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SYNOPSIS An outburst of warm springs together with the development of an extensive area of high pore-water pressures occurred during the first filling of the 50m high earth and rock fill Itezhitezhi Dam on the Kafue River in Zambia. These and other unanticipated events led to extensive geological and hydrogeological investigations that resulted in the implementation of unusual remedial measures. The remedial work was completed before the reservoir reached its full supply level. The dam has since performed successfully. The problems are reviewed in terms of the significance of the site geology. The hydrogeologic problems were found to be caused by the presence of a modified karstic terrane developed on a mineralized, faulted and deeply weathered bedrock of granite and associated rocks. Small differences between the river levels and the piezometric levels in deep orings contributed to a delay in problem identification. The problems encountered and their causes are thought to be without recedent.

ESCRIPTION

tezhitezhi Dam is a storage structure with a height of about 50m n the Kafue River in Zambia. The dam consists of rock fill hells, a core of residual clay, and suitable transitions.

The right abutment, Itezhitezhi Ridge Hill, is a granite ridge hrough which two diversion tunnels 15m high and 13m wide ere driven successfully with virtually no support. The left butment is a gently sloping hillside underlain by residual soils eveloped on granite. Beyond the left abutment is a knob of elatively unweathered but fractured granite in which the spill-ay was excavated. Still farther to the northeast, some 1500m om the spillway, is the borrow area for core material. Here, sidual soils, developed on a tourmaline granite, reached a depth f 10 or 15m. Upstream from the axis of the dam on the left side f the reservoir is another granite outcrop that was exploited as e quarry for the rock fill.

Just above the damsite the Kafue River makes a right-angled end. A tributary, the Musa, entered the Kafue River at this bend. he Musa valley, in which the major portion of the reservoir is cated, is aligned with the Kafue downstream of the bend. These lationships are shown on Figure 1.

The surficial geology and the preconstruction borings made ong the axis of the dam indicated that the river flowed within portion of a rift valley characterized locally by a down-faulted, aben-like depression in the granitic rocks. The alluvium neath the floor of the Kafue valley is underlain in places by diments of the Karroo series. The sediments reached a thick-ss of about 100m beneath the axis. A section through the valley ong the axis is shown in Figure 2. Borings extending through e Karroo were generally terminated at or a few feet within the derlying granite, the top of which was often noted to have a ll developed weathering profile. Water levels in drillholes extending into the granite beneath the Karroo sediments were at or within one meter above river level.

It was considered that the stability of the dam would be a function primarily of the strength of the Karroo sediments, commonly designated as mudstones, which had been influenced locally by faulting caused by differential settlements near the valley walls. The underlying granite was considered to be the firm basement and was not investigated in any detail. This conclusion was reinforced as construction progressed and granite of good quality was exposed in the diversion tunnels and quarry. A cross section through the dam showing the relatively flat slopes adopted on account of the mudstone is given in Figure 3. Great care was exercised in treating the surface of the mudstone and assuring that its strength would not deteriorate between the time of exposure in the river bottom and placement of the first layers of fill.

EVENTS DURING FILLING

The design elevation of the reservoir at maximum pool is 1029.5m; tail-water level is 985m. The river hygrograph exhibits a flood peak in March, a rapid decrease until June, a slower decrease to minimum flow in November, and a fairly rapid rise from December until March. The reservoir was allowed to rise after the flood of March 1976, during the falling hydrograph, to assure a slow and controlled rate of filling. The water level reached 990m at the end of May, remained at 1002m from mid-June to early September, reached 1006m by the end of October, and stood at 1007.3m at the end of November. This elevation corresponded to 50 percent of the final head of the reservoir. After evaluating conditions at this reservoir level, during the period of low inflow, it was planned to raise the level to about 1015m by the end of the next high water.

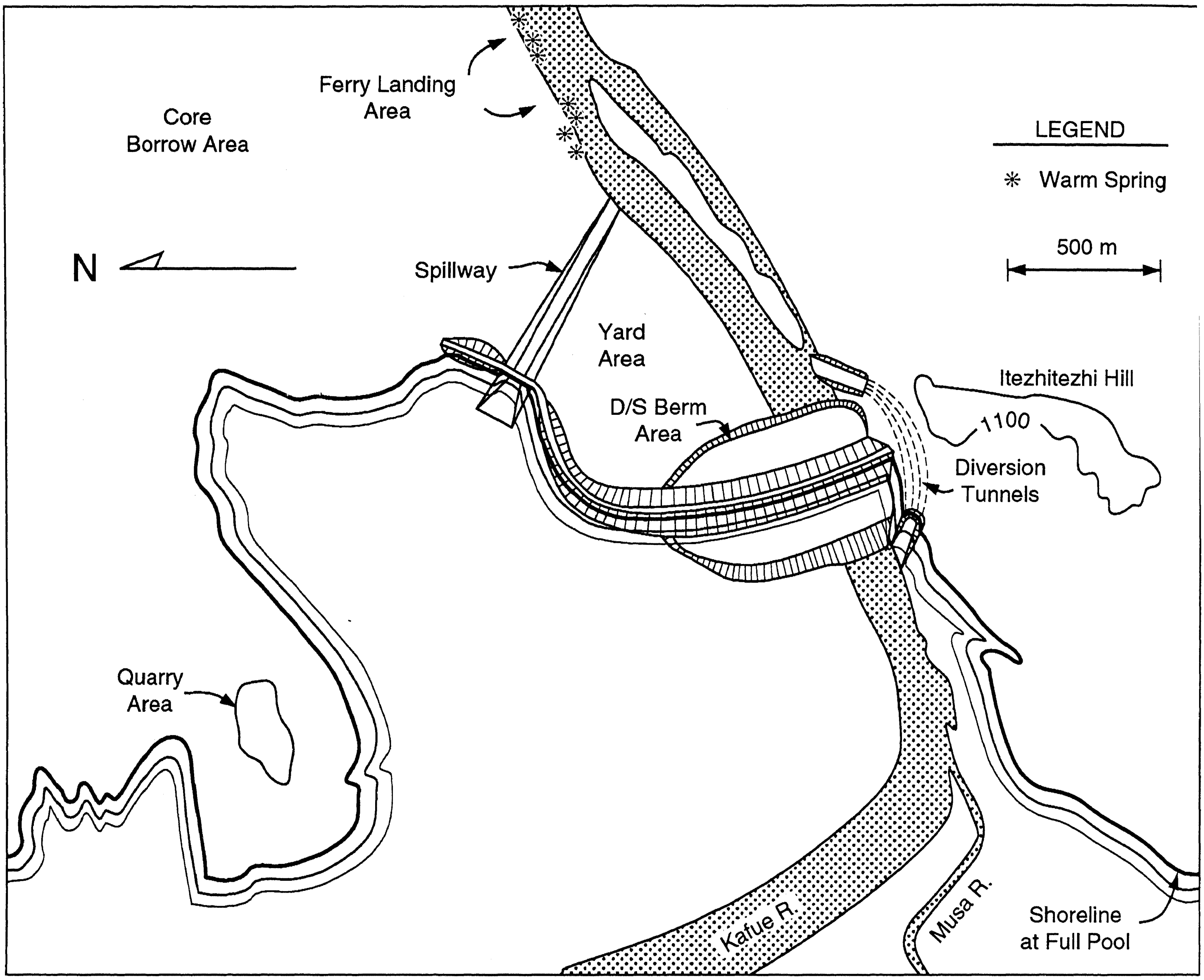


Figure 1. Plan view of the Itezhitezhi Dam site.

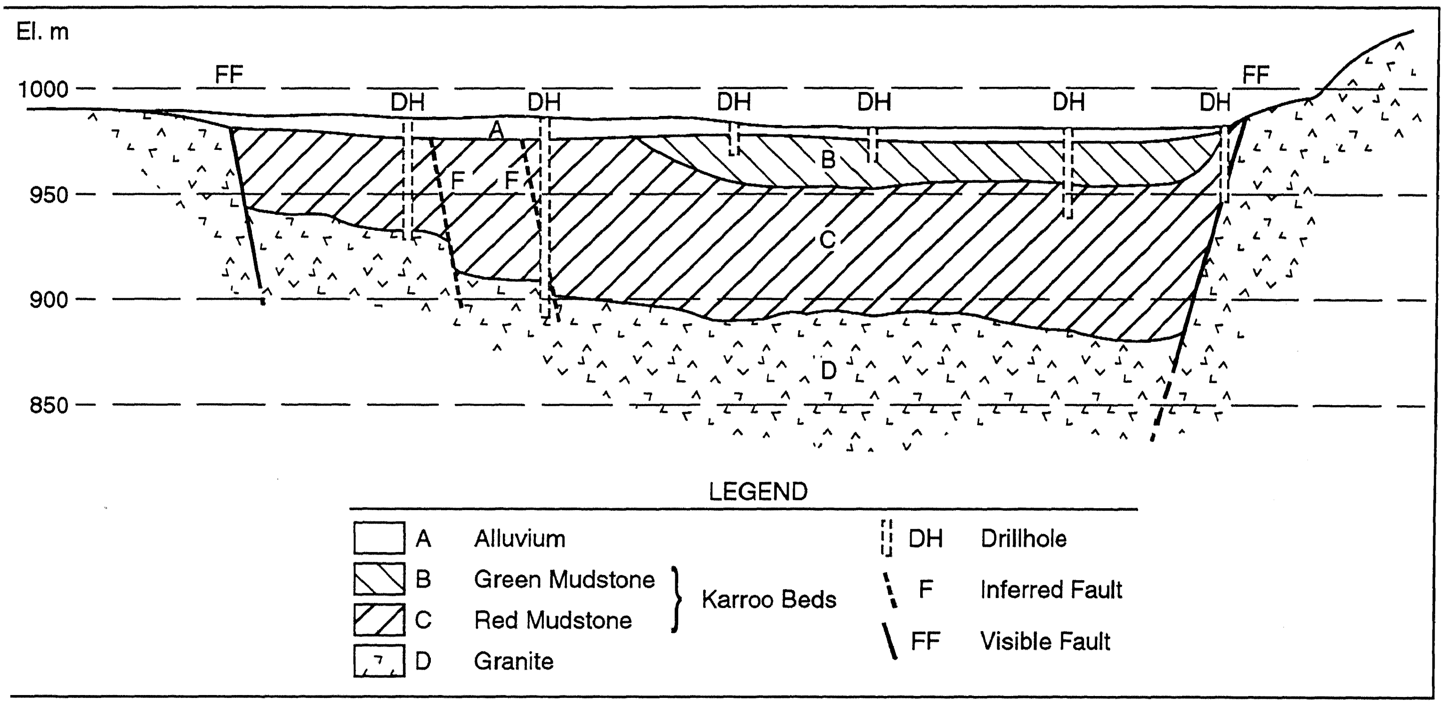
However, in late August 1976, with the reservoir at elevation 1002m, springs appeared in the flood plain downstream of the dam, accompanied by an efflorescence leaving a white deposit around the smaller seeps where considerable evaporation had occurred. As the reservoir continued to rise to a maximum elevation of 1016m, a notable increase in the spring activity occurred, and portions of the river bank developed local instability and slides took place. The water emerging from the springs had a maximum temperature of 35 to 36° C, in contrast to the reservoir temperature of about 20°. Drillholes into bedrock near the springs indicated artesian pressures, but the magnitudes were questionable because the casings were not tightly sealed in the overlying materials.

Hot springs were not unknown in the vicinity. Longola Hot Springs, some eight kilometers to the southeast, perennially discharged from 10 to 12 liters per second, at elevation 998m, with water at a temperature of 70 to 85° C.

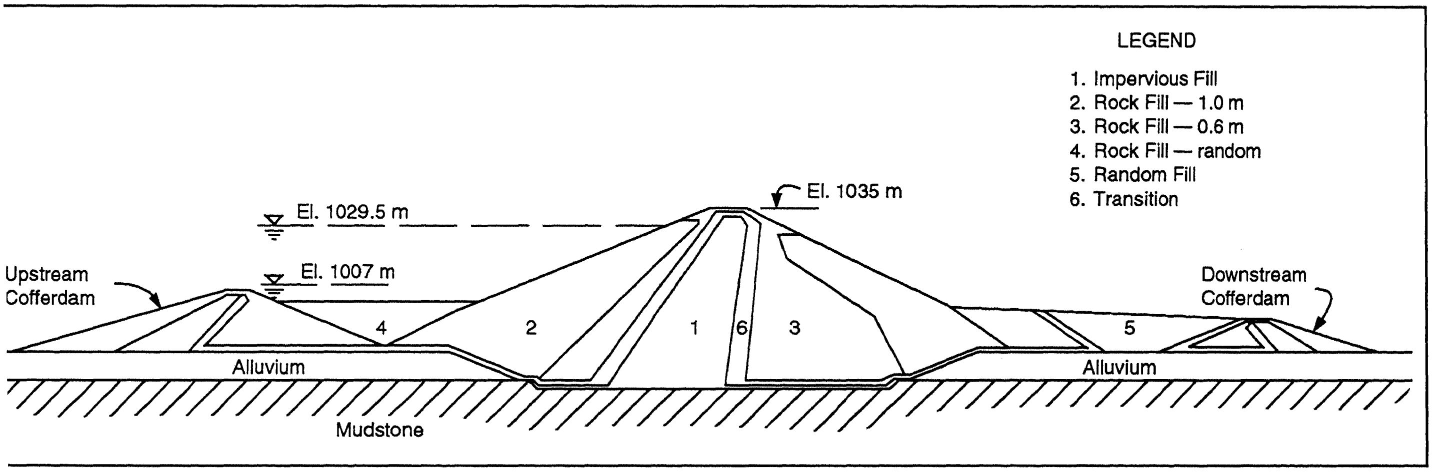
The unexpected springs and evidence of riverbank instability downstream of the dam led to a series of actions:

1. The reservoir was lowered to facilitate the installation of piezometers with proper seals and to permit the construction of relief wells if this should be found desirable. By lowering the reservoir, excess fluid heads that would otherwise be encountered during these installations would be eliminated or greatly reduced.

2. To reduce the piezometric levels acting at or below the dam foundation, it was decided that the piezometric level at the base of the mudstone should be maintained permanently at or below elevation 998m. Calculations indicated that stability against sliding of the dam or of the dam and underlying mudstone was not endangered at even higher levels, but at levels above 998m the downstream riverbanks became unstable.



igure 2. Cross section through the valley along the axis of the Itezhitezhi Dam.



gure 3. Cross section through the Itezhitezhi Dam.

Test wells were installed to judge the effectiveness of relief wells in lowering the piezometric level at the base of the mudstone.

Piezometers were installed to ascertain the piezometric conditions in the bedrock, especially below the mudstone. Many of these piezometers were provided with recorders.

Attempts to detect other springs, particularly those that might discharge into the river itself, were made by use of thermal imagery of the water surface and barefoot traverses of the river bottom. Thermal measurements of the surface of the alluvium were made along several traverses.

6. An extensive program of drilling, coring, field geology and airphoto interpretation was undertaken.
7. To investigate the thickness of the mudstone, extensive geophysical seismic surveys were taken, including refraction traverses on land and continuous seismic profiling in the river and reservoir.
8. Studies of water chemistry, particularly of 0^{18}, deuterium, and tritium, were undertaken to attempt to judge the extent to which the water emerging from the downstream springs originated in the reservoir.
9. Attempts were made to measure the discharge from the springs and relief wells.

FINDINGS

As a result of the investigations, several facts emerged that indicated complex conditions and required explanation for proper understanding of the situation. One of the more surprising facts was the appearance of bubbles in the reservoir when its elevation was lowered to or below 1007m. Some of the bubbles appeared close to the upstream toe of the embankment. Others extended in a line upstream along the former Musa River for a distance of several kilometers. Subsequently, when the reservoir was again raised above elevation 1007m, the bubbles ceased. Chemical analysis indicated that they consisted of carbon dioxide.

After installation of many piezometers sealed into the bedrock, it was found that the piezometric level was strongly influenced by reservoir level, but that it was nearly constant from points upstream of the dam to points as far as a kilometer downstream. That is, the hydraulic gradient in the bedrock beneath the mudstone was very small. Nevertheless, flow from the springs and boreholes was substantial (several thousand liters per minute when the reservoir level was at 1007m) and the maximum temperature of the water continued to be about 35° C. The flow could not be determined precisely, because it was found that several large springs did indeed emerge under the bed of the river downstream of the dam.

The recording piezometers established in the bedrock exhibited a cyclic variation of up to 12cm with a period corresponding to that of lunar- and solar-induced earth tides.

Two experimental relief wells of 30cm diameter were installed in the granite with equipment available at the job. They produced substantial flows and resulted in a decrease of piezometric level in the bedrock on the order of a meter for a considerable distance from the wells. Yet, isotope studies and conductivity measurements indicated little trace of reservoir water in the effluent.

Additional drillholes indicated that the degree of weathering and permeability of the granite underlying much of the mudstone in the graben forming the valley at the damsite were greater and extended to greater depth than had been inferred from the initial drilling program.

PRACTICAL QUESTIONS

Many of the findings at first seemed paradoxical. The granite beneath the mudstone was unquestionably very permeable in some locations and the flow from measurable springs was roughly proportional to the reservoir level, but, at least during the first two cycles of partial filling of the reservoir, the warmest water appearing downstream did not appear to come from the reservoir. The tidal effects on piezometric observations suggested that much of the permeability of the granite might originate in narrow joints the dimensions of which could be altered significantly by the changes in stresses associated with the gravitational forces of the sun and the moon. The permeability of the granite beneath the mudstone did not appear to be compatible with the quality of the granite seen in the diversion tunnels. Thus, it became apparent that a satisfactory comprehension of the engineering aspects of the observations would require a better understanding of the geology and hydrogeology of the site. Nevertheless, as this understanding was being developed, three practical questions emerged.

1. How many relief wells (or what total discharge) would be required to keep the piezometric level downstream below elevation 998m?
2. Could relief wells drilled into the unweathered granite be completed in such a way as to avoid erosion of the overlying weathered material, with possible consequent development of piping beneath the mudstone?
3. Would it be safe to raise the reservoir to elevation 1029.5m after the previous maximum of 1016m.

PRACTICAL ANSWERS

The practicality of relief wells under full reservoir conditions would depend on the relation among discharge that could be achieved from the wells, reservoir level, and the bedrock piezometric levels. If such a relation could be established for reservoir levels below 1016m, it could be extrapolated to full reservoir level, and the relief wells designed on this basis. The relation was investigated two ways.

A complex hydrogeological model, developed by the designers, was fitted to the observational data and used successfully for forecasting. In addition, considerable insight and sufficiently reliable forecasts were achieved by an empirical approach in which the discharge from the test wells was correlated with the excess head ratio (EHR) at piezometers in the vicinity of the wells. The EHR is the dimensionless ratio of the piezometric head above tailwater (excess head) to the gross head acting of the dam. From the correlation, the total well discharge was predicted that would be required to maintain piezometric levels below 998m under conditions of maximum head and most unfavorable tailwater.

It was found that the correlation was not valid when the reservoir was lower than 1007m, but that it could be preserved by assuming the head to remain at 1007m during the period of lower levels. This assumption would imply that the excess head recorded by the piezometers was produced by an artesian pressure in a deep-seated aquifer.

The foregoing finding was made during the early stages of the drawdown of the reservoir. Subsequently, the reservoir was drawn down to 990m before refilling began. During the entire period that the reservoir remained below 1007m the piezometric levels in the artesian aquifer exceeded reservoir level. The difference reached as much as 10m. With the progressive development of the relief wells, the artesian pressure gradually decreased.

The hydrogeological model and the empirical correlation gave similar results and permitted the conclusion that a sufficient number of relief wells could be installed to keep the downstream piezometric levels below elevation 998m even at high reservoir.

To avoid the creation of erosion tunnels in the mudstone and in weathered granite just below the mudstone, it was apparent that the relief wells would have to be sealed to depths appreciably below the top of unweathered granite to ensure that the flow of water into the screened portions would occur only through sound granitic rock. Thus, in each relief well the hole above the top of the screen was sealed for a minimum of 5m into the sound granite. To prevent the occurrence of artesian flows, which could cause erosion during installation and development of the wells, the wells were installed from embankments high enough to assure a positive head at any stage of construction. As a further precaution, casing in each relief well was placed from the surface to a point just above the base of the mudstone and cemented into place before any drilling was done into the artesian aquifer below. In all, 30 wells were developed. Six were located on the downstream berm, five in the Yard area 600m downstream, and 19 at the Ferry Landing 1500m downstream (Figure 1).

In May and June of 1978, as the reservoir was being allowed to rise to maximum level for the first time, three small earthquakes occurred near the site. Their Richter magnitudes ranged from 5.2 to 5.6. Earthquakes of this magnitude had been experienced previously in the vicinity. Hence, the effect of the reservoir was probably only to have caused the earthquakes to occur during first filling rather than at some later date. However, immediately following the earthquake of June 8-9, the piezometric level in the granite rose about one meter. This occurrence raised the possibility that earthquakes in the future might increase piezometric levels above elevation 998 before additional relief wells, if needed, could be installed. Tests demonstrated that air lift pipes, which were installed in some of the relief wells and were operated by a standard air compressor, would be extremely effective in reducing piezometric levels in the vicinity. It was decided, therefore, to provide such installations for possible emergencies. After these installations were made, no further earthquakes of comparable magnitude and piezometric rises of this sort were noted.

The foregoing steps appeared to constitute a reasonable engineering approach to the problems associated with the deep granite aquifer. However, without a reasonable geological and hydrogeological framework by which the observed facts could be explained, the engineering steps could be considered no more than expedients. To be satisfied that the adopted solutions were fully adequate, it was considered essential to understand at least in a general way the geologic history of the area and its consequences with respect to the present hydrogeology.

HISTORICAL GEOLOGY

At the time the project was conceived, only rather broad studies of the regional geology had been carried out. Griffiths (1976) of the Zambia Geological Survey had begun to work in the area at about the same time the project was initiated, and considerable cooperation developed between the Survey in its general studies and the investigators of conditions at the dam site. As a consequence of these studies, the following extremely brief outline of the historical geology emerged.

1. Deposition and lithification of one or two series of sediments in early pre-Cambrian times, including some carbonate rocks (limestones and dolomite).

2. Granitization and granitic intrusions as well as metamorphism of pre-existing sediments that remain as scattered pendants and zenoliths. The carbonate rocks were transformed into marbles.

3. Development, still in pre-Cambrian times, of a regional shear zone and associated intrusions of tourmaline granites. The shear zone, generally less than one half kilometer in width, connects two present day outcrops of carbonate rocks located some 20km from the damsite in either direction. This ancient shear zone extends beneath the foundations of the main dam and passes through the core borrow area. The tourmaline granites contain interstitial calcite which appears to account for the deeper weathering profile developed on these rocks.

4. A prolonged period, several hundred million years in duration, of weathering, erosion, and partial solution of carbonate materials occurring in stringers, as joint filling and as interstitial grains in the granites and metamorphic rocks. Local collapse, stress relief, and differential weathering occurred as a result of solution activity.

5. Sedimentation of the continental Karroo deposits (late Paleozoic to early Mesozoic age), mostly mudstones and sandstones.

6. Regional faulting during and following the Karroo period.

7. Prolonged weathering and erosion, for a period of some 200 million years. Much of the Karroo was removed during this time and only small remnants were left locally, such as those beneath the dam foundation. During this period additional solution, deposition, and re-solution of calcite, quartz and chalcedony occurred where there were open and calcite- and silica-filled fractures. A deep groundwater flow system developed along the major zones of previous faulting and where carbonate bearing rocks had been present.

8. In Pleistocene to Recent times, deposition of Kalahari sands in adjacent areas resulting in a blockage and rearrangement of the major river valleys. Continuation of weathering and solution of carbonate rocks. Also, probable occurrence of rift activity or other regional tectonic stress readjustments that would account for the current seismic activity. The site is now recognized to lie within a branch of the East African Rift Zone, although the pronounced topographic expression of the other better known rift valleys is nearly absent at this site.

SIGNIFICANCE OF SITE GEOLOGY

The foregoing thumbnail sketch of the historical geology has the following implications with respect to the engineering problems at the site:

1. The carbonate-rich granites and metamorphic rocks permitted a type of weathering and erosion not normally associated

with the geomorphology of igneous rocks. This condition, and the long repeated weathering, faulting, and mineralization, led to a modified karstic terrane. The areas of present high relief, such as the right abutment and the quarry, consist of granites with low carbonate content and with less faulting and brecciation than the low areas. The low areas, including the main Kafue valley, Musa valley, and deeply weathered zones at the left abutment, had developed over tourmaline granite and other calcite bearing igneous and metamorphic rocks as well as rocks that had been subjected to intensive faulting and brecciation.

The existence and significance of the tourmaline granites locally in the bottom of the graben and in the core borrow areas were not recognized during the initial exploration because the initial borings were discontinued at or shortly below the granitic surface under the sediments.

Marble was not encountered until one of the last of nearly 100 drillholes was completed in the reservoir about half a kilometer upstream from the dam. This hole encountered 50m of partly weathered granite breccia with marble and sandstone (Karroo?) fragments.

2. The groundwater flow system that developed in the solution openings was of regional extent, areally pervasive and very deep-seated. The high permeability of the near-surface bedrock and soil was confirmed by the lack of integrated surface drainage in the reservoir and other adjacent areas as determined from airphotos taken prior to construction. Thus, the granite may be considered "karstic", but the size of the openings, unlike those in karstic limestone, was limited on account of the limited extent of the calcareous inclusions.

3. Before the reservoir was filled, some of the regional flow discharged locally into the base of the Kafue River under low differential piezometric heads. Following reservoir filling the direction of flow was reversed beneath portions of the reservoir nearest the dam because the piezometric head in the deep regional flow system was still strongly affected by the low piezometric head existing downstream of the dam. However, the effect of the reservoir was to produce a local impediment to the discharge of the regional flow system and so cause a general increase in piezometric levels of the deep flow system in the reservoir area. This is similar to the hypothetical case described by Patton and Hendron (1974). This increase caused piezometric levels downstream from the dam to rise some 10m or more above their pre-reservoir levels, which were, however, still below the corresponding reservoir levels. Because of the occurrence of the Karroo mudstones and perhaps other still unknown hydraulic aquitards in the Kafue valley near the damsite, the deep bedrock aquifer remained relatively separate from the reservoir waters. However, the discharge of the deeper and warmer waters was increased by the presence of the reservoir.

   Some of the data suggest that the piezometric level at depth in the regional flow system in the granites was relatively constant in the dam and reservoir area at about elevation 1007m, the critical elevation with respect to release of gas bubbles.

4. The temperature of 30 to 35° C of the warmest springs suggests that a significant part of the flow path is at a depth of 300 to 700m or more, far below the contact between the mudstone and the granite.

5. Studies of reservoir induced seismicity (RIS) have been continued by the project engineers aided by an extensive study undertaken by the Central Water and Power Research Station, Pune, India (Tarapore, 1989). Following the seismic activity described earlier, the site underwent a quiescent period of about three years from 1979 to early 1982, whereupon the seismicity sharply increased in August, 1982. Tarapore's study of microearthquakes recorded over the period March 1981 to April 1987 identified several thousand events with a median Richter magnitude of about 1.3. Most epicenters occurred within the reservoir and a high concentration of these were located near the dam. The great majority of this microseismic activity occurred in the period from 1982 to 1984. The two largest earthquakes in this period had magnitudes of 4.4 and 4.0. From January 1984 to April 1987 the activity in the reservoir area decreased to background levels and activity was almost absent near the dam. Given the geology present, the microseismic activity could have been related to collapse of solution cavities and/or deep-seated carbonate rock pillars due to changes in effective stresses caused by the reservoir filling and the initial reservoir drawdowns as well as to local tectonic activity.

CONCLUSION

The conditions at the site appear to be without precedent. The significant features were obscured because the granites in the outcrops were of superior quality to those beneath the river valley, and because the piezometric levels in the deeper aquifer were nearly identical to the river levels and normal groundwater levels.

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