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TUCURUI DAM: NON-WOVEN GEOTEXTILE AS ONE OF THE ANTI-PIPING BARRIERS

LE BARRAGE DE TUCURUI: LE GEOTEXTILE NON-TISSE COMME UNE DES BARRIERES CONTRE LES EROSIONS TUBULAIRES

DER TUCURUI-STAUDAMM: TEXTILVLIES ALS ANTI-EROSIONS-BARRIERE

Tucuruí Dam, one of the largest in the world,was recently inaugurated.Its construction gave rise to several unusual problems, one of the most serious was the foundations of the earth and rockfill structures which presented very complex geology. In the region of the dam known as "metabasic", investigations it was found that the foundation,in some stretches,presented high permeability which is considered abnormal for the type of soil. These permeabilities were due to the occurrence and great concentration of tubular cavities with diameters that varied from millimeters up to more than 0.20 m.
This paper describes in detail the diverse foundation treatments carried out with the object of reducing seepage through or under the foundation.
It especially gives details of an additional safety measure adopted which consists of covering the downstream face of the cut-off trench with non-woven geotex -

1. INTRODUCTION

The Tucuruí Dam is situated in the Amazonian Region of the north of Brazil, in the valley of the Tocantins River (Fig. 1). Construction was begun in 1976, and the dam was inaugurated at the end of 1984. Is is one of greatest hydro-eletric utilizations in Brazil and it was built for navigation and for power generation.

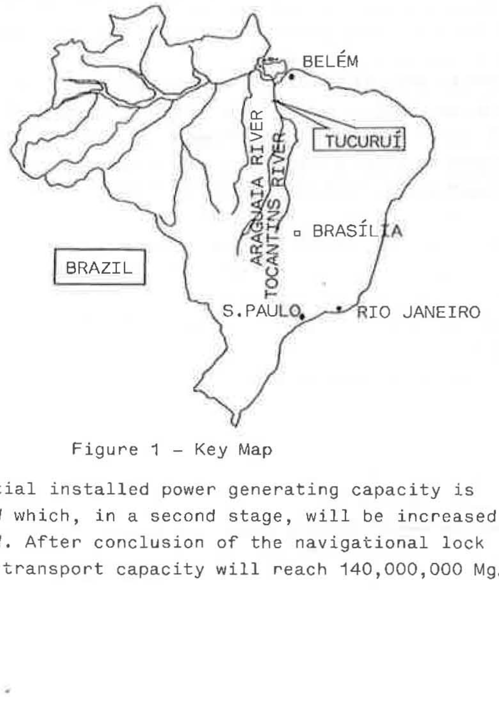


Figure 1 – Key Map

The initial installed power generating capacity is 4,000 MW which, in a second stage, will be increased to 8,000 MW. After conclusion of the navigational lock system, transport capacity will reach 140,000,000 Mg/year.

Der Staudamm von Tucurui, einer der groessten der Welt, wurde vor Kurzem eingeweiht. Seine Errichtung verursachte verschiedene aussergewoehnliche Probleme.Unter ihnen,die Fundament der Erd-und Schotter-Struktur in recht komplexer geologischer Zusammensetzung.Auf dem hier als "Metabasis" benannten Teil der Staumauer fand man nach den ersten Untersuchungen einen Untergrund vor,welcher in einingen Strecken hohe Durchlaessigkeit vorwies,was bei diesem Typ Boden als anormal angesehen wurde.Diese Durchlaessigkeit war auf eine betraechtliche Ansammlung roehrenfoermiger Hoehlungen in Durchmessern von Millimetern bis zu 0,2 m zurueckzufuehren. Diese Arbeit beschreibt im Einzelnen die verschiedenen Fundamentbehandlungen um den Abfluss durch den Untergrund einzuschraenken. Insbesondere erlaeutert sie ausfuehrlich eine zusaetzliche Sicherheitsmassnahme,welche in der Abdeckung der Boeschung an der Unterseite des Absticches durch ein Textilvlies besteht.

The total length of the main dam works is 8,530 m, 7,250 m of which consisting of earth and rockfill embankment, and 1,280 m of concrete structures, Besides these structures, there are 7,550 m of complementary dikes. The main dam presents the following characteristics:

TABLE 1 – MAIN CHARACTERISTICS OF THE TUCURUÍ DAM

maximum height of the embankment dam	103 m
compacted earthfill (incl. cofferdams)	80,000,000 m^3
soil excavation	23,000,000 m^3
rock excavation	22,000,000 m^3
concrete	5,200,000 m^3
spillway capacity	110,000 m^3/s
reservoir area	2,160 km^2
total volume of the reservoirated	43×10^9 m^3

2.GENERAL DESCRIPTION OF THE EARTH AND ROCKFILL DAM DESIGN

Geological Aspects

The geology along the foundations of the earth and rockfill dams is quite complex. There are diverse lithologies, a high degree of laterization of the residual soils, tubular cavities in the residual and saprolitic soils, etc. Igneous and sedimentary metamorphic rock, affected by tectonic actions, are evinced by faults and folds (1,2,3, and 4).

The following lithologies were found in the various stretches of the foundations (residual and/or saprolitic soils with some outcroppings of solid rock) :

. left bank : basalt interspersed with metasandstone and graywacky metasediments;

. river channel : graywacky metasediments, metabasics and chlorite schists. The metasediments are separated by a thrust fault which cuts obliquely across the dam's axis.

. right bank : metabasics and rhythmic, graphitic and quartzous phyllites. There is a diabase interspersed with the phyllite pack, as well as the occurrence of thin quartzite layers. Over the phyllite there is an alluvial terrace gravelly sand of up to 25 m in thickness. All the foundations soils on this bank are covered by 2 to 3 m thick colluvial clayeysand. The residual and saprolitic soils reach thicknesses of up to 40 m. In the residual soils, tubular cavities were detected with centimetric diameters and depths of as much as 25 m.

Description of the borrow materials

Various borrow materials of diverse origins were used in the construction of the embankment dam (5, 6, 7 and 8). The soils used on the right bank are made up of:

Type C : colluvial clayey sands with the following average characteristics : density of soil ρ = 2.71 Mg/m^3, liquid limit W_L = 29%, plasticity index I_P = 12%, maximum density of dry soil $\rho_{d\ max}$ =1.95 Mg/m^3 optimum water content W_{op} = 11%, initial void ratio e_o = 0,34, Compression index C_c = 0.09, effective cohesion c' = 49 kPa, and effective angle of internal friction ϕ' = 35º

Type D1 = colluvial clayey sands and sandy clays : (ρ = 2.71 Mg/m^3, W_L = 56%, I_p = 29%, $\rho_{d\ max}$ = 1.69 Mg/m^3 W_{op} = 18.5, e_o = 0.57, C_c = 0.09, c'= 94 kPa, ϕ' = 26º);

Type T - alluvial terraces (gravelly sands) : (ρ = 2.71 Mg/m^3 ,W_L = 30%, I_p = 12%, $\rho_{d\ max}$ = 2.14 Mg/m^3 W_{op} = 7.3%, e_o = 0.26, c'= 59 kPa, ϕ' = 40º).

On the left bank, the soils originated from "in situ" decomposition of the mother rocks and consist mainly of: Type D2 - basaltic residual soils: (ρ= 2.88 Mg/m^3,W_L =67%, I_p = 30%, $\rho_{d\ max}$ = 1.57 Mg/m^3, W_{op} = 27.7%, e_o = 0.91,C_c =0.19, c'= 51 kPa, ϕ'=28º -Type M-metasediments residual soils: (ρ = 2.81 Mg/m^3, W_L = 55%, I_p = 27%, $\rho_{d\ max}$ = 1.58 Mg/m^3, W_{op} = 0.25%, e_o = 0.71, C_c = 0.19, c'= 55 kPa, ϕ' = 27º).

The soils initially used in the river channel section were taken from the left bank. After deviation of the river through the sluice gates, borrow material from the right bank was used. It should be pointed out that, in the borrow materials from slight depths, the residual soils were intensenly laterized, with the occurence of a high percentage of lateritic concretions.

It is clear, therefore, that the materials used presented a wide granulometric range, from silty clays (basalt), to sands with gravel (alluvial terraces), with variations of up to 50% in the plasticity index,optimum water content of 7 to 32%,and maximum dry unit weights of 1.42 to 1.95 Mg/m^3

The various materials presented low permeability (less than 10^{-7} m/s) with the exception of the terraces where average values were between $5x10^{-6}$ m/s and $5x10^{-7}$ m/s.

Design conceptions

The final conception of foundation treatment and of elaboration of the diverse typical sections for different stretches of the earth and rockfill dam was greatly influenced by several factors, among which were the large volume of civil works, geologic-geotechnical complexity of the foundations and borrow areas, topographical irregularities, the great volume of earthmoving, limited construction schedule and logistic aspects of construction and hydrometeorology (6).

3. DESCRIPTION OF THE FOUNDATION AND EMBANKMENT CORRESPONDING TO THE METABASIC STRETCH

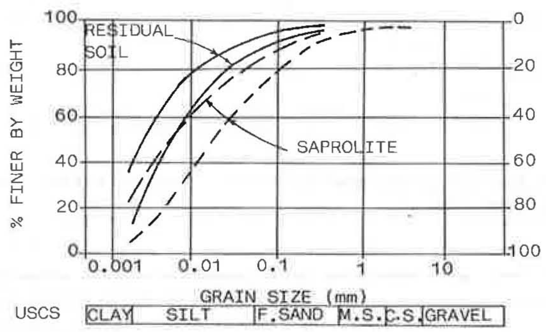
This section of the dam, known as "metabasic", consists of a stretch of approximately 250 m situated on the right bank near the Tocantins River. Construction activities were begun in 1980 with the excavation of the cut-off. Construction of the earthfill was begun in November, 1982, and finished in June, 1984, and was carried out at the same time as the adjacent stretch of the river channel of approximately 1,250 m in length.

Synthesis of the geologic-geotechnical characteristcs of the foundation

Studies and surveys carried out on this stretch(metabasic) showed the following geologic-geotechnical characteristics starting from the surface (3):

- colluvial deposits with an average thickness of about 2m (fine and medium sand, very slightly clayey, in general loose), with a predominance of penetration resistance indexes N (standardized result of the Standard Penetration Test-SPT) between 2 and 4 blows;
-alluvial terrace (in some places), under the colluvium (medium sand with gravel and lateritic crusts at the base) with thickness varying from zero to 3 m;
-metabasic residual soil underlying the colluvium and/or alluvial terrace (silty-sandy clay), with thickness varying from 3 to 15 m. Predominant permeability registered at SPT values varying from N = 6 to 19 blows was below 1×10^{-6} m/s;
- the residual soil gradually gives way to the saprolitic, also made up of silty-sandy clay, with thickness varying from 3 to 15 m (N over 11 blows). In several stretches the soil is quite porous, with dry unit weight on the order of 1.08 Mg/m^3;

-underlying the saprolitic soil there is the occurrence of a horizon of soft altered rock with thickness varying from 4 to 6 m. This horizon is highly fractured and interbebbed with soil, passing to hard altered rock and/or solid rock, very slightly fractured. The altered rock registered high loss of water, with a predominant permeability coefficient on the order of 10^{-6} m/s, as well as several stretches with total absorption of the pump's outflow capacity. The solid rock, although less permeable, revealed some stretches with high loss of water. It should be pointed out that, in spite of revealing permeability coefficients of less than 10^{-6} m/s the metabasic residual and saprolitic soils presented high permeability in some stretches (including loss of circulation water and total absorption of the pump's outflow), considered abnormal for the type of soil tested. Characteristics of the metabasic soil are presented in Figure 2.



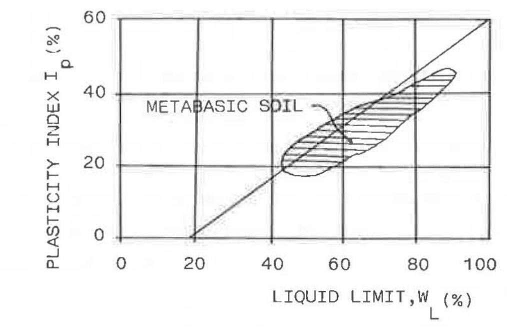


Fig.2-Syntesis of average geotechnical characteristics

Later investigations by means of testpits and walls of the cut-off showed that the high permeabilities were brought about by great concentration of tubular cavities with diameters varying from millimeters to more than 0,2 m (Photographs 2 and 3). In general, these cavities present sub-vertical developments and can reach great depths (over 20 m) and some are interconnected with the open fractures of the underlying altered rock.

Table 2-Syntesis of average geotechnical characteristics

AVERAGE VALUES	RESIDUAL SOIL	SAPROLITE
ρ (Mg/m^3)	1.88	1.60
W_{nat} (%)	32	49
e_o	1.12	1.66
S_r (%)	85	85
P_a (kPa)	570	290
Cc	0.38	0.83
c'(kPa)	30	0
Ø'(degree)	25	20

Legends : W_{nat} = natural water content; S_r = degree of saturation; P_a = pre-consolidation pressure.

of other stretches of the dam, in the metabasic stretch these cavities proved to be more subject to erosion when submitted to concentrated flows of water.
It should also be noted that, besides the great compressibility of these materials, the saprolites present low shearing strenght.

General description of the earthfill design

A zoned earthfill section was adopted for the metabasic stretch, using colluvial soils (types C and D1) upstream form the vertical chimney filter. In the downstream zone, the use of all investigated material from the right bank (C, D1 and T) was allowed. Near the crest, it was found to be technically and economically feasible the use of clayey gravel from the terrace (type Tm) which presents excellent characteristics of workability and traffic supporting capacity (Figure 3).

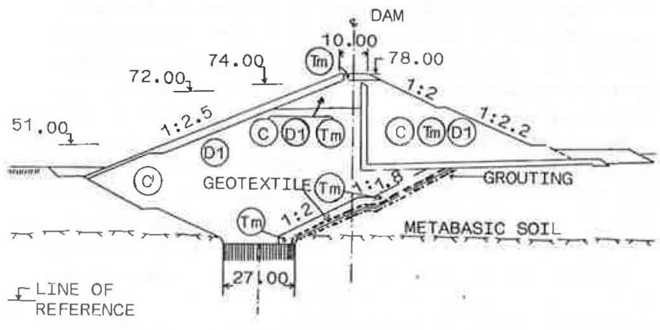


Figure 3 - Cross section 25+00 (metabasic stretch)

The cut-off was excavated down to the soft altered rock upstream from the dam's axis.

Foundation treatments

Based on the various geologic-geotechnical factors of the foundation, the following treatment in the metabasic stretch were programmed and carried out (3): a)complete removal of the coating of colluvial soil which presents low strength and is subject to sudden settling by removal of colluvial supervicial soil which presents intercepting all the foundation soil and the permeable altered rock; c) covering of the bottom of the cut-off with a concrete layer (approximatelx 0,30m thick); d) cleaning of the surface of the cut-off trench by tetting of compressed air to allow identification and clearing of the tubular cavities. These cavities were then meticulously identified and filled with grout by means of gravity; e) cleaning of the lower (rock) face of the cut-off and removal of loose blocks. On the upstream face the most affected zones was treated with a thin shotcrete cover on the downstream face, due to the occurence of fractures, a sand transition was placed between the altered rock and the earth fill (Figure 6); f) construction of downstream stabilizing berm due do the low shearing resestance of the metabasic saprolite; g) shallow grouting in the bottom of the cut-off, to seal rock discontinuity; h) exploratory grouting 25m maximum depth 10m apart was done from the bottom of the consisting of a non-woven geotextile was applied on the exploratory holes, additional holes were made. 23,000 kg of cement were injected in a total of 2,350 m of drill holes, revealing a relatively low average grout i) as a preventive mesure, an additional safety device, piping of soils from the compacted earthfill through a compacted earthfill was placed over the geotextile downstream face of cut-off in order to stop possible possible undetected (unplugged cavities. A strip of using a self-sealing material (slightly clayey alluvial gravelly sand) which could, in the remote case of failure of the geotextile, obstruct an insufficiently injected cavity, or a cavity which may have remained undetected during the careful inspections and grouting from the excavation surface.

5. GEOTEXTILES AS ANTI-PIPING BARRIERS

The transversal cross section of the dam in the metabasic stretch is shown in Figure 3 where the position of the geotextile is indicated. The use of non-woven geotextiles was recommended due to its mechanical and filtering characteristics which are commented on below. - Mechanical Propertie Requirements - Int the metabasic stretch, even after meticulous detection and filling the tubular cavities, with ciment grout, it is reasonable to conceive that any undetected cavities with a maximum diameter of 0,05 m continue unfilled. In these cavities, the geotextile becomes deformed under stress as is shown in Figure 4. The greatest tension on the geotextile occurs at the central point of the cap thus formed. The maximum effective stresses foreseen are on the order of 800 kPa for a maximum diameter of 0,05 m of tubular cavity. Considering the low shearing resistance of the foundation material, puncturing of the geotextile on the edges of the cavity is an unforeseen occurrence. - Retention of Fines - The main function of the geotextile is to act as an antipiping barrier, retaining the clayey gravel of the cut-off. The grain size of the pretected material (clayey gravelly sand) is presented in Figure 5. It presents a broad range of particle sizes with a low percentage of clay (approximately 10%). Using the standard retention criterium: $O_{max} \leqslant d_{85}$

O_{max} - maximum percent opening size; d_{85} - diameter

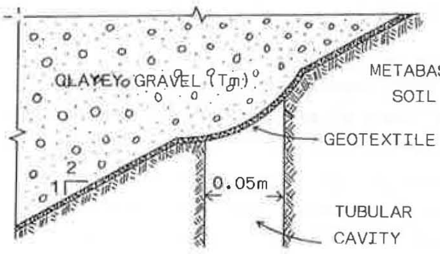


Fig.4- Elongation of the geotextile in a tubular cavity

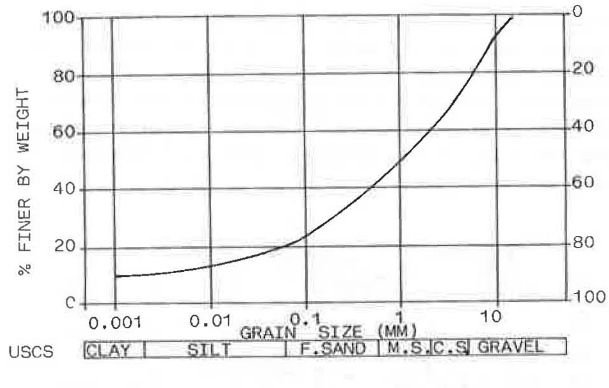


Fig.5-Average granulometric curve of the alluvial gravelly sand (Tm)

corresponding to 85% by weight of finer particles. It is clear that the geotextile's opening size must be less than 7,000 µm, therefore very conservative. The retention criterion established by Giroud (9), for dense soils and with $C'_u > 3$ (C'_u -linear coefficient of uniformity) demands that we have a O_{95} opening size of the geotextile equal to or less than 383 µm. As this criterium was developed for granular soils (without cohesion), and considering that the material in question is cohesive, we can conclude that the geotextile which satisfy this criterion is on the safe side. - Permeability - The permeability of type tm clayey gravelly sand, on the order 5×10^{-6} m/s, low gradients (on the order of 1) foreseeable in the proximity of the geotextile. This type of gradient is insufficient to cause clogging of the geotextile. On the other hand, the criterion of permeabitlity established by Giroud (9) demands that the geotextile should have a minimum permeability of 5×10^{-7} m/s (1/10 of the permeability of the soil).

Specifications of the geotextile used

The geotextile used in this case was Bidim type OP-60 (here called BD600), non-woven continuous polyester filaments manufactured by Rhodia S/A. Its main characteristics are the following:

Table 3 - Bidim OP-60 characteristics

Tensile strength (CFG)	38KN/m
Elongation (CFG)	41%
Bursting strength (AFNOR G07112)	6,000 kPa
Normal permeability	2.2×10^{-3} m/s
Apparent opening Size - O_{95} (CFG)	59 µm

Under the conditions demanded "in situ", we have the following results: a) Bursting Strength - The maximum estimated value for the bursting strength corresponding to the maximum diameter of the tubular cavity(0,05m) is, 4,200 kPa (considering constant the bursting strenght product of the geotextile x diameter of the circular hole). b) Normal permeability - The estimated permeability for a confinement pressure of 800 kPa is approximately 4.0×10^{-4} m/s.The factors of safety provided by the BD600 for bursting strength and for permeability are respectively 5.25 and 80, which are quite conservative. However, the choice of the product was justified by the fact that we are dealing with an application in an inaccessible zone after construction of dam, together with the fact that experience accumulated in relation to the use of geotextile in similar circumstances is still slight. The initial estimative was for the use of 20,000 m of geotextile. However, during the 68,000 m /s high flooding pass through the narrowed river section due to partial construction of river diversion cofferdam, an accentuated erosion of the natural soil foundation of the right bank was registered, substantially reducing the application of the geotextile (reduction of appproximately 9,000 m). To minimize the time of exposure to the sun's rays, placement of the geotextile was, whenever possible, carried out immediately prior to the earthfill operation. The geotextile was placed over the previously regularized cut-off face with minimum overlapping as indicated in Figure 6 and photograph 4. Special care was taken during compacting to avoid damage to the geotextile by compacting equipment.

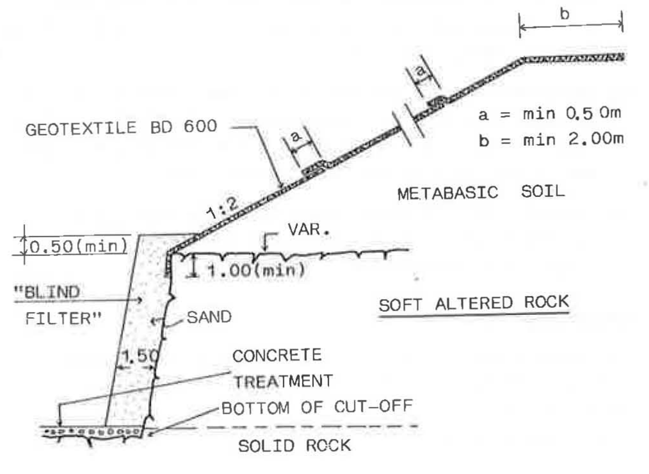
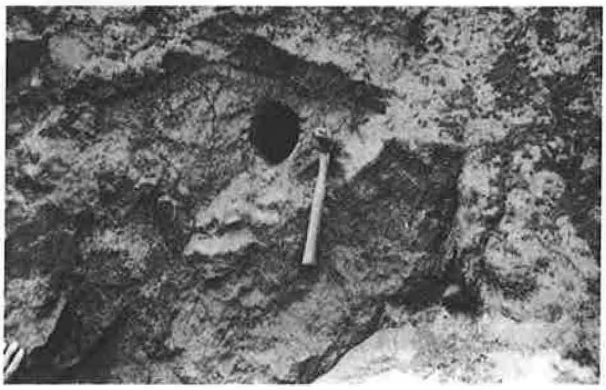


Fig.6-Detail of placement of the geotextile over the metabasic soil.There was a minimum overlap of 10 m of the geotextile over the phyllite soil of the adjacent stretch.

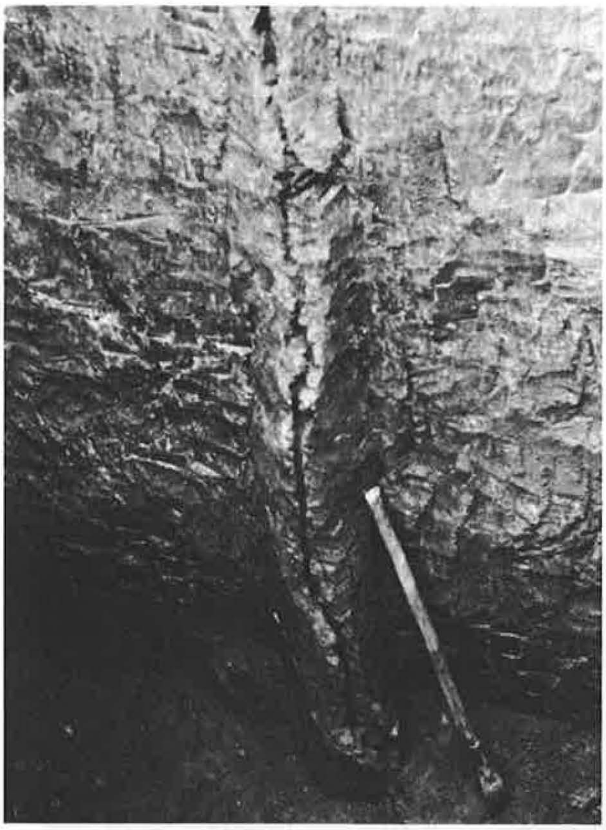
6. CONCLUSIONS

The foundation treatments adopted in Tucuruí,especially in the metabasic stretch, involved a certain degree of justifiable conservatism due to the unusual occurence of tubular cavities in conjunction with the diverse factors presented. Execution of the cut-off and of the other treatment makes it possible to conclude that the risk of seepage of fines trought the tubular cavities and/or fractured rock horizon is pratically null.
The placement of geotextile over the downstream embankment of the cut-off allied to the utilization of self-healing gravel in compacting of the earthfill overlying the geotextile, was considering to be suficient as a second line of defense in the case of possibly an identified cavities. It is important to point out that at present (Sept/85), one year after the beginning of the reservoir filling and approximately six months with the reservoir stabilized at it's maximum normal level (72.00 m quota), based on the auscultation instruments installed, it was observed that the water flow through the compacted fills (including cut-off) are not yet fully established revealing a slow percolation as was foreseen (low permeability of the earthfills). Thus, the treatments executed downstream face of the cut-off and adjacent area were, in practice, not yet submitted to the percolation of water.

Photograph 1-Partial view of Tucuruí Dam's construction



Photograph 2 - Detail of a tubular cavity.



Photograph 3-Longitudinal section of a tubular cavity.

Photograph 4 - Placement of the BD600 over the metabasic soil. During work stoppages the geotextile was protected with opaque plastic covering sheets.

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Acknowledgments

The authors wish to express their thanks to "CENTRAIS ELÉTRICAS DO NORTE DO BRASIL S/A - ELETRONORTE" and to THEMAG ENGENHARIA LTDA" for providing the opportunity to prepare and publish this paper.