Geotechnical engineering in Mexican tailings dams

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ABSTRACT
Geotechnical engineering has a great influence in the planning, project development, construction, supervision, quality control, operation, conservation and closing of the Mexican tailings dams, in order to achieve environmental safety, economically, maximum stability of the embankments and the best resistance to liquefaction due to an earthquake or explosion, the piping, erosion, and overtopping of the crown container curtain, as well as other geotechnical aspects included in the official Mexican codes.

RESUMEN
Se insiste en la influencia que la ingeniería geotécnica ha tenido en la planificación, el proyecto, la construcción, la supervisión, el control de calidad, la operación, la conservación y el cierre de las presas de jales mexicanas, para lograr su seguridad con economía, la máxima estabilidad de taludes y la mejor resistencia a la licuación por sismo o explosión, la tubificación, la erosión y el derrame sobre la corona de la cortina contenedora, tomando en cuenta siempre el medio ambiente. Se presentan algunas propiedades y conceptos fundamentales especialmente para las cortinas contenedoras, así como otros aspectos geotécnicos incluidos en las normas oficiales mexicanas.

1 INTRODUCTION

According to Fernel Arvizu Lara of the Mexican Metallurgist and Geologic Engineers Association (AIMMGM), the first formal studies for tailing dams in Mexico were done by the distinguish engineer Jose Vicente Orozco y Orozco back in the 60's. By the influence of engineer Vidal Muhech Dip, a great Mexican promoter of this discipline, a leading research on the tailings dams of Taxco, Guerrero, was presented in México (Leon, 1969). It was Mr. Muhech, active member of the Mexican Society for Geotechnical Engineering (Sociedad Mexicana de Ingeniería Geotécnica, SMIG), who commissioned the author of this paper to develop the first Spanish version of the Manual for Tailings Dams and Deposits (AIMMGM, 1993), in order to have an initial guide for the understanding of these engineering works.

The residues of the mineral grinding in a mineral concentration plant are called tailings ("jales"), a very complex viscous-elastic behavior soil and highly susceptible to phenomena such as rainfall erosion, piping, and liquefaction caused by an earthquake or explosion.

Normally tailings dams were built and operated simultaneously and without a defined project, following the generational empiric practices of each individual mining company and in some cases, involuntary spills occurred that rapidly turned into a partial or total failure of the curtain, depending on how quickly the deficiency was repaired. In some cases, the loss or programmed leakage of tailings into creeks or rivers, mainly in the rainy season, was routine.

With the objective of establishing a proper normative for Tailing Dams, the Mine Chamber of Mexico (CAMIMEX) started a development plan (Orozco, 1991). Following, an Official Committee was Formed for this purpose, with participation of the following Mexican institutions: Secretarías de Desarrollo Urbano y Ecología (SEDUE), Energía, Minas e Industria Paraestatal (SEMIP), CAMIMEX, Universidad Nacional Autónoma de México (UNAM), Comisión Nacional del Agua (CNA), Comisión Federal de Electricidad (CFE), Sociedad Mexicana de Mecánica de Suelos (SMMS), and others. The working group of this Committee drafts, in 2003, the documents to finally issue the present Mexican Official Norm NOM-141-SEMARNAT, in 2004.

2 PURPOSE

To emphasize, to disseminate tailings dams knowledge in order to interest young geo-technicians in the need to go further and in depth on the research in the field of tailing dams. These dams possess special conditions and are used for the storage of solid residue, product of crushing and concentrating natural materials of the mining activity, once the valuable minerals have been extracted (Gold, Silver, Lead, Zinc, Copper, etc.). In other words, Geotechnical Engineering needs more "followers" of this specialty.

3 PURPOSE OF TAILING DAMS

It has been said in other meetings (Orozco et al., 2005 and 2006, Flores et al., 2002 and Orozco, 2009) that the dams to store water are conceived essentially for the hydroelectric generation, irrigation or the flooding prevention through the control of rivers (CFE, CNA), but not so is the case of tailings dams ("presas de jales" or "presas de colas" in the Mexican mining process, or "presas de relaves" in the South American industry), where they store SOLID RESIDUES plus the water that is incidentally used to help transport them, and also the water from rain. The tailings model sandy and silty slime beaches as it gradually sediments in the dam reservoir.

4 QUALITY OF THE PROJECT

The responsibility of complete quality, in the environment, is illustrated in figure 1, much emphasis must be given to the planning stage, since it contains all the rest of the activities (Project, construction, operation conservation and quality control). This project must be permanent, environmentally friendly in its design, aesthetic, safe, and economically feasible, rather it be a new dam or a restored one.

Figure 1. Principal activities that intervene in a tailings dam

The levels of quality, synonymous of detailed specifications, in geometry (Arched form and stable slopes, etc.) and finishing's (resistant to erosion, aesthetic design, etc.), as well as in materials (available to be used, from quarries, etc.), and good constructive procedures (the most suitable or selected purposely). These concepts must be stated clearly for all cases and project items, both in the blueprints and in the construction documentation, so that the builder can assure such quality levels, the supervisor can verify those quality levels, and the quality control person can certify this. But also, the people responsible of the conservation and operation of the dam can keep the up to said levels of quality. In order to get these detailed specifications, the persons in charge of diverse studies (hydrological, geological, geo-hydrological, soil and rock mechanics, etc.) should analyze the project with much knowledge, ability and care. These activities must be complied in accordance to the references expressed in figure 2 (Orozco, 2009).

5 CHARACTERISTICS AND CONCEPTS

5.1 Fundamental properties

The principal feature of the curtain in a water storage dams is their water tightness and as a contrast, the tailing dams are understood as filtering structures. Therefore, the PERMEABILITY is the basic characteristic of the containment curtain in a tailings dam.

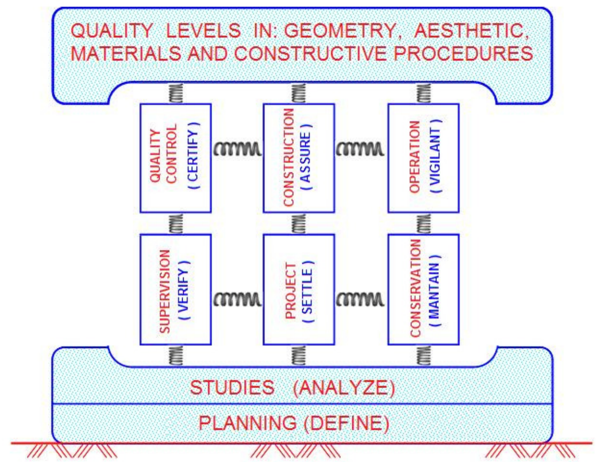


Figure 2. Activities responsible for quality level

On the other side, the tailings dams are one of the few engineering works that are built and operated simultaneously.

It is worthwhile to insist that the SAFETY of the project comes first, physical as well as environmentally, during the construction, operation and after it is full and closed. Other fundamental characteristics that are detailed latter on, primarily for the containment curtain, are resistance to: liquefaction, to piping, to large embankment displacements, to erosion, and to negligent spills. As always, ECONOMICS must be present.

The other characteristics, for each element of the tailings dam, are as follows:

a) Dam Curtain. It must be permeable and resistant. Resistance principally in reference to erosion (either rain and wind or accidental spills), piping (physical or chemical), liquefaction (earthquake or explosion), large embankment displacements (by uncontrolled saturation or general instability). The slope stability (static and dynamic) must be evaluated considering the complete water flow for variable heights, according to the development stages, conceived within the useful life (or economic) planned (or assigned) to the project. It must not be forgotten that the free and clarified water pond, from solids sedimentation, has to be as far as possible from de crest of the containment curtain in such a way that it has an ample enough beach to insure the general curtain stability.
b) Dam reservoir. Must be well defined, by the divides, roads, channels, ditches and counter ditches, etc. besides, it must have stable hill sides in the reservoir area.
c) Drainage Decanter System. It must be large in capacity (More than calculated needs) and structurally resistant, besides having an

hydraulic section that allows drainage of free water pond and rain water.

d) Spillway. It must have a generous hydraulic section and be lodged in natural solid ground ("in bone").

The fundamental characteristics to satisfy the safety requirements and the quality levels of the project, as well as the permeability and the containment curtain resistance are expressed in table 1.

Table 1. Fundamental characteristics of a Tailings Dam.

WORK	SAFETY	• Robust Arch shaped curtain (Resistant and permeable) • Clarified water pond (as far as possible) • Drainage Decanter System (portal section) • Generous Spillway (On solid ground)
	QUALITY LEVEL	• Geometry • Finishing • Materials • Constructive procedures
CURTAIN	PERMEABILITY	• Draining materials • Adequate constructive procedures • Balanced geometry • Environmentally friendly superficial finishing
	RESISTANCE	• Liquefaction by earthquake or explosion • Physical piping • Erosion from rain or wind • Over-curtain spillage

I like to mention that the Engineering Institute from UNAM has conducted research on the static and dynamic behavior of tailings (Flores and Romo, 1999, Flores et.al., 2002, Flores, 2008).

When the use of tailings or other residues as construction materials is desirable, for example, using the "downstream method" (Figs. 3 to 5) and the "upstream" method (Figs. 6 and 7) or combined (Figs. 8 and 9), these materials must be used as compact as possible, this is, with the maximum concentration of solids.

When a complete evaluation of a containment curtain, built with the upstream method, is required, it is convenient to use the specialized Cone Penetration Testing (CONECTEC, 1997).

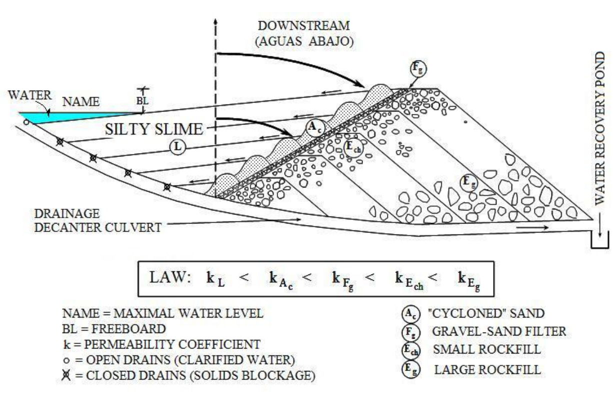


Figure 3. "Downstream" constructive method with rockfill

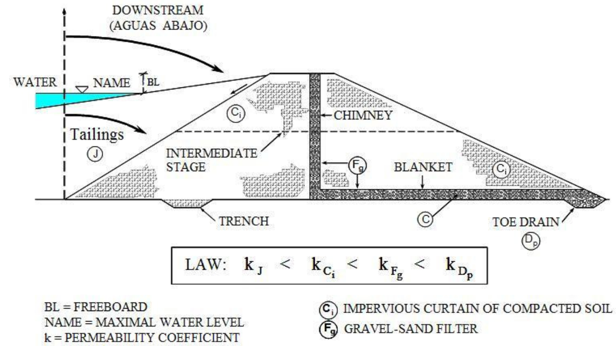


Figure 4. "Downstream" constructive method with a chimney and blanket for drainage

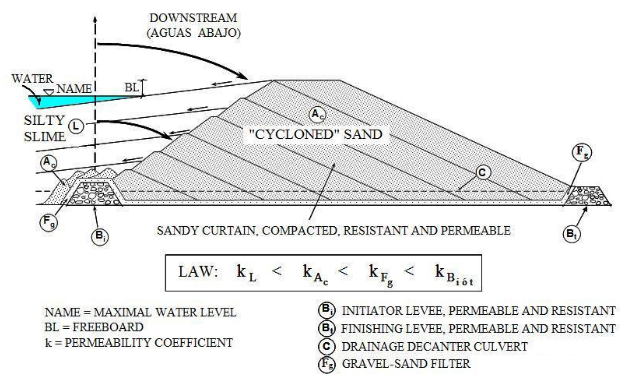


Figure 5. "Downstream" constructive method with compacted "cyclonic" sand

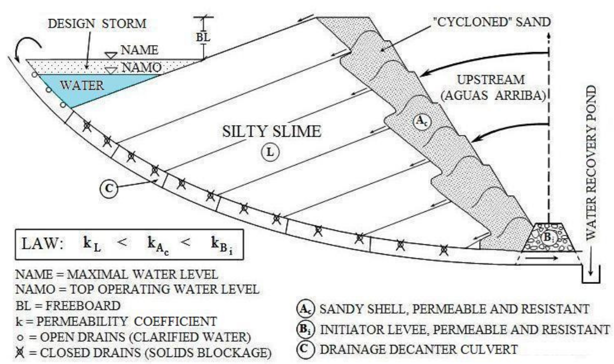


Figure 6. "Upstream" constructive method with "cycloned" sand

5.2 Fundamental Concepts

As it was explained at the end of point 5.1, one of the most important concepts in Geotechnical Engineering is the compactness which represents the concentration of solids. Compactness (C) is defined as the relation between solids volume and the total volume of a given material (Orozco, 1978, 2004, and 2006). In addition, C is equal to 1/(1+e), where **e** is the Voids Ratio (see equation.2); in other words the **e** reciprocal has a physical meaning: the concentration of solids (C). For practical purposes, steel has a compactness of 100% and air of 0%. A tailings material can have values of C ≈ 50% or more, depending on the way it is deposited, as it is illustrated in Fig. 10c (Flores et al., 2010).

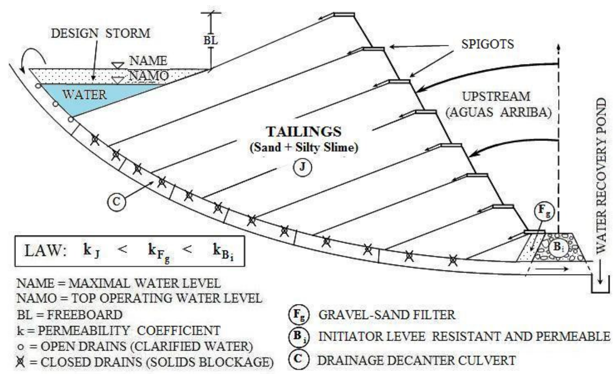


Figure 7. “Upstream” constructive method with spigots.

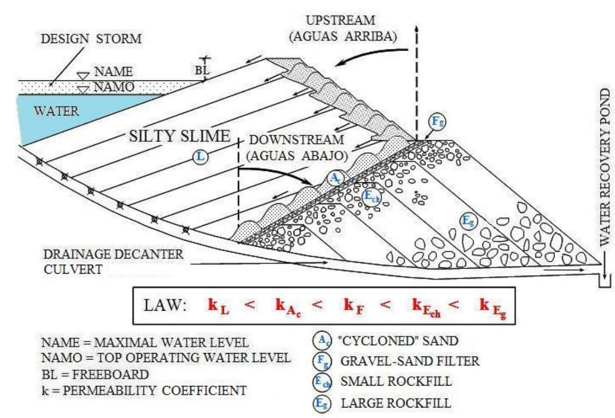


Figure 8. “Downstream” and “Upstream” constructive method with a rockfill and “cyclone” sand.

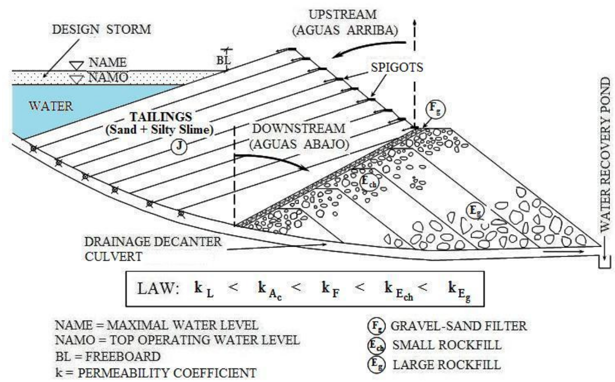


Figure 9. “Downstream” and “Upstream” constructive method with a rockfill and spigots.

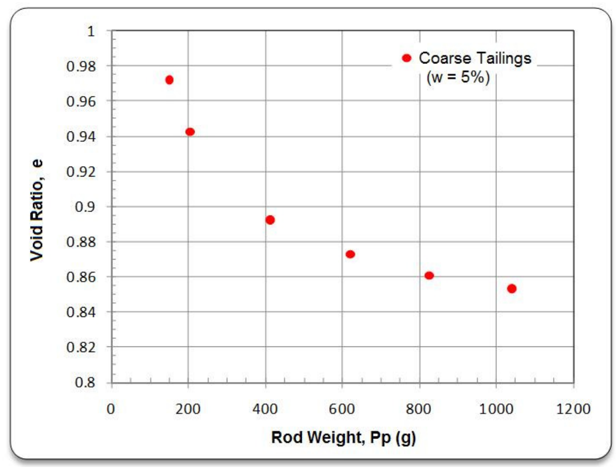


Figure 10 a. Laboratory results on reconstituted tailings

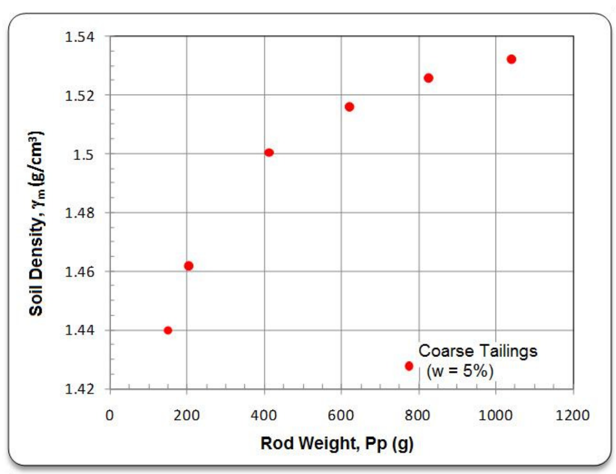


Figure 10 b. Laboratory results on reconstituted tailings

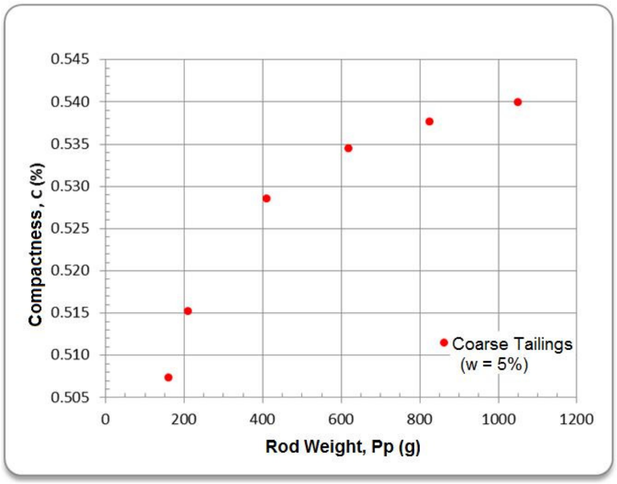


Figure 10 c. Laboratory results on reconstituted tailings

As an additional illustration, in tables 2 and 3 laboratory results to be used in the slope stability analyses are presented. (Flores et al., 2010)

Table 2 Angle of friction and cohesion for a specimen tested in partially saturated conditions

Compactness C %	Test Descriptor	Confinement Stress σ_c kg/cm^2	Shear Stress $\tau_{máx}$ kg/cm^2	Apparent Friction Angle Φ_{ap} degrees	Cohesion c kg/cm^2
	JAL-UU-0.5	0.50	0.48		
1.52	JAL-UU-1.0	1.00	0.76	21.67	0.13
	JAL-UU-1.5	1.50	1.05		

Table 3 Angle of friction and cohesion for a specimen tested in saturated conditions

Compactness	Water Content	Effective Stress	Shear Stress	Pore Pressure	Friction Angle		Cohesion	
					Total Stress	Effective Stress	Total Stress	Effective Stress
C %	w %	$\sigma_{c'}$ kg/cm^2	$\tau_{máx}$ kg/cm^2	u kg/cm^2	Φ degrees	Φ' degrees	c kg/cm^2	c' kg/cm^2
	4.56	0.51	0.422	0.135				
	4.61	1.00	0.565	0.320	12.535	17.869	0.227	0.186
	4.49	1.50	0.690	0.486				
1.52	4.98	0.50	0.297	0.167				
	4.75	1.00	0.436	0.407	14.051	20.327	0.105	0.081
	4.36	1.50	0.620	0.539				

For the quality control of the fundamental characteristics, during construction, it is necessary to always have in mind the following concepts

- Initial and final Compactness
- Initial and final Water content
- Initial and final Degree of saturation
- Content of fine grained soils
- Content of colloid substances

The use of a "CWS" (Compactness Water-Saturation) diagram to show graphically the equal characteristics curves or "isocharacteristics" for several properties, is convenient for the following (Orozco, 1978, 2005 and 2006):

- Initial and final Permeability
- Density changes
- Initial and final shear stress resistances
- Stiffness module
- Damping
- Number of cycles to cause Liquefaction

To construct the CWA diagram the following equations are used

$$C = V_s / V_t = \gamma_d / \gamma_s \quad (1)$$

$$C = \frac{1}{1+e} = \frac{1}{1+\frac{w}{S_r}G_s} \quad (2)$$

Where:

C = Compactness = solids concentration

V_s = Solids volume

V_t = Total Volume

Υ_d = Dry density

Υ_s = Solids density

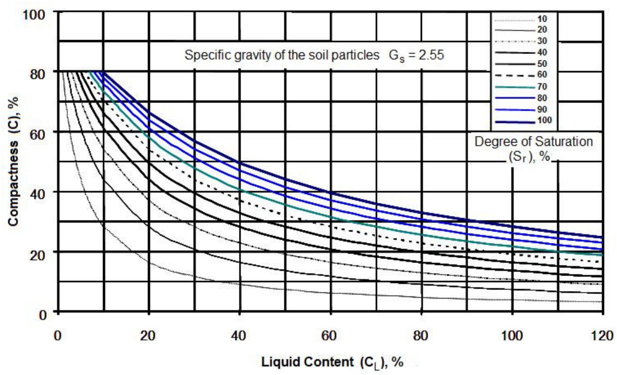
e = Void Ratio = volume of voids / volume of solids

w = Water content = weight of water/ weight of solids

S_r = Degree of saturation = volume of water / volume of voids

G_s = Solids relative density

The figure 11 outlines the CWS diagram (Orozco, 2009).



$$C = \frac{1}{1 + \frac{C_L}{S_r} G_s}$$

Figure 11. CWS Diagram (Compactness – Water or Asphalt – Saturation)

6 DECANTED DRAINAGE SYSTEM

When selecting a portal section culvert (1.25 m width and 1.65 m height, as a minimum), as the main element for the drainage system, the following functions can be complied with simultaneously (Orozco et al., 2006)

a) Collect clarified water, which is sent downstream from the containment curtain to a recuperation pond. The water recuperated this way is sent back to the concentration plant, and reused to convey the new tailings.
b) Function as a spillway during the dam's operation (operation spillway). It can also function as permanent secondary spillway besides the one built specifically on solid ground, when the dam is full and shutdown permanently.
c) Serve as inspection gallery (curtain and reservoir) during the construction and operation of the project and subsequently.
d) It can be used, when planned for, as a filtration gallery, when porous hydraulic concrete is used (Conventional / without sand or giant aggregates), or dry and porous masonry, or an appropriate combination. This will increase the safety of the project because the increase in extracting water from the tailings, thus increasing: the effective stresses, the shear stress resistance, the safety factor against slope failure, and the resistance to liquefaction, piping, erosion, etc., especially if the containment curtain is built with tailings (considered as construction materials).

7 CLASIFICATION OF THE MEXICAN TAILINGS DAMS

Depending upon the topography, hydrology and seismic activity of the site where the tailings dam is to be built, a classification system was proposed for the code that was accepted by the Federal Government (SEMARNAT, 2004), according to the following combinations (Orozco, 1991, 2002 and 2006):

Site Topography			**Zone Hydrology**			**Regional Seismicity**			**Number of Categories**
(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	
Mountains	Hills	Flat	Cyclonic	Humid	Dry	Intense	Moderate	Very Low	3 x 3 x 3 = 27

In order to select the constructive method, the embankment stability analysis method, the monitoring instrumentation and the decanted drainage system, tables 4 and 5, present 27 categories,(Orozco,2002 and 2006; SEMARNAT, 2004). Category 1 corresponds to the most difficult case scenario, such as The "Peña Colorada" site in the state of Colima, Mexico.

Table 4. General classification of the Mexican Tailing Dams. Constructive method.

Group	Subgroup	Category	TOPOGRAPHY LAND			HYDROLOGY ZONE			SEISMICITY REGION			CONSTRUCTIVE METHOD								
			M	L	P	C	H	S	S	P	A	C_s	↑ A_c	↑ A_e	↓ A_E	↓ A_{ch}	↓ A_c	↕ A^c_E	↕ A^e_E	S_g
I	1	1	x			x			x			2	-	-	1	1	1	3	4	1
		2	x			x				x		2	4	3	1	1	1	2	3	1
		3	x			x					x	2	4	3	1	1	1	1	2	1
	2	4	x				x		x			2	4	3	1	1	1	2	3	1
		5	x				x			x		2	4	3	1	1	1	1	2	1
		6	x				x				x	2	3	2	1	1	1	1	1	1
	3	7	x					x	x			2	4	3	1	1	1	1	2	1
		8	x					x		x		2	3	2	1	1	1	1	1	1
		9	x					x			x	2	2	1	1	1	1	1	1	1
II	4	10		x		x			x			2	4	3	1	1	1	2	3	1
		11		x		x				x		2	4	3	1	1	1	1	2	1
		12		x		x					x	2	3	2	1	1	1	1	1	1
	5	13		x			x		x			2	4	3	1	1	1	1	2	1
		14		x			x			x		2	3	2	1	1	1	1	1	1
		15		x			x				x	2	2	1	1	1	1	1	1	1
	6	16		x				x	x			2	3	2	1	1	1	1	1	1
		17		x				x		x		2	2	1	1	1	1	1	1	1
		18		x				x			x	2	1	1	1	1	1	1	1	1
III	7	19			x	x			x			1	3	2	1	1	1	1	2	1
		20			x	x				x		1	3	2	1	1	1	1	1	1
		21			x	x					x	1	2	1	1	1	1	1	1	1
	8	22			x		x		x			1	3	2	1	1	1	1	2	1
		23			x		x			x		1	2	1	1	1	1	1	1	1
		24			x		x				x	1	1	1	1	1	1	1	1	1
	9	25			x			x	x			1	2	1	1	1	1	1	1	1
		26			x			x		x		1	2	1	1	1	1	1	1	1
		27			x			x			x	1	1	1	1	1	1	1	1	1
													Up Stream		Down Stream			Up Stream and Downstream		
			Mountains	Hills	Flat	Cyclonic	Humid (Rainy)	Dry	Intense	Moderate	Low	Solids Concentration	"Cycloned" Sand	Spigots	Rockfill	Homogeneous with Filter	"Cycloned" and Compacted Sand	Rockfill and "Cycloned" Sand	Rockfill and Spigots	Zoned Earthfill Dam
												I	II	III	IV	V	VI	VII	VIII	IX

Note: The number 1 corresponds to the most advisable option, for a given case.

Table 5. General classification of the Mexican Tailing dams. Stability analyses, instrumentation and decanted drainage systems.

Group	Subgroup	Category	STABILITY ANALYSES					INSTRUMENTATION				DECANTED DRAINAGE SYSTEM			
			E_c	E_f	P_e	S_f	S_n	P	I	R	S	S_p	C_c	B_b	S
I	1	1	4	1	4	1	2	1	2	1	1	1	2	-	-
		2	3	1	3	1	2	1	3	1	2	1	2	3	-
		3	2	1	-	-	-	2	-	1	-	1	2	3	4
	2	4	4	1	4	1	2	1	2	1	1	1	2	3	-
		5	3	1	3	1	2	1	3	1	2	1	2	3	4
		6	2	1	-	-	-	2	-	1	-	1	2	2	3
	3	7	3	1	3	1	2	1	2	1	1	1	2	3	4
		8	2	1	2	1	2	1	3	1	2	1	2	3	4
		9	2	1	-	-	-	2	-	1	-	3	2	1	2
II	4	10	2	1	2	1	2	1	2	1	1	1	2	-	-
		11	2	1	2	1	2	1	3	1	2	1	2	3	-
		12	2	1	-	-	-	2	-	1	-	1	2	3	4
	5	13	2	1	2	1	2	1	2	1	1	1	2	3	-
		14	2	1	2	1	2	1	3	1	2	1	2	3	4
		15	1	2	-	-	-	2	-	1	-	1	2	2	3
	6	16	2	1	2	1	2	1	2	1	1	1	2	3	4
		17	2	1	1	1	2	1	3	1	2	1	2	3	4
		18	1	2	-	-	-	2	-	1	-	3	2	1	2
III	7	19	2	1	2	1	2	1	2	1	1	1	2	-	-
		20	2	1	2	1	2	1	3	1	2	1	2	4	-
		21	2	1	-	-	-	2	-	1	-	1	2	3	4
	8	22	2	1	2	1	2	1	2	1	1	1	2	4	-
		23	2	1	2	1	2	1	3	1	2	1	2	3	4
		24	1	2	-	-	-	2	-	1	-	1	2	2	3
	9	25	2	1	2	1	2	1	2	1	1	1	2	3	4
		26	1	2	1	2	2	1	3	1	2	1	2	3	4
		27	1	2	-	-	-	2	-	1	-	3	2	1	2
			Static			Seismic						Culvert			
			Conventional	Finite Element	Pseudo-Static	Finite Element	Neuronal Nets	Piezometers	Inclinometers	Surveying references	Seismographes	Portal Section	Circular o square section conduit	Raft pumping	Siphons

Note: The number 1 corresponds to the most advisable option, in a given case.

Other typical transversal sections for the containment curtain are presented in figures 12 and 13 (SEMARNAT, 2004); For the case of a conventional dam for water storage o where the tailings are deposited in the river bed, the case showed in figure 13 can be applied. Asphalt concrete can also be used (Figs. 14 and 15), where the asphalt is placed in hot layers, compacted and protected with wedges of frictional material (Orozco, 2004 and 2008).

For better knowledge on the mining residues in general, a consultation of related themes is recommended, among which there are: the site characterization, project, construction, operation and disposal of mining residues; geotechnical considerations; waterproof coverings; covers and barriers; hydrology and geochemistry; remediation and treatment; recovery, reprocess and reuse; new technologies and procedures; and also consultation of case histories, as those published by the University of Colorado, USA (CST, 2001 to 2010).

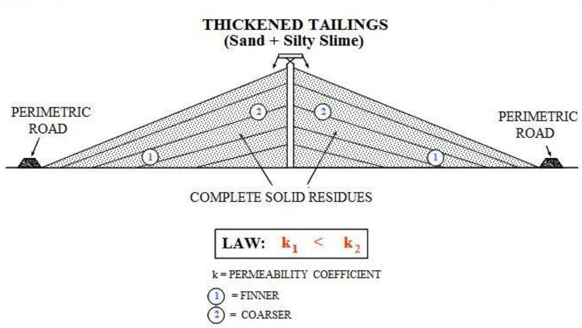


Figure 12. Constructive method: solids concentration (TTD)*.

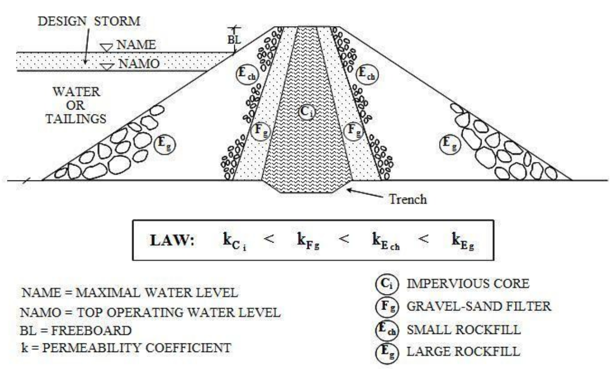


Figure 13. Conventional zoned embankment dam.

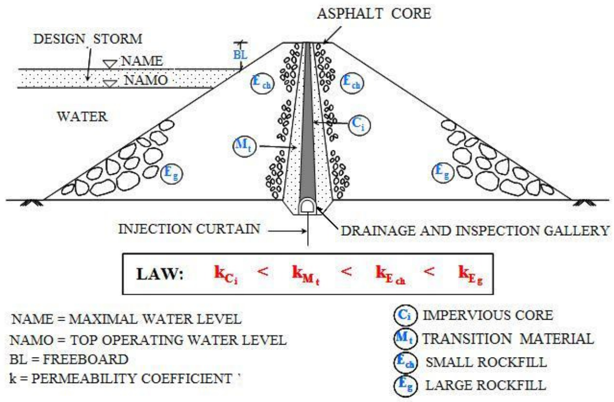


Figure 14. Compacted arch curtain of zoned section with a variable asphalt concrete core

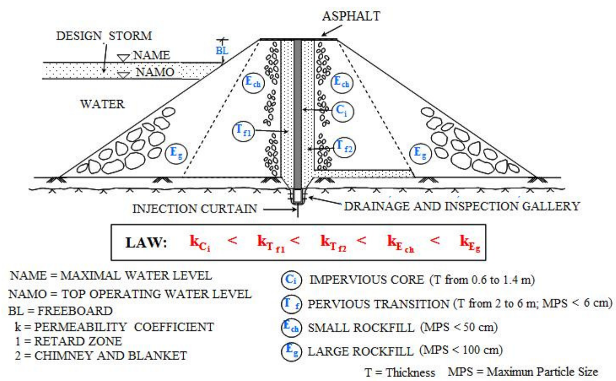


Figure 15. Compacted and arched curtain with zoned section and constant asphalt concrete core.

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