Copeton Dam Spillway — Geological Investigations and Performance

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SUMMARY The geological investigations undertaken in connection with the design and construction of Copeton Dam spillway are described, together with the factors influencing the spillway location and type of structure finally constructed. Following two minor discharges through the spillway extensive scour occurred in the discharge area, which necessitated additional geological and engineering investigations including stress measurements and resulted in remedial and additional construction work being performed at a total cost of $1.3M. The fundamental cause of the problem was found to be the occurrence of high horizontal stresses of up to 20 MPa in the rock over this area. The mechanism of spillway scour here encountered is thought to be unique.

1 INTRODUCTION

Copeton Dam is a 113 metre high earth and rockfill structure on the Gwydir River near Inverell in northern New South Wales. The spillway is in a saddle through the right hand ridge some 500 metres from the dam, Fig. 1. Rockfill for the dam was obtained from a separate quarry located about one kilometre from the dam on the downstream left hand ridge system. Construction of the dam was commenced in 1968 and completed in 1976 using a three stage construction programme. (Douglas, 1979).

The spillway consists of a 156 metre wide concrete ogee crest supporting nine radial gates, each 13.01 metres high and 14.63 metres wide. The chute downstream of the control structure is lined for the first 55 metres and then passes through a 1 on 50 excavation to meet the natural surface. The design outflow capacity of the spillway is 14 800 m^3/s. The drop from the design flood level to the river bed downstream of the spillway is 130 metres with an average overall gradient of 1 on 4.

2 INVESTIGATIONS

Copeton Dam is located in an area of coarse grained porphyritic granite of Permian age which has been intruded by one main mass of fine grained granite and a number of smaller such bodies. Later intrusion by a series of dykes of basaltic composition of probable Tertiary age has occurred along a number of well defined orientations to produce a series of lineaments easily observable in aerial photographs, Fig. 1. The spillway is located in a saddle about 500 metres from the dam along the right hand ridge in predominantly coarse grained granite intersected by the Dingo lineament which crosses the saddle. The granite in the saddle is more deeply weathered than is generally the case in this area and these poorer foundation conditions for the structure were realised early in the investigations.

The spillway area was investigated by geological mapping, magnetic and electromagnetic geophysical surveys, trenching and diamond drilling of twenty five holes totalling 1297 metres in length together with borehole TV inspection of certain holes. Two of these holes were drilled downstream of the structure to test the rock conditions of the discharge area. These showed generally sound granite with moderately spaced joints and were not inspected using the borehole TV apparatus. The spillway design finally adopted is shown in Fig. 2, the concrete units and the gates being constructed under two separate contracts.

The location of spillway adopted was determined by the expected cost saving differential of a separate spillway and quarry over a spillway cum quarry, which tended to favour a minimum excavation spillway which was achieved at the location of the saddle. The quarry was located in the main mass of fine grained granite which had minimal overburden. The type of spillway was largely determined by the decision to use stage construction by the addition of gates. Due to the topography, alternative spillway locations considered required a spillway cum quarry arrangement or were not suitable for the addition of gates. The only viable alternative, a spillway cum quarry was at site B in the ridge to the right of the adopted spillway.

The spillway as designed was similar to the recently constructed new Wyangala Dam spillway, also situated on granitic rock, except that due to the topographic differences of the two sites, the head drop and gradient along the discharge path were considerably greater at the Copeton spillway. The spillway of the original Wyangala Dam (now replaced by a new dam with a new spillway) had one feature in common with the Copeton spillway in that it discharged into a natural gully and also experienced considerable scour (Thomson, 1967).

Some scour potential at the downstream end of the chute was realised and this was one factor favouring the use of nine gates rather than a lesser number. Flow velocities at the end of the chute for the maximum design discharge exceeded 15 m/s.

The spillway discharge area downstream of the excavation was generally covered by a significant depth of soil which greatly restricted geological mapping of this area. As the two exploratory holes drilled in the excavation cut area of the discharge channel had shown generally good quality granite, no effect was envisaged which would scour the downstream material to the extent necessary to significantly affect the granite in the excavation cut. Thus the stability of the spillway structure seemed assured. As no problem was anticipated, the normal spillway flows would be allowed to remove the soil and loose rock from this area.

The investigations of the lineaments in the spillway area revealed that the Dingo lineament consisted of a series of basaltic dykes and vertical weathered shear zones curving across the saddle area. To eliminate any possible scour of this lineament, the chute concrete and right hand training wall was extended to cover this feature. The Hardinge lineament was found to consist of one wide dolerite dyke together with associated faulting. The small gully into which the spillway discharged was not considered a major geological feature of this area in comparison with the adjacent lineaments.

3 CONSTRUCTION

Construction of the tunnel and the initial spillway excavation was carried out by day labour prior to the dam contract being let. The first indication of high stresses being present in the rock was noticed in the tunnel excavation where popping of the roof and floor of the tunnel occurred soon after driving commenced and continued for most of the length of the tunnel. It was considered at this stage to measure the stresses involved as an aid to solving this problem. This was never carried out firstly, as the construction problems were solved by altering the roof shape to a peak and bolting and meshing the roof region where the dangerous popping slabs occurred and secondly, the equipment to measure such stresses was not on hand nor readily available. As it was not considered that such stresses would in any way affect a relatively shallow surface excavation, and as popping failure was not observed in any of the subsequent surface excavations of the low and high level diversion cuts, spillway cut or the quarry excavation, no further consideration was given to the measurement of these stresses.

Although disced core in the investigation diamond drilling did occur for short sections in a few of the holes in the dam site area, it was not recognised at this time as being an indicator of active stress. After the occurrence of popping in the tunnel, further diamond cored holes were drilled into the roof of the tunnel which revealed highly disced cores whereas the earlier investigation holes in this area showed little or no such effects.

During the complete excavation of the spillway, detailed geological mapping of the excavated surface was carried out but this work did not disclose any new significant information beyond that already discovered during the investigation period.

The civil contract was completed in December 1973 and the spillway gate contract in March 1976.

4 PERFORMANCE

In January and February 1976 the first discharges from the Copeton spillway (maximum outflow 460 m^3/s) scoured a narrow (10 m wide) but unusually deep channel along the existing gully downstream of the concrete chute. (Carter, 1979). The scour produced by this comparatively small discharge showed several unusual and apparently related features including the occurrence of rockbursts in the floor of the scour channel and the great depth to which the downstream half of the channel had penetrated sound, unweathered granite. (Maximum depth below original natural surface 30 m, maximum penetration into unweathered granite 20 m).

The 1976 floods were passed through various combinations of the six right hand spillway gates while the three left hand gates were not opened. In addition to the main scour channel the floods also produced some minor undermining of backfill concrete at the downstream end of the spillway chute due to the removal of granite blocks bounded by weathered,

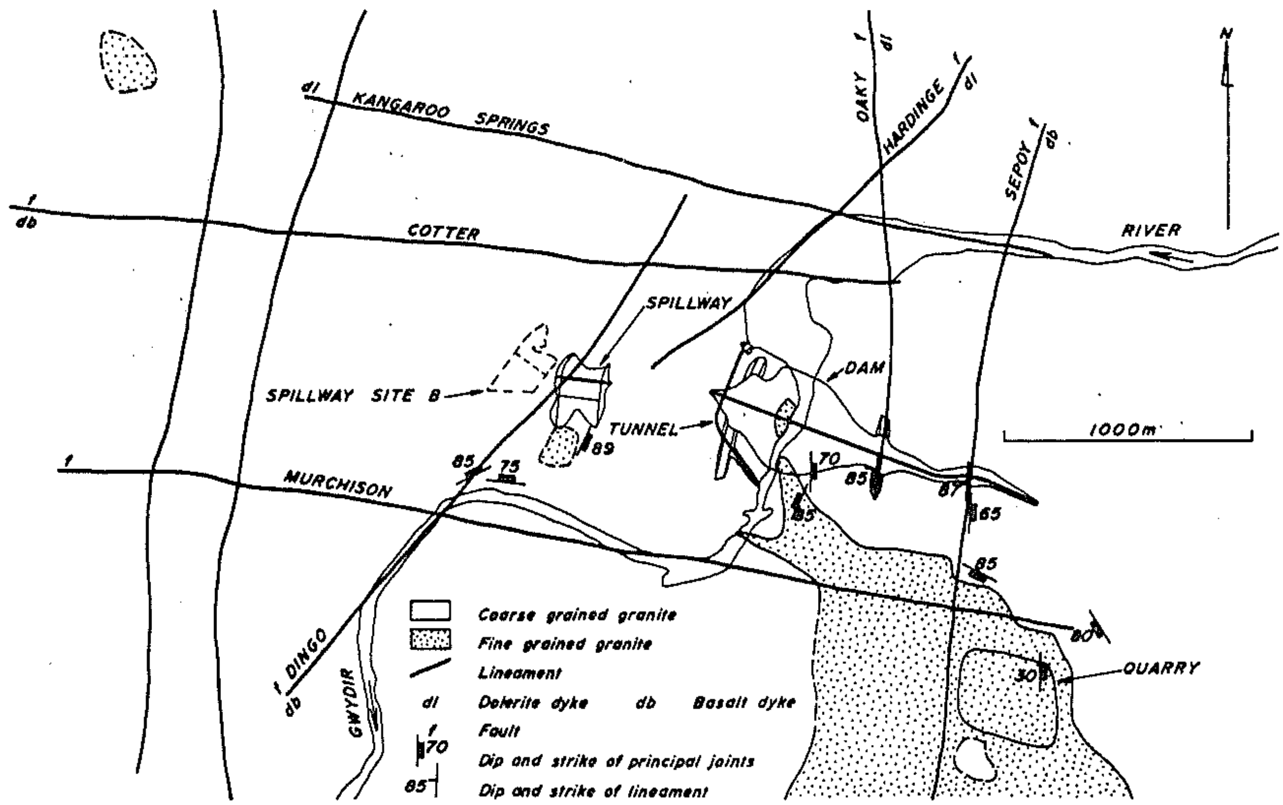

Figure 1 Regional Geology of Copeton Dam

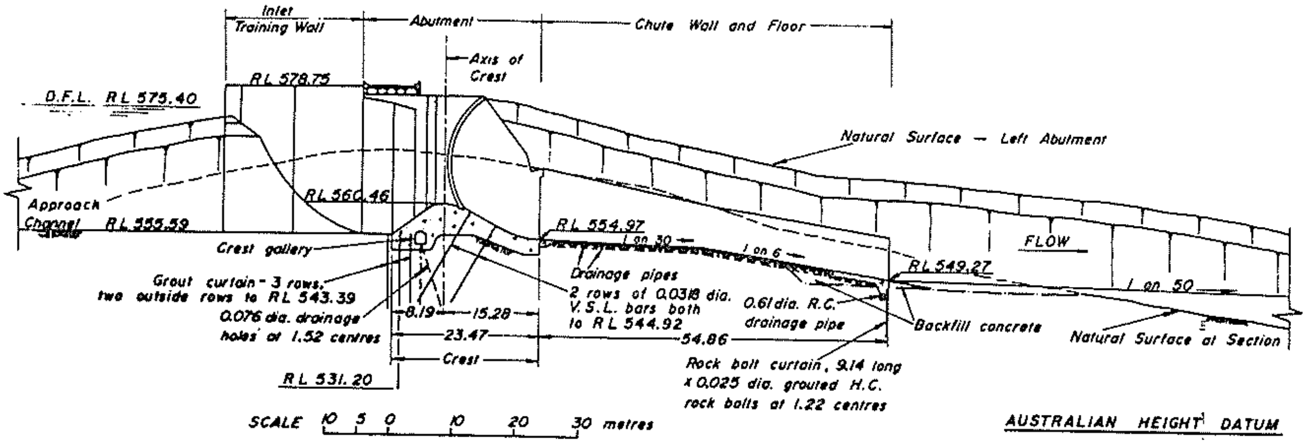

Figure 2 Adopted Spillway Design

erodible joints. The spillway structure itself sustained no damage during the 1976 floods.

For a long period following the cessation of the flood discharge the rock in the main scour channel showed significant deterioration due both to continued rock popping failure in the floor of the channel and also to the opening up on exposure of very extensive vertical, laumontite coated joints in the rock forming the walls of the scour channel.

The main scour channel appeared to owe its formation to a previously unrecorded mechanism of stress related scour (the removal of slabs of rock which had failed by upward buckling under high, horizontal in-situ stress). This scour mechanism had two unusual characteristics which indicated the need for some form of remedial works to ensure the future safe operation of the spillway.

Firstly the mechanism responsible for the formation of the main scour channel gave no indication of being self limiting. In a future major flood the deep scour channel could continue to migrate upstream towards the spillway structure and eventually be in a position to undermine the concrete chute. Secondly the removal of rock would continue for the duration of the flood. The unweathered granite in the floor of the scour channel had a high scour resistance before fracturing due to stress failure, but once failure occurred the rock slabs could be removed by even the smallest flow. The quantity of rock scoured by this mechanism during a flood event would thus depend more on the duration of the flood rather than on the peak discharge. This can be contrasted with the normal (not stress related) scour of resistant rock where the flow is capable of scouring rock for only a relatively short period at the peak of the flood. The quantity of rock removed under this normal scour mechanism depends mainly on the peak discharge and usually does not depend to any significant extent on the total duration of the discharge from the spillway.

The Copeton spillway is expected to operate on average once in three years with some discharges of up to six months duration. The combination of stress related scour with a major flood could thus present the possibility of serious damage to the spillway structure. The occurrence of this type of rock failure under stress in a spillway presents a situation quite different and much more serious than similar rock failure in a location not subject to the removal of failed rock by water flow. It is the removal of the failed rock which permits further continuing rock failure to occur without limit.

Geological investigations carried out following the 1976 floods consisted of the following:

- Surface stress measurements in the main scour channel and the adjacent spillway excavation. (Bowling and Woodward, 1979).
- Detailed geological mapping of the spillway excavation and the discharge area downstream of the excavation. (Fig. 3).
- Diamond core drilling in and adjacent to the main scour channel.

The spillway discharge area downstream of the concrete chute divided naturally into right and left hand areas separated by the central scour channel area.

Left Hand Area:

The left hand side of the spillway cut floor was still covered with construction rubble since the three left hand gates were not opened during the floods. The geological structure and hence the scour resistance of this area could not therefore be accurately assessed at this time.

It was not until after the testing of the secondary spillway following completion of the remedial works that it was possible to examine this area in detail. The rock floor on the left hand side of the spillway cut was then seen to be generally unweathered, massive granite with only a few, narrow zones of laumontite coated joints. Downstream of the excavation these joints become more frequent and these jointed zones eventually merge into the major zone of laumontite coated joints in the downstream half of the main scour channel.

Main Scour Channel Area:

The main scour channel commenced at the centre of the spillway near the end of the concrete chute and progressed downstream, becoming deeper as it did so, along an "en echelon" series of laumontite coated joints and faults. These joints strike slightly oblique to the channel and form its near-vertical side walls. The floor of the scour channel was located almost entirely in unweathered granite and consisted of stress relief fractures dipping downstream at 10° - 30° which were either pre-existing joints or fractures newly formed during the flood. The downstream half of the scour channel followed one major zone of laumontite coated joints and it was here that it attained its greatest depth with two

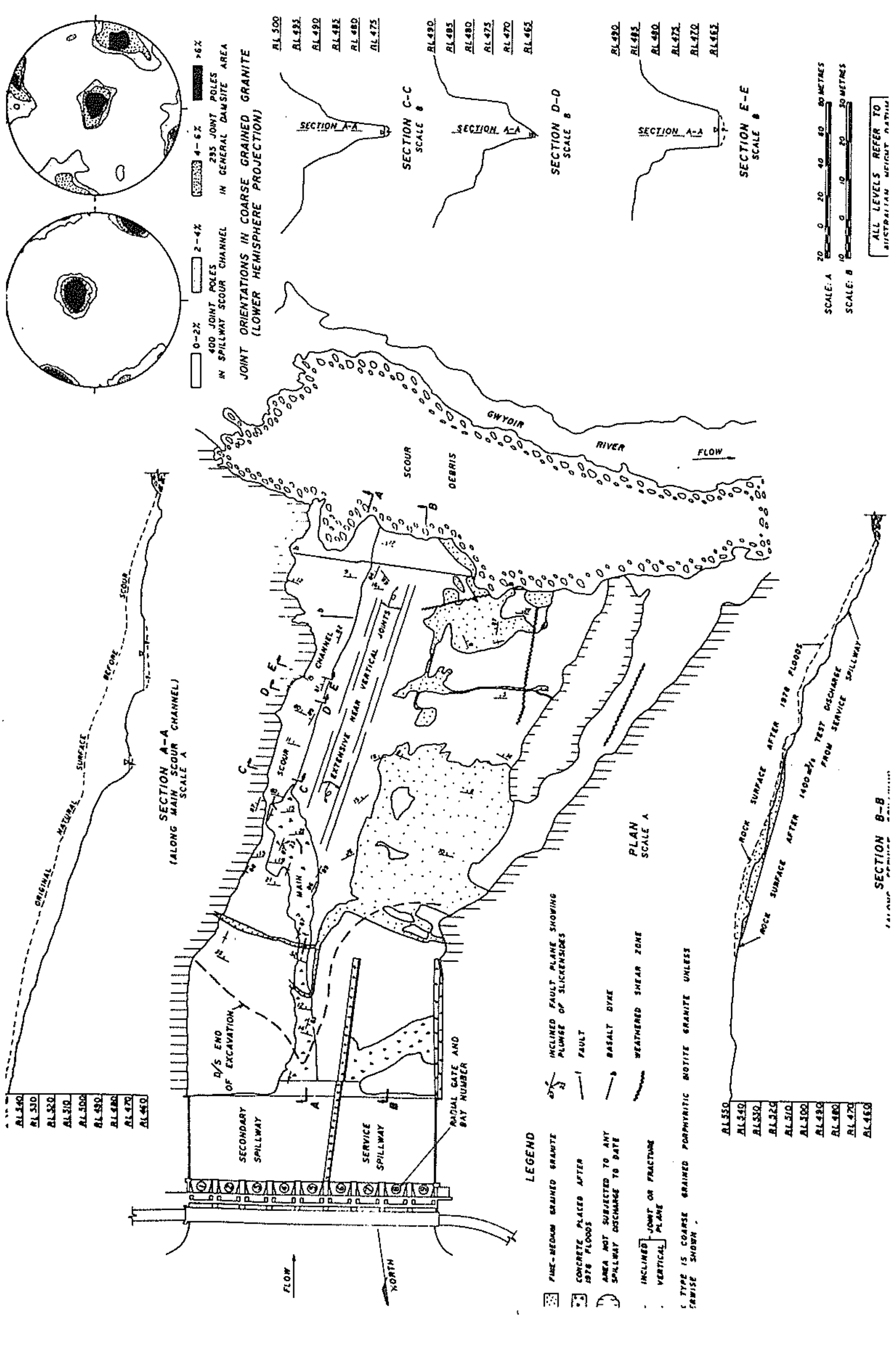

Figure 3 Copeton Spillway - Geological Plan and Sections.

scour holes up to 30 m deep below the original natural surface. There was every indication that future floods would cause these deep scour holes to migrate upstream towards the spillway chute.

Right Hand Area:

The right hand half of the spillway cut floor had suffered a certain amount of relatively minor scour controlled by weathered, erodible joints (not related to failure under stress). Generally however the granite on this side of the spillway cut was only sparsely jointed and appeared to have a high scour resistance. In particular the laumontite coated joints and faults so common in the main scour channel were almost entirely absent from this side of the spillway cut. Immediately downstream of the right hand half of the spillway cut a flat-lying sill-like body of fine grained granite outcroped. Diamond core drilling showed this fine grained granite to have a maximum thickness of about 10 m and to contain weathered, erodible joints as well as being generally more intensely jointed than the coarse grained granite within the cut immediately upstream.

5 REMEDIAL WORKS

The scheme of remedial works adopted consisted of constructing a training wall from the pier separating gates 5 and 6 so that the four right hand gates could be operated as a service spillway discharging up to 2800 m^3/s and the five left hand gates (including gates 4 and 5 which discharge directly into the scour channel) would then be operated only as an emergency secondary spillway (Fig. 3). The service spillway concept was feasible because of the very massive, sparsely jointed rock present on the right hand side of the spillway excavation. There was thus no possibility of a second scour channel developing which could migrate upstream into the service spillway area and undermine the right hand side of the spillway chute.

In addition to the construction of the training wall the following work was also carried out:

Concrete lining anchored to the rock of the upstream half of the scour channel floor to prevent scour on the rare occasions when it would be necessary to release water from the secondary spillway.

Concrete lining of the right hand wall of the spillway cut, downstream of the chute to protect numerous weathered and erodible joints exposed in the wall of the cut.

Extensive concrete lining of areas within the service spillway immediately downstream of the chute where weathered, erodible joints were exposed in the floor.

The training wall was constructed on massive granite to the right of the main scour channel and terminated about level with the downstream end of the right hand spillway cut wall thus stopping short of the fine grained granite sill just beyond the end of the spillway cut.

Under design flood conditions both sides of the training wall would be subject to water flow and to obtain a totally secure foundation for the wall it was necessary to site it well clear of the right hand wall of the main scour channel. This necessitated an alignment somewhat skewed to the right rather than one parallel to the spillway flow.

The construction of these remedial works commenced early in 1977 and was completed in January 1978. Since that time the remedial works have been tested up to the following maximum discharges by controlled releases:

Service Spillway	1400 m^3/s
Secondary Spillway	140 m^3/s

The flow duration at these maximum discharges was very short (1-2 hours). The general conclusions reached as a result of these tests are that the Service Spillway will be capable of safely discharging its designed capacity of 2800 m^3/s. Discharges from the Secondary Spillway are likely to cause further major scour downstream of the spillway without however endangering the safety of the spillway control structure. The probability of further scour and the possible requirement for further remedial work in this area is considered acceptable in view of the anticipated infrequent operation of the Secondary Spillway.

6 REVIEW OF ORIGINAL SPILLWAY DESIGN

The geological investigations carried out following the 1976 floods indicated that the factors responsible for the unusual scour were:

(i) the rock underlying the discharge gully was more jointed than the surrounding granite both by vertical, laumontite coated joints and faults and by near horizontal, pre-existing stress relief joints. The natural stress concentrating effect of the original gully profile probably meant that these pre-existing stress relief joints parallel to the topography were more intensely developed beneath the gully than elsewhere. In the near surface rock (about the upper 10 m) these joints were generally weathered and some were filled with erodible material.

(ii) the granite in the Copeton spillway area is carrying a virgin, horizontal, compressive stress in the range 15 - 20 MPa. Scour of the jointed rock in the gully produced a notch-like channel resulting in a concentration of this virgin stress which was then sufficiently high to cause the granite to fail by upward buckling (the rockbursts observed in the floor of the scour channel). The failure of the granite under high, horizontal compressive stress is believed to be the major factor responsible for the great depth to which the scour was able to penetrate the sound unweathered granite.

The failure of near surface rock under high stresses is unusual but several instances are recorded from various surface excavations around the world. However the occurrence of this phenomenon in a dam spillway leading to a major scour problem does not appear to have been previously reported.

The Copeton spillway, as originally constructed was closely based on the successful new Wyangala Dam spillway design. Both these spillways consist of a gated crest structure capable of handling the Probable Maximum Flood (of similar magnitude in both cases) with a short concrete chute which leads to an unlined channel excavated in granitic rock. Once the discharge leaves the spillway cut it flows over the natural surface to return to the river, no energy dissipation being provided in either case.

TABLE I

COMPARISON OF COPETON AND WYANGALA SPILLWAYS

Feature		Copeton	Wyangala
(A)	Width (m)	156.06	138.38
	Lined Length (m)	70.14	61.19
	Head drop (m) from design flood level to: - end of chute	26.13	22.77
	- river bed	130	77
(B)	Maximum discharge to date (m^3/s)	460	1 870
	Maximum Design Capacity (m^3/s)	14 800	14 700
*	Theoretical power of discharge per unit width at river bed level: - Maximum to date (kW/m)	3 700	9 800
	- Maximum discharge capacity (kW/m)	120 000	80 000
(C)	Topography of discharge area	Spillway discharges directly into a gully which runs from the spillway cut down to the river. Overall slope of discharge path from concrete chute 14 degrees. (1 on 4)	Spillway discharges over a broadly convex ridge which disperses flow. Overall slope of discharge path from concrete chute 4 degrees. (1 on 13)
	Geology of discharge path	Zones of vertical laumontite coated joints approximately parallel to flow. Concentrated flow in gully scoured a notch-like channel by erosion along these zones.	Significant geological structures normal to flow. One major shear zone dental concreted during construction.
	In-situ stress conditions	In-situ, horizontal compressive stress = 15-20 MPa. Stress concentration due to initial scour notch caused rock failure by upward buckling.	In-situ stress too low to cause rock failure.
(D)	Scour performance	Deep scour in unweathered granite underlying discharge gully.	No significant scour of unweathered rock.

* Theoretical value assuming no dispersion or concentration of flow downstream of the spillway cut and also no energy loss between reservoir and river bed below the spillway. Due to concentration of the flow in the downstream half of the main scour channel at Copeton, the actual maximum value to date could have been as high as 30,000 to 40,000 kW/m (assuming 1/2 - 3/4 total flow in channel).

This type of spillway design accepts the fact that a large amount of soil and weathered, near surface rock will be scoured from the natural surface downstream of the spillway cut and dumped in the river bed below the spillway. The basic assumption is however that this scour will be self-limiting, with non-erodible, scour resistant rock at a comparatively small depth below the natural surface and that once the scour reaches this depth a more or less stable situation will develop before there is any risk of damage to the spillway structure.

At Wyangala Dam this assumption has proved correct while at Copeton Dam this has not been the case, at least in the central gully area now occupied by the main scour channel. This does not mean however that the quality of the rock downstream of the Copeton spillway was significantly inferior to that assumed during the design of the spillway. The unweathered granite outside the zones of laumontite coated joints can only be described as excellent quality rock (joint spacings generally in excess of 3 m; R.Q.D. generally 90-100 per cent). Even within the zones of laumontite coated joints where joint spacings are generally in the range 0.1 m to over 1 m the majority of the rock would still be described as of good quality (R.Q.D. 75-90 per cent).

The design assumption of good quality rock in the Copeton spillway was therefore quite correct and it is necessary to look elsewhere for the cause of the unsatisfactory scour performance during the 1976 floods. The great similarity of the Wyangala and Copeton spillways from the geological, design and operational aspects suggested that the detailed comparison shown in Table I would be instructive.

The major factors whose combined effect was responsible for the Copeton scour and which were absent at the Wyangala spillway can be summarised as follows:

1. Spillway discharge flowed directly into an existing gully. The topography and geology of the gully area permitted the development of the initial, notch-like scour channel.

2. High in-situ, horizontal compressive stress in the near surface rock in the spillway area.

Having regard to the generally very good quality of the granite in the spillway area the absence of either one of the above factors would very probably have prevented the development of the major scour that did occur during the 1976 floods, the magnitude of which was accentuated by the high head, steep slope and concentration of flow in the discharge gully.

It is interesting to speculate whether a different location and/or design of spillway at Copeton Dam could have avoided the major, stress-related scour problem. Since alternative sites were never investigated in detail it is impossible to be certain but nevertheless it does appear to be a plausible speculation that a spillway of the same design at site B (about 150 m to the right of the existing spillway) may not have experienced the problems that did occur in the 1976 floods. The reasons for this belief are as follows:

A spillway at site B would have discharged eventually into the Dingo Lineament Gully and major scour would have occurred there but this gully would not have run directly upstream into the spillway cut and thus scour in the gully itself could not have posed a threat to the spillway structure. There is also a possibility that the in-situ stresses may not have been as high west of the Dingo Lineament as at the existing spillway site. Bowling and Woodward suggested a possible relationship between the stress field at Copeton Dam and the various faults (lineaments) in the area and there was some evidence that the stresses in the existing spillway area might be somewhat higher than elsewhere in the Copeton Dam area.

With regard to the possibility of providing a concrete chute over most of the discharge path it must be remembered that water flow over an irregular rock surface is aerated to a much greater extent than flow in a concrete lined chute. Had a long concrete lined chute been constructed at Copeton the lack of aeration during major flood discharges would have resulted in very high energy flows being directed onto the rock downstream of the chute with the possibility of major scour and also cavitation damage to the chute concrete.

The important role played by high in-situ rock stresses in the development of the Copeton scour indicates the desirability of establishing some guidelines as to what level of in-situ stress is likely to give rise to this type of problem.

According to Cook (1976) slabbing or buckling failure occurs when the stress actually being carried by the rock approaches a third to a half the uniaxial compressive strength. The actual stress in the rock depends on the virgin stress level and on the stress concentration factor, if any, which applies to the particular location in question.

Photoelastic model tests carried out by the Hydro-Electric Commission, Tasmania to interpret the results of the surface stress measurements in the Copeton spillway indicated that the maximum stress concentration factor likely to be encountered in the floor of a notch-like scour channel is about three.

From a knowledge of the virgin in-situ stress and the compressive strength of the rock it would then be possible to assess the probability of rock failure in the floor of any scour channel which might develop downstream of a partially lined spillway.

7 CONCLUSIONS

In view of the apparently unique nature of the stress related scour mechanism experienced in the Copeton spillway, it is not surprising that it was not anticipated during the design of the spillway.

The good quality of the granite in the Copeton area generally and the spillway site in particular did justify the type of spillway design adopted (partial lining with no energy dissipation). However, the Copeton spillway site had a high scour potential due principally to the high head and steep slope of the discharge path, even without the added factors of high in-situ rock stresses and unfavourably orientated geological structures.

Although at Copeton the high rock stresses were a major and probably a necessary casual factor in the scour which occurred, it can be said that generally it would be undesirable to site a high head spillway such that it will direct high energy discharges into an existing gully which continues directly into the spillway cut. In general a gully must be expected to be underlain by rock which is at least to some extent, less scour resistant than rock elsewhere where natural erosion processes have not created a topographic depression.

A spillway location which may be quite acceptable for spillways with low heads or infrequent operation may not be suitable for frequently operating high head spillways.

In the light of the Copeton experience it would be prudent to assess in-situ rock stress levels at any potential site for an unlined or partially lined spillway. Although sites where stresses are high enough to cause rock failure must be rare, nevertheless if such failure were to occur it could create a very serious situation for the safety of the spillway structure. In particular the possibility must be investigated of initial normal scour along an erodible geological feature creating a notch which then may concentrate the virgin stress by a factor of up to three. The Copeton scour clearly demonstrated that a major problem can develop even though the virgin stress itself is not high enough to cause rock failure.

8 ACKNOWLEDGMENTS

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