2012**.** *Modeling of epithermal gold and porphyry copper deposits from metaliferi mountains (Romania)***,** Romanian journal of mineral deposits, Geological Institute of Romania Society of Economic Geology of Romania, ISSN 1220-5648, vol 85 issue 1, Bucharest, 2012

[13] RMGC project, http://www.rmgc.ro/

[14] U.S. Environmental Protection Agency Office of Solid Waste Special Waste Branch, *Design of Tailings Dams and Impoundments*