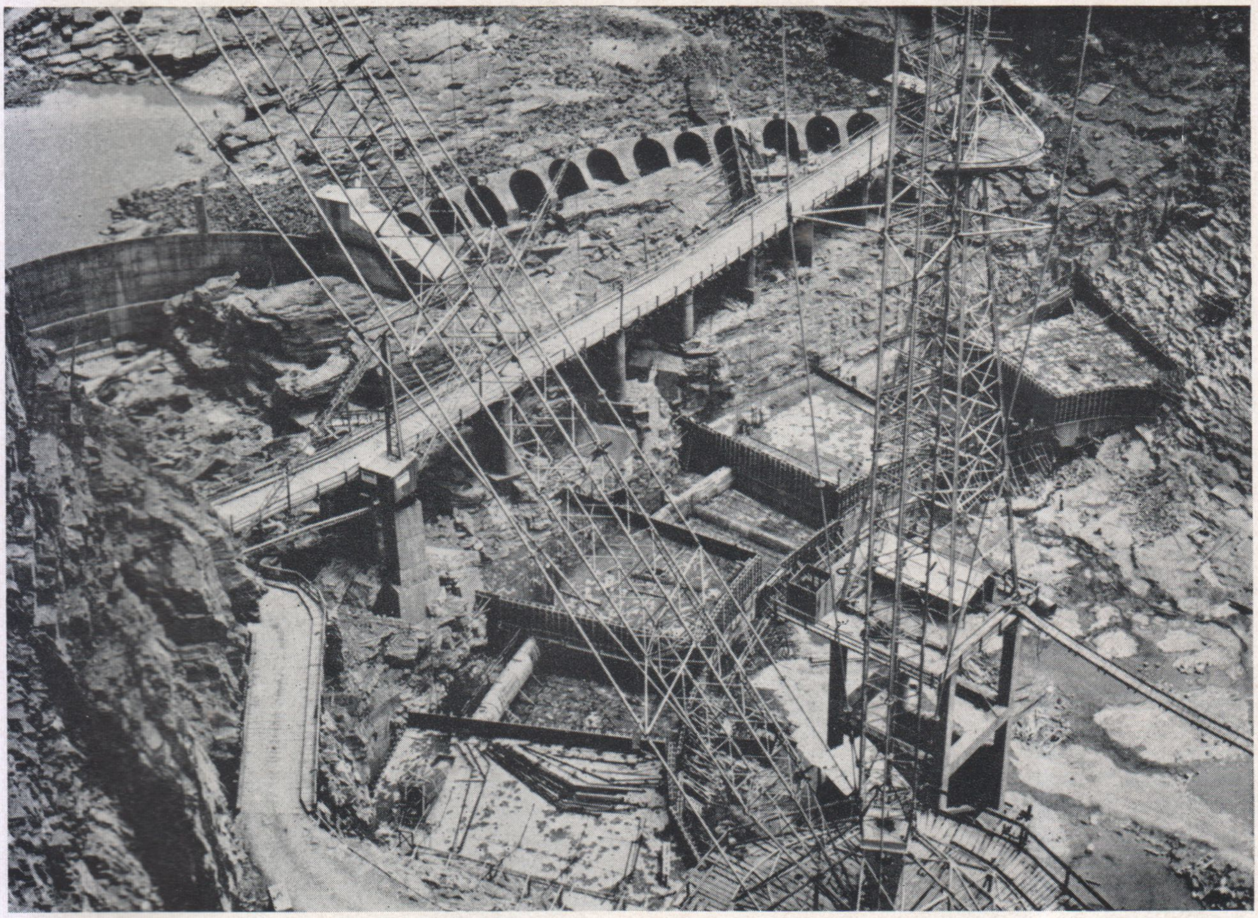


Fig. 1. Cambambe dam at an early stage of construction

The Middle Cuanza Development

An account is given of the construction of the first dam and power station, of 260-MW capacity, at Cambambe on the River Cuanza in Angola. The Middle Cuanza represents one of the major water-power resources of Africa

By GONCALO SARMENTO* and P. C. AFONSO*

PART ONE

THE ruins of an ancient fortress at the entrance to the construction camp remind one that Cambambe, where the first plant of the Cuanza hydro-electric development is under construction, is connected with the history of Angola from the beginning of the Portuguese occupation in the sixteenth century.

When studies were undertaken to determine the feasibility of an irrigation development of the vast coast plain on the lower basins of the Cuanza and Bengo Rivers, it was considered that a hydro-electric scheme on the Cambambe rapids, at the end of the navigable course of the Cuanza, should form the basis for such an enterprise. In the study presented by the Hydrotechnic Corporation (N.Y.) a run-of-river plant at Cambambe with a capacity of 80 MW was envisaged. Of this capacity 30% was allocated to the irrigation development (100,000 ha), 8% to Luanda and its industries, and 52% to a nitrogen fertiliser plant.

The surveys and studies carried out by the Hydrotechnic Corporation were afterwards followed by the Brigada de Estudos do Cuanza, Bengo e Lucala of the Overseas Ministry, who elaborated the first Cambambe project. This project proposed the diversion of the Cuanza upstream of the Cambambe rapids by means of an overflow dam with a maximum height of 23 m, followed by a headrace canal about 5 km

---

* Respectively Chief Engineer and Chief Design Engineer of the Hydro-Electric Development Department of SONEFE, Lisbon.

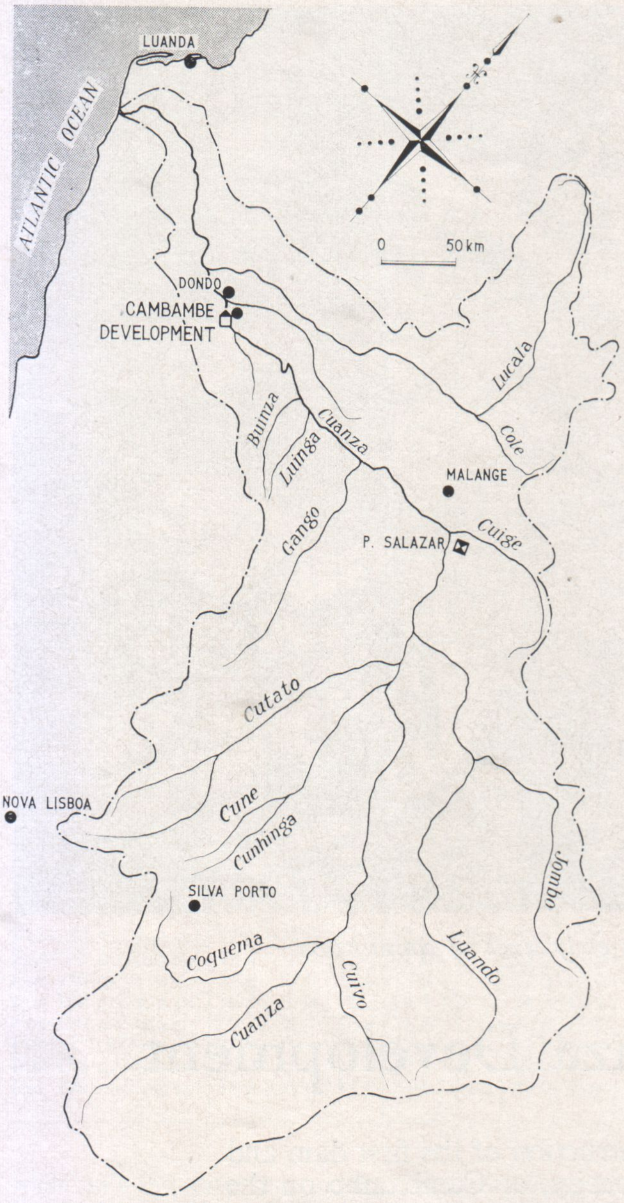


Fig. 2. Map of the Cuanza catchment

long, to utilise a head of about 100 m. In the first stage the diverted flow would be 150 m^3/sec and the installed capacity 130 MW, in two units of 65 MW; the second stage would have a third 65-MW unit.

In September 1957, the concession for the hydroelectric development of the middle course of the River Cuanza, between Cambambe and Ponte Salazar, near Condo Falls, about 240 km upstream, was granted to SONEFE (Sociedade Nacional de Estudos e Financiamentos de Empreendimentos Ultramarinos). The concessionaire assumed the engagement of executing the works of the first plant, in Cambambe, according to a project approved by the Government, within four years and a half. SONEFE was also under the obligation to study a general scheme for the middle Cuanza system within 5 years, and a general plan of hydraulic developments in the Cuanza basin within 10 years. The preliminary works for the execution of the Cambambe plant were started at the beginning of 1958 and the temporary diversion of the river was made at the end of the dry season of 1959. In the meantime SONEFE entrusted to the engineering services of Hidroeléctrica do Zêzere the design of the definitive works.

In these articles an outline will be given of the Cuanza-basin characteristics and of the principal aspects of the Cambambe project and its construction.

Hydrology of the Cuanza Basin

The total area of the Cuanza basin (Fig. 2) is 155,000 km^2. More than two-thirds of this area corresponds to the upper basin of the principal watercourse, on the Angola plateau, above an elevation of 1,000 m. Upstream, the watershed is common with that of some of the great rivers of the African continent. To the south are the Cubango, the Cuito and the Cuando, which run in the opposite direction towards the internal depression of the Kalahari desert; to the east and north-east rise some of the most important tributaries of the Zambeze and Congo.

The Cuanza River has its origin at the centre of the Angola plateau, at an elevation above 1,500 m, and its total course is about 1,000 km. During more than half its course, the river remains at elevated levels, and flows between low banks in a northerly or NNW direction. Near Malange, it diverts to the west in the direction of the sea, plunging down from elevation 1,000 m to near sea level on the coast plain of Angola. This section of the river (Fig. 3), which extends through rocky gorges and over a series of falls, is about 160 km.

In this transition zone the Cuanza basin takes the form of a progressively narrowing strip, of greatly reduced area, and thus the characteristic elements of the Dondo hydrometric station, near Cambambe, downstream of the rapids, can be taken as representative of the plateau basin. All the great tributaries—on the right bank, the Cuivo, the Luando and the Cuige, and, on the left bank, the Coquema, Cunhinga, Cutato and Gango—excepting the Lucala, the confluence of which is situated downstream of Dondo, are affluents of the plateau zone.

The topographic and geological characteristics of the plateau basin, on the two sides of the principal watercourse, are noticeably different. On the irregular relief of the left bank the mountains attain altitudes of about 2,000 m and the soil is constituted of metamorphic formations of the base complex. On the right bank sandy formations of the Quaternary and of the Superior Kalahari prevail; here the relief is slightly undulated and the watercourses wander, with gentle slopes, on immense plains which become flooded. The great storage capacity deriving from the geomorphological characteristics of this side of the basin has a highly beneficial effect on the moderation of its régime. The regularity of the Cuanza's régime is also related to the type of rains in Angola, which are

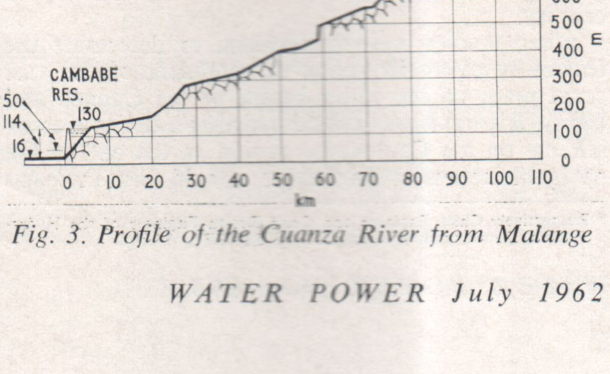


Fig. 3. Profile of the Cuanza River from Malange

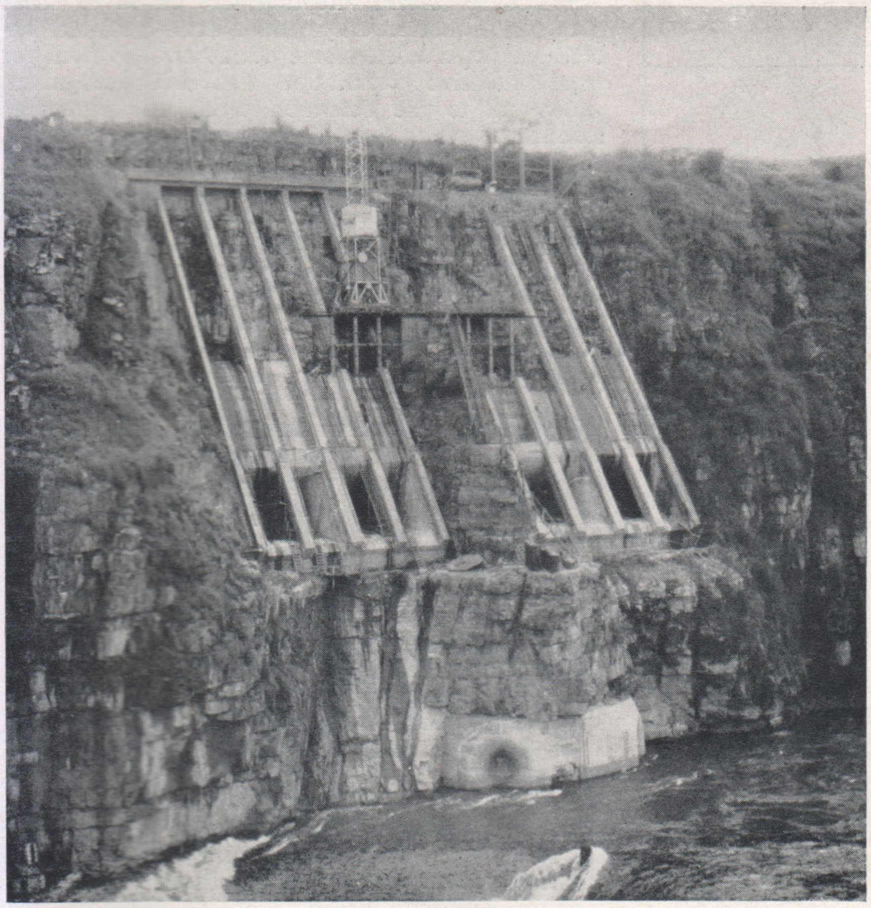


Fig. 4. Intake works for Cambambe No. 1 station

essentially convectional, and with the low variability coefficient of annual rainfall, which, on the plateau zone, is between 15 and 25 %. The mean annual rainfall on the Cuanza basin at Dondo is estimated at 1,230 mm, and the rainy season extends over seven months, from October to April, with transition periods in September and May.

Regular measurements of Cuanza flows started in 1952, at Ponte Salazar, and later at Dondo, near Cambambe. The principal characteristics of the hydrographic basin at Dondo gauging station are as follows:

Drainage area	122,780	km^2
Mean flow	540	m^3/sec
Specific flow	4·4	lit/sec/km
Mean annual rainfall	1,230	mm
Mean annual run-off	138	mm
Run-off/rainfall coefficient ..	0·11	
Relation to mean flow of averaged mean annual flows:		
maximum	1·1	
minimum	0·7	
Relation to mean flow of averaged mean monthly flow:		
maximum	2·1	
minimum	0·35	

From these elements result the great seasonal and year-to-year regularity of the Cuanza régime, as a consequence of the favourable geomorphological characteristics and of the precipitation régime itself.

Although the period of available hydrometric observations is too short to enable it to be taken as a definitive basis for a critical flood, the results of statistical analysis reveal the great capacity of the plateau basin to moderate the flood peaks; the probability of occurrence descends rapidly from 1/100 to 1/10,000, when the flood discharge passes from 1,900 m^3/sec to approximately 2,500 m^3/sec, a value identical to that estimated for the greatest flood reported at the old village of Dondo, less than five times the mean flow. It is intended to install six gauging stations each year until the conclusion of the general plan of hydraulic developments now under study.

Measurements already made of sediment transport show that the mean annual solid flow of the Cuanza can be estimated at $1{\cdot}5 \times 10^6$ tons and that fine materials predominate; 64% have dimensions below 60 microns and 16% below 20 microns.

Middle Cuanza Hydro-Electric Development

The beginning of the transition between the plateau basin and the coast plain is situated on the fall of the Salto do Cavalo, near elevation 1,000 m, close to the stones of Pungo Andongo and to the confluence of the Gango (Fig. 2). From this point to the confluences of the Luinga and Buinza Rivers, above elevation 800 m, the gentle stream bed is more and more broken by low falls and rapids, during a course of almost 60 km. Then downstream it plunges down to elevation 16 m, at Cambambe, through chasms and over a series of rapids and cascades. Upstream of this reach of steeper slopes, the basin's configuration is favourable for the establishment of reservoirs with great storage capacity, which will make it possible to achieve a high degree of regulation of the upper Cuanza. Assuming the possibility of obtaining, with one or more reservoirs, a regulated flow of 500 m^3/sec —the topographical surveys and site investigations in progress will shortly enable this value to be determined—the annual producibility of the Middle Cuanza will attain about 30,000 GWh. One can say that in the Middle Cuanza is concentrated one of the great potential power reserves of Africa.

The first plant of the Middle Cuanza hydro-electric development is under construction at the Cambambe rapids, where natural conditions are very favourable, as the river falls over 40 m, passes through a rocky gorge, and describes a sharp bend. The top water level was fixed at elevation 130 m, raising the dam 80 m above the river bed, and the tailwater level at elevation 16 m at the bottom of the rapids. The gross head of 114 m will ultimately be developed in three power stations (Fig. 5), with short underground hydraulic circuits bypassing the bend.

Before the construction of a proposed large storage plant higher up the catchment (indicated in Fig. 3) the upper layer of the Cambambe reservoir, having

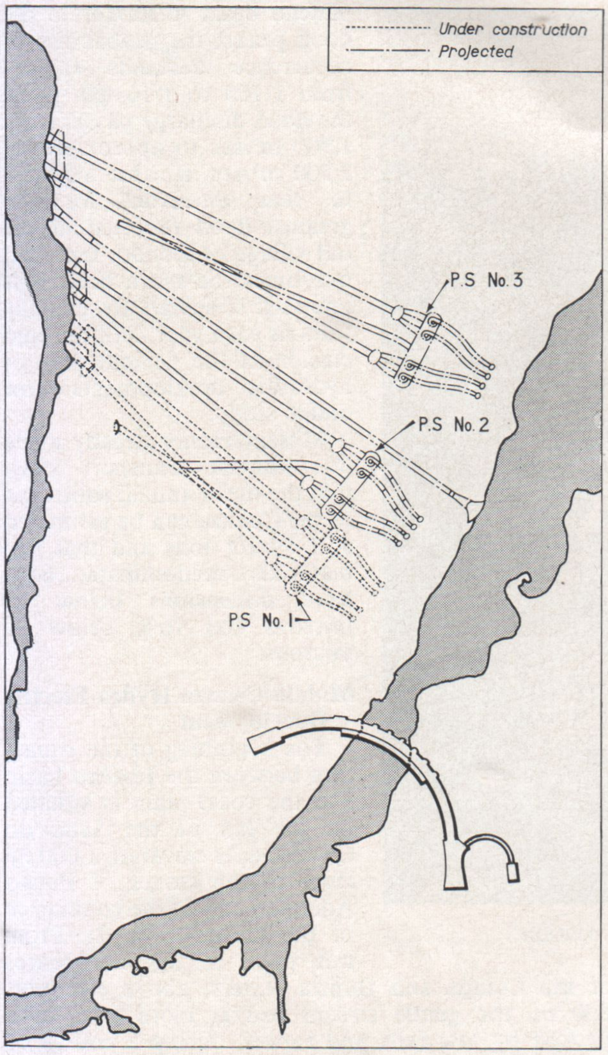


Fig. 5. Plan of site showing Cambambe No. 1 power station and the proposed Nos. 2 and 3 stations

a thickness of 10 m and capacity of 50 × 10^6 m^3, will be used as valuable compensation of the inflows during the critical dry-season period in September and October. During a dry year like 1955, the minimum available flow will be raised from 130 m^3/sec to 166 m^3/sec. The corresponding annual firm output will then be 1,250 GWh. Taking as a basis the exceptionally dry year of 1958, this value reduces to 1,020 GWh.

The Dam

The dam is situated at the top of the Cambambe Rapids, leaving the greater part of the right upstream bank free for the establishment of successive hydraulic power circuits, in correspondence with the demand for power and with the regulated flow from the storage works higher up the catchment (Fig. 5).

The geological structure of Cambambe site is formed by an igneous metamorphic complex, on which rests a sedimentary series with interbedded layers of consolidated shales, sandstones and conglomerates. Though the initial geological investigations, comprising prolonged boring and microseismic exploration, showed that foundation conditions could be made satisfactory only by removing superficial fractured belts on the valley sides, when excavation works were started attention was called to shear planes in subhorizontally bedded strata and other undetected important tectonic accidents. The need for more intensive exploration was then recognised, which led to the definition of all the particular features of the tectonic structure of the local rocks. Besides the occurrence of frequent thin argillaceous films between alternating beds of sandstone and shale, three major faults were detected, one at the base of the steep, rocky wall located on the right side of the valley; another running SW–NE, downstream, on the left abutment, parallel with the general structure of the region, and a third, not so important by the width of the fractured zone as by the direction and continuity of its surface, almost parallel to the right side of the canyon. After these complementary geological investigations, foundation treatment at the dam site became a major item in the project.

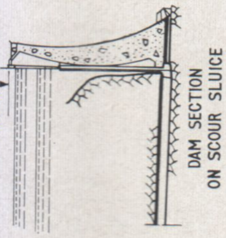
The study and the complete solution of the new problems is still in progress. Fundamentally the treatment proposed, and in part already executed, consists of replacing the ground and claylike materials in the fractured zones by concrete, and in systematically washing and grouting all altered and fissured rocks included in the zone to a depth of about twice the thickness of the abutments, where the loads transmitted by the dam to the foundation are distributed. The more-frequent occurrence of slip planes at higher levels—elevation 105 m on the left side and 102 m on the right side—led to the adoption of artificial gravity abutments. These and a continuous saddle, which also acts as a transition structure, distributing and reducing stresses in the rock, warranted a symmetrical layout to the arches. In former designs the structure was conceived as a double-curvature arch with single-centre circular arches of variable thickness; later, after the less-favourable foundation conditions were recognised, the arch was improved, with advantage to the abutments and to the structural behaviour, by the adoption of triple centred arches. The following values are representative of the geometrical characteristics of the arch:

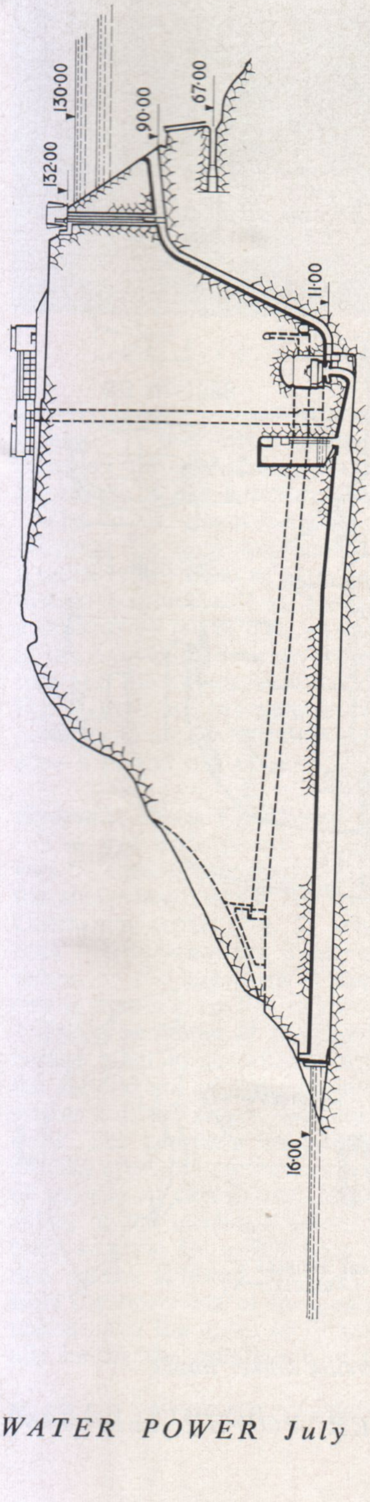
Maximum height	80 m
Length including abutments	300 m
Top thickness at crown	3·0 m
Base thickness at crown	13·3 m
Volume, including abutments	217,000 m^3

A complete analysis was made by the trial-load method, with triadjustment, and by model tests in which foundation singularities were considered. Stresses determined by analytical and experimental methods were in accordance; the inclusion in the model of a weaker zone at the left abutment, between elevations 70 m and 90 m, with a deformability five times greater than the rest of the foundation, did not have a significant influence on the static behaviour of the structure.

Moreover, the model tests disclosed the existence of high tensile stresses, upstream, in the saddle of the central cantilevers, so that the value was recognised of arranging a joint from the face of the dam to one-quarter of its thickness, where it was verified that tensile stresses were inferior to compression, corresponding to dead load.

The importance of uplift forces to the stability of the foundations at the site, where sandstone, silt and argillaceous shales are interbedded in subhorizontal strata, led to the reinforcement of the usual relief drains with a lower drainage-gallery system in the interior of the foundation zone; this gallery system





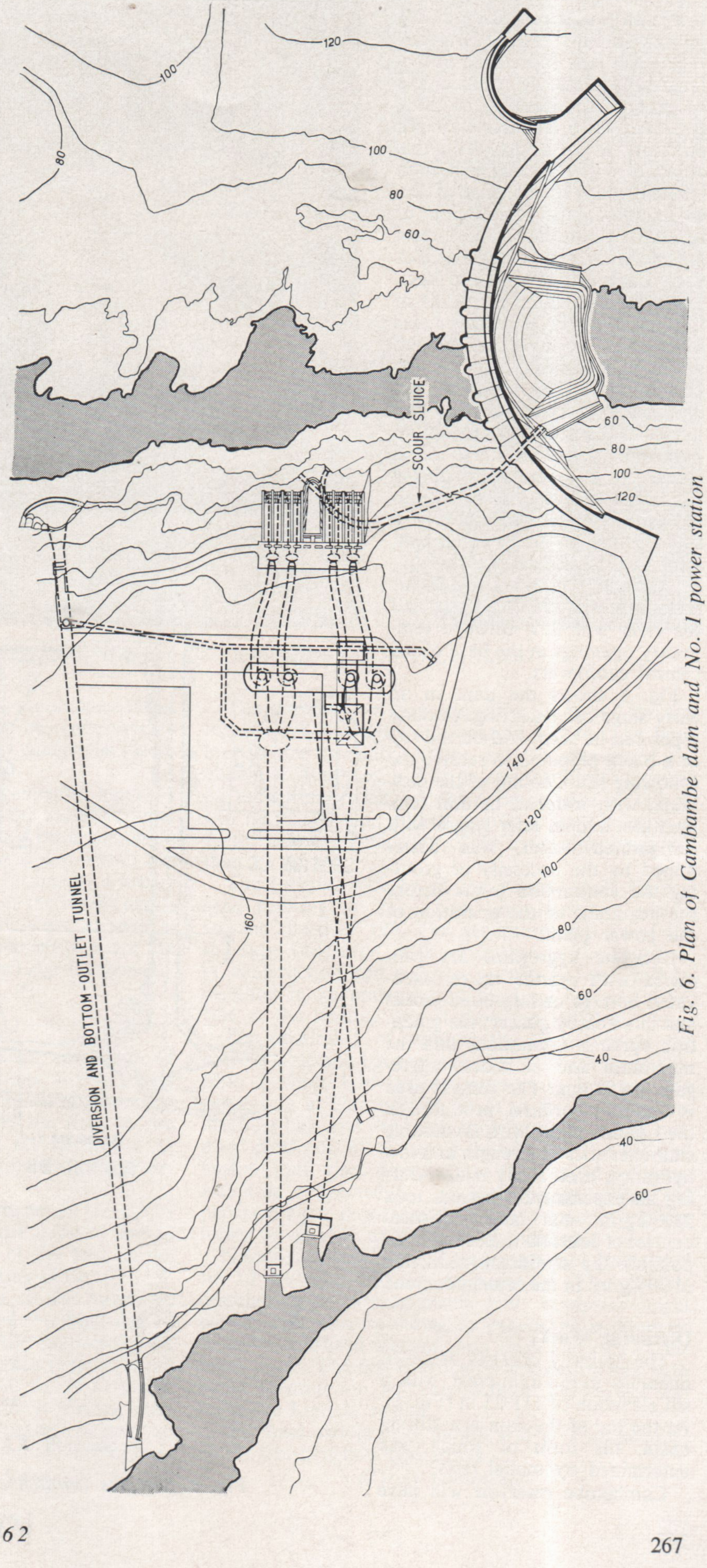


Fig. 6. Plan of Cambambe dam and No. 1 power station

will also improve the grouting pattern and the general control.

The relevant importance of tectonic upheavals determined the necessity of an efficient controlling system to ascertain the standard of safety at all times. With this objective, the instrumentation scheme, which is still under study, contemplates the installation of reversed pendulums and strain meters, with invar wires, in holes drilled deeply into the rock mass.

Work at the dam was started in October 1959 when the river was diverted. The diversion tunnel, which will be used later as the bottom outlet (Figs. 7 and 8), was designed for a capacity of 500 m^3/sec at full flow. Thus the entire dam site is available for initial construction operations during the low-flow period, from July to November, under protection of a thin concrete arch cofferdam; later, in the rainy season, the tunnel capacity will be exceeded, the cofferdam will be overtopped, and the river will flow through temporary openings in the base of the central cantilevers.

Fig. 1 shows the dam in an early stage of concreting. Cooling pipes can be seen, laid on the top of a block prepared to receive the following lift. Cooling of the concrete, with water at natural temperature, and in later stages with refrigerated water, was determined by the necessity of grouting the contraction joints before the beginning of the operation of the power plant.

Concrete aggregates are produced with granite rocks, excavated both in underground works and in a nearby quarry; the gradation curve is continuous and the maximum size of coarse aggregate is 150 mm. The cement used is standard portland, produced at the Luanda plant, with favourable characteristics of strength and low hydration heat. Early mixes, during an experimental period, took 230 kg/m^3, but later statistical control of concrete mixes rendered possible the significant reduction of 30 kg/m^3 in the cement content.

Discharge Works

The spillway consists of seven openings in the dam crest, with a sill elevation of 111·25 m (Fig. 6). At the toe of the dam is a stilling basin, the form of which was determined by model tests.

Cambambe reservoir will have

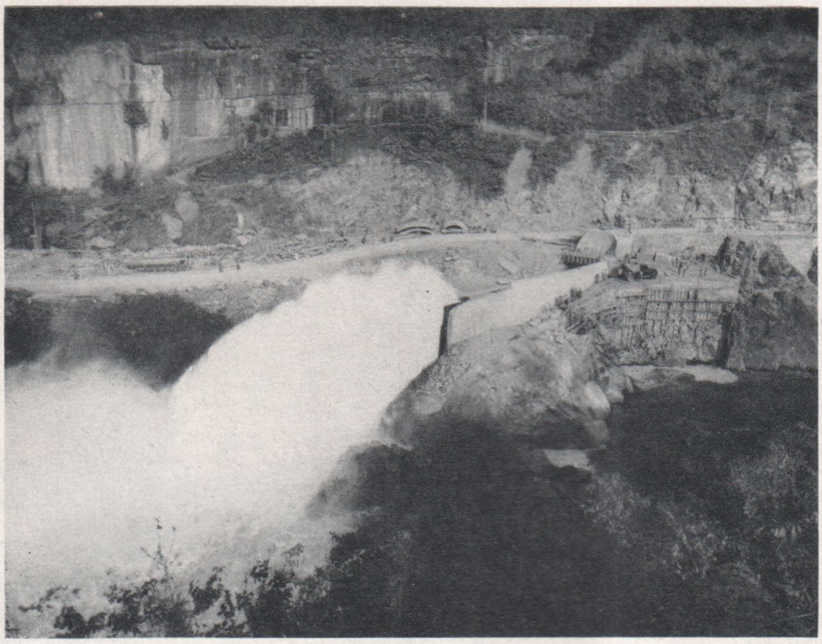


Fig. 7. Discharge from bottom-outlet and diversion tunnel

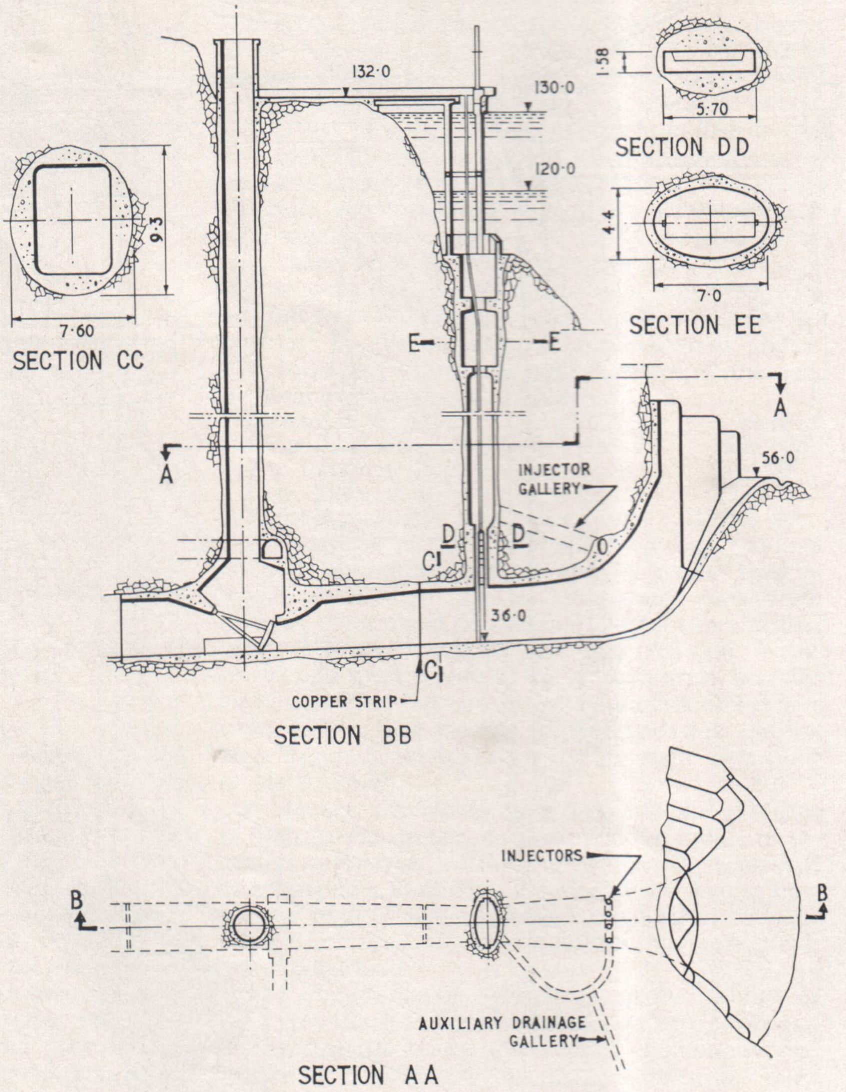


Fig. 8. Sections through diversion-tunnel intake

Fig. 9. A view inside the combined bottom-outlet and diversion tunnel

a large-capacity bottom outlet and a scour sluice (Figs. 6 and 7); the scour sluice will be continuously operated during the rainy season to ensure the desilting of the intake structure (Fig. 8).

The bottom outlet has been conveniently made by adapting the diversion tunnel by the installation of a radial-type regulating gate, designed for a maximum discharge of 800 m³/sec. The scour sluice, which has a capacity of 140 m³/sec, was also formed by a tunnel in the right bank between the toe of the intake structure and the downstream toe of the dam, as seen in Fig. 6. Both are equipped with injectors to scour the portals and ensure that they are unclogged, especially after a period out of service (Fig. 8).

Hydraulic Power Circuit

The hydraulic power circuit takes advantage of very favourable topographic conditions, as it bypasses the sharp bend which the river describes down the Cambambe rapids (Fig. 5). Whereas the slope of the river bed between the intake and the tailrace is 35 m/km, on the alignment of the hydraulic power circuit it amounts to 100 m/km.

The programme of the development of the Cambambe plant in accordance with the demand led to the subdivision of the equipment of the first power station into two stages, each consisting of two 65-MW units. The complete independence of the hydraulic circuits upstream of the turbines led to a high degree of security in exploitation and to the suppression of valves at the scrollcase inlets. Intakes (Fig. 6) were built with the sill at elevation 90·00 m, 21 m under that of the spillway openings, thus rendering possible the operation of the generating sets before the execution of the upper section of the dam and especially before the installation of the gates.

The tailrace level is at elevation 16 m and the top water level was fixed at elevation 130 m. The head loss in the hydraulic circuit, for the maximum discharge of 70 m³/sec, is 2·28 m, and the effective power on the turbine shaft, for the average head of 112 m, will be 92,500 h.p., corresponding to an efficiency of 90%; the overall efficiency of the hydraulic circuit will then be 88·5%.

The turbines will be of the vertical-shaft Francis type running at 231 r.p.m. and having a metric specific speed of 198. The generators will be of the self-supported type, with advantage to the sequence of construction and erection operations, and will be installed in an underground machine hall on either side of the loading bay at elevation 19·70 m.

The possibility of building the substation on the narrow tableland between the river canyons made possible a short bare-copper connection between the generators at elevation 16·60 m in the underground machine hall and the main transformers, on the outdoor platform, at elevation 147·00 m. The lift and busbar shaft rises directly into the control building, which is connected to the high-voltage switchyard platform by a short tunnel. A transformer workshop forms an annexe to the control building.

Nominal generating and transmission voltages will be 10 kV and 220 kV respectively. The 220-kV double-busbar arrangement will comprise eight panels, four corresponding to generating equipment, three to overhead transmission lines and one to the bus coupler. The first overhead transmission line, now under construction, will extend about 200 km and will serve the Luanda region.

Our final article next month will give an account of the construction operations.

(To be continued)