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RCC a Construction Technique with Economic and Planning Advantages (Staged Construction)

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RCC : A CONSTRUCTION TECHNIQUE WITH ECONOMIC AND PLANNING ADVANTAGES (STAGED CONSTRUCTION) (*)

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1. INTRODUCTION

The construction of dams using Roller Compacted Concrete (RCC) technique yields technical and economic advantages. Technical gains ensue from the RCC properties as compared to those of conventional concrete, and also to the quick execution. Economic advantages are reflected in the RCC low cost and quickness of works.

Among technical advantages, we may highlight the easiness of use, added to a highly cohesive and solid material allowing a wide range of planning solutions, as for example **phased construction of the dams.**

This advantage makes RCC in a highly favourable position relative to traditional building solutions using conventional mass concrete.

The purpose of this paper is to discuss the planning possibilities for these structures and the economic advantages coming from the use of

(*) *Béton compacté au rouleau : une technique de construction présentant des avantages économiques et de planification (construction par étapes).*

RCC, as well as to indicate the verification analyses needed on the overall structure behavior.

2. USUAL PRACTICE

The practice adopted for planning, when using RCC, should take into account the following aspects :

- use the pouring high-speed to reach high elevations within a short period of time;
- reduce the heights of cofferdams, also due to the possibility of counting of the concreting speed;
- reduce the dimensions of the diversion works (tunnels, channels, etc.), using a shorter recurring time and admitting the possibility of larger flow overtopping the dam. This means admitting the risk of overtopping.

These remarks, although encompassing a number of advantages, create a need in the execution aspect, that is, to produce large volumes of concrete right at the beginning of the works, exactly when equipment and manpower are in a phase of adjustments and warming up.

However, considering RCC as an admirable variation or mixture of the techniques employed in conventional concrete construction and rockfill construction, one may take advantage of the planning premises of both technologies using other advantageous aspects and evading the problem of needing high production rates early in the works.

3. ALTERNATIVE PLANNING

This planning variation enables the successful examination of the possibility for the execution of joints on the RCC " embankment ", whether lengthwise or crosswise to axis of the dam, or vertical or inclined, with slopes varying as far as the vertical direction.

This allows the execution of the dam " embankment " in phases, including the construction inside the structure of access roads, strips for cranes, blockouts and other auxiliary practices.

The project can be executed, for instance, in a first phase, by constructing only a part of the dam, as shown in Fig. 1, and leaving the remaining part for a second phase, to be considered as a widening or raising of the first phase.

This option enables the construction of a dam in phases by successively complementing the previous phase. The execution of each phase may be planned in order to meet certain planning conditions, which may be :

- Leveling/reduction of the initial peak of the production histogram and placement of RCC, and consequently reducing the initial cost of the project;
- Replacement of the main cofferdam for river diversion by partially raising a section of the dam up to the elevations required for the period of river diversion;
- Construction of access roads for the placement of RCC inside/outside the dam in order to simultaneously meet the requirements of the previous and subsequent phases;
- Construction of a temporary downstream strip for the installation of cranes and/or for access to the opposite bank;
- Minimize the environmental and landscape impact at the dam site by reducing/eliminating excavation works for outside accesses.

It is worth emphasizing that for each planned phase there should be an inspection and verification of the stresses developed and of the structural stability. The analysis should take into account the effects of possible differences in concrete properties and ages.

The point " A ", designated in Fig. 1 as the toe of the downstream slope for Phase I, should be chosen based on the array of conditioning factors described below :

- the most favourable concrete production histogram;
- the elevation that shall be reached for ensuring the advantages in the reduction of the works and temporary structures for deviation and handling of the river;
- that the time for restarting concrete placement works, Phase II, be considered in the stress and stability analyses, in order to make up for any differences in concrete properties of both (or even more) phases.

4. EXAMPLE

This alternative was adopted for the construction of the Capanda Hydroelectric Project (Angola), with the following general information [1] :

Owner	GAMEK - Gabinete de Aproveitamento do Médio Kwanza	
Capanda Dam	Maximum height (m)	: 110
	Crest length (m)	: 1 200
	Volume of concrete ($\times$ 1 000 m^3) :	
	Total of dam	: 1 154
	Roller Compacted Concrete	: 757
	Conventional mass concrete	: 104
	Other structures	: 293

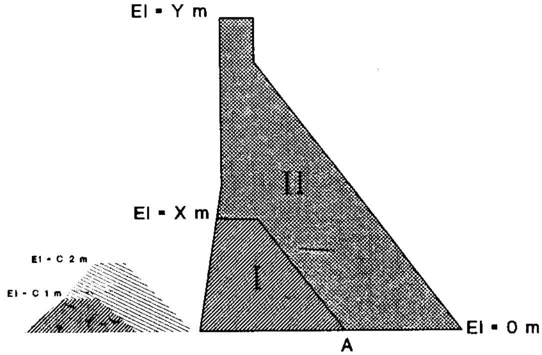

Fig. 1

Alternative Planning Scheme for the RCC Technique

Schéma de construction utilisant la technique du BCR

C_1	Temporary cofferdam crest	*C_1*	*Crête du batardeau provisoire*
C_2	Original cofferdam crest	*C_2*	*Crête du batardeau initial*
O	Foundation level	*O*	*Niveau de fondation*
X	Temporary dam crest	*X*	*Crête du barrage provisoire*
Y	Final dam crest	*Y*	*Crête du barrage final*
I	First phase	*I*	*Première phase*
II	Second phase	*II*	*Deuxième phase*
A	Toe	*A*	*Pied*

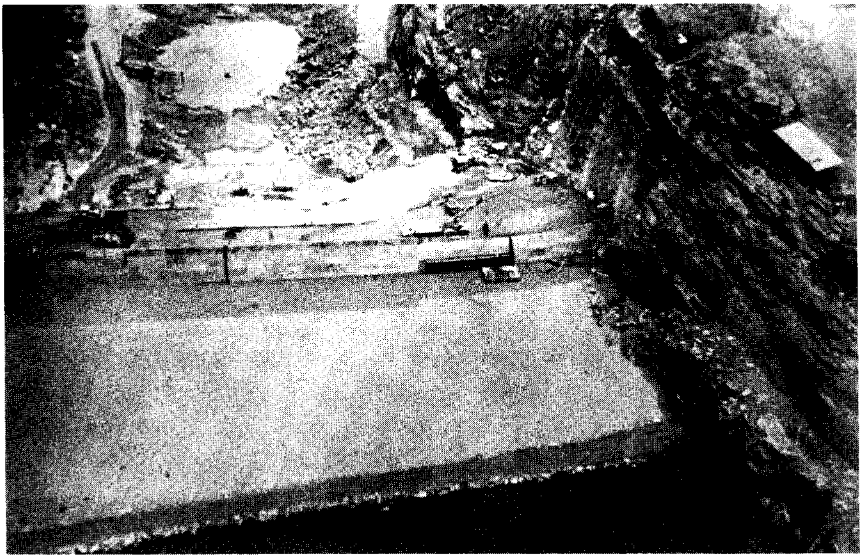

Fig. 2

Air view of Capanda-Angola project, showing phase I, finished, and the level of upstream water having surpassed that of the cofferdam

Vue aérienne du chantier de Capanda (Angola), montrant la phase 1 terminée et le niveau d'eau amont ayant dépassé le niveau de la crête du batardeau

Fig. 3

Air view at later phase, highlighting the advance of phase II and the cofferdam which had been surpassed during a flood which occurred in the execution of phase I

Vue aérienne, à une phase postérieure, mettant en relief l'avancement de la phase II et le batardeau qui a été submergé durant une inondation survenue pendant la phase I

5. DIMENSIONS OF PHASE I

The selection of the point " A" (toe of the downstream slope) next to the central part of the dam base requires practically half of the volume of concrete necessary for reaching the same height in case the entire section of the dam had been considered. This means, in a simplistic way, half of the monthly production necessary for reaching the same elevation.

Thus, the resources initially required can be more pliant and less demanding.

For the construction planning of the Capanda Dam, six distinct phases were considered for the execution of the RCC :

Phase I : Construction of the Dam at the Bottom of the Canyon

During this phase, the base of the dam was executed in all its length which comprised the entire bottom of the canyon. The planning condition was to reach the elevation of the water level to ensure the execution of the river diversion works, of 3 600 m^3/s, corresponding to a Recurrence Period of 25 years.

Phase 2 : Partial Raising of the Dam/Cofferdam

After ensuring the non-flooding of the work area, the dam/cofferdam was raised up to El. 880 m, which was the elevation initially stipulated for the main cofferdam required for diversion. This work was carried out with the protection of a precofferdam reduced to the El. 867 m, which would ensure the execution of the works until the beginning of the rainy season. The speed of the construction works of the cofferdam was determined by the level of upstream water for each month, by considering a Recurrence Period of 25 years.

Phase 3 : Complementation of the Dam up to El. 880 m

This complementation was carried out, still partially, leaving a 12-meter wide access strip between elevations 870 m and 880 m, next to the downstream face. For the downstream access to elevation 870 m it was employed a temporary access. During this period, the water flow reached 3 550 m^3/s, which was very close to the limit adopted for the diversion. The water level reached 1.5 m below the crest.

Phase 4 : Partial Raising of the Dam up to El. 902 m

By using the access built between El. 870 m and El. 880 m for the circulation of construction equipment, the dam was partially raised on the upstream side by means of the construction of another access between El. 880 m and El. 902 m. The El. 902 m was the safety elevation of the dam for a flow of 5 400 m^3/s and was considered the maximum flow for the diversion tunnel and block out of the bottom outlets. At this stage, the crest of the dam was connected to the existing upper access of the canyon.

Phase 5 : General Complementation of the Dam up to El. 902 m

With the circulation of construction equipment being done through the upper access of the canyon (El. 902 m), all downstream part of the dam, from the access at El. 870 m, was rapidly complemented, leveling the dam.

Phase 6 : Raising the Dam to El. 912 m and El. 952 m

From El. 902 m, the access to the works could be made through the slightly sloped abutments up to El. 952 m of the crest of the dam. At El. 912 m, the dam was again executed in partial sections by establishing a vertical joint, lengthwise to the axis of the dam, in order the enable the construction of a 15-meter wide access road for the installation of a crane necessary for the conventional concreting works and for the preparation of the spillway gates.

6. BEHAVIOR ASPECTS OF THE STRUCTURE

The raising of dams is a procedure already known and employed in dams of conventional and mass concrete, of several magnitudes and heights, which has been adopted in several countries.

For example, we can mention the following :

GRANDE DIXENCE	[2]	SWITZERLAND	(in the 50s)
GURI	[3]	VENEZUELA	(in the 70s)
MACÁGUA		VENEZUELA	(in the 90s)

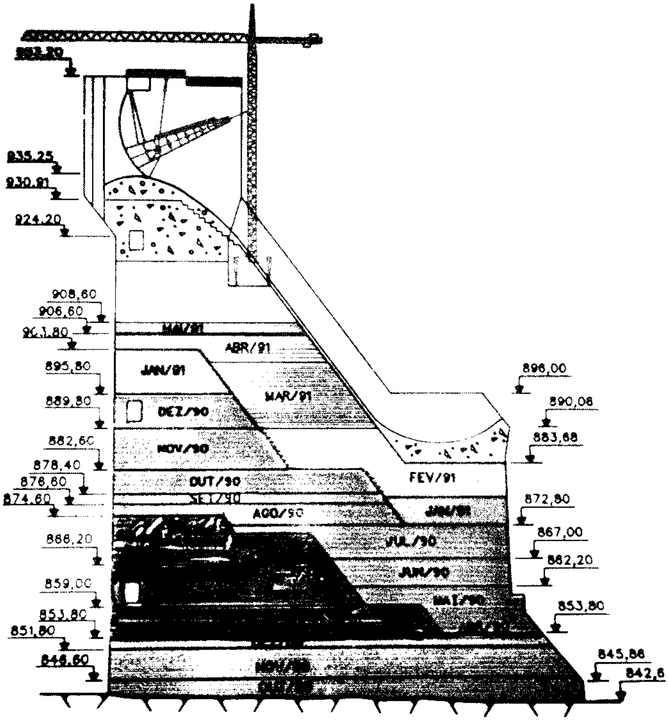

Fig. 4

Steps adopted for Capanda-Angola Dam

Étapes adoptées pour le barrage de Capanda (Angola)

The conventional stability analysis provides a quick and simple verification of the stability conditions of the structure for each of the phases and for the final condition. Nonetheless, there are a few specific aspects that may escape from the conventional stability analysis, as the ones below :

- differences in the elastic properties of concrete placed in the distinct phases;
- conditions of global thermal behavior of the structure resulting from the phased construction.

From the perspective of the Rolled-Concrete Technique, we could perhaps add another verification analysis regarding the connection between the two layers of this type of concrete, i.e., the link between the RCC of Phase I and Phase II.

The performance of the Creep and Modulus of Elasticity depends on the age of the load, as well as on the characteristics of the aggregates and cementitious materials. It is known that the Modulus of Elasticity increases and the Creep decreases with age.

On the other hand, the direction of the stresses will not be changed because of the differences in properties, but the distribution of stresses near the foundation (or concrete slab) may be distinct. Considering that the concrete of Phase I has greater Modulus (older), this region will tend to absorb more load, as shown in Fig. 5.

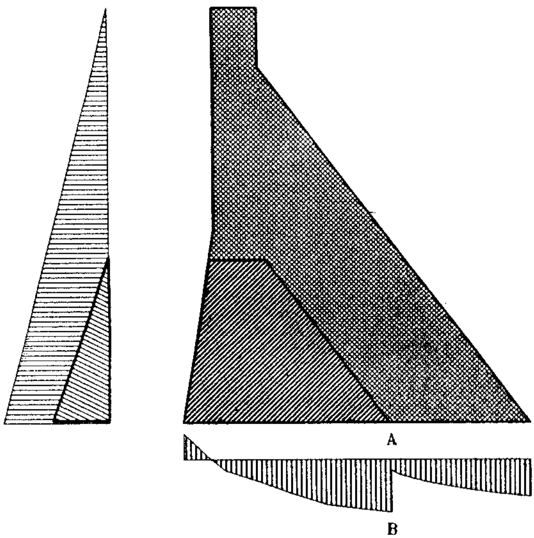

Fig. 5

Schematic Simulation of the Vertical Stresses near the Foundation
Représentation schématique des contraintes verticales près des fondations

The difference in stress values shown in section " A-B " (Fig. 5), as a consequence of Phases I and II, will tend to become smaller as the differences in age between the phases decreases.

From the perspective of thermal behavior, it is clear that the reduction of the base extension, and consequently of the concrete volume, will provide a better thermogenic condition to the structure. The base reduction sets a more favourable condition regarding the safety against the occurrence of fissures of thermal nature. However, a new potential condition of thermal-related problems may occur. This is exactly the construction joint that is formed between the two phases. The risk is increased, again in this case, as the difference in age between the two phases also increases, as a result of the increase in " restriction " (difference due to the increase of the Modulus of Elasticity of both concrete phases).

This behavior must be verified.

The shear stress that may occur along the construction joint formed between the two phases is another essential evaluation to be conducted. The type and degree of treatment to be applied to ensure a monolithic condition between the phases will depend on the magnitude of such stress.

From the perspective of behavior, it is easy to notice that the designed joint, in a plan parallel to the downstream slope, and also practically parallel to the direction of the main stresses, will be, theoretically and practically, compressed by the action of its own weight originated from the mass applied at Phase II. In this way, there will be no normal stresses of considerable concern along the joint.

These evaluations must be added to the verification of the aspects related to the loads caused by seismic events.

7. CONSIDERATIONS REGARDING RCC

In addition to providing easier application of these premises, the adoption of the RCC Technique does not change the array of verifications to be made. Nonetheless, doubts may arise as to the properties of the RCC and the behavior of the structures built under this technique. The reason for this could be mostly due to the novelty of the technique itself than to any specific reason, since the RCC is simply a type of concrete resulting from a construction process, with properties similar to those of other types.

The observation of the properties of RCC [4] [5] [6] accounts to the following :

- For the initial ages (up to 28 days), the Modulus of Elasticity for RCC, of low cement content, present smaller values than those of conventional concrete produced from the same materials. As the age increases, the Modulus of Elasticity of conventional and RCC converge.

Type of Concrete	Percent Evolution	Age (days)						
		7	28	90	180	365	1 820	3 650
Conventional Rolled	In relation to 28 days	73 50	**100** **100**	107 122	117 135	120 140	122 145	125 150

- The Creep is normally expressed by an equation of the type :

ϵ = $1/E + f_{(k)} \log (t + 1)$, where :
E = Modulus of Elasticity
$f_{(k)}$ = Creep Coefficient
t = Time under constant load

Note that the Creep is affected by the Modulus of Elasticity of the concrete, as well as by the Creep Coefficient which is a typical characteristic of each type of concrete and obtained through tests.

Type of Concrete \ Percent Evolution	1/E						$f_{(k)}$					
	7	28	90	180	365	1 000	7	28	90	180	365	1 000
Conventional Rolled	146 150	**100** **100**	78 70	73 54	68 46	63 40	150 154	**100** **100**	60 65	50 51	40 44	36 38

The parameters shown indicate that the differences due to age evolution between the two types of concrete produced with low cement content, and with the same materials, are around 10 %.

When the alternative planning considers that the difference in age between the execution of the two phases will be within 180 days and one year, and that the requirements related to normal loads (hydrostatic load and natural weight) may significantly act between 28 and 180 days after the completion of Phase II (reservoir impounding), then the differences of the parameters related to such elastic characteristics, as to age, will be around 25 % to 35 %. That is, the dam built in Phase I will be more rigid than its complementation (Phase II) at about 25 % to 35 %.

The magnitude of such difference, although it could be calculated, has a very small effect on the distribution of stresses near the foundation. This denotes that the stress and supporting conditions will remain within the tolerable limits for the building period.

These conditions were evaluated and considered for the Capanda Dam Project and observed by means of instruments during the construction works. They did not present any remarkable increases in terms of stress.

The performance of other dams already built [7] [8] [9] [10] [11] in conventional concrete, considering the raising of the dam in several phases, and verified through monitoring instruments, certify that the procedures considered in the planning do not introduce additional stresses of great significance.

8. ADDITIONAL MEASURES TAKEN DURING CONSTRUCTION WORKS

In order to ensure embankment homogeneity as to distribution and stress, when the RCC technique is employed, special attention is paid to the behavior of the construction joints, particularly specially to inclined joints, existing between the two phases.

Thus, for the construction of the Capanda Dam, it was decided, as an additional safety element, to place a layer of conventional concrete (of about 0.3-0.5 m thick) in the contact area between the RCC of the two phases. This conventional concrete was of the same mix as that of the face concrete with MSA = 38 mm and cement content around 180 kg/m^3, was placed after the surface treatment of the joint, in steps, and executed by means of pressurized water jet, and executed immediately before the placing of the RCC for each phase.

We shall point out that the RCC for this joint was formed by steps, whose compaction employed vibratory plates type Dynapac CM-20. The resistance of the steps was compatible with the resistance specified for the dam embankement, as demonstrated by several trials conducted on cores extracted from this contact area.

This construction sequence produced an adequate adherence between the two concreting phases, which was aimed at providing a monolithic condition between them.

9. CAPANDA RCC PROPERTIES

The Capanda RCC (with cement content of 70 kg/m^3 to 80 kg/m^3 and MSA = 76 mm of sandstone aggregate) properties were tested according to a planning that considered studies and quality control procedures, during the construction. The general data are shown on Fig. 6.

Properties	Age (days)	Values	Unit
Specific Weight	–	24.09-24.14	kN/m^3
Compressive Strength (specimens D 25 × 50 cm) (drilled cores)	28 90 180 128-223	7.4-7.8 9.3-9.8 9.3-10.7 11.4-13.9	MPa MPa MPa MPa
Coefficient of Variation During the Control	–	8-18	%
Splitting Test Value/Compressive Strength	–	9-13	%
Modulus of Elasticity	28 90	150-200 220-250	100 × MPa 100 × MPa
Shear Strength	28 90	1.5-2.2 2.4-3.8	MPa MPa
Friction	28	42-49	ANGLE
Creep Coefficient (f_k)	7 28 90 180 360 1 000	14 9.3 6 4.7 4.1 3.5	10^{-6}/MPa 10^{-6}/MPa 10^{-6}/MPa 10^{-6}/MPa 10^{-6}/MPa 10^{-6}/MPa
Permeability	90	10^{-11}-10^{-9} m/s	

Fig. 6

Capanda RCC properties
Propriétés du BCR de Capanda

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SUMMARY

In addition to providing economic and chronological advantages, the adoption of the roller compacted concrete technique may propitiate planning options in a way to facilitate construction phases and ensure safe procedures for the execution of structures with the same performance and safety and quality levels of structures in conventional concrete.

This paper focuses on the alternative planning option incorporated to the construction works of the Capanda Hydroelectric Project, in Angola, with the development of phases of successive overaising.

This planning condition enabled advancing part of the upstream part of the dam, in a first phase, by replacing the main cofferdam which ensured the protection against predicted floods during the diversion works. It has also allowed the reduction of the dimensions and characteristics of the diversion works, with no harm to operation and handling of the Kwanza River, and maintaining the levels of safety throughout the works.

As to structural behavior and stability, the properties of the RCC determined by a comprehensive laboratory study enabled the calculation of the safe performance of this technique for dam building.

RÉSUMÉ

La technique du béton compacté au rouleau, en plus de la possibilité d'obtenir des avantages économiques et chronologiques, permet d'établir des options de planification, telles qu'elles permettent de faciliter les diverses étapes de construction et de garantir des procédés de construction sûrs d'ouvrages en béton, présentant des niveaux de sécurité et de qualité comparables à ceux obtenus avec des bétons conventionnels.

Le rapport présente une solution de planification où la construction du barrage de l'aménagement hydro-électrique de Capanda (Angola) a été prévue par étapes successives.

Cette planification a permis de faire avancer la construction de la partie amont du barrage dans une première étape, en remplaçant le batardeau principal, ce qui a permis de garantir la protection nécessaire contre les crues prévues pendant les travaux de dérivation. Elle a permis aussi de réduire les dimensions et caractéristiques des ouvrages de dérivation, en maintenant les niveaux de sécurité exigés pendant les travaux.

Du point de vue du comportement et de la stabilité de l'ouvrage, les propriétés du béton compacté au rouleau, étudiées de façon approfondie en laboratoire, permettent de considérer comme sûre cette technique de construction du barrage.