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Lessons learnt from design and construction of dams in Brazil

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ABSTRACT

This paper deals with design and construction of dams built in Brazil. A brief introduction on the history of these dams is followed by the main types of dams, that due to the environment, site topography, climate, foundation conditions and borrow materials, have been considered the most adequate and economical both for irrigation purposes or power generation.

A second item deals with peculiar behaviour of the residual soils used as construction materials regarding flow aspects and construction pore pressures. The use of saprolitic soils is also discussed as well as of rock materials that disintegrate under drying and wetting cycles.

The shear strength parameters of these materials obtained in laboratory and field tests are presented. The compressibility and the stability of the dams, and the measured flows through the foundations are reported.

INTRODUCTION

Design and construction of dams in Brazil, began over a 100 years ago. The first dams were built in the Northeastern area for irrigation purposes, followed by dams in the Southern region for power plants.

The continental size of the country and the abundance of large rivers with relatively flat abutments made earth and earth rock-fill dams attractive and economical.

The first dams built were based on empirical knowledge and experience of professional engineers, but soon after the advent of modern soil mechanics, the design and construction of Brazilian Dams have incorporated soil mechanics principles and increasing technological resources (Cruz 1996). A short description of various types of dams constructed in Brazil is given below.

BRAZILIAN DAMS

The name of Terzaghi was soon incorporated to assist in the design and construction of earth dams, followed by Arthur Casagrande and many other consultants who together with Brazilian engineers have designed and built over 200 large dams since the 1940's up to date. New dams are now under construction.

In the Vigario Dam built in 1948, afterwards named as the Terzaghi Dam, the concept of a vertical sand drain, followed by a horizontal sand blanket, was firstly introduced by Terzaghi himself, with the purpose of intercepting the phreatic line, within the homogeneous "earth" dam built with the residual soil from gneiss.

This very simple dam, shown in Fig. 1, known today as the "Brazilian Dam", has been quite successful and served

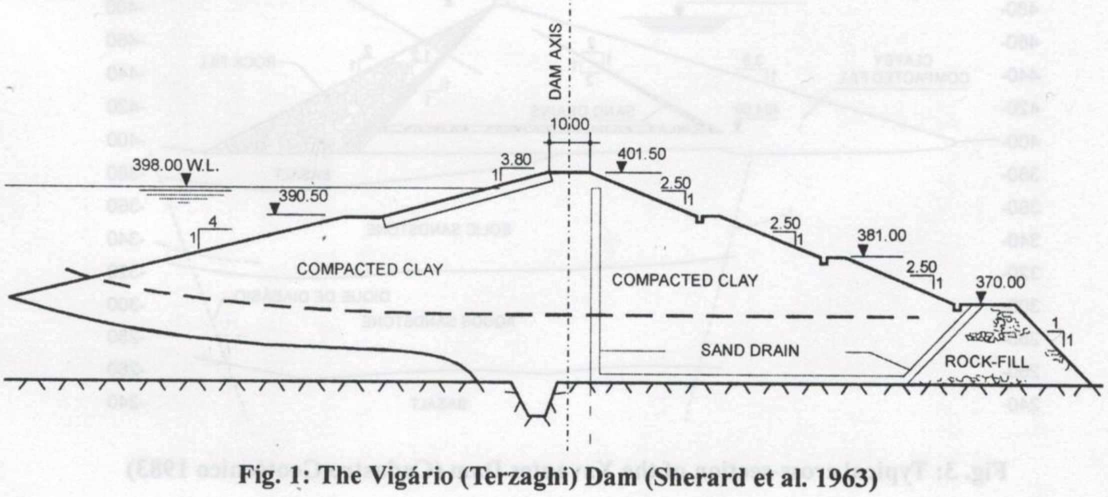


Fig. 1: The Vigário (Terzaghi) Dam (Sherard et al. 1963)

as a design principle adopted in a large number of dams, built all over the country.

In some cases a pseudo nucleus was introduced by changing the compaction water content in the central zone making it wetter and keeping the outer zones dry of optimum, as in the case of the Capivara Dam (Fig. 2).

This type of simple dam is quite appropriate for open valleys, with deep profiles of residual soils, that have shown to be excellent borrow materials, easy to compact and have low compressibility, and high shear strength.

More accurate cross-sections became necessary in narrow gorges, where rock fill material were available due to the necessary excavations for the concrete structures. Zoned dams as shown in Fig. 3 and 4 were then designed and built using the local borrow materials: earth and rock.

In more recent years, concrete-faced rock fill dams became attractive in two relatively extreme environments: in dry areas of the Northeastern States, where the soil profile is very thin and the rock abutments are sound, and the wet areas of some Southern States, where the temperatures are low, the rainy season is very long and the residual soils with high natural water content (from 15% to 20% above Proctor Optimum) are abundant making the compaction difficult and slow, in this later case. In spite of the fact that the upper layers of the rock (mostly basalt) can be altered in these rainy areas, arrangements and details of the plinth have been developed, as well as the rock treatments, and very high dams built are performing quite properly (Fig. 5 and 6).

BORROW MATERIALS

Mainly the following three types of material are used for the construction of dams.

Colluvium and residual soils

As mentioned before, residual soils have been used extensively as borrow materials for the construction of dams in Brazil.

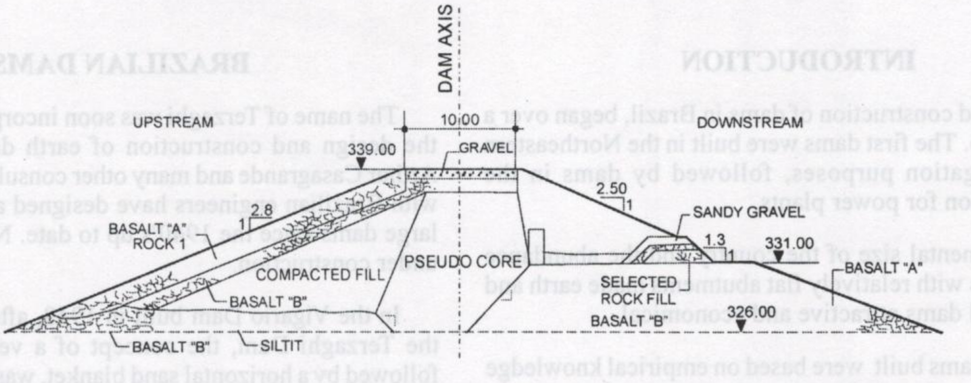


Fig. 2: The right embankment of Capivara Earth Dam (Cadastro Geotécnico 1983)

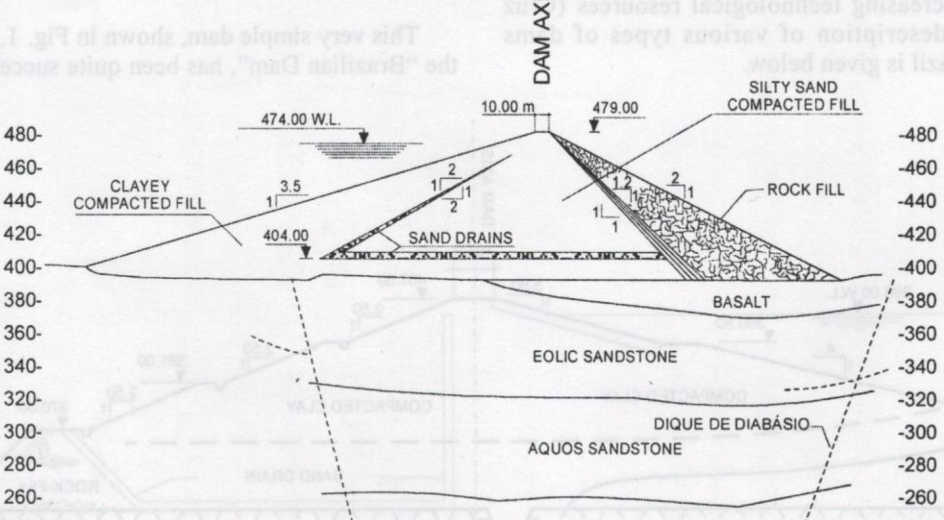


Fig. 3: Typical cross-section of the Xavantes Dam (Cadastro Geotécnico 1983)

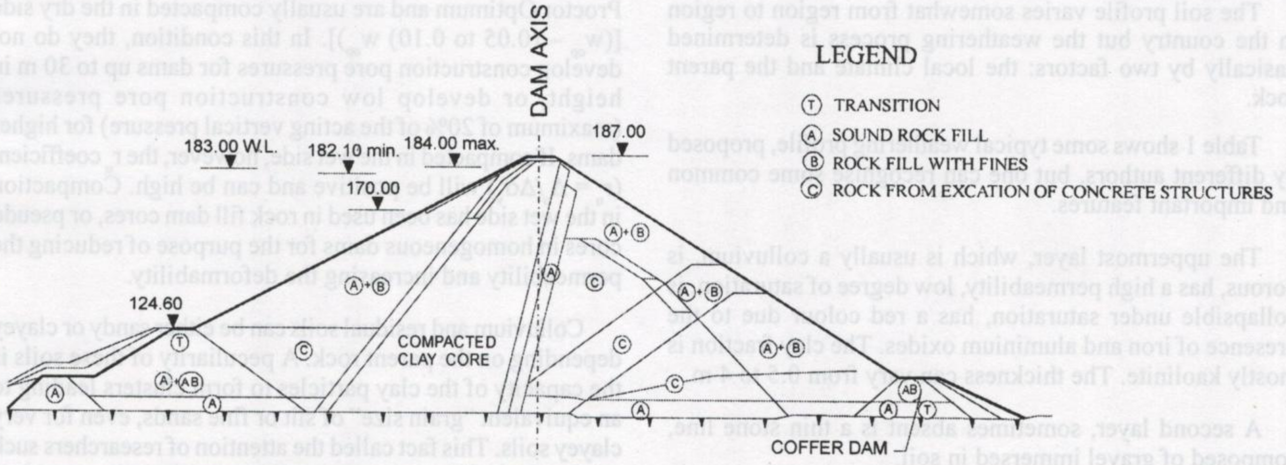


Fig. 4: The Itauba Dam, cross-section along ST 11 (CBGB/ICOLD/CBGB 1982)

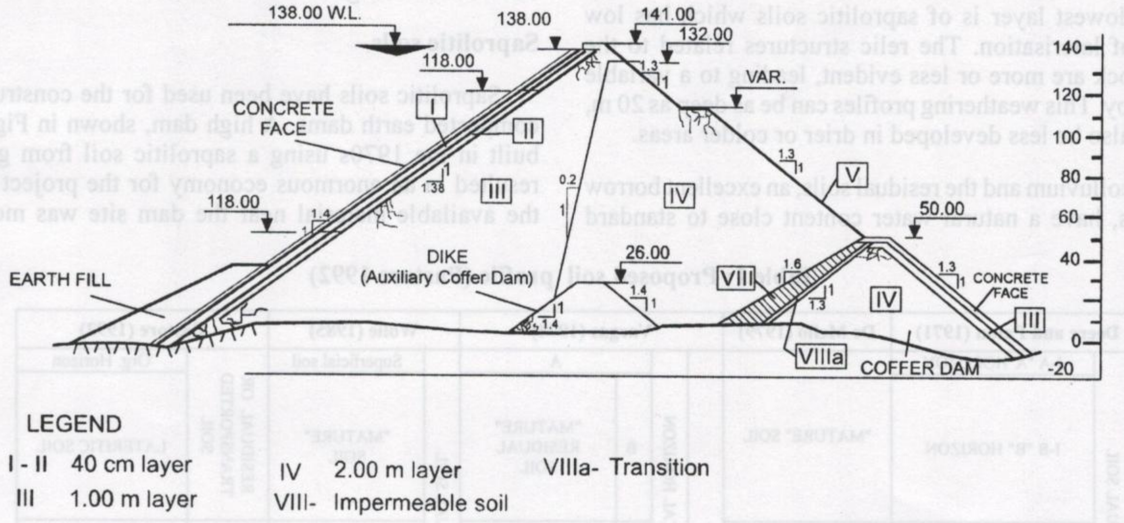


Fig. 5: The Xingó Dam (After Promon, personal communication 1991)

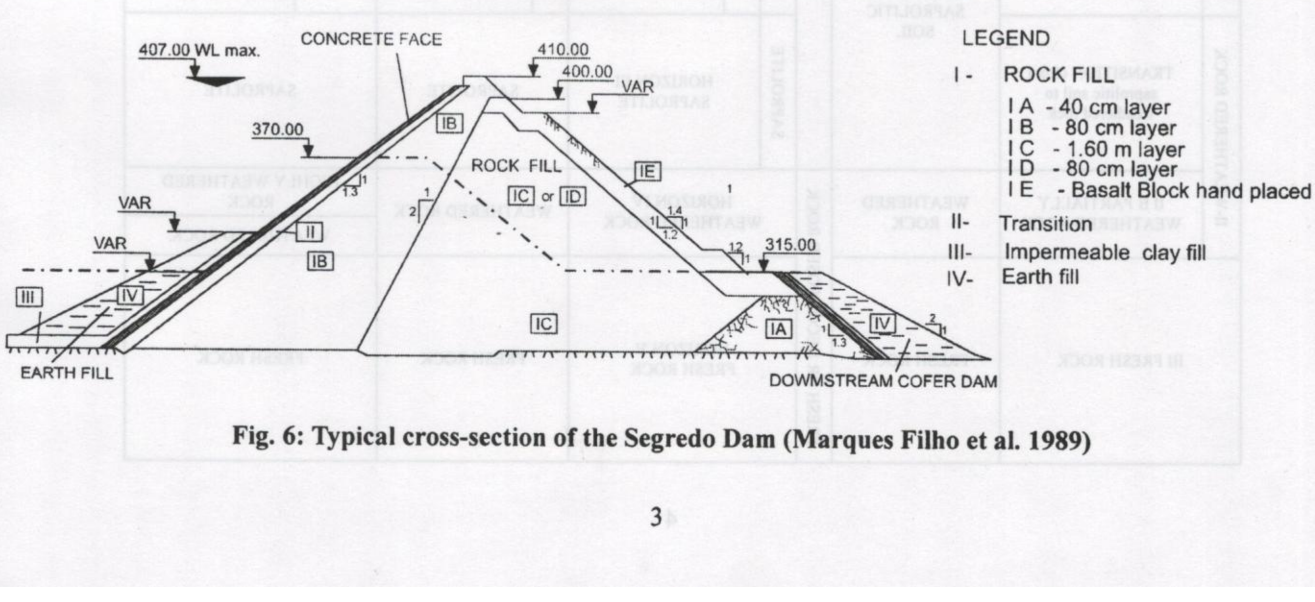


Fig. 6: Typical cross-section of the Segredo Dam (Marques Filho et al. 1989)

The soil profile varies somewhat from region to region in the country but the weathering process is determined basically by two factors: the local climate and the parent rock.

Table 1 shows some typical weathering profile, proposed by different authors, but one can recognise some common and important features.

The uppermost layer, which is usually a colluvium, is porous, has a high permeability, low degree of saturation, is collapsible under saturation, has a red colour due to the presence of iron and aluminium oxides. The clay fraction is mostly kaolinite. The thickness can vary from 0.5 to 4 m.

A second layer, sometimes absent is a thin stone line, composed of gravel immersed in soil.

The third layer is of residual soil which lateritic in nature with decreasing permeability, variable porosity, quite homogeneous, and not affected by stress history.

The lowest layer is of saprolitic soils which has low degree of laterisation. The relic structures related to the parent rock are more or less evident, leading to a variable anisotropy. This weathering profiles can be as deep as 20 m, but can also be less developed in drier or colder areas.

The colluvium and the residual soils, an excellent borrow materials, have a natural water content close to standard Proctor Optimum and are usually compacted in the dry side $[(w_{op} - (0.05 \text{ to } 0.10)\ w_{op})]$. In this condition, they do not develop construction pore pressures for dams up to 30 m in height, or develop low construction pore pressures (maximum of 20% of the acting vertical pressure) for higher dams. If compacted in the wet side, however, the r_u coefficient $(r_u = \Delta_u/\Delta\sigma_v)$ will be positive and can be high. Compaction in the wet side has been used in rock fill dam cores, or pseudo cores in homogeneous dams for the purpose of reducing the permeability and increasing the deformability.

Colluvium and residual soils can be either sandy or clayey depending on the parent rock. A peculiarity of these soils is the capacity of the clay particles to form clusters leading to an equivalent "grain size" of silt or fine sands, even for very clayey soils. This fact called the attention of researchers such as Dr. Peter Vaughan who said that the Brazilian residual soils, even clayey, tend to behave like silts or fine sands. In grain size analysis made with and without defloculants and shaking, the difference in the clay fraction is remarkable as can be seen in Fig. 7.

Saprolitic soils

Saprolitic soils have been used for the construction of compacted earth dams. A high dam, shown in Fig. 8, was built in the 1970s using a saprolitic soil from gneiss. It resulted in an enormous economy for the project because the available material near the dam site was mostly the

Table 1: Proposed soil profile (Pastore 1992)

Deere and Paton (1971)		De Mello (1979)	Vargas (1974)				Wolle (1985)		Pastore (1992)	
I-RESIDUAL SOIL	I-A "A"HORIZON	"MATURE" SOIL	RESIDUAL SOILS	PEDOLOGICAL HORIZON	A		RESIDUAL SOIL	Superficial soil	RESIDUAL OR TRANSPORTED SOIL	Org. Horizon
	I-B "B" HORIZON				B	"MATURE" RESIDUAL SOIL		"MATURE" SOIL		LATERITIC SOIL
	I-C "C" HORIZON	RESIDUAL OR SAPROLITIC SOIL			C	HORIZON II INTERMEDIATE		SAPROLITIC SOIL	RESIDUAL	SAPROLITIC SOIL
II-WEATHERED ROCK	TRANSITION (from saprolitic soil to weathered rock			SAPROLITE		HORIZON III SAPROLITE		SAPROLITE		SAPROLITE
	II B PARTIALLY WEATHERED ROCK	WEATHERED ROCK	FRESH OR DECOMPOSED ROCK			HORIZON IV WEATHERED ROCK		WEATHERED ROCK		HIGHLY WEATHERED ROCK WEATHERED ROCK
	III FRESH ROCK	FRESH ROCK				HORIZON V FRESH ROCK		FRESH ROCK		FRESH ROCK

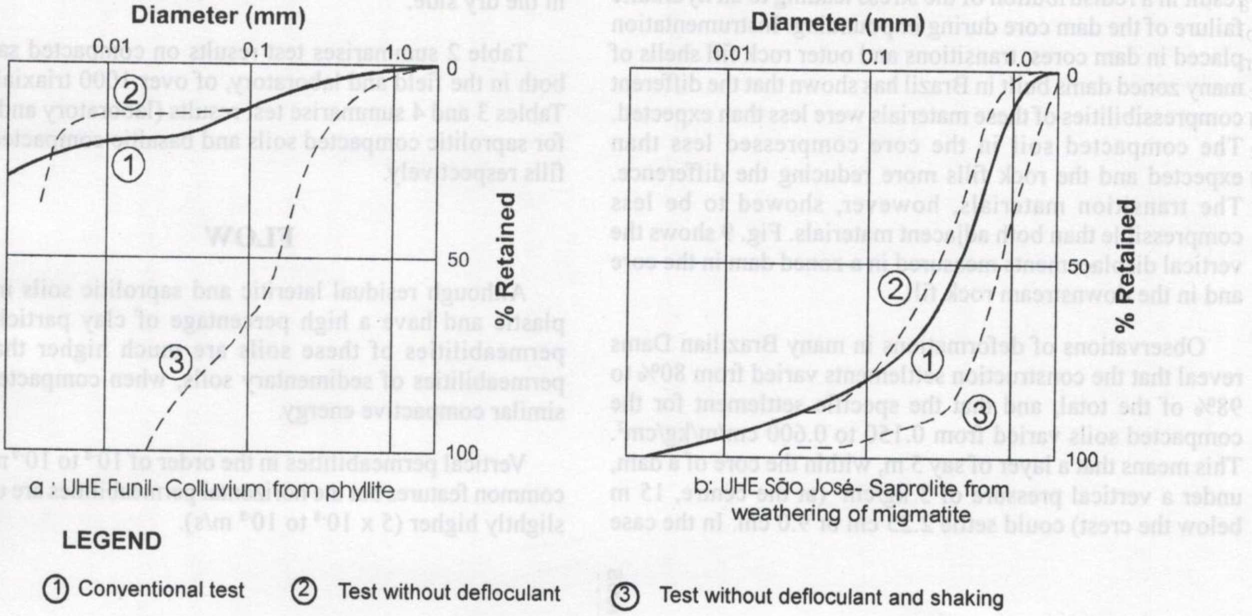
saprolitic soil. The upper lateritic layer, more clayey and more resistant to erosion, was used as a protective layer of the downstream shell.

The use of saprolitic soils as borrow materials requires some additional works related to the placement, water content and the compaction equipment due to the inherent relic structures present in saprolitic soils. The optimum water content can vary with the level of disturbance to which the soil is submitted during excavation, hauling and compaction. Test fills are recommended. The tamping roller was shown to be the best compaction equipment for the saprolitic soil used in the construction of the Paraibuna Dam.

An interesting case to be reported (Euclides da Cunha Dam) is built in the 1950s, where only the upper layer of the soil profile used borrow material. In the 1980's the dam was overtoped and partially destroyed. During the reconstruction, the same borrow area was used, but the borrow material was the saprolitic soil (for lower layer) that was not considered appropriate in the first design and construction when there was not enough experience in the use of such soil.

Weathered, weatherable, and sound rock fill

The presence of easily weatherable minerals such as smectite (or ?nontronite) in some rock formations make them quite vulnerable to cycles of drying and wetting. An apparent sound rock can easily disintegrate under those cycles, a common feature in basalt. This fact brings problems to the construction of dams, where large volumes of the borrow material comprises for the such rocks fill dam or such rocks are to be piled for later uses.



a : UHE Funil- Colluvium from phyllite

b: UHE São José- Saprolite from weathering of migmatite

Fig. 7: Grain size of soils

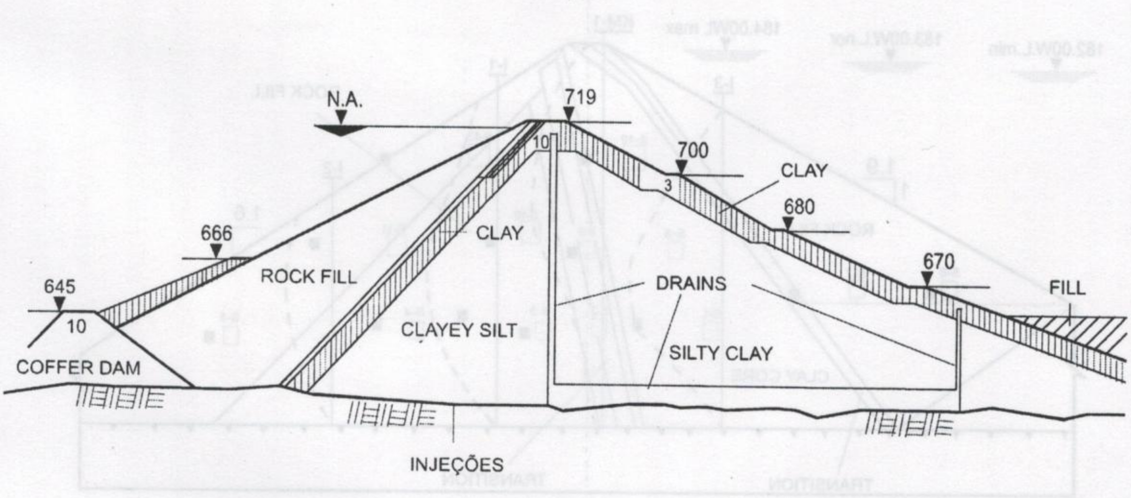


Fig. 8: Typical cross-section of the Paraibuna Dam (Mello 1975)

The practice in this case is to reduce the exposure of the rock in the site for cycles of sun and rain; use the rock in inner zones of the dam, that are protected by outer zones of sound rock; and design the dam using a reduced shear strength envelope for this material.

The long time observation of the behaviours of this rock fill in old dams has shown that the weathering process is limited to the first 2 or 3 m below surface. An example of a dam built with weatherable basaltic rock is the Itauba Dam (Fig. 4)

RELATIVE COMPRESSIBILITY

One of the main concerns in the design of zoned dams is the different compressibility of adjacent materials, that may result in a redistribution of the stress leading to an hydraulic failure of the dam core during impounding. Instrumentation placed in dam cores, transitions and outer rock fill shells of many zoned dams built in Brazil has shown that the different compressibilities of these materials were less than expected. The compacted soil in the core compressed less than expected and the rock fills more reducing the difference. The transition materials, however, showed to be less compressible than both adjacent materials. Fig. 9 shows the vertical displacements measured in a zoned dam in the core and in the downstream rock fill.

Observations of deformations in many Brazilian Dams reveal that the construction settlements varied from 80% to 98% of the total, and that the specific settlement for the compacted soils varied from 0.150 to 0.600 cm/m/kg/cm^2. This means that a layer of say 5 m, within the core of a dam, under a vertical pressure of 3 kg/cm^2 (at the centre, 15 m below the crest) could settle 2.25 cm or 9.0 cm. In the case of a rock fill the specific settlements can vary from 0.10 to 0.30 cm/m/kg/cm^2 and for a similar layer the value would be 1.50 cm to 4.50 cm.

SHEAR STRENGTH

The shear strength of the residual soils compacted near the Optimum has been investigated within the last 35 years in terms of pore water pressure and effective stress, and within the last 15 years in terms of both pore air and pore water pressures.

A typical triaxial test result is shown in Fig. 10a, b. The lower envelopes in Fig. 10b represent the shear strength for samples moulded near Optimum in the wet side, and the upper envelopes the shear strength of the samples molded in the dry side.

Table 2 summarises test results on compacted samples both in the field and laboratory, of over 1000 triaxial tests. Tables 3 and 4 summarise test results (laboratory and field) for saprolitic compacted soils and basaltic compacted rock fills respectively.

FLOW

Although residual lateritic and saprolitic soils may be plastic and have a high percentage of clay particles the permeabilities of these soils are much higher than the permeabilities of sedimentary soils, when compacted to a similar compactive energy.

Vertical permeabilities in the order of 10^{-8} to 10^{-9} m/s are common features but the horizontal permeabilities are usually slightly higher (5×10^{-8} to 10^{-8} m/s).

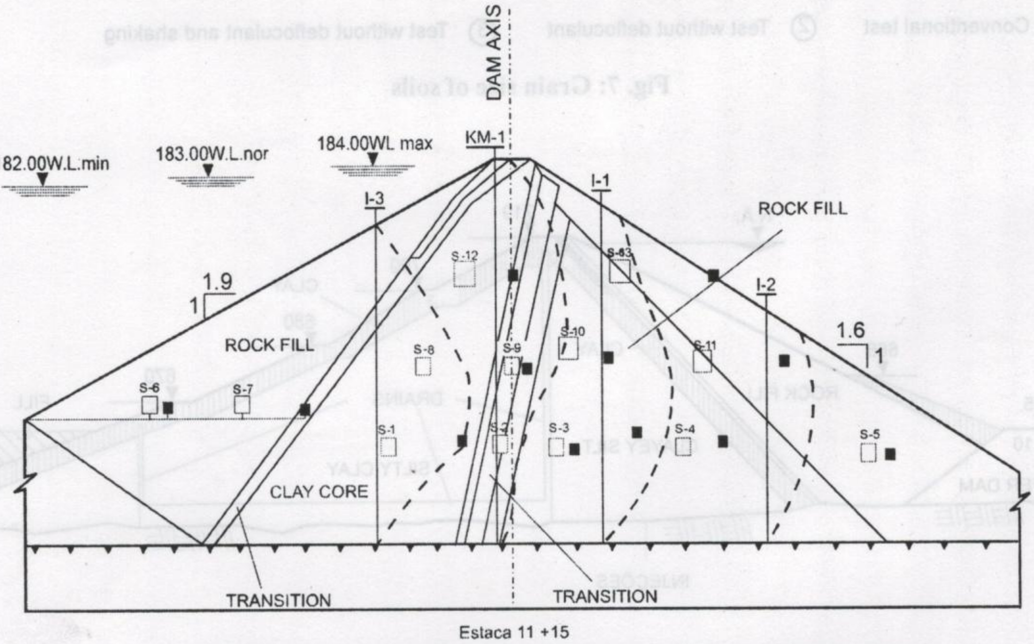


Fig. 9: Measured vertical displacements at the Itauba Dam (Signer 1982)

The anisotropy of permeabilities measured from back analysis of piezometric readings shows that it is higher at shallow depths and decreases with increasing pressures in the soil mass, becoming even almost null for earth cores of high dams.

Due to the geological and topographical conditions that prevail in the dam sites, the earth dams are mostly founded on rock (weathered or sound) in the river bed and on residual or colluvial soils on the abutments.

The flow through the dam and foundation measured in many dams give average values of 0.5 up to 4.0 litres/minute per linear metre of dam in the soil foundation, and 1 to 5 litres/minute per linear metre of dam in rock foundations. The last figures usually double for the case of concrete dams, in which the seepage path in the foundation is much shorter.

Another figure of interest is that the permanent or stabilised flow within the dam and the foundations tend to come to equilibrium within 2 or at the maximum 4 years

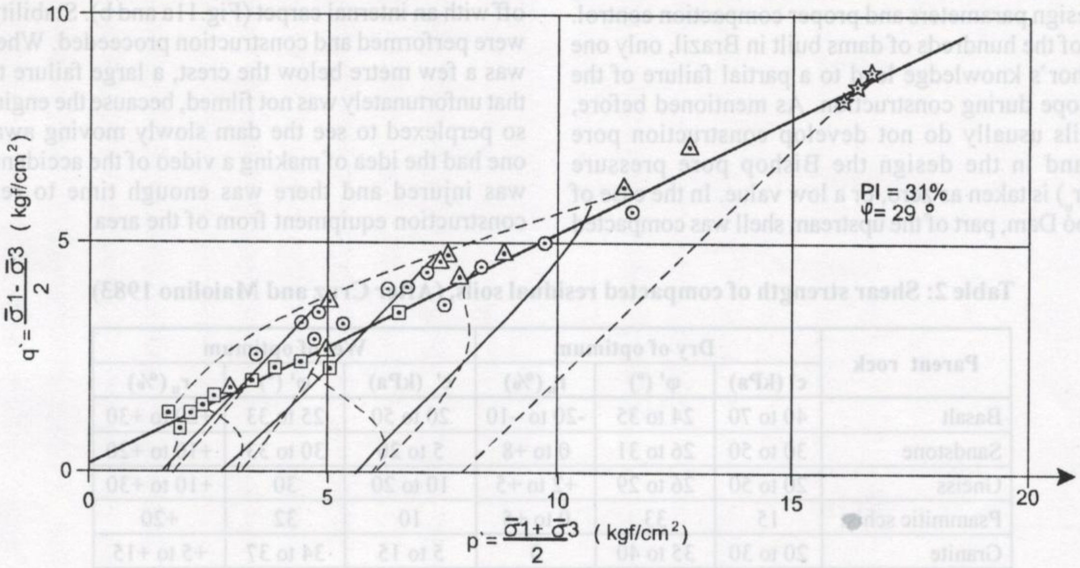


Fig. 10a: Juquiá (Type I) residual soil from migmatite Group I

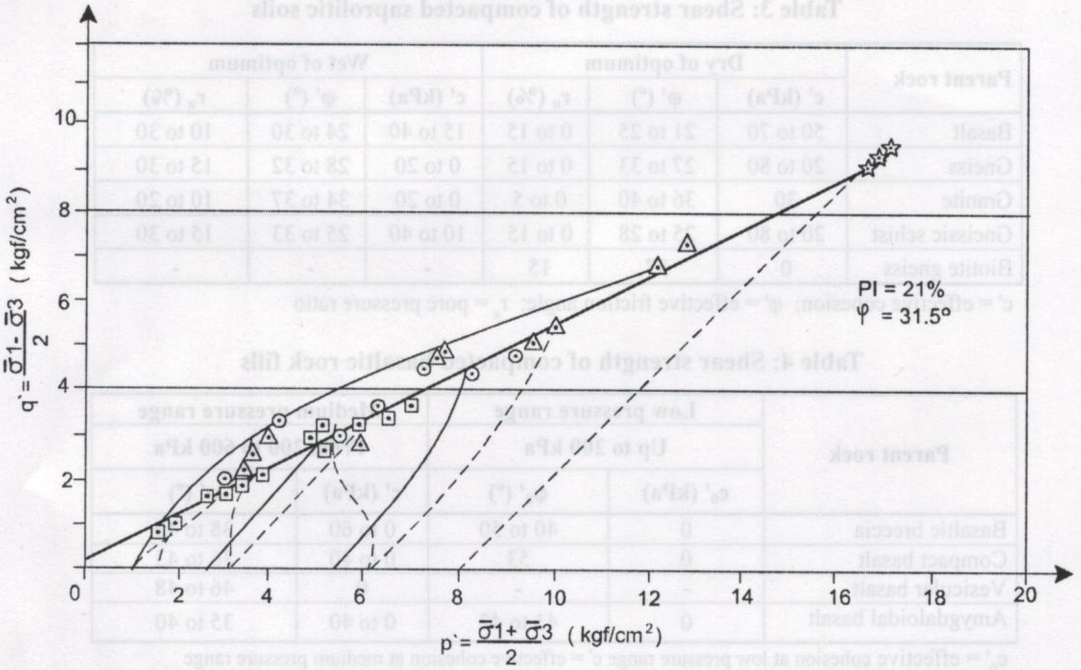


Fig. 10b: Juquiá (Type II) residual soil from migmatite Group I

after the impounding of the reservoir. This does not mean that the water can cross the dam in such a short period, but that the construction pore pressure tends to dissipate quite fast and that the soils becomes almost saturated in that period.

STABILITY OF THE DAMS

In dam design it is a common practice to analyse their stability in two ways: the stability of the dam slopes of the outer shells, and the overall or global stability related to the dam and its foundations.

The stability of the outer shells is easily attained using adequate design parameters and proper compaction control. In fact, out of the hundreds of dams built in Brazil, only one case of author's knowledge lead to a partial failure of the upstream slope during construction. As mentioned before, residual soils usually do not develop construction pore pressures and in the design the Bishop pore pressure parameter (r_u) is taken as zero, or a low value. In the case of the Cocorobó Dam, part of the upstream shell was compacted with a soil that had a water content above the Optimum and when compacted developed unexpected pore pressures and a part of the shell failed.

A case of overall instability is the case of the Açu Dam, reported by de Mello in 1982. Two cross sections of the dam are shown in Fig. 11a and b. The original dam design had a clay core, outer shells of sandy gravel and a deep cut-off upstream to control seepage within the sand foundations.

During the construction, the engineers had some doubt about the permeability of the sandy gravel, and considered adequate to interconnect the clay core with the upstream cut off with an internal carpet (Fig.11a and b). Stability analyses were performed and construction proceeded. When the dam was a few metre below the crest, a large failure took place that unfortunately was not filmed, because the engineers were so perplexed to see the dam slowly moving away that no one had the idea of making a video of the accident. Nobody was injured and there was enough time to remove the construction equipment from of the area.

Table 2: Shear strength of compacted residual soils, (After Cruz and Maiolino 1983)

Parent rock	Dry of optimum			Wet of optimum		
	c' (kPa)	φ' (°)	r_u (%)	c' (kPa)	φ' (°)	r_u (%)
Basalt	40 to 70	24 to 35	-20 to –10	20 to 50	25 to 33	+20 to +30
Sandstone	30 to 50	26 to 31	0 to +8	5 to 20	30 to 33	+10 to +20
Gneiss	20 to 50	26 to 29	+2 to +5	10 to 20	30	+10 to +30
Psammitic schist	15	33	0 to +5	10	32	+20
Granite	20 to 30	35 to 40	0	5 to 15	34 to 37	+5 to +15

c' = effective cohesion; φ' = effective friction angle; r_u = pore pressure ratio

Table 3: Shear strength of compacted saprolitic soils

Parent rock	Dry of optimum			Wet of optimum		
	c' (kPa)	φ' (°)	r_u (%)	c' (kPa)	φ' (°)	r_u (%)
Basalt	50 to 70	21 to 25	0 to 15	15 to 40	24 to 30	10 to 30
Gneiss	20 to 80	27 to 33	0 to 15	0 to 20	28 to 32	15 to 30
Granite	30	36 to 40	0 to 5	0 to 20	34 to 37	10 to 20
Gneissic schist	20 to 80	25 to 28	0 to 15	10 to 40	25 to 33	15 to 30
Biotite gneiss	0	37	15	-	-	-

c' = effective cohesion; φ' = effective friction angle; r_u = pore pressure ratio

Table 4: Shear strength of compacted basaltic rock fills

Parent rock	Low pressure range		Medium pressure range	
	Up to 200 kPa		From 200 to 600 kPa	
	c_0' (kPa)	φ_0' (°)	c' (kPa)	φ' (°)
Basaltic breccia	0	40 to 50	0 to 60	38 to 45
Compact basalt	0	53	0 to 40	36 to 43
Vesicular basalt	-	-	0	46 to 48
Amygdaloidal basalt	0	43 to 47	0 to 40	35 to 40

c_0' = effective cohesion at low pressure range c' = effective cohesion at medium pressure range

φ_0' = effective friction angle at low pressure range φ'= effective friction angle at medium pressure range

What was wrong? The stability analyses. All failure surfaces were considered circular, but the real failure happened within the core and the clay blanket in a clear non circular pattern. The dam was rebuilt with the original cross section, and no problems of excessive seepage in the foundation were noticed until today.

Therefore, the lessons learnt from these two cases can be summarised as follows:

Water content control during construction is very important. If our "residual" soils are compacted below the Optimum, even at a 0.5% difference, pore pressures should be of no concern for dams up to 30 m in height. For higher dams small pore pressures have been measured.

If during construction a dam cross section is modified, including changes in the construction material, mostly in the outer zones, a complete set of stability analysis considering all possible failure surfaces must be done, and the construction specifications have to be properly revised.

THE CONSULTANTS

As a last consideration regarding the lessons learnt from design and construction of dams in Brazil, it is necessary to recognise the fruitful experience of Brazilian engineers with consultants.

What has been the role of an individual or of a board of consultants in the design and construction of Brazilian Dams?.

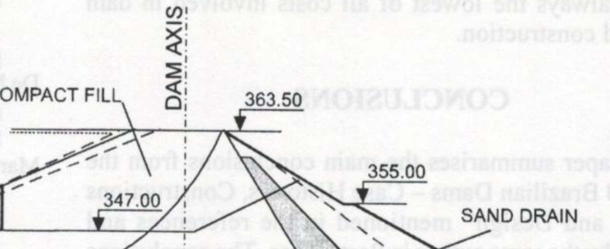


Fig. 11a: Cross-section of the rebuilt Cocorobó Dam (Mello 1975)

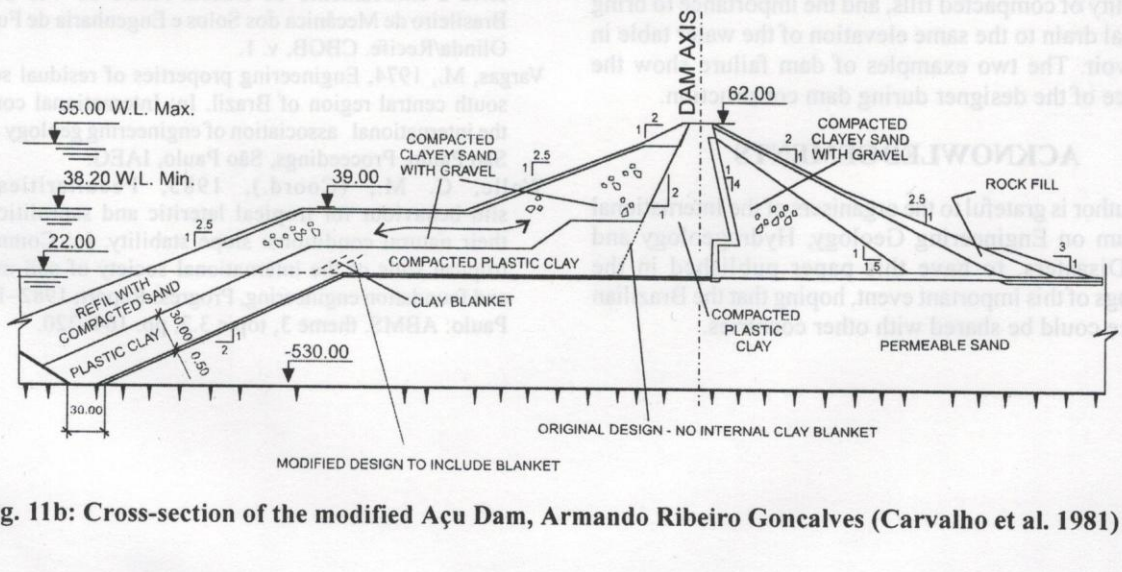


Fig. 11b: Cross-section of the modified Açu Dam, Armando Ribeiro Goncalves (Carvalho et al. 1981)

It is the discussion of design principles and construction procedures with all the participants of the project. Consultants have to seat down with the local group to exchange experiences and to learn together.

It is of great importance that consultants should be called in all phases of a project, even when the local group feels quite happy about their design and materials. An outside observer can see not the aspects of either design and construction not properly considered by the local group but he will also be informed on some particular aspects of the foundation or the borrow materials that would be not possible to see when the dam is already under construction. If consultants are called when the "house is already under fire" the solutions to the problems will be more complicated and certainly more costly.

And it is always good to remember that the consultants' costs are always the lowest of all costs involved in dam design and construction.

CONCLUSIONS

This paper summarises the main conclusions from the book "100 Brazilian Dams – Case Histories, Constructions Materials and Design" mentioned in the references and published by the same author in Portuguese. The conclusions below represent, in the author's point of view, the key lesson he learnt from the design and construction of a large number of dams in Brazil within the last 40 years.

The first dams built were based on empirical knowledge and experience of professional engineers. But after the advent of modern soil mechanics, the principles of soil mechanics were incorporated. In Brazil, the colluvial, residual and saprolitic soils have been used quite successfully as construction materials. Grains or particles of the soil tend to form clusters in the natural condition, with important consequences to filter design and compaction procedures. The attention must be paid for the very high anisotropy of permeability of compacted fills, and the importance to bring the vertical drain to the same elevation of the water table in the reservoir. The two examples of dam failure show the importance of the designer during dam construction.

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