EL CAJÓN DAM, MEXICO. FURTHER DATA ABOUT ITS BEHAVIOR AND A QUICK ANALYSES OF A PRAGMATIC DESIGN APPROACH

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Abstract: El Cajón dam, Mexico, has a 188 m high concrete-face rockfill dam. A very extensive campaign of investigations was carried out for its design, as described in a previous paper [1]. Some additional data about his behavior after completion confirm the good results coming from a good theoretical design added to a pragmatical approach. The field investigations included two large test fills, which were fundamental to define the final design and construction specifications. The behavior of the dam, after completion, has been excellent. Some instrumentation results additional to the ones given in the original paper are presented here, as well as a description of how a more practical interpretation of the investigation results, supported by the suggestions of well-known consultants, resulted in important simplifications in construction specifications and design details, without impairing its performance.

Key words: Concrete Face rockfill dams

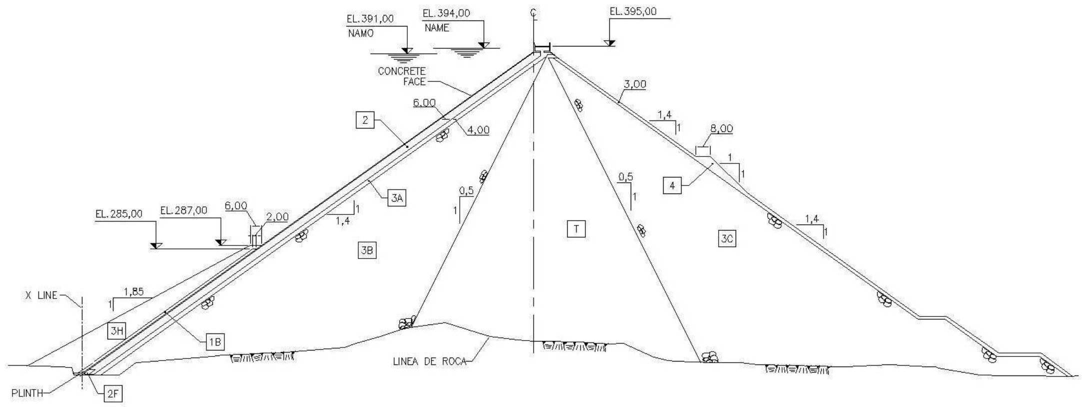
1. Introduction

El Cajón Hydroelectric Plant, in Mexico, located upstream of The well known Aguamilpa dam, 845 MW of power, has a 188 m high concrete-face rockfill dam. Construction was completed in 2006 and the dam behavior has been excellent so far. Deformations are very small and total seepage is stabilized around 150 l/s. The project, owned by Comisión Federal de Electricidad (CFE), had its conception defined by this entity, with the final design carried out by the consortium INTERTECHNE Consultores. Associados (Brazil) and TECHNO-PROJECT (Mexico), INTT-TP.

As in previous CFE projects, El Cajón was extensively studied by means of laboratory tests, mathematical 3D models and field tests, including two large test fills. In this paper, a brief analysis of the main results is presented and its consequence for the final design and construction specifications discussed in terms of a more pragmatic approach. Some of the instrumentation results during construction and reservoir filling are commented on, and are compared to the results of FEM analyses and empirical method approaches. Most of this paper was based on a previous one by the same authors [1], complemented by some additional data about its behaviour and some comments about the pragmatical approach method.

2. Main dam features

Figure 1, shows the dam zones and the materials and compaction procedures adopted.



ZONE	LAYER M	TYPE OF ROLLER	N° OF PASSES
1B	0.3	COMPACTED BY DOZER	NA
2F	0.3	10.6 TON VR	6
2	0.3	10.6 TON VR	8
3A	0.3	10.6 TON VR	8
3B*	0.8	12.2 TON VR	6

ZONE	LAYER M	TYPE OF ROLLER	N° OF PASSES
T*	1	12.2 TON VR	6
3C*	1.4	12.2 TON VR	6
3H	0.4	COMPACTED BY DOZER	
NA			
4	NA	PLACED BY BACKHOE	

*compacted adding them 200 liter of water per m3 of material

Figure 1: Zoning of the dam and compaction specifications

The campaign of laboratory investigation included large-diameter triaxial tests (specimens of 30 cm of diameter and 70 cm of height) and medium-to large-sized (110 x 100 cm) oedometric tests. Main results, as mentioned in [3], were:

	Dry	Saturated
❖ Confined Deformation Modulus (Moc)(MPa)	110-200	70-150
❖ Unconfined Deformation Modulus (MPa)	70-120	35-90
❖ Friction angle (drained triaxial tests, σc = 100 kPa)	58.5º	

The rockfill materials came from the required excavations and a nearby quarry. Local rocks are riodacitic ignimbrites, i.e. welded piroclastics of acid nature, grey colored, massive to pseudo-stratified. Main parameters are shown below.

❖ γr – Dry Bulk Specific Gravity of the Rock (kN/m³)	~23.4
❖ γs– Dry Specific Gravity of Rock Solids (kN/m³)	~26.0
❖ Absorption (%)	5
❖ Los Angeles (%)	27
❖ Unconfined compressive strength, dry (MPa)	113
❖ Unconfined compressive strength, saturated (MPa)	90

3. Test fill results

Two large test fills were built by CFE. The first ONE (2002) [3], used a 7.5 ton vybratory roller and the second one a 12.4 ton roller. The aim was to define excavation methods, placement and compaction specifications, giving emphasis to the specific gravity of the compacted rockfill, its void ratio and deformability modulus. The results of the field and lab tests were used to define the zoning of the dam and to make a forecast of its behavior during construction and reservoir filling. Three layer thicknesses – 40, 60 and 90 cm - were tested. In El Cajón, the rockfill specifications were fundamentally based in the specific gravity of the compacted rockfilll, as well as in its void ratio and deformation modulus. Therefore, the test fills were oriented to get those parameters, requiring, a great number of test pits and special procedures.

The average results of the first test fill are shown below.

ROLLER WEIGHT (ton)	N º OF ROLLER PASSES	LAYER THICKNESS (cm)								
		40			60			90		
		γ_{e*}	εt	εe	γ_{e*}	ε_t	ε_e	γ_{e*}	ε_t	ε_e
7.5	4	20.6	0.27	0.19	19.5	0.34	0.20	18.5	0.41	0.26
	6	20.9	0.26	0.13	20.4	0.30	0.14	17.0	0.39	0.23
	8	21.5	0.21	0.09	20.3	0.29	0.15	19.3	0.35	0.21
10.60	4	20.8	0.25	0.13	20.2	0.29	0.16	20.2	0.28	0.16
	6	21.5	0.21	0.09	20.7	0.26	0.13	19.3	0.35	0.21
	8	21.5	0.21	0.09	19.5	0.34	0.20	19.0	0.38	0.23

Table 1: First test fill.- Average dry specific gravities and void ratios of the compacted rockfill.- *- kN/m³

Two void ratio definitions were used, due to CFE practice – εt, calculated with a γs of ~26.0 kN/m³ (determined in the minus # 4 (4.75 mm), sieve fraction, and in the # 4 to 3" fraction, crushed material, by the picnometer method – density of rock solids) – and εe, calculated using a γr of ~23.4 kNm³ (measured in pieces of rock). The εt values were used by CFE to evaluate the rockfill parameters. The εe values are the ones used in the literature to compare different rockfills; γe is the dry bulk specific gravity of the compacted rockfill.

Grain size analyses revealed a very well graded rockfill, with an average percentage of non plastic fines inferior to 4% and very high uniformity coefficients Cu [4], average values of 58 in the 3B material and 44 in the T material. Differences of grain size between the 3B material (sound ignimbrite) and the T and 3C ones (slightly weathered ignimbrite) were not significant.

The deformation modulus Ev (construction modulus) obtained in confined plate tests gave average results of 92, 87, and 110 MPa, for the 40, 60 and 90 cm thick layers. The deformation modulus measured by means of settlement cells in the 7,5 ton roller test fill, for 6 passes, layer thickness of 40 cm , 60 cm and 90 cm, gave lower values of, respectively, 70, 50 and 30 MPa, probably a consequence of the low confinement. Matsuo-Akai permeability tests confirmed the free draining conditions of the rockfill.

The second test [5], used only 3B material, layer thicknesses ranging from 63 to 88 cm, with an average value of 83 cm for the thicker layers and 66 cm for the thinner ones. Compaction was carried out using a 12.4 Ton roller, with 3-4, 6 and 8 passes, using 200 l of water per cubic meter of rockfill. Average results are shown in Table 2 and Figure 2.

ROLLER WEIGHT (TON)	**N º OF ROLLER PASSES**	**LAYER THICKNESS (cm)**					
		66 *			**83 ***		
		γe **	**εt**	**εe**	**γe ****	**εt**	**εe**
12.4	3				19.4	0.34	0.20
	4	20.1	0.29	0.16			
	6	20.3	0.28	0.15	18.6	0.40	0.25
	8	20.9	0.24	0.12	19.0	0.36	0.23

Table 2: Second test fill. - Average results of specific gravity and void ratios of the compacted rockfill.- * Average Layer Thickness - ** - kN/m³

Because of the lack of time, other layer thicknesses were not investigated and this was a factor that required a practical approach to decide the final thicknesses, considering that in the initial studies there was a clear preference for thinner layers [2], as shown below.

Alternative	Zone 3B	Zone T	Zone 3C
I	0.6 m	0.8 m	0.8 m
II	0.6 m	0.8 m	1.2 m
III (J.Alberro)	0.6 m	0.6 m	1.2 m
IV (J.B.Cooke)	0.8 m	0.8 m	1.6 m
V (D.Resendiz)	0.6 m	0.8 m	1.0 m

Table 3: Proposed Layer Thicknesses.

The adoption of thicker ones, as commented later on, resulted both from a more pragmatic analysis of the test fill results and from the suggestions of the late consultant J. Barry Cooke.
A very important result from the field-tets is that densities of more then 20.50 kN/m³ were attained only in the 40 cm thick layers, the ~60 cm layers gave densities between 19.50 and 20.70, and the ~80 cm layers gave lower densities, ranging from 18.50 to 19.60 kN/m³. However, it is possible to see that εe void ratios inferior to 0.25, considered in the literature to correspond to rockfills of very low deformability and high compressibility modulus, are already obtained with rockfill specific gravities of ~19.0 kN/m³.
The grain size analyses of the compacted material confirmed the results of the first test fill that the materials are very well graded, with heterogeneous but very high uniformity coefficients – 55 average for the thicker layers and 80 for the thinner ones. These high Cu values explain the very low εe figures got in the test fills, as well as the very high deformation moduli measured in the dam.

4. The mathematic model

A 3D mathematic model [6] was used to predict deformations and stresses during construction and reservoir filling. Its results were important for the final dam design and construction specifications. The deformations given by the model resulted quite near the measured ones, except for the settlement figures and maximum slab deflection that were much higer in the model than in the prototipe. This was caused by the conservative values of deformation modulus used in the model, as shown below.

	Material	γe (kN/m3)	Ev (MPa)	Et (Mpa)
Used values	3B	21.80	70	140
	T	20.50	40	80
	3C	20.00	20	40
Proposed by ITT-TP	3B		100	250
	T		60	150
	3C		40	100

Table 4: Deformation modulus used in model

Ev – construction modulus
Et – transversal modulus (reservoir filling)
The transversal or infilling modulus, Et, was estimated by CFE using a hardening coefficient of 2.0, commonly mentioned in the literature, and ITT-TP used a coefficient of 2.5, that took in account the narrow El Cajón valley. Both sets of Ev and Et values were inferior to the measured ones.
Also the reduction of the Ev modulus from 70 MPa in the 3B material, to 40 and 20 MPa in the T and 3C materials, was excessive, considering that the last ones were expected to have grain size parameters very similar to the 3B ones, and the T material is much more confined then the outer shells. As a consequence, the model gave a maximum deflection of the concrete slab of 44 cm [6], instead of the 16 cm measured in the prototype

5. Changes in the final specifications

CFE, based on previous experiences, adopted quite conservative numbers and criteria in its original specifications for the dam [8], which specifically required rockfill densities of 2030, 1990 and 1940 t/m³ for the 3B, T and 3C materials and specified minimum εt void ratios of 0.28, 0.30 and 0.34, respectively, corresponding to very low εe values of 0.15, 0.17 and 0.20. Rockfill processing was also considered.
From tables 1 and 2, it may be seen that these values were not easy to attain and not very practical to require, needing to adopt more then 8 passes in the 80 cm thick layers or adopting layer thickness of 40 to 60 cm, and/or processing the rockfill materials. The forecasts of deformation modulus and its consequences were in part conservative, in part somewhat confusing. The requirements of the slab deflection after infilling of the lake, for instance, was that it should be inferior to 60 cm, something easy to attain considering that in Foz do Areia (Ev of ~30 MPa, 160 m of height) the maximum deflection measured ~70 cm).
A more pragmatic approach, based on the grain size parameters obtained in the test fills, led both CFE and ITT-TP to adopt less conservative estimates for the expected deformation moduli and suggested the use less rigorous specifications, like the elimination of rockfill processing and reducing the difficult to attain specific gravity values and void rations, since lower values already indicated a rockfill of very low deformability. ITT-TP initial estimates, made using the empirical method proposed by Pinto & Marques [10], considered that the deformation modulus could be in the range of 100 to 200 MPa and consequently that the maximum deflection of the slab should be much inferior to the above mentioned value, possibly in the order of 30 to 17 cm [9]. Some of its considerations are commented hereafter.

The void ratio values that correspond to the range of rockfill specific gravity got in the test fills confirm that specific gravities of 18.60 to 19.00 kN/m³ already indicate rockfills of low void ratios.

γe	εt	Ee
1860	0.32	0.26
1900	0,28	0.23
1950	0,26	0.20
2000	0,22	0.17
2050	0.19	0.14

Table 5: Relation Void ratios-Dry Density

Table 6 gives the void ratios and deformation molduli measured in similar dams. It shows that the void ratios measured are similar to the ones found in the test fills, and correspond to Ev values ranging between 135 to 225, which should be considered the probable range of Ev values to be expected in El Cajón, [6].

Dam/type of rock	εe	Ev (MPa)	A/H²
Cethana (Quartzite)	0.26	135	2.0
Anchicaya (Diorite)	0.22	145	1.1
Murchison (Riolite)	0.17	225	2.0
Lower Pieman (Dolerite)	0.24	160	2.4
Bastian (Graywacke)	0.23	160	3.4

Table 6: Void ratios and deformation modulus.

This, for the 3B and also the T materials, and not very different for the 3C material.
Using the empiric method of evaluation proposed in [10], similar values are obtained. El Cajon has a shape factor A/H² of 3.0, that corresponds to a narrow valley, and using the curve of Ev x εe for dams in narrow valleys proposed in this paper, the above mentioned values of void ratios should correspond, as well, to deformation modulus ranging from 140 to 230 MPa. It may be noted that the above

mentioned literature values were obtained in dams built with rockfill layer thicknesses around 80 cm, in the first half to 1/3 of the dam width, and 100 to 160 cm in the remaining zones.
As a result of the test fills, the use of a heavier vibratory roller, the experience of its engineers, the opinion of well know consultants and considerations similar to the ones presented above, CFE changed the construction specifications to more practical ones. The layer thickness for the 3B, T and 3C materials were increased to 80, 100 and 140 cm, to be compacted with 6 passes of the 12.4 ton vibratory roller; the mention of specific densities and void ratios was eliminated, on the evidence that the compaction method specified, in layers of the above mentioned thickness, with 200 l of water per cubic meter of rockfill, was enough to guarantee acceptable values of Ev (in fact much higher then those initially required). Rockfill processing was eliminated, as well, bringing the El Cajón specifications much closer to the ones usually adopted in similar dams [2].
The behavior of El Cajón during construction and reservoir filling confirmed the correctness of those changes. The results of the instrumentation system [11], and the data mentioned in [12], confirm this fact as well as the excellent performance of the dam. The εt values measured in the 3B, T and 3C resulted very similar one to the other, averaging a value of 0.39, corresponding to an εe value of 0.25. The rockfill density was measured as 18.70 kN/m3, average.
The construction modulus (Ev), obtained from the settlement cells, averaged 90 to 100 MPa for the 3B material, 120 to 160 MPa for the T material and 70 MPa for the 3C, where the greater value measured in the T zone is due to its greater confinement.
It must be noted that in the dams mentioned above, the values of construction moduli comes from settlement cells located near the dam axis at mid height, showing that the values of 120 to 160 MPa, measured in the T material, are the more representative of El Cajón, when comparing with other CFRDs. Concerning slab deflections, the maximum settlement measured at mid height of slab 21 corresponds to a deflection of 16 cm and the maximum settlement of 22 cm, measured in slab 26 corresponds to a deflection of 18 cm. This same paper mentions a vertical settlement, during construction, at the central zone of the dam, of ~80 cm. This value, using the traditional equation used to calculate the Ev values mentioned in the literature, which usually does not introduce correction factors, results in an Ev of ~200 MPa for the T material, which is possibly, a more representative number for El Cajón.
CFE had concerns with possible higher deflection of the slab near the crest, based on the example of Aguamilpa. In El Cajon, this problem was evidently inexistent because of the similarity between the three materials, as foreseen in the mathematical model and measured in the prototype. The relation of the deflection of 11 cm, measured at the crest, and the maximum one of 16 cm at mid height, gives a value of 1.45, similar to the relation found in the majority of the dams compacted in 80 cm thick layers in the upstream zone and 160 cm layers in the downstream shell, which does not represent any risk of Aguamilpa type cracks.

6. Informatión after 2005

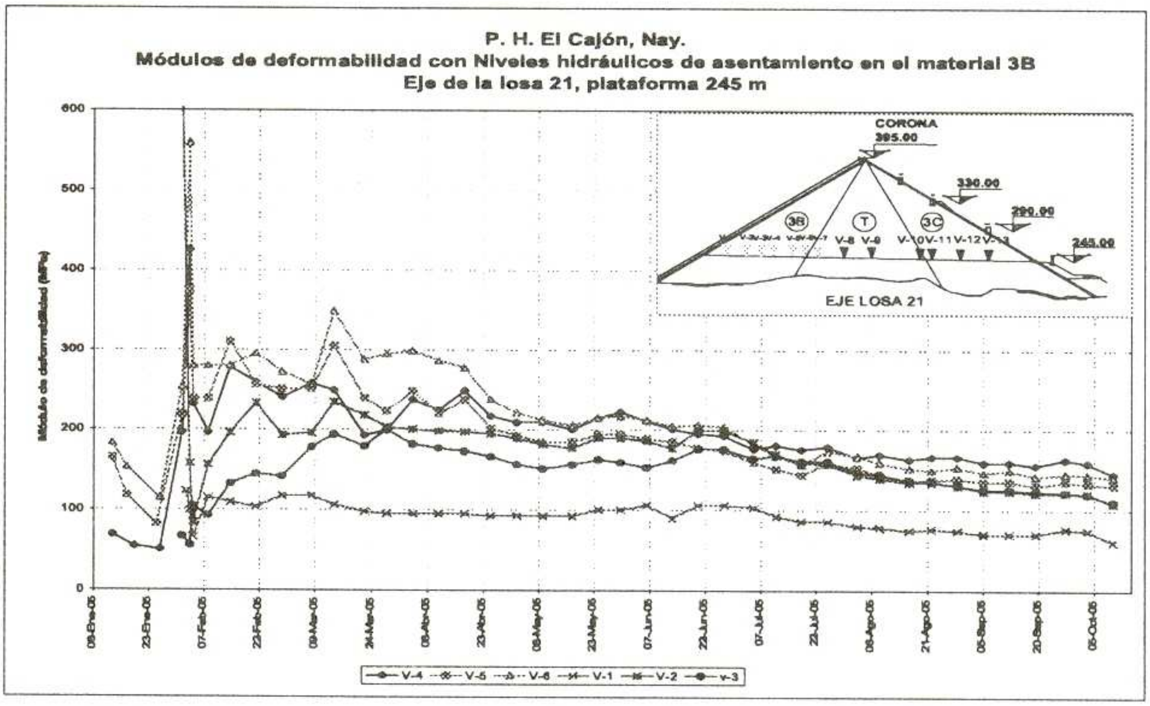
Some additional data about vertical settlements and moduli, [2], [12],permitted to more preacisely estimate Ev and Et.

	Material 3B	**Material T**
Construction modulus (Mpa) Ev	83-116	101-135
Construction modulus (Mpa) Ev adopted for CFE at the end of construction *	160	140
Deformability modulus final of first filling (Mpa) Et	181- 288	223-271

Table 8- Modulus calculated from instrumentation

Figure 2 [14] illustrates the variability of the deformability modulus in function of time. Based in these data, some instruments installed in the material 3B presented high values at the beginning (more than 300Mpa), tending to reduce and turn more similar in the cells, ranging between 100 and 200 Mpa.

Figure 2: Modulus values of material 3B in function of time (from Ref (13)



7 Conclusions

El Cajón is a good example of the use of a pragmatic approach in the design of a CFRD and so deserves a more extense final comment.

More then 100 Concrete Faced Rockfill Dams were built in the last 20 years, some very high. In spite of this, there still lacks a complete understanding of the mechanics involved in their behavior.

Although even large leakages do not raise risks of failure in CFRD's, except in abnormal cases, a certain amount of leakage is considered unavoidable and is considered a measure of their behavior. Disregarding leakages through foundation and damaged water stops, the leakages result from cracks in the concrete slab caused by exessive tensile stresses in the concrete panels, or, as seen in recent dams, from compressive stresses, in both cases as a result of the rockfill deformations. The tensile cracks occur where a high degree of convex curvature of the slabs results from its accommodation to the rockfill deformations. The cracks may be sub-horizontal, caused by excessive differences of deformability between the upstream and the downstream shells, like in Aguamilpa, or inclined like those found in Xingó and Itapeby, related with the topography of the foundation. Cracks caused by compressive stresses occur in the central slabs of very high dams, caused by the tendence of the rockfill to move that way during reservoir filling.

In all these cases, the problem is really transferred to the understanding of the rockfill parameters - shear strength, that control slope stability and internal slides, and the compressibily modulus, that control constructive settlements and deformations.

Large sized equipment are needed to get precise figures about these parameters but, being difficult to get, are being replaced by smaller sized equipment. At El Cajón, a long program of this type was carried out, showing that even well performed tests, in large or smaller sized equipment, may give somewhat misleading results, when they are carried out in materials that are not really representative of the prototype. Chief factors to consider are rock strength, shape and size of the rock fragments, thickness of layers, energy of compaction, rockfill gradation. Emphasis is usually given to the rock strength, but experience has shown that rockfill made of very strong rocks, like basalt, are sometimes more deformable than ones made of weaker rocks, showing that other parameters, chiefly the rockfill gradation, are frequently more important – an observations that is basic for the crescent use of weaker rocks in dams. The definition of the gradation parameters to be obtained in the prototype usually require tests that reproduce the conditions of the prototype and the difficulty to get these numbers ahead of construction is one of main causes of imprecision of the mathematical models. Lab tests are indispensable to get basic parameters but able to give some misleading figures relative to compressive moduli and similar parameters. Field embankments, even simpler types, compared to the ones carried out in El Cajón, seem to be a more reliable method. And that's where the empirical evaluation methods come into value, both to orient the lab and field tests in a more straightforward manner, and to get numbers that may not be the final ones but that are sufficiently correct to get a safe design and basic forecast of the dam's behavior.

Concerning shear strength, the difficulties to get precise measurements led to the well known observation of the late J. Barry Cooke that these analyses, except for weak, poorly known, rocks, are seldom critical. This concept is opposed by many designers as leading to sometimes low safety factors slopes, but is usually confirmed by the fact that no critical downstream slope slides are known in CFRD's. The great number of cases studied by Albert and Frossard [15] - rockfill dams ranging from 30 to 200 m of height, with downstream slopes of 1.3 to 1.7, with materials that can be considered free-draining rockfill - indicate that even in cases where a somewhat low factor of safety are got, deep seated slides are practically unknown. And these figures do not take in consideration that slopes between road berms, frequently 30 to 50 m high, frequently have inclinations of 1V:1.25H or steeper. So, in most cases, the analyses serve to prove that the slopes proposed by experience are normally adequate.

Concerning deformability, measurements made in lab tests are still more difficult to interpret, as shown for El Cajón. In the case of this dam, in spite of the large number of tests, some made up with large diameter equipment, the deformation moduli measured were lower than the ones forecasted by empirical methods and measured in the prototype. For this work, the method proposed by Pinto and Marques [10] gave more reliable results than the lab ones. This method takes in account the shape of the valley and are based on the well known concept that grain-size parameters, such as void-ratio (εe) and uniformity coefficient (Cu) are basic indexes and that they prevail even over some factors like rock strength. They show that a well compacted rockfill, with values of εe inferior to 0.25, and Cu values greater than 40-50 are already so dense that the rock breakage and possible consequent deformations are reduced to very low values. For El Cajón, the void ratios and uniformity coefficients got in the test fills already showed the modulus to be expected to be around 150 MPa, and not, as measured in lab tests, around 60 MPa, Table 1. The maximum slab deflection predicted by this method for El Cajón was much closer to the measured value of 16 cm than the 44 cm forecasted by the mathematical model.

Other methods have been proposed to forecast deformability moduli and should be analysed with some care, like the one presented by Hunter and Fell, where the dependence on parameters such as the strength of the rock (difficult to apraise and use) or the D80 grain size (which seems insufficient to characterize a well graded rockfill), make its use less reliable.

However, in any case, the example of El Cajón, where a large program of laboratory tests and the use of sophisticated mathematical models didn't led directly to the final design, shows that a pragmatically oriented approach, based on experience and simple but more reliable tests, may lead to a more straightforward investigation campaign and result in better design and construction methods.

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