Filter ratio between materials in a rockfill dam

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ABSTRACT
In Dam Engineering, the distribution of materials in a concrete face rockfill dam is well known in what refers to specifications and convention codes for their identification. Material 2 is the continuous support for the concrete face and prevents seepage; at the same time, material 3A protects material 2. In the case studied, grain size and permeability specifications were provided by the owner, but once the permeability tests at the dam under construction were executed, the results were satisfactory for material 2 but not so for material 3A. Analyses of the information were made to determine the impact and, if applicable, to establish the acceptance criterion for placement of materials

RESUMEN
En Ingeniería de Presas, la distribución de materiales en una cortina de enrocamiento con cara de concreto sigue convenciones casi de aceptación mundial en cuanto a su granulometría e identificación. El material 2 constituye un apoyo uniforme de la cara de concreto y protege contra efectos de filtración; a su vez, el material 3A protege al material 2. Para el proyecto analizado se tenían las especificaciones dadas por el propietario para la granulometría y para la permeabilidad; sin embargo, conforme se iniciaron las pruebas de verificación de la permeabilidad en el campo, éstas indicaron el cumplimiento para el material 2 y no así para el material 3A. Se realizó el análisis de la información para determinar cuál era el impacto y en dado caso cuál sería el criterio de aceptación para la colocación de los materiales.

1 BACKGROUND

1.1 Objective of this paper

This report has been prepared to serve as the basis for technical discussion in academic terms and not as an analysis of the management performed in the specific situation of a particular project; therefore, personal and institutional information has been deleted, retaining the minimum technical data necessary for its discussion.

1.2 Reference framework

September 2002 was the starting date of a bidding process to build a hydroelectric project in Mexico after many years had elapsed without executing in the country one dam of such magnitude and for which the Basic Engineering available was based on the design of a so-called rockfill embankment with concrete facing. Among the specifications provided by *The Owner* those corresponding to the constituting materials for the embankment were available.

The work was awarded in 2003 to *The Contractor* and detail engineering was included as part of the scope.

The first year of the work schedule comprised works related to diversion structures and the retaining work construction started in 2004. After materials started to be placed it became necessary to for *The Contractor* to propose to *The Owner* an adjustment to the specifications because in one of the guidelines set forth, specifically the ratio between the permeability of two adjacent materials, was not being accomplished. The technical approach to solve this situation involved the definition of the applicable guidelines so as to reach the objective of the conception provided by the basic engineering in what refers to the behavior of materials in terms of the filter rate.

2 SPECIFICATIONS

Figure 1 shows zoning of the materials from the concrete face to the rockfill.

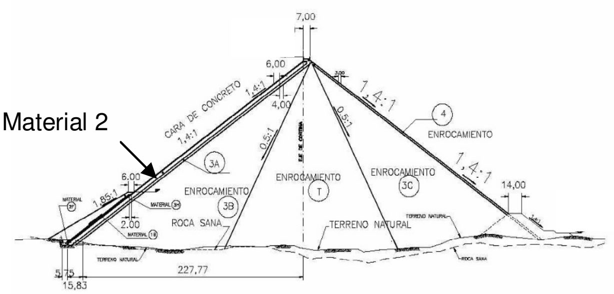

Figure 1. Distribution of materials in the dam.

Material 2 constitutes a uniform support for the concrete face and protects it against seepage effects; in turn, material 3A protects material 2 and should serve as filter and transition between materials 2 and 3B; it was therefore designed according to filter criteria.

The width of zone 2 is of 6 m and that of zone 3A is of 4 m. By specification, the permeability of material 2 should be equal to or smaller than 10^{-3} cm/s and it was required that after being compacted it would have a void ratio equal to or smaller than 0.22.

For the case of material 3A the permeability should exceed 10^{-1} cm/s, with a ratio higher than 100 with respect to that of material 2 and it should have a void ratio smaller than 0.24 after being compacted.

The initial permeability tests in the embankment showed compliance with material 2, but not so for material 3A for which values smaller than those specified were obtained

3 ANALYSIS OF THE SITUATION

3.1 Sequence of analysis

When confronted to the situation referred to above the approach to the problem by *The Contractor* implied in the first place how to deal with this incompatibility of materials for the embankment because, in the one hand the specifications were issued by *The Owner* and on the other, the detail engineering corresponded to *The Contractor*.

It was decided to carry out first a retrieval of the information available from the project itself and from the methods that could contribute values aimed at performing an assessment of the situation in addition to analyzing the results of field tests to finally propose a sustainable approach for *The Owner* to make a decision in what refers to the adjustment of the specification, if applicable.

3.2 Bibliographic research

Besides the specifications provided by *The Owner* consultation was made of references established by authors of texts on Soil Mechanics. The grain size distribution of 3A should be well graded and have an intermediate grain size distribution between 2 and 3B. Filter requirements (Marsal and Reséndiz, 1975; CFE, 1980; and Das (1999) are given as follows:

a) Resistance to internal erosion. Diameter D_{15F} (Material 3A) should be smaller than five times the diameter D_{85S} (Material 2); and

b) Have higher permeability. To comply with this, diameter D_{15F} (Material 3A) should be equal to or higher than five times diameter D_{15S} (Material 2).

Primarily, the first condition is the most important taking into account that material 3B is much more pervious. The first ratio assumes that the grain size distribution is sufficiently wide to prevent the smallest particles to be carried away by the seepage force of water, i.e. the soil is likely to show “hydrodynamic stability”.

For a diameter D_{15F} (Material 3A) ranging from 0.28 to 0.90 mm and a diameter D_{85S} (Material 2) from 25.4 to 49.0 mm, the first condition is fully complied with. For the second one, related to the permeability, diameter D_{15S} falls between 0.15 and 0.26 mm and the ratio between diameters D_{15F} and D_{15S} becomes in general smaller than 5.0, unless a combination is made of the conditions corresponding to the upper extreme boundary of one material with the lower extreme boundary of the other.

The grain size distribution bands of the three materials involved were plotted to identify the variation among each of the materials. Figure 2 depicts such graphs. It can be observed that the grain size distribution specified for 3A is quite close to that corresponding to material 2, and therefore the permeability ratios are not so wide and there is no possibility of shifting to the coarse part because a similar case would be obtained for 3B.

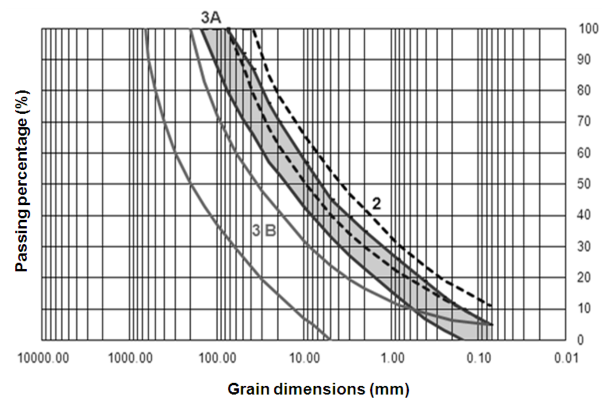

Figure 2. Grain size distribution curves for the materials.

It was determined that one condition of the filter rate was not satisfied; the permeability value was then estimated based on a correlation with the grain size distribution because at the job site this type of test was carried out in samples recovered from huge open test pits.

If the results of the permeability inferred from this ratio had complied with the specifications, its application could have been proposed as verification indicator.

If the formula of Hazen (CFE, 1980) is applied, in which the permeability K is determined as a direct function of the square of the diameter corresponding to 10% of particles smaller that that size (Eq. 1), then:

$$K = 100\ D_{10}^2 \qquad (1)$$

where:

D10 is the diameter for which 10% of the material is retained; for material 2, diameter D10 in the specified curves may vary from 0.16 to 0.067 mm whereas for material 3A it ranged from 0.60 to 0.16 mm.

3.3 Field tests

It was assumed that the coefficient of permeability can be calculated by means of laboratory tests under constant and variable head, by means of field tests in boreholes such as those of Lefranc and Nasberg, and by means of pumping tests in trenches or wells.

Materials with a permeability equal to 10^{-4} cm/s can be considered to have good drainage, assuming that for a mix of clean sand and gravel it is possible to arrive at a coefficient of permeability ranging from 10 to 10-3 cm/s (Terzaghi and Peck, 1973).

The construction specifications established the execution of Matsuo-Akai tests in wells or trenches to obtain the coefficient of permeability. This procedure involves hypotheses of homogeneity and isotropy of the soils and established regime that are not always satisfied rigorously in practice, particularly in the case of rockfills.

This type of test also evidence lack of accuracy related to the exact dimensions and geometry of the filtering surface, therefore affecting the value of the coefficient when applied to the formulas used.

The result is by itself an integration of the horizontal and vertical permeability values and of the void ratio and uniformity reached during compaction.

According to the results obtained, the ratio $100(k_{3A}/k_2)$ was never reached except in one case. Data available were processed and it was obtained that the permeability ratios were smaller than 10 as it can be observed in Table 1.

Table 1. Results of permeability tests

	Material 2 (cm/s) $x10^{-3}$	Material 3A (cm/s)$x10^{-3}$	k_{3A}/k_2
1	0.370	0.780	2.11
2	0.535	9.100	17.00
3	0.453	1.170	2.58
4*	0.153	80.000	522.90
5	1.036	0.920	0.89
6	0.576	0.810	1.41
7	0.064	0.530	8.28
8	0.988	1.820	1.84
9	0.257	5.630	21.91
10	1.482	15.740	10.62
11	1.420	6.550	4.61
12	0.484	1.090	2.25
Average	0.697	4.013	6.68*

*Data shown in line 4 of this table were omitted for purposes of obtaining the average values. The average between both permeability values is obtained after calculating it using the values of the last column.

To rule out that the permeability values could be affected by erratic parameters inherent to the construction process, the values of the index properties of the samples were reviewed and it was concluded that this was not the case because quality of the materials, and their placement, compaction and control were subjected to well established system agreed by the parties for such purpose.

Actually, the results of the grain size distribution tests, dry unit weights and void ratios, obtained after compaction of the material, were in general terms highly stable and their average values are presented in Table 2.

Table 2. Average results of compaction of materials 2 and 3A.

Property	Material 2	Material 3A
Unit weight (kg/m^3)	2301	2108
Specific density	2.76	2.61
Void ratio	0.1989	0.2371

After the information was collected, the interpretation of all data as a whole was carried out using an integral approach by the technical staff of *The Contractor,* its *Designer* and *The Owner*.

4 INTERPRETATIONS

Even though a field test should reflect with higher accuracy the value of the permeability, it is also true that in each test such as those proposed by Matsuo-Akai, variables exist that can distort the results.

Values obtained for the permeability may show large variations so that it was intended to infer the values of permeability from the grain size distribution of the materials, obtained from samples compatible with the rock sizes in each layer.

Values inferred from the ratio with diameter D_{10} are compatible with those obtained from field tests; it was therefore decided to apply this criterion to estimate more reliably the coefficient of permeability.

After the analyses were carried out it was determined that material 3A indeed satisfied the function of filter as protection against internal erosion and as material to retain the particles of material 2. The condition of ratios between permeability values was not complied with; however, by far the condition to prevent migration of material is the most important and it was possible to guarantee the "hydrodynamic stability" of materials 2 and 3A.

Material 3A indeed satisfied the requirements of being a transition between material 2 and rockfill 3B, as it can be verified by the practice of design of this type of embankment dams.

According to the grain size distribution band specified for material 3A and to the results of the field tests carried out, it was not possible neither to achieve a permeability of 1 x 10-1 cm/s, nor the ratio of being 100 times more pervious than material 2, by using field tests of the Matsuo-Akai type.

The grain size distribution of materials 2 and 3A that were placed in the embankment satisfied the range established in the specifications and the curves are very close between them; therefore, the condition for material 3A to retain the particles of material 2 is complied with, thus preventing the risk of internal erosion and piping.

According to the results of the Matsuo-Akai field tests, the ratio between the permeability values of material 3A and material 2 is not fulfilled; the results of empirical and theoretical nature applying the criterion of Hazen indicate that such ratio is not complied with either. On the other hand, the results obtained using empirical/theoretical procedures with grain size distribution parameters and the criteria inferred from the results presented by the *Manual de Diseño de Obras Civiles* published by the *Comisión Federal de Electricidad* (CFE, 1980) from several researchers, indeed satisfy the permeability ratio.

The values of the coefficients of permeability that were obtained from the graphs of the *Manual de Obras Civiles* of the CFE (CFE, 1980) are more compatible with the results derived from field tests (Table 1), and it is therefore recommended to apply this procedure for purposes of estimating the coefficient of permeability in a more reliable and rational approach, as a function of D_{10} and of the void ratio.

5 CONCLUSIONS

During construction of the embankment dam conditions established in the specifications were complied with in what refers to grain size distribution, compaction and behavior as a filter to protect against internal erosion or migration of material 2 toward material 3A; however, the specified permeability ratio could not be reached.

The fact that the dispersion of the compaction results had been low made it possible to conclude that placement and control of materials was satisfactory and therefore this was no reason for non compliance of the specifications.

Closeness between the respective grain size distribution curves of the fine fraction of both materials indeed restricts compliance with one of the filter material requirements. It was decided not to modify the grain size distribution curve of material 3A because otherwise it could transfer the non compliance effect to materials 3A and 3B.

From the analysis carried out to estimate the values of permeability it was considered that in spite of non compliance with the ratio of five times between diameters D_{15} of both materials, the behavior of the general configuration of the materials would remain undisturbed after integrating in a given band materials 2 and 3A, still complying with the filter rate toward the rockfill labelled 3B.

Although this case is based on a theoretical analysis, it also evidence the benefits derived from a team work among all parties involved in a project after having developed a technical opinion during the execution of the job and in this way make it possible to proceed with the works.

It is considered that for this type of projects the specifications could be subjected to adjustments provided all participants are involved in making technical decisions about the project and the modifying proposal is fully justified as such.

Further technical details of this project can be found in Cruz, Filloy and Yáñez (2006).

6 REFERENCES

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