RELATION OF PERMEABILITIES BETWEEN MATERIALS 2 AND 3A OF THE "EL CAJÓN" DAM

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Abstract: Material 2 of the El Cajón dam, constitutes a uniform support of the face of concrete and protects against filtration effects; as well as material 3A protects to material 2. By specification, k2 must be equal or smaller than 10-3 cm/s and k3A greater than 10-1 cm/s, with a relation of k3A/k2 = 100. Tests of permeability in the curtain indicated fulfilment of material 2, not that material 3A where smaller values to the specified ones were obtained. Detailed analyses more indicate that material 3A himself fulfils the function of filter by resistance to the internal erosion and like material of retention of material 2. The condition of greater permeability is not fulfilled, nevertheless, by the first condition is most important much, thus is guaranteed "hydrodynamics stability" of materials 2 and 3A.

Key words: Transition materials permeability

1. Antecedents

The curtain body of El Cajón dam has the distribution showed in Figure 1. The material of zone 2 constitutes a protection zone, relieving of leaking effects that could occur on the concrete face through its joints or cracking. It forms a uniform surface where the concrete slab is settled. In the construction Specifications (CFE2002) it is stated that this material “is product from the rock bank El Vertedor, classified as silty gravel sand with a fine content between 6 and 10% and a percentage higher to 40% of material passing mesh Nº 4; once the material has been compacted, the voids ratio must be equal or less to 0.22 and a permeability coefficient equal or less to 10-3 cm/s.

For material in zone 3A, the same specifications establish that “this material is product from the rock bank El Vertedor, well graded, with a maximum size of 20 cm. It must be placed in layers of 30 cm thickness with an ideal water content, compacting with plain vibratory roller of 104 kN (10.6 Ton) minimum static weight in the drum and the necessary number of passes to obtain a void ratio equal or less to 0.24. The permeability coefficient must be 100 times higher than that of material 2 and no less than 10-1 cm/s”. This material constitutes a filter/transition between materials in zones 2 and 3B, with the grain size distribution shown in Figure2, obtained once it was placed and compacted with no segregated zones.

Thus, material 3A forms a strip in the curtain body that serves as protection to zone 2 material, with two main functions: first, to facilitate the filtration of the water that could pass from the slab to material 2 and as a second: to avoid the migration of material 2 towards material 3B zone; consequently, it had to fulfill the filter conditions, as follows: a) to have a permeability higher than that of material 2 and b) to have a grain size thicker with respect to material 2, but not exceeding a such size as to avoid the passing or loosing of this material.

In the construction specifications (CFE 2002), it was stated that for 2 and 3A materials, a Matsuo-Akai field test had to be carried out for each 10 layers compacted. This instruction was performed during the construction process.

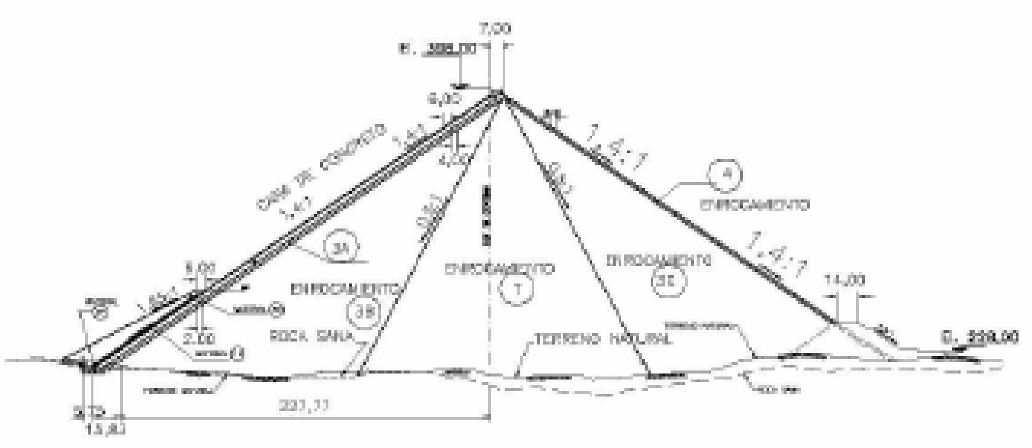

Figura 1. Cross section and zones of El Cajon dam

2. Construction of the fill or embankment test

The filter conditions are (Marsal and Reséndiz 1975; CFE 1980; and Das 1999): a) Internal scour resistence, for this D15F (3A material) must be less to 5 times D85S (material 2) and b) to have higher permeability, for this D15F (material 3A) must be more or equal to 5 times D15S (Material 2). The first condition is far the most important considering that material 3B is much more permeable. The first relation assumes that the size distribution is large enough to avoid the smallest particles to be swept out by the water filtration force; that is to say, it must ensure that the soil has "hydrodynamic stability".

For a D15F (Material A) of 0.28 to 0.90 mm and a D85S (Material 2) of 25.4 and 49.0 mm with complete grading, and of 2.5 and 2.8 mm of adjusted at 100% grading of sieve Nº 4, the first condition is widely fulfilled. For the second condition (permeability), the relation is of 2.3 in place of 5.0; even though, if estimated with the average, the relation is of 3.67

In Figure 2 the three grading strips of the materials involved are presented. It is possible to note that the grading specified for material 3A is quite close to that of material 2, and consequently, the permeability relations are not so broad. The specification of the grading strip of material 3A should, in fact, have been moved to the thick side, particularly in its fine/thin fraction, to center it between the 3B rockfill strip and that of material 2.

The permeability coefficient is the property of the soil that indicates the relative facility with which water can flow through it due to hydraulic gradient effect. It depends on water and soil properties; viscosity, specific weight and polarity have an influence on the first; grading size, void ratio (compacity), mineral composition, structure and saturation degree influence the second.

Hazen proposed to assess the permeability coefficient through the characteristic size of D10.

In fact, he suggests that permeability varies with the square of the mentioned particle diameter, which according to his proposal corresponds to 10% of particles smaller than that size. In relation to this, various researchers have found through laboratory tests that permeability coefficient K, apart from being function of D10, depends on the void ratios (relation propose in CFE 1980), and it is possible to be estimated through equation 1 (Cruz 2006). These calculations are presented in Table 1 for the strips specified of materials 2 and 3A.

$$\boldsymbol{k = A\, D_{10}^{\alpha}} \qquad \textbf{(1)}$$

where: k in cm/s; A = 581 - 470e; á = 3.46 - 1.85e; e is the soil void ratio and D10 is the effective diameter in cm.

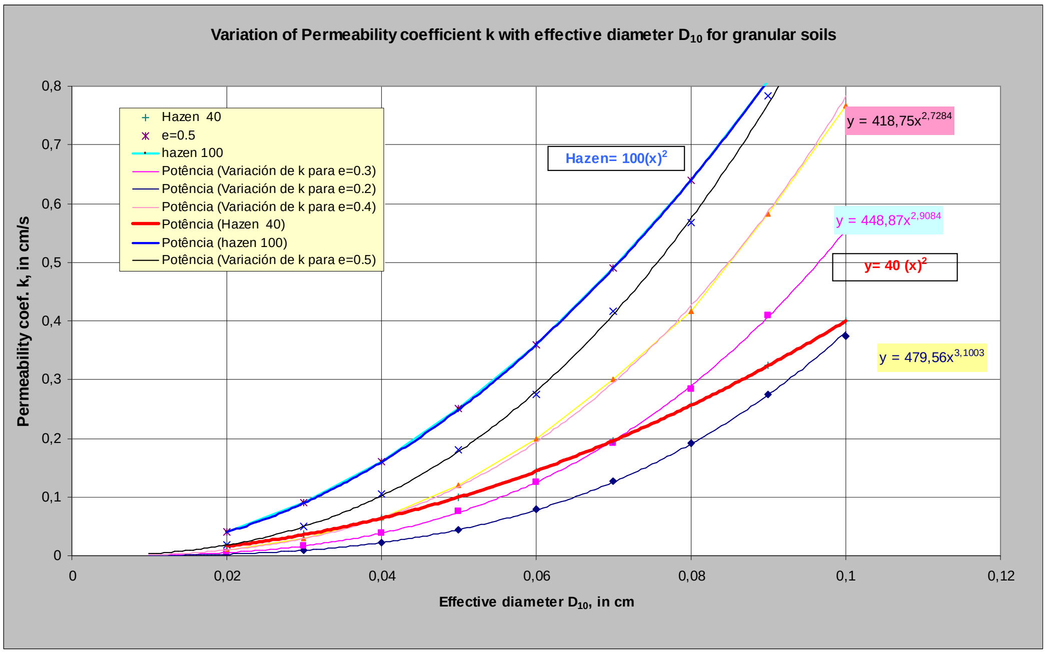

Figura 2. Relation K and void ratio according to Ref (4)

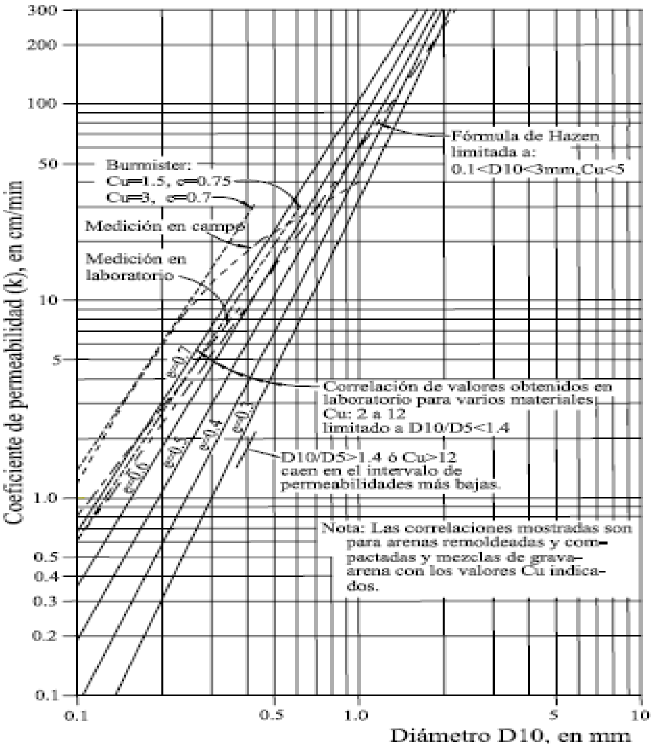

Figura 3. Relation K and void ratio according to CFE Manual

According to the experience along the development of soil mechanics, it can be asserted that the relation 100 of filter permeabilities (material 3A) with respect to the protecting material (material 2) could hardly be obtained in theory. Even though, according to the criteria following the results presented by the Manual of Design-CFE (CFE 1980), with a void ratio of 0.20, the highest line is close to a value of 60.23, as can be seen in the next figure.

Tabla 1. Permeability coefficients (k) according to Hazen criteria and the equation 1 (Cruz 2006), for 2 and 3A materials and the limits or strips presented in figura 2 (CFE 2002)

Specified grading ranges	Material 3A			Material 2			Relation k_{3A}/k_2	
	Diameter D_{10} (cm)	Permeability Coefficient k_{3A} (cm/s)		Diameter D_{10} (cm)	Permeability Coefficient k_{3A} (cm/s)		Hazen	MDOC-CFE
		Hazen $100*D_{10}^2$	MDOC-CFE		Hazen $100*D1_0^2$	MDOC-CFE		
Superior	0.060	0.36	0.0783	0.016	0.0256	0.0013	14.06	60.23
Inferior	0.016	0.0256	0.0013	0.0067	0.0045	0.000088	5.69	14.77

The permeability coefficient can also be tested through lab tests at constant and variable load, field tests by means of drillings as Lefranc, Matsuo- Akai and Nasberg determinations and through pumping tests and ditches or pits (SRH 1970 and CFE 1980). Material with a permeability of up to 10-4 cm/s are considered of a good drainage, taking into account that for a mixture of clean sand and gravel, the permeability coefficient resulting could be between 10 and 10-3 cm/s (Terzaghi and Peck 1973).

The measurement of permeability is highly influenced by the soil natural conditions and by the test conditions. The inherent difficulties of the tests in situ require great care to minimize the source of mistakes.

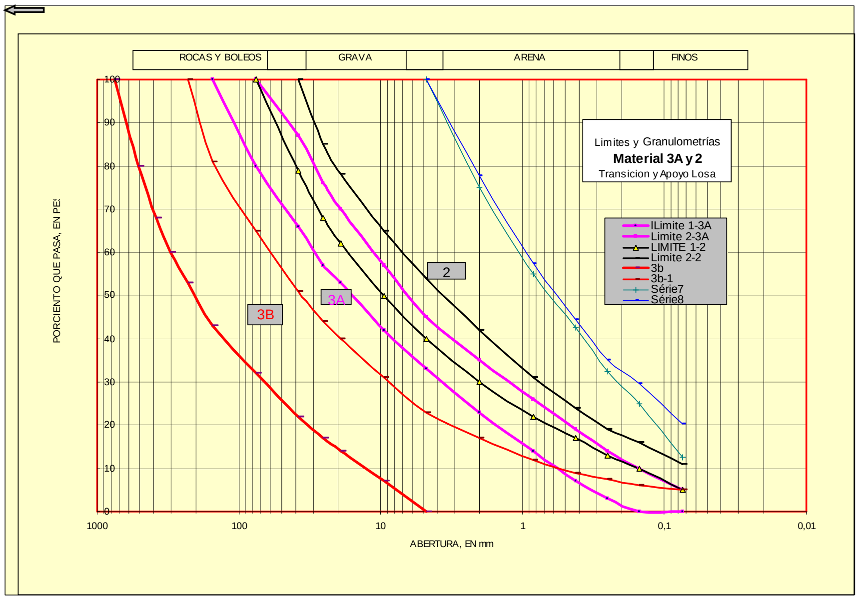

Figure 2. Grading ranges of material 2, 3A and 3B of El Cajón dam curtain according to specifications.

The construction specifications (CFE2002) indicate the development of tests in situ in pits or trenches (Matsuo-Akai) to obtain an order of magnitude of the permeability coefficient. This procedure involves homogeneity hypothesis and isotropy of the soil and of an established infiltration regime. These are not always strictly fulfilled in practice, especially in embankments. This sort of tests also presents inaccuracies related to the exact dimensions and the leaking surface geometry, which influences the coefficient value, and thus participates in the used formula. The result itself is integration of horizontal and vertical permeabilities, and of the void ratio and its uniformity fulfilled with compaction.

The next Table 2 presents a summary of permeability tests results performed in situ, following the specified Matsuo-Akai methodology. According to these results, the 100 relation between both materials (k3A/k2) is not fulfilled, except for one case (523). When considering an average value of the obtained permeabilities, a relation of 15, 86 is reached; this shows that comparing tests results in an isolated way turns out to be incorrect, any time that the tests are specific and with a low statistical representation of the whole.

Table 2. Permeability coefficiets determined through Matsuo-Akai field tests right on the curtain for materials 2 and 3A

No. Of tests	Material 2		Material 3A		Relation between permeabilities, k_{3A}/k_2
	Layer	Permeability Coefficient k_{3A} k_2 (cm/s) x10^{-3}	Layer	Permeability Coefficient k_{3A} k_{3A} (cm/s)x10^{-3}	
2	34	0.370	35	0.78	2.11
3	46	0.535	47	9.1	17.0
4	57	0.453	58	1.17	2.58
5	70	0.153	71	80.00	522.90
6	81	1.036	81	0.92	0.89
7	143	0.576	144	0.81	1.41
8	170	0.064	175	0.53	8.28
9	216	0.988	217	1.82	1.84
10	216	0.257	217	5.63	21.91
11	216	1.482	217	15.74	10.62
12	260	1.420	261	6.55	4.61
13	276	0.484	277	1.09	2.25
Promedio		0.652		10.34	15.86*

* Obtained using the average of k3A and k2

In table 2 it is possible to note that the permeability of material 3A was, in general, higher than that of material 2.

The results of grading tests and volumetric heights, as well as the void ratio obtained once the material has been compacted, indicated a pretty narrow range of values. For this reason, it is possible to assert that the quality, in grading as well as in the placement of the curtain body was properly controlled.

The permeability coefficients can also be determined through parameters resulting from the grading tests. In this way, table 3 shows the values of the permeability coefficient for material 2, and table 4 the ones corresponding to material 3A, calculated from the grading curves of samples from volumetric pits. In both tables, the values registered are obtained through Hazen´s expression and by means of equation 1. For the latter case the permeability coefficient was determined for an average total void ratio (e). The values presented in Tables 3 and 4 show that the ones obtained through equation 1 are more compatible with the ones obtained in field tests (table2); for this reason the application of this criterion is recommended to estimate the most reliable permeability coefficient according to D10 and the void ratio. As for material 3A, the permeability coefficient was also estimated considering an effective void ratio (ee), which considers the porosity of particles bigger than sieve Nº 4.

Table 3. Permeability Coefficients calculated from grading curves of material 2 compacted in the curtain body.

Pit (layer)	Grading of material 2								Permeability coefficient, k(cm/s)x10-3	
	Gravel (%)	Sand (%)	Fines (%)	$D_{10(2)}$ (cm)	$D_{15(2)}$ (cm)	$D_{60(2)}$ (cm)	$D_{85(2)}$ (cm)	C_u	Hazen $100D_{10}^2$	MDOC-CFE e2=0.20
62(86)	53	37.9	9.1	0.008	0.016	0.95	2.5	119	6.4	0.15
63(88)	50	40	10	0.0074	0.016	1.05	2.8	142	5.5	0.12
64(90)	55	34.8	10.2	0.0074	0.016	1.3	3.2	176	5.5	0.12
66(94)	46	40.4	13.6	0.006	0.01	0.8	2.15	133	3.6	0.062
67(96)	57	33.4	9.6	0.0077	0.018	1.5	3.2	195	6.4	0.15
69(98)	52	39.2	8.8	0.009	0.015	0.95	2.7	106	8.1	0.22
Average	52.17	37.62	10.22	0.0076	0.015	1.09	2.76	143	5.9	0.137
Average value of k_2 estimated on D_{10} = 0.0076									5.8	0.13

Table 4. Permeability coefficient calculated from grading curves of material 3A compacted in the curtain body.

Pit (layer)	Grading of Material 3[a]								Permeability coefficient, k(cm/s) $x10^{-3}$		
	Gravel (%)	Sand (%)	Fines (%)	$D_{10(3A)}$ (cm)	$D_{15(3A)}$ (cm)	$D_{60(3A)}$ (cm)	$D_{85(3A)}$ (cm)	C_u	Hazen $100D_{10}^2$	MDOC-CFE	
										e_{3A}=0.22	e_{e3A}=0.12
72(85)	59	34.9	6.1	0.02	0.042	1.4	3.8	70	40.0	2.92	2.0
73(87)	62	33.8	4.2	0.03	0.042	2.0	4.3	67	90.0	10.14	7.3
74(89)	59	37	4.0	0.041	0.065	1.8	4.1	44	160.0	26.45	20.0
75(91)	66	32	2.0	0.021	0.042	2.0	4.0	95	44.1	3.39	2.4
76(93)	61	35.5	3.5	0.06	0.09	1.6	4.3	27	360.0	85.15	66.5
77(95)	68	27.8	4.2	0.041	0.085	2.6	5.5	63	160.0	26.45	20.0
Average	62.5	33.5	4.0	0.0355	0.061	1.9	4.33	54	142.0	25.75	19.7
Average value of k_{3A} estimated on $D_{10(3A)}$ = 0.0355									126.0	17.0	12.5

Considering the average values of the permeabilities of materials 2 and 3A, theoretically determined according to tables 3 and 4, the following relations to fulfill the filter conditions are obtained:

Condition of retain material 2,

$$\frac{D_{15(3A)}}{D_{85(2)}} < 5\ ;\ \ \frac{D_{15(3A)}}{D_{85(2)}} = \frac{0.061}{2.76} = 0.022$$

The condition is satisfied

Condition to be more permeable,

$$\frac{D_{15(3A)}}{D_{15(2)}} \geq 5\ ;\ \ \frac{D_{15(3A)}}{D_{15(2)}} = \frac{0.061}{0.015} = 4.07$$

The conditon is not satisfied, however is very close to the required value.

For the specified condition between the permeabilities of both materials, 3A and 2, taking the average value, the next results are obtained:

Applying Hazen criteria:

$$\frac{k_{3A}}{k_2} = \frac{142x10^{-3}}{5.9x10^{-3}} = 24.1$$

The condition is not satisfied

According to the values of k calculated with equation 1, and for a total void ratio, e3A= 0.22 and e2= 0.20:

$$\frac{k_{3A}}{k_2} = \frac{25.75x10^{-3}}{0.137x10^{-3}} = 188.0$$

The condition is satisfied

According to the values of k_{3A} calculated with equation 1, and for an effective void ratio, $e_{e3}A$=0.12 y e_2=0.20:

$$\frac{k_{3A}}{k_2} = \frac{19.7x10^{-3}}{0.137x10^{-3}} = 143.8$$

The condition is satisfied

For the condition of relation of permeabilities between the materials 3A y 2, considering the characteristic average diameter D_{10} from the grading curves, the next results are obtained:

With Hazen criteria:

$$\frac{k_{3A}}{k_2} = \frac{126x10^{-3}}{5.8x10^{-3}} = 21.72$$

The condition is not satisfied

According to the values of k calculated with equation 1, and for a total void ratio, e_{3A}= 0.22 y e_2= 0.20:

$$\frac{k_{3A}}{k_2} = \frac{17.0x10^{-3}}{0.13x10^{-3}} = 130.8$$

The condition is satisfied

Considering the k values calculated with the equation 1, and for an effective void ratio, e_{e3A}=0.12 y e_2=0.20:

$$\frac{k_{3A}}{k_2} = \frac{12.5x10^{-3}}{0.13x10^{-3}} = 96.2$$

The condition is practicallyis satisfied

According to the results of the Matsuo – Akai field tests (table2), the relation of permeabilities is not fulfilled. The empirical-theoretical results applying Hazen criterion, show that such relation is not fulfilled either; however, the empirical theoretical calculations applying the grading parameters and the inferred criteria (ec.1) from the results of various researchers presented by the “Manual de Diseño de Obras Civiles de la Comisión Federal de Electricidad (CFE 1980 y Cruz 2006)”, indicate that the relation of permeability is fulfilled. The latter procedure presents a noticeable advantage over Hazen´s criterion as, beyond considering D10 (effective diameter), it takes into account the void ratio presented by the soils, which is significant for different degrees of compactness.

Due to the numerous variables to be controlled in a Matsuo Akai field test, the permeability values obtained are not uniform and because of this, they are not quite reliable, showing important disagreements between one test and the other, which is not very coherent with the results of grading tests, dry volumetric weights and void ratios obtained once the material has been compacted, where a quite narrow range of values is observed. Therefore, it is assumed that the quality, in the grading as well as in the laying and compaction of the curtain body, was properly controlled in these materials.

3. Conclusions

Material 3A fulfills the functions of transition between material 2 and the 3B embankment as it is proposed by the design practice for this type of dams.

According to the grading curve specified for material 3A, and the field tests carried out, it is neither possible to fulfill permeability of 1 x 10-1 cm/s, nor the 100 times more permeable than material 2 relation, through Matsuo-Akai type field tests, as it was demanded in the construction specifications.

The grading curves of materials 2 and 3A which were placed in the curtain fulfill the range established in the specifications and are located quite close from one another; for this reason the material 3A retention condition of the particles of material 2 is fulfilled, avoiding the risk of internal erosion and piping.

According to the Matsuo-Akai field tests results, the permeability relation between material 3A and material 2 is not fulfilled; the theoretical-empirical results applying the Hazen criterion indicate that such relation is not fulfilled either; while results obtained applying empirical-theoretical procedures with grading parameters and the inferred criteria from results presented in Manual de Diseño de Obras Civiles (CFE) by various researchers, indicate that the permeability relation is fulfilled.

The permeabilities coefficients values obtained through the application of equation 1 are more compatible with the results obtained in field tests (table2), for this, it is advisable to apply this procedure to estimate more reliably and rationally the permeability coefficient according to D10 and the void ratio.

To compare isolated results of grading tests turns out to be incorrect, any time that the tests are specific and one alone is not representative of the whole; it must be considered a general average of tests.

The results of grading tests, dry volumetric weights and void ratios obtained when the material in the body curtain has been compacted show a quite narrow range of values. It is possible to conclude, then, that the quality, in the grading as well as in the laying and compaction in the body curtain was properly controlled in materials 2 and 3A.

References

[1] CFE (1980). “Geotecnia. Propiedades físicas y mecánicas de los suelos”, *Manual de Diseño de Obras Civiles*, Fas. B.2.2.,Comisión Federal de Electricidad, México.

[2] Das, B. M. (1999). *Principios de Ingeniería de Cimentaciones*, Trad. José de la Cera Alonso, UAM-U Azcapotzalco, Ed. Internacional Thomson Editores, México.

[3] CFE (2002). “Especificaciones de Construcción de Obra Civil del P. H. El Cajón, Nay.”, *Bases de Licitación, Sección 8, capítulo 15*, Comisión Federal de Electricidad, México.

[4] Cruz, A. (2006). “La tubificación en suelos y su solución mediante filtro”, Memorias de la XXIII Reunión Nacional de Mecánica de Suelos, Publicación SMMS,

[5] Tuxtla Gutiérrez, Chis. Marsal, R. J. y Reséndiz, D. (1975). *Presas de Tierra y Enrocamiento*, Ed. Limusa, México.

[6] SRH (1970). *Manual de Mecánica de Suelos, Secretaría de Recursos Hidráulicos*, México.

[7] Terzaghi, K. y Peck, R. (1973). *Mecánica de Suelos en la Ingeniería Práctica*, Trad. Oreste Moretto, Ed. Ateneo, España.