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Heightening of Malawi's Kamuzu II dam

A. Yziquel and J.M. Monclar, Sogreah, France
M.J. Chirwa, Lilongwe Water Board, Malawi

Heightening of the Kamuzu II dam in Malawi, to meet increasing water demand for the capital city Lilongwe was achieved in one year, without interfering with the operation of the scheme. The design and implementation of the project are described here.

The city of Lilongwe became the capital of Malawi on 1 January 1975. Since then, its population has grown at a rate of 8 per cent a year. Water demand has been met by building two dams, Kamuzu I and Kamuzu II.

To continue meeting the ever-increasing demand, the Lilongwe Water Board decided to heighten Kamuzu II dam, to double the live storage capacity of the reservoir from 8.9×10^6 m^3 to 19.8×10^6 m^3 by raising the water level a further 5 m.

The solution adopted was to install concrete fusegates. This avoided any risk of submersion during the works phase, while at the same time shortening the works by a half.

General layout of the scheme

Fig 1. shows a plan view of the structures before and after the dam height was increased

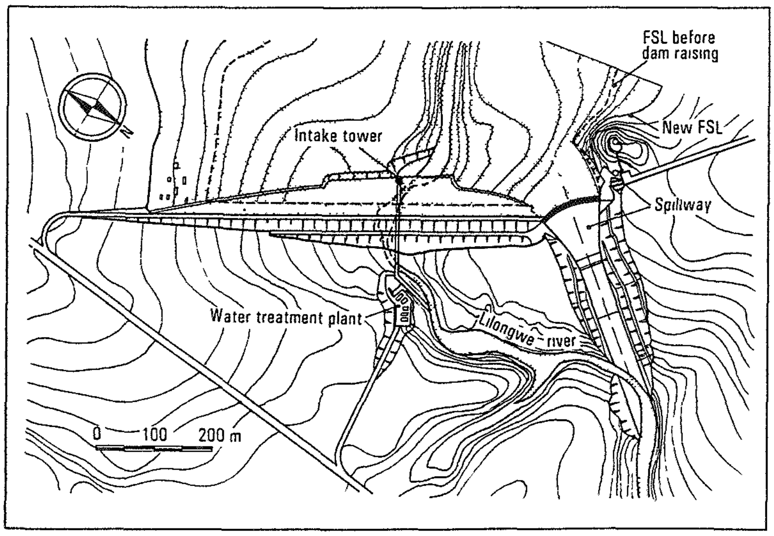
The original scheme included a 22 m-high earthfill dam, with a crest length of 700 m The upstream batter is 3H/1V, and the downstream batter, 3H/1V.

The ungated spillway, which has a sill length of 105 m, is on the left bank, as shown in the photograph.

The picture, showing the rock outcrops, also clearly reveals that the downstream part of the spillway chute was not lined during the original construction, as it was believed that the foundation rock was of equivalent quality to the concrete used to construct the spillway chute. After six years of operation, the rock was severely worn. At the same time as the heightening of the dam, it was decided to study a way of protecting the rock within the chute, and also downstream of the spillway. These works will also be described in this article.

The outlet structure consists of a reinforced concrete intake tower in the reservoir, with a maximum flow capacity of 8 m^3/s.

Fig 1 Plan view of structures



Natural features of the site

Spillway geology

The foundation rock is exposed in the spillway chute. It consists of foliated gneiss bars of extremely variable hardness, dipping downstream at an angle of E65°. Because of the orientation of the bars, it is clear that flow has a marked tendency to run to the left.

In addition, boreholes drilled at the beginning of the dam heightening project revealed that the sill was resting on completely weathered biotite gneiss.

Hydrology

Mean annual inflow is estimated at 139×10^6 m^3, representing 14 times the original reservoir volume

The maximum probable flood has a discharge of 2500 m^3/s and the design flood (the 1000-year flood), a maximum discharge of 1500 m^3/s.

The maximum flood for the construction phase was the 10-year flood, which has a peak discharge of 240 m^3/s.

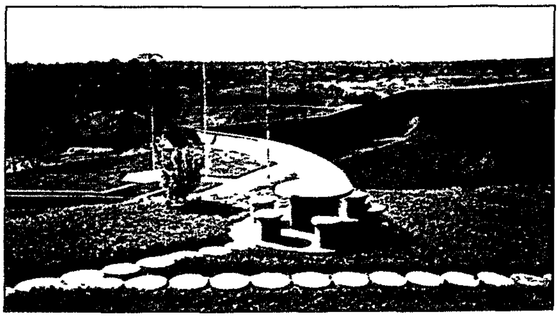
Given the low discharge capacity of the outlet structures, it was clear that practically all the construction flood would have to flow over the spillway as it was being built.

Operating conditions

Fig. 2 shows the way in which the reservoir is operated. It gives the mean levels as well as the mean levels plus or minus a standard deviation for the period 1991-1997, that is, for the six years of operation of Kamuzu II dam.

It can be seen that the spillway overflows for four months, from mid-January to mid-May. The reservoir is kept full for seven months. The base of the sill (el. 1087) is submerged for 10 months of the year.

This reservoir is the main source of water for Lilongwe during the months of dry weather. One of the requirements that the operator had to contend with



View of the sill prior to raising.

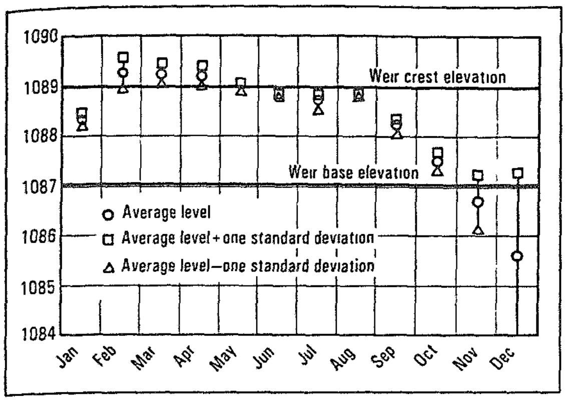


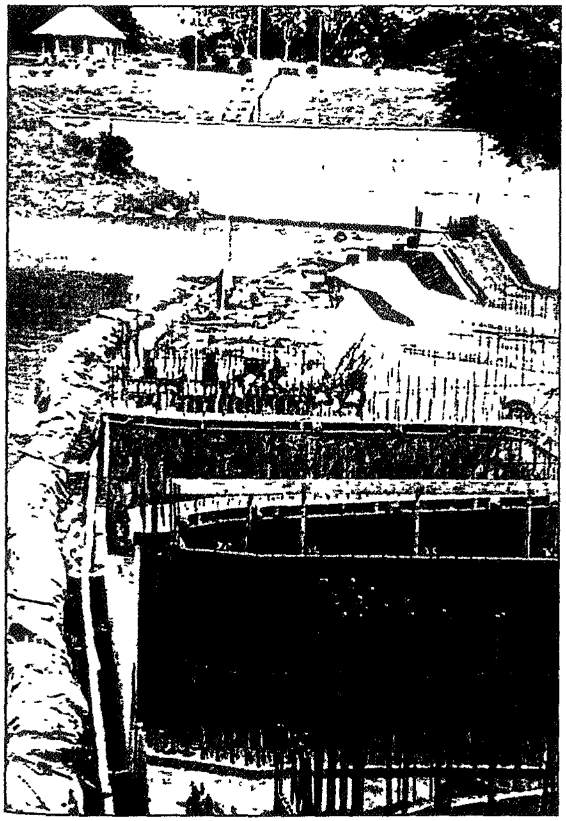
Fig. 2. Operation of the Kamuzu II reservoir

was that the dam should be heightened without any loss of water supply.

Solution adopted for increasing the dam height

The call for tenders to heighten the dam was made on the basis of a traditional solution involving increasing the elevation of the existing sill by 5 m and then heightening the earth dam and side walls of the spillway by 5 m. Raising the side walls adjacent to the dam meant excavating down to a depth of 3 m below the normal pool level, that is, to el. 1086. The time allowed for the work to be carried out under the protection of cofferdams was only five months, including the time for actually constructing the cofferdams.

In view of the reservoir management conditions and peak discharge of the construction flood, building the side walls meant that there was a risk of submerging the earthfill dam. The programme of works was therefore spread over two years, with very strict limits in terms of works phasing.



Construction of fusegates during flood periods.

Table 1: Main characteristics of the fusegates	
Number of fusegates	14
Height of fusegates (m)	5
Length of sill equipped with fusegates (m)	105
Length of each fusegate (m)	7.5
Bottom elevation of fusegates (m)	1089
Top elevation of fusegates (m)	1094

The successful contractor, CMC di Ravenna, however proposed an alternative for increasing the dam by means of concrete fusegates.

The cost of this bid was slightly lower than the lowest one for the basic solution, but its main advantage was that it would solve the problem of protecting the dam during the works while at the same time enabling the project to be completed in 12 months instead of 24.

It was for these reasons that the solution involving concrete fusegates was adopted.

The concrete fusegate solution

The solution adopted involves using 13 concrete fusegates of the labyrinth type, and one smaller straight fusegate on the right side of the spillway.

The choice of concrete as the main construction material was dictated by the desire to reduce maintenance costs.

The main characteristics of the fusegates, which are numbered from 1 to 14 from right to left along the spillway, are as shown in the Table.

No. 1 is a straight concrete fusegate that overturns for a flood with a return period of 200 years, that is, equivalent to a flow of 769 m^3/s. This fusegate is located against the right side wall. Provision has been made in the contract for the client to retain shutters, spare wells and seals to enable a quick replacement of this gate to be carried out behind stoplogs installed to a height of 2 m above the sill.

A progressive overturning schedule was defined first of all, with a view to fixing the elevations at which the fusegates would overturn.

This was then further examined using a scale model, to determine the best overturning sequence to avoid waves being formed as a result of the asymmetric flow.

Work programme

The quantities involved for heightening the dam using fusegates were compared with those of the traditional solution.

The amounts of concrete and fill represented 50 per cent and 14 per cent, respectively, of those required for the traditional solution.

In addition, the principle of the solution adopted meant that the fusegates could be built during flood periods (see photograph, left).

The contractor could thus propose a one-year construction schedule, instead of the two years envisaged for the traditional solution.

Effect of fusegate overturning on water supply reliability

One of the main concerns expressed by the owner in relation to the use of fusegates was the possibility that the upper part of the reservoir would be lost when the first fusegate overturned.

The contractor proposed that the fusegates should

Table 2: Water levels before and after heightening of the dam

Level	Before	After
Normal pool level	1089	1094
Max. high water level	1093.8	1095.67

overturn for a flood with a return period of 200 years.

Although this was a low probability risk, the owner was not completely satisfied.

If the flood were to occur, the owner would still have to meet his commitments to supply water during dry weather flows.

It was demonstrated by Hydroplus International that as the volume of the reservoir represents 14 per cent of the mean annual inflow, replacing a fusegate for an event with a 200-year return period, if done within a short time, would not lead to any loss of water for the owner.

It was therefore decided that the first fusegate to overturn would be a straight one of reduced width and that provision be made to implement a speedy reconstruction of the fusegate.

Detailed description of the structures

Heightening of the dam

The normal pool level and highest water levels before and after heightening of the dam are shown in Table 2.

It can be seen that the normal pool level is only 20 cm higher than the highest high water level before the project.

As the crest of the dam before the heightening was at el. 1095, it was simply a question of placing fill up to the highest high water level and adding a parapet.

Modification of the sill

The sill was modified as shown in Fig. 3.

In view of the limiting factors associated with controlling the water level, the platform required for installing the fusegates was built on the downstream part of the existing sill.

As mentioned earlier, exploratory boreholes were drilled at the start of the project to check whether the rock foundation was of sufficient quality to withstand the forces associated with heightening the dam. These showed that the foundation rock was in fact completely weathered gneiss.

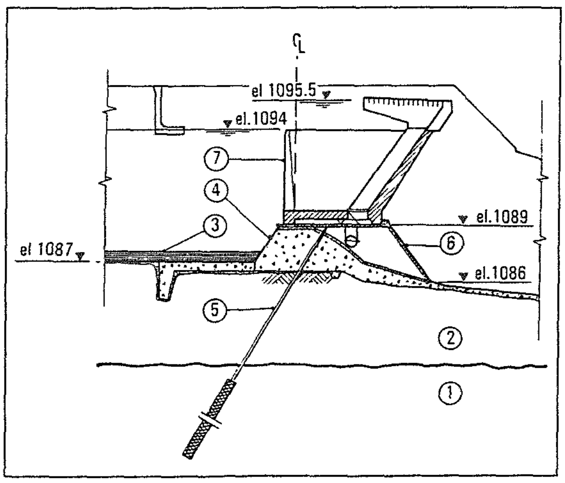
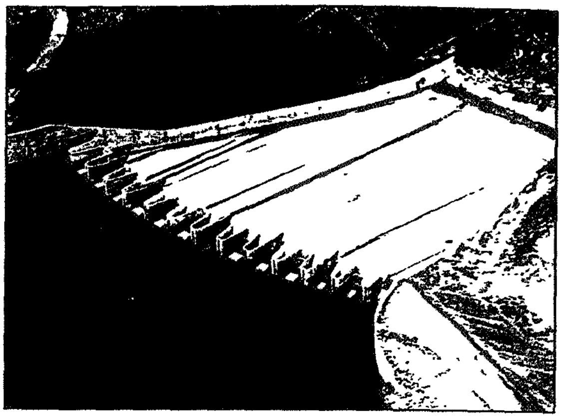


Fig. 3. Modification of existing sill. 1 = highly weathered gneiss; 2 = completely weathered gneiss; 3 = clay blanket; 4 = existing sill; 5 = prestressed tendons; 6 = new sill; and 7 = Hydroplus fusegate.



View of the completed spillway.

This difficulty occurring at the start of the works was overcome by installing 14 post-tensioned anchors anchored 17 m lower, in the weathered rock. It should be noted that this foundation problem had no effect on the schedule. Installing the post-tensioned anchors did indeed delay finishing work on the sill, but it was completed before the arrival of the fusegate forms on site. It would have been quite a different situation with a traditional sill, where the installation of anchors would have been on the critical path.

The upper part of the sills was concreted after the anchors had been tensioned. Concreting was done in alternate blocks, with the reinforcement bars crossing through the joints between the blocks. In this way the sill forms a monolithic unit, so that the forces can be redistributed if an anchor should fail.

Description of the fusegates

As mentioned earlier, two types of fusegate were used at Kamuzu:

- Labyrinth type fusegates, consisting of a caisson opening upstream, with its crest in the shape of a labyrinth. This layout means that the nappe formed by moderate floods is relatively small. The total length of a labyrinth is about three times that of the sill. Thirteen elements of this type are fitted on the dam sill (numbers 2 to 14).
- A straight-crested fusegate. It was decided to incorporate a fusegate of this type, as the client wished to be able to replace the first one easily.

With the exception of the replacement fusegate, all the original elements were made of concrete cast in situ. The labyrinth fusegates were formed with a steel mould consisting of three parts. The lowest part was used to form the fusegate chamber, and the other two parts for the partitions. Each labyrinth fusegate required 45 m^3 of concrete.

The straight concrete fusegate was of very simple design and did not require an elaborate mould.

About 15 m^3 of concrete was required for its construction.

The 14 fusegates were divided into seven groups. The first three gates are each supplied by their own well. The other fusegates are designed to overturn in pairs or triplets.

Overturning of a group is initiated by a so-called master fusegate with a well. As it overturns, it opens an aperture in the sill, so that the overflowing water enters the chamber of the other fusegate(s) in the same group.

The wells fitted to the master fusegates were made of steel and were bolted to steel inserts set in the fusegate concrete. A device on the well lip was used to set the toppling elevation accurately, thus avoiding problems with construction tolerances.

Scale model studies

Because of the convergence caused by the spillway chute and the progressive toppling of the fusegates, flow conditions are three-dimensional.

A scale model study was the only way of finalising the flip bucket needed to improve energy dissipation downstream of the spillway, and to define the fusegate overturning sequence with certainty.

A 1:60 model was therefore built at Sogreah's hydraulics laboratory in Grenoble.

As indicated above, in view of the rapid deterioration of the rock inside the chute, the downstream part of the left-bank side wall risked being undermined by flow diverted by the beds of hard gneiss.

It was therefore necessary to design an energy dissipating device that would eliminate the risk of undermining by frequent discharges, that is, up to the discharge which would overturn the first fusegate (749 m^3/s, with a return period of 200 years).

It was then necessary to check that erosion in the downstream channel would remain acceptable for the design flood and PMF.

The solution adopted was to construct six teeth, as shown in the photograph below.

The convergence caused by the side walls indeed concentrates flow in the middle of the spillway.

The underlying principle of these teeth is first to force the jet to spread outwards, so as to obtain a more homogeneous distribution of flow, and then to spread it in a downstream direction by the alternating teeth and horizontal parts of the chute.

After many tests, it was possible to determine an overturning sequence which minimised both spilling over the side walls of the chute and erosion downstream of the teeth.

On conclusion of the scale model tests, the overturning sequence was defined.

One concern often expressed in relation to a design featuring fusegates is what happens to them after they have overturned.

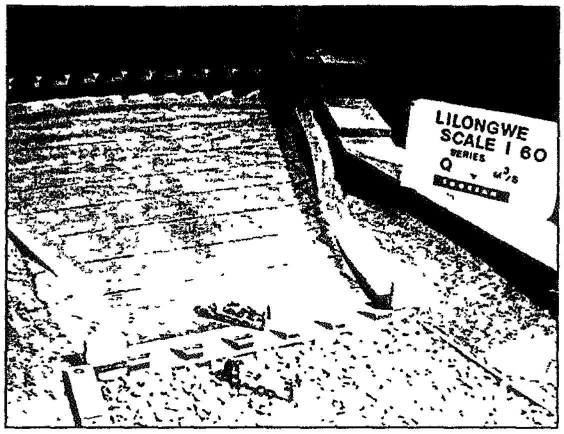
In the case of Kamuzu II, and especially in view of the existence of the teeth at the downstream end of the spillway, it seemed advisable to study the behaviour of the most critical fusegate, that is, no. 14, as this is the heaviest one which would overturn with the lowest discharge.

A ballasted fusegate meeting the necessary similitude conditions was therefore overturned on the model, and its trajectory was monitored. In these conditions, it was demonstrated that the 120 tonne fusegate not only bounced over the teeth, but it was immobilised about 60 m downstream of the spillway.

Conclusion

The dam heightening works were completed within the one year construction period, as planned by CMC di Ravenna, and the Lilongwe Water Board was able to store water one year earlier than originally envisaged.

The main advantage of the solution proposed by CMC di Ravenna was that it reduced the risks of submersion during construction work. Indeed, the sill was modified and the fusegates built without interfering with the dam and, in particular, without having to excavate the side walls 3 m below the normal pool level.



View of the scale model.

This greater freedom during the diversion stages meant that work to heighten the dam could be completed in 12 months instead of the 24 which would have been needed if a traditional solution had been adopted.

The systematic use of a scale model made it possible to study the complex hydraulic operation of such a spillway in detail. This would not have been possible with any other method. ◊

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A. Yziquel is the Manager of the Large Projects Division, International Branch, at Sogreah, and is the Project Director of the Third Lilongwe water supply project. For the past 25 years he has been involved in the design, preparation of tender documents and construction supervision for dams and hydropower schemes, in particular Kouris (Cyprus), Bagré (Burkina Faso), Turkwel (Kenya), Katse (Lesotho) and Yali (Vietnam). In addition he acts as expert advisor on geotechnical problems and specialized design calculations within this field of activity.

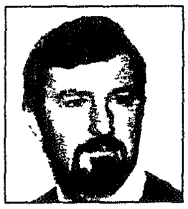
J. M. Monclar works in the Large Projects Division of the International Branch of Sogreah. He is the Resident Engineer for the construction of the Third Lilongwe water supply project. For the past 25 years he has specialized in the supervision of works as resident civil engineer for irrigation schemes, dams, hydro plants and other major hydraulic developments, in Egypt, Iraq, Mali, Kenya and Lesotho. Between 1990 and 1994 he was resident engineer for construction management of the New Esna hydro plant on the Nile in Egypt.

Sogreah Consultants, 6 rue de Lorraine, 38130 Echirolles, France.

M. J. Chirwa is a registered Civil Engineer and Corporate Member of the Malawi Institution of Engineers. He is currently pursuing a postgraduate degree in Construction Project Management in the UK. His experience includes site supervision the Mzuzu dam and water treatment works in Malawi, project identification, design and implementation of urban systems, as well as being a Project Engineer for the Lilongwe Water Board.His current position is Project Implementation Manager for the Third Lilongwe water supply project involving heightening of the Kamuzu dam II and three other construction projects to expand water supply facilities in the City of Lilongwe.

Lilongwe Water Board, PO Box 96, Lilongwe, Malawi.

A. Yziquel



J.M. Monclar

M.J. Chirwa