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Fusegates enhance safety and increase capacity at Eikenhof

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In 1998, the Eikenhof dam in South Africa was heightened by 2 m, increasing the storage capacity by 19 per cent to 29 × 10^6 m^3. The project combined a fixed reinforced concrete labyrinth on the service spillway with straight-crested reinforced concrete Hydroplus fusegates on the auxiliary spillway sill, allowing the designers to improve the overall safety levels for the dam, while leaving the embankment crest level unchanged. Storage was increased by approximately 4.5 × 10^6 m^3, for a total project cost of US$ 250 000.

Eikenhof dam, on the Palmiet river in the Western Cape, South Africa, is a 47 m-high fill embankment dam with a service and an auxiliary spillway discharging over the right flank abutment. The service spillway is concrete lined, and comprises a steep chute terminating in a deflector/flip-bucket, which turns and throws discharges back into the river course. The auxiliary spillway comprises an unlined channel cut into weathered rock, with discharges spilling over an upstream concrete sill, which is positioned about 2.5 m above the service spillway sill level. The dam was originally constructed in 1977 and heightened by 1 m in 1988, at which time the auxiliary spillway was added.

The Groenland Irrigation Board, owner of the dam, supplies water primarily for apple and pear irrigation during the summer months of the year (October to April). Summer irrigators each own a portion of the dam's storage, which is filled by winter rainfall between May and September. Winter water users purchase water, which would otherwise be spilled from the dam, at a lower unit rate.

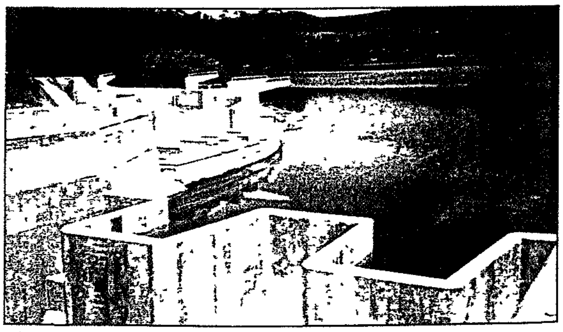
The second heightening of the dam, in 1998, was awarded as a turnkey contract, with the main contractor Hydroplus International sub-contracting ARQ Specialist Engineers and Stocks South for the civil design and construction respectively. The contract was initiated in March 1998 and the project was completed and impounding water to the new full supply level (FSL) by late August of 1998. By the time the first waters were being drawn for crop irrigation in early summer, the water level had reached approximately 300 mm below the new FSL. Accordingly, the Irrigation Board was able to realise almost the full benefit of the additional yield developed by the heightening within less than a year of the contract award.

Adapting the existing configuration of Eikenhof dam to accommodate a 2 m raising of the full supply level presented several interesting challenges to the designers. The dam had originally been constructed with a small side-channel spillway, of 200 m^3/s maximum capacity, running down the steep right abutment and returning flows into the river almost perpendicular to the direction of its course. Even though the large surface area of the dam in relation to its catchment, and the significant available spillway freeboard, give rise to a pronounced flood peak attenuation, this spillway capacity could be seen to be inadequate. At the time of the first heightening in 1988, it was decided that additional spillway capacity should be provided, and an auxiliary spillway was constructed to bring the total nominal spillage capacity to 790 m^3/s.

While the auxiliary spillway was only intended to spill water for a flood with a return period of in excess of 50 years, it was constructed as a cutting in weathered rock and the line of this chute traverses a fault of highly fractured and very soft rock. With slopes of more than 1 in 3 and a vertical height of more than 40 m, high velocities will be experienced during higher discharges and significant erosion and undercutting can be anticipated on this spillway. During the lifespan of the dam so far, the largest flood yet experienced would equate approximately to a 1 in 20 year event, and accordingly, the durability of the auxiliary spillway has yet to be tested

The capacity of the service spillway chute is restricted to approximately 200 m^3/s ignoring bulking at the final contraction, approximately one third of the way down from the crest. While the 1988 heightening made provision for a crest and top chute spillway capacity of 290 m^3/s, the capacity of the lower chute was never increased, and accordingly very low probability floods would not be entirely contained within the spillway chute In view of the highly erodible material alongside the spillways and the high velocities inherent to the service spillway, severe damage can be anticipated when flow is not retained within the concrete channel. This implies that significant damage to both the service and the auxiliary spillways could have been incurred during the passage of low probability floods. With a high likelihood of prolonged spillage and/or a lesser flood soon after a severe flood, considerable advantage could be seen in preserving, as far as possible, at least one of the spillways through a severe flood event.

Considering the combined operation of a service and auxiliary spillway, the pronounced flood absorption characteristics of the reservoir and the inherent sensitivity of operation of Hydroplus fusegates to actual attenuated hydrograph shapes, a high level of accuracy for the flood hydrology was considered necessary. Previous phases of development of Eikenhof dam had not required such a detailed hydrological analysis, and accordingly it was necessary to re-work the flood hydrology from first principles.



The service and auxiliary spillway sills

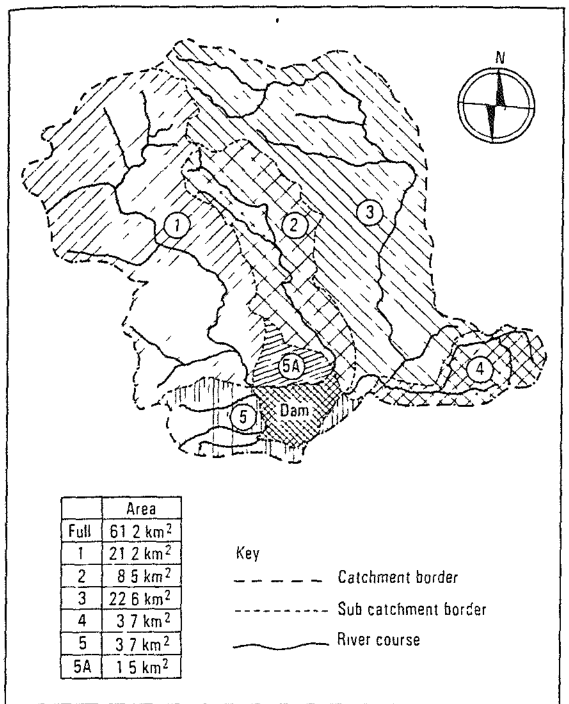


Fig 1. The catchment composition

Regional and catchment hydrology

Although Eikenhof dam drains a catchment of just 61 km², the area in question is relatively mountainous and experiences some of the highest rainfall in South Africa. Whereas the flatter areas to the west, inland from Cape Town, are subject to mean annual precipitations (MAPs) of the order of just 600 to 1000 mm, the mountainous areas of the Eikenhof catchment receive more than 1500 mm of rainfall per year.

A study of the existing hydrological information showed it to be rather too coarse in nature for the design of the proposed labyrinth service and fused auxiliary spillway combination. Because the performance of the proposed spillway and the sequence of fusegate tip offs are inherently sensitive to the shape of each flood hydrograph, it was considered necessary to derive these data relatively accurately, as a means to facilitate an effective fusegate design and operation.

On close inspection, the Eikenhof dam catchment, although relatively small at 61 km², can be seen to comprise five separate sub-catchments, each with significantly different runoff response times and each feeding the dam largely independently (see Fig. 1). Because the earlier hydrological analyses had assumed a single river course and a single homogeneous catchment, the associated hydrographs developed did not reflect the disparate arrival time of flood peaks from each of the various sub-catchments. The result is that the earlier hydrographs exhibit a broad base with a narrower, single peak. They also reflect higher peak flow values than is actually likely to be realistic, and indicate longer times to peak and develop higher peaks for longer storm durations.

It would not usually be considered appropriate or worthwhile to sub-divide a catchment of such limited extent to ensure a greater degree of accuracy for inflow hydrographs.

However, in view of the particular nature of the Eikenhof catchment, the pronounced flood absorption characteristics of the reservoir, the inherent requirement of the Hydroplus system for realistic hydrology and the sensitive design of a combined service and auxiliary spillway, a comprehensive hydrological review of the dam's catchment was undertaken.

Table 1: Adjusted average 1 in 200 year catchment rainfall intensities

	Point rainfall for indicated storm durations (mm)						
Storm duration (h)	2	4	6	8	10	12	16
Earlier hydrology	196	249	278	300	315	331	347
New hydrology	195	247	264	274	280	286	292

Hydrology input data

To quantify the respective validity of the various input data, all the data were evaluated from first principles.

The Eikenhof catchment lies on the eastern side of False Bay and presents the first mountainous area to frontal weather approaching the Cape over the Atlantic Ocean from the southwest.

The general configuration of the Eikenhof catchment suggests that relatively short duration storms are likely to yield maximum inflow flood peaks and that flood volumes will not increase greatly for longer duration storms, as peak flows drop quickly. This fact was confirmed by each of the flood determination methods applied for the Eikenhof flood hydrology study.

A detailed review of the input data applied for the earlier hydrological calculations revealed discrepancies in the data sources, and unusually high intensity rainfall for longer storm durations at the rainfall gauge close to the centre of gravity of the catchment. The 24 hour 1 in 200 year storm rainfall intensity applied for the Eikenhof catchment in earlier work was approximately equivalent to the PMP values applicable to the winter rainfall region in which the dam is located. While studies by Görgens et al [1987[1]] observed that rainfall in the mountainous areas of the Cape tends to be significantly more intense than in the surrounding areas, and that it is perhaps more appropriate to factor rainfall intensities for storm durations of less than 24 h by the more extreme summer rainfall factors, this should only affect storm durations of less than one day. The consequence of these discrepancies in the earlier studies was a significant exaggeration of rainfall intensities for storm durations of 6 h and longer, as shown in Table 1.

Derivation of design and safety evaluation floods

The unit hydrograph method was the primary tool applied for the purposes of the analyses addressed here. However, to provide a check of flow peaks

Fig 2 The Eikenhof composite catchment

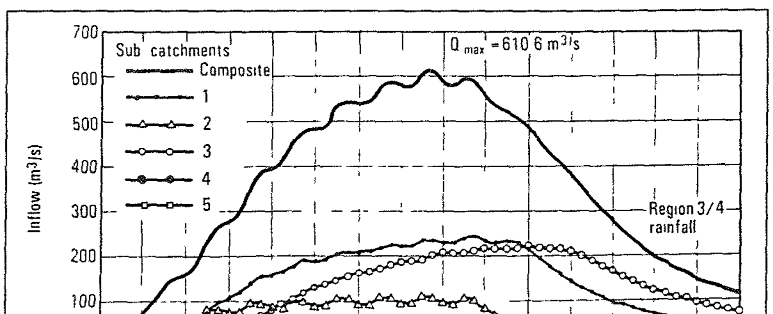


Table 2: Flood peak comparisons

Catchment variation/hydrology	Recurrence interval flood peak (m^3/s)		Critical storm duration
	1 in 200 years	PMF	(hours)
Earlier hydrology: single catchment	528	744	8 and 6
New hydrology:			
Single catchment	511	720	4 and 3
Composite catchment	435	673	4

Table 3: Flood volume comparisons

Catchment variation/hydrology	Flood volume in first 15 hours (10^6m^3)			
	Storm duration (h)			
Earlier hydrology - single catchment	2	4	6	8
1 in 200 year flood	-	-	12.7	13.6
PMF	-	-	19.4	20.5
Single catchment				
1 in 200 year flood	8.1	11.3	11.4	11.4
PMF	13	15.6	17.6	18.3
Composite catchment				
1 in 200 year flood	8.0	10.5	11.6	12.2
PMF	13.0	15.3	17.8	18.9

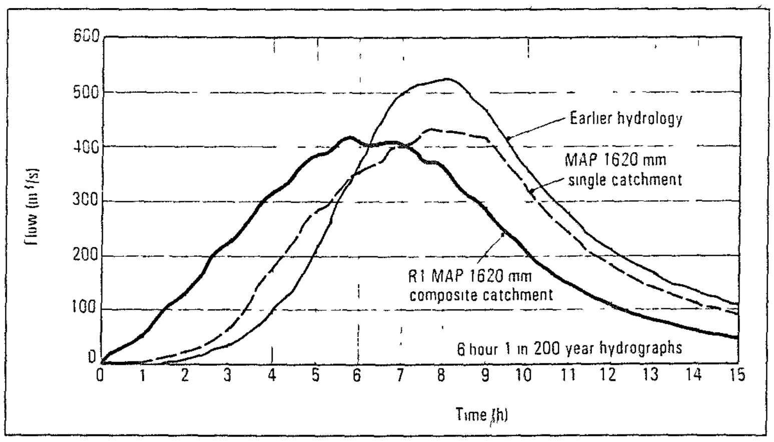


Fig. 3. Comparative hydrographs.

derived by this means, calculations using the empirical and regional maximum flood (RMF) methods were done. Each of the five sub-catchments was subjected to the same storm, on the same time base, and the associated inflow hydrographs were added together as they arrived at Eikenhof dam, to produce a single, composite catchment inflow hydrograph, for each of the floods under investigation. Fig. 2 shows each of the sub-catchment hydrographs on the same base scale as the composite hydrograph for an 8 h duration, PMF storm.

Tables 2 and 3 highlight the salient data for the 1 in 200 year and PMF inflow floods at Eikenhof, compared on the basis of the earlier and new hydrology and for a single and composite catchment. Fig. 3 shows the inflow hydrograph for the 6 h storm duration 1 in 200 year flood, for the composite catchment.

On the basis of the analysis, it was considered appropriate to apply the inflow flood hydrographs developed for the composite catchment, using the new hydrology.

For safety evaluation and a review of available spillway capacity at extreme flood flows, the inflow hydrograph for the PMF developed for the composite catchment was considered appropriate. The actual 'zero freeboard capacity' of the combined spillways was established by routing the PMF inflow hydrograph, factored by a range of multipliers, to isolate the hydrograph which yields a 'zero freeboard' outflow. If the corresponding ordinate multiplier were 1.25, then it could be stated that the zero freeboard capacity of the spillways is 25 per cent greater than the PMF, or that the spillways can accommodate a flood equivalent to 1.25 times the PMF, or that the flood surcharge capacity of the spillways is 25 per cent greater than the PMF.

For the design and safety evaluation, the following inflow floods were applied:

• RDD: Routed discharge for the 1 in 200 year, 6 h storm, producing an inflow peak of 417.5 m^3/s for the composite catchment.
• SED: Routed discharge for the 6 h storm PMF, producing an inflow peak of 656 m^3/s for the composite catchment.

In South Africa, the recommended design discharge (RDD) is applied for spillway design and the safety evaluation discharge (SED) is applied to assess absolute dam safety, at which the overall integrity of the dam must be maintained, although significant damage can be tolerated.

Spillway review

To establish the hydraulic characteristics of both the service and auxiliary spillways for Eikenhof and to ensure thereby that the options considered for raising the crest height were compatible with the existing spillway hydraulics, mathematical modelling of both chutes, using HEC-RAS software, was undertaken. This review indicated a critical capacity of 200 m^3/s for the chute of the service spillway. Furthermore, the hydraulic control point moves downstream from the spillway sill to the first contraction of the chute at higher flows. An absolute maximum capacity of approximately 590 m^3/s for the auxiliary spillway was also determined.

The early concepts for the heightening of Eikenhof dam using Hydroplus fusegates had been formulated around the installation of labyrinth fusegates on the service spillway. In revealing the shift in flow control point from the sill on the service spillway to the contraction a short distance downstream with higher flows, the hydraulic analysis demonstrated that this option no longer offered merit. With the control point downstream, tipping of gates on the spillway sill would obviously be of no benefit in terms of enhancing the discharge capacity, and furthermore, it was evident that the overall safety levels could be improved by restricting the maximum flow down the service spillway.

For maximum spillway discharges, the highest anticipated flow velocities were calculated as 25 and 22 m/s for the service and auxiliary spillway chutes respectively.

Spillway hydraulic design and dam safety

The key opportunity in heightening the Eikenhof dam using fusegates was to allow for the full supply level to be raised without requiring the raising of the embankment non-overspill crest level. On the basis of the spillway hydraulic review and the goal of improving overall levels of safety at the dam, the following design concepts were applied:

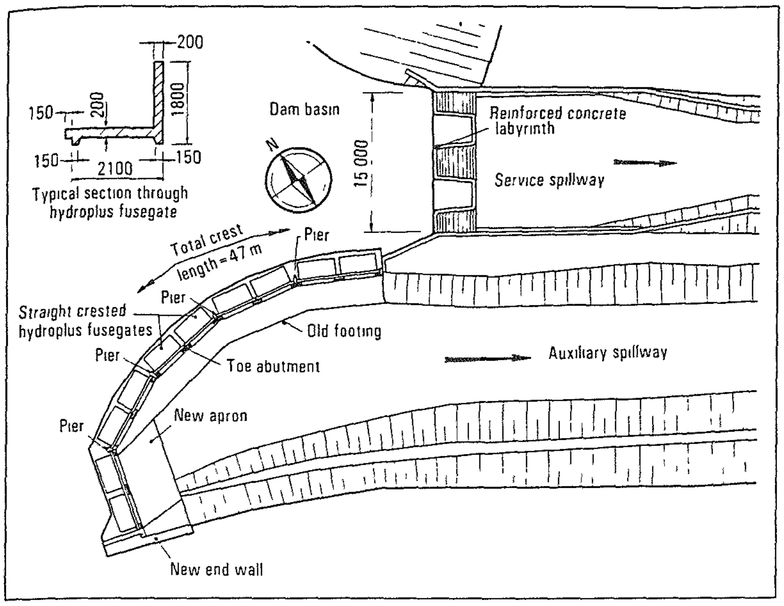


Fig 4 Spillway arrangement.

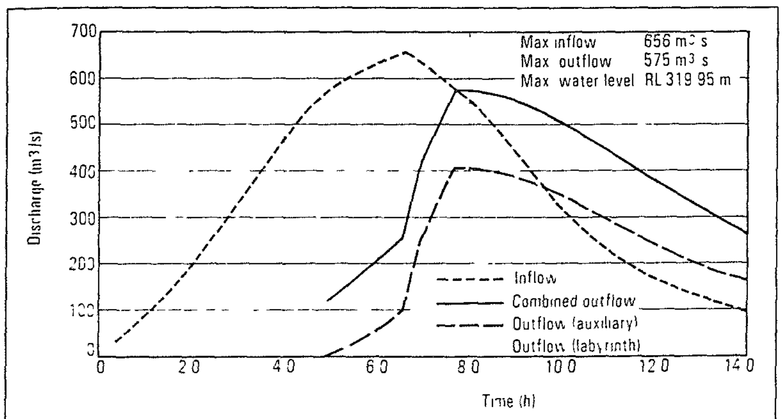


Fig 5 Discharge over the labyrinth and over the auxiliary versus combined outflow.

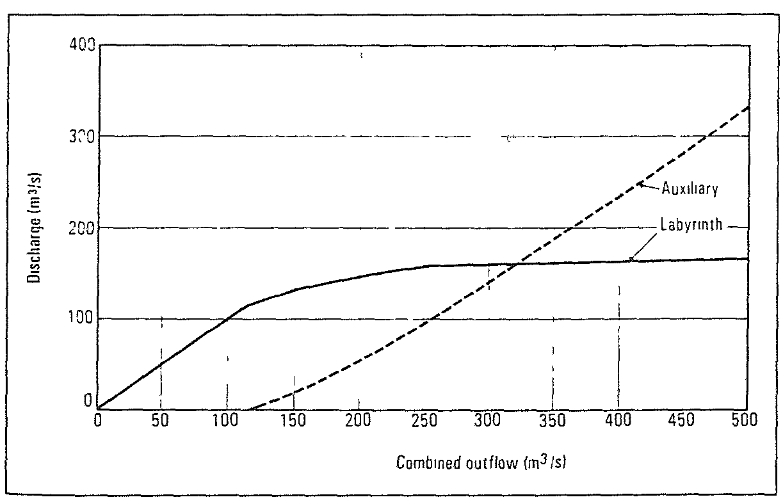


Fig. 6 Probable maximum flood. Inflow and outflow versus time relationship.

- The service spillway must be able to discharge at least a routed 1 in 50 year flood before the auxiliary spillway comes into action.
- At the RDD (1 in 200 year), flow in the auxiliary spillway must be kept as low as practically possible.
- Flow down the service spillway must not exceed 200 m^3/s in any circumstances.
- In the case of a major flood, it would be preferable to minimise damage to the service spillway, thereby allowing the continued safe operation of the dam during the rehabilitation of any flood damage experienced on the auxiliary spillway.

With the above as the primary design criteria, a set of the critical inflow hydrographs and a full hydraulic review of the spillways, a solution was conceived encompassing a fixed labyrinth sill for the service spillway (instead of labyrinth fusegates) and straight-crested fusegates on the auxiliary spillway.

The layout of the service and auxiliary spillway crest arrangement is shown in Fig. 4.

With this solution, the lower intensity (more frequent) floods are routed exclusively down the service spillway. The fixed labyrinth provides excellent discharge performance for comparatively low overflow depth. However, for larger floods, discharge down the service spillway will become restricted (which was previously not the case) as the critical capacity of the chute is approached (200 m^3/s), because of submergence of the labyrinth, with all excess flow routed down the auxiliary spillway. The throttling of the main spillway is also aided as total discharge increases by the change in location of flow control, from the labyrinth sill to a contraction in the chute channel a short distance downstream.

For even larger floods (in excess of the 1 in 500 year event) the capacity of the auxiliary spillway is significantly enhanced by the sequential tipping of the straight-crested fusegates.

The 1 in 200 year flood and PMF flood inflow hydrographs developed contain total water volumes of 8 and 19 × 10^6 m^3 respectively, within the first 15 h. This can be considered in relation to an available total surcharge storage capacity of more than 9 × 10^6 m^3 for the impoundment. The surcharge storage accordingly provides significant attenuation of inflow floods and correspondingly each of the inflow flood hydrographs developed for the catchment was routed through the dam and combined spillways. In this way the design and safety evaluation hydrographs for spillway discharge were generated (see Fig. 6).

The salient flood routing information is summarized in Table 4.

As can be seen in Table 4 the 6 h duration storm is critical at the PMF, yielding the highest spillway discharges, while the 8 h duration storm is critical for the 200 year recurrence interval flood event.

Differences are minor however, and it can be stated

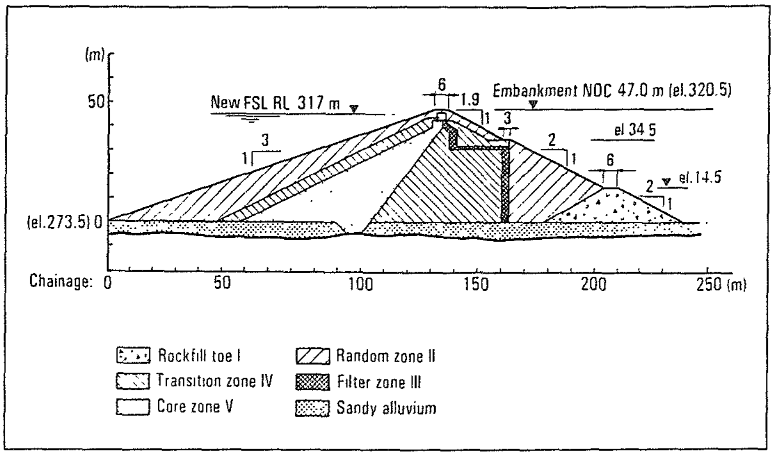


Fig. 7. Typical embankment section for Eikenhof dam.

Table 4: Routed flood peaks and reservoir water levels

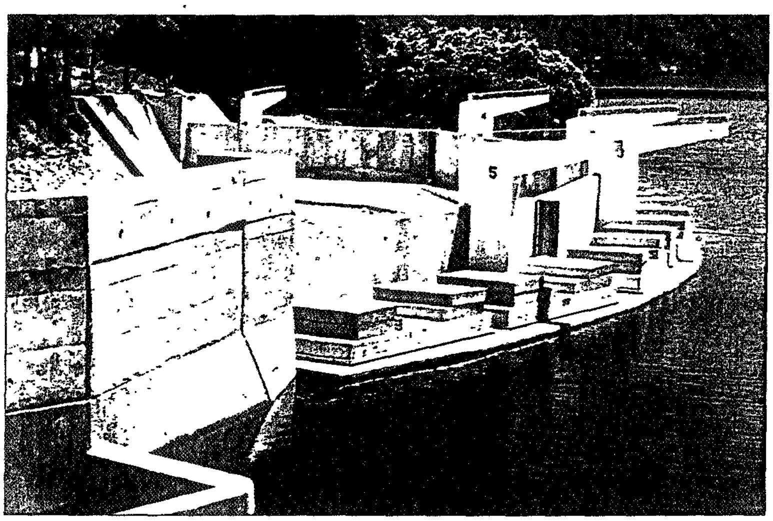
Flood recurrence interval	Storm duration (hours)	Q_{max} inflow (m^3/s)	Q_{max} outflow (m^3/s)	Q_{max} in service spillway	No. of gates tipped	Max. water level (m)
1 in 200 year	6	417	225	153	0	319.46
	8	377	232	155	0	319.50
PMF	6	656	575	175	8	319.95
	8	610	574	175	8	319.94
PMF × 1.45 (No freeboard)	6	951	779	190	10	320.47

that the maximum spillway discharges are developed for storms of a 6 to 8 h duration.

The original sill of the auxiliary spillway was placed 2.5 m above the previous full supply level, which is equivalent to 0.5 m above the new FSL. The hydraulic analysis revealed this sill level to be too high to allow the design criteria to be met, and it was necessary to reconstruct the auxiliary spillway sill, to carry 1.8 m-high straight-crested fusegates, at a level 0.23 m below the new FSL.

This required breaking away 0.73 m of reinforced concrete, while overall stability necessitated a block of reinforced concrete on the upstream side of the new sill, supporting the fusegates.

The new sill was extended beyond the extent of the original, to create a total length of 47 m, and the new crest was reinforced continuously to avoid the possibility of leakage past the seals on the sill joints.



Fusegates on the auxiliary spillway sill.

Embankment stability review

While the Eikenhof dam main embankment was not heightened as part of the 1998 storage capacity increase, water loading on the zoned 47 m-high fill (see Fig. 7) will obviously be increased under normal operating conditions. Accordingly the structural stability of the embankment was checked for higher water levels, using Bishop's modified method of slices, on the basis of material property test results dating back to the 1988 heightening.

The factors of safety determined for the various critical loading cases were found to be well within generally accepted limits.

The fusegate system

The fusegate system designed for Eikenhof dam comprised 1.8 m-high straight-crested fusegates, with five 'pairs' of fusegates, each being 4.5 m wide, constructed of reinforced concrete and weighing approximately 10 t each.

One unit of each pair is equipped with a well, through which water is routed to provide uplift pressure in the base chamber when the fusegates are intended to tip. A pipe embedded in the sill connects the two base chambers of one pair. The two fusegates of each pair are also connected by a shear key in their vertical walls: this ensures that they will tip simultaneously. Once they have tipped, however, they will separate as they are washed down the chute of the auxiliary spillway, thus reducing the chance of any blockage occurring.

The fusegate layout was designed using the software of Hydroplus International, which allows various inflow hydrographs to be routed through different types and configurations of fusegates. With the fixed labyrinth of the main spillway at Eikenhof, it was possible to accommodate a first fusegate tip-off at the 1 in 500 year flood without requiring the additional discharge capacity of labyrinth fusegates.

The hollow base chambers were formed with wooden shutters which had to be removed later by a jacking process. This also made it possible to check that no bond had formed between fusegate chamber beams and the spillway sill.

A period of three months was scheduled for construction of the dam heightening. However, a late go-ahead meant that construction ran into the wet season of winter. In spite of this, the total duration of the project, including design, was approximately six months.

Construction

The late start for the contract and the fact that it ran into the wet season made it necessary to control the impoundment level a little later than originally intended. Construction was initiated at the beginning of May 1998, with substantial completion in late September and a total project design to completion period of just six months. A blasting sub-contractor was brought in for the breaking of the original auxiliary spillway sill by 1.03 m and to form a key into the crest of the service spillway, for construction of the labyrinth. In this exercise it was important to avoid damage to the existing and adjacent structures and carefully planned relays, with low explosive charges were applied successfully.

With the programmed construction, the risk of spillage during critical operations was minimal and the dam's outlet proved adequate to pass typical inflows, making use of some buffer attenuation storage. At the outset of construction, the impounded water level was 5 m below the original full supply level, where it remained for a little more than a month, before slowly climbing to a maximum controlled level of approximately 1.5 m below the original FSL at the completion of construction.

With the fixed labyrinth on the service spillway constructed first, there was a sensitive period during construction when the broken down sill of the auxiliary spillway was approximately 0.5 m below the new service spillway sill.

The full 3 m-high, 30 m developed length labyrinth of the service spillway was cast in a single pour and in a single lift. An excellent finish quality was achieved, and the structure has proved completely watertight. The 47 m-long and 3 m-wide sill of the auxiliary spillway was subject to tight construction tolerances, to accommodate effectively the concrete fusegates, which were finally cast on the completed sill. Piers were constructed between each pair of fusegates so that the curved spillway layout could be negotiated in straight chord lengths of 9 m.

Conclusion

The combination of a fixed labyrinth service spillway and a fusegated auxiliary spillway provided an innovative and effective solution for the heightening of Eikenhof dam. The merits of both systems are combined in a way that has allowed fine-tuning and optimisation of the spillage discharges within the constraints of the existing dam configuration, thereby significantly improving overall safety of the dam during extreme flood events. ◊

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Quentin H.W. Shaw is the Principal in charge of the dams and water activities of ARQ Specialist Engineers. He graduated from the University of Birmingham UK, and has 15 years of experience in the planning, design and construction of dams. To date he has been involved in more than 50 schemes in eight countries, including dams ranging from 5 m to 220 m high. Projects he has worked on include the 70 m-high Wolwedans RCC dam in South Africa, the phased 45 m/85 m Sounda dam in Congo, the 220 m Baynes dam on the Kunene river, the Cine RCC dam to be built in Turkey, and the Thukela water project in South Africa.

D G Cameron-Ellis

David G. Cameron-Ellis is mainly involved in the water service activities of ARQ Specialist Engineers. He graduated from the University of Pretoria, South Africa, in 1990, and has nine years of experience in the design and construction of bulk water services, dams and hydraulic structures. In the field of dams, projects he has been involved with include Sterkspruit (27 m massive arch buttress), Shiya-lo ngubu dam safety and monitoring (23 m concrete arch), the Epupa hydropower project, the Biri dam (44 m embankment), and the Welgevonden dam (16 m masonry arch).

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Bill (W.D.) Hakin graduated from the University of Bradford, UK, in 1982 with a B Eng Honours degree, and has 17 years of experience in various aspects of bulk water supply, ranging from pipelines and reservoirs to dams. As far as dams are concerned, he has had key involvement in all aspects, including planning, design, construction and dam safety/rehabilitation, where, on occasions, the introduction of innovative approaches have been instigated. He is currently Chief Executive of Hydroplus International (South African Branch).

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