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Geological Factors in Spillway Terminal Structure Design

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SUMMARY Fourteen spillways designed or operated by the Water Resources Commission of New South Wales were studied with respect to the geological, topographic and operational factors which influence the type of terminal structure provided. In the case of frequently operating spillways of moderate head and moderate unit discharge at design flood, unlined or partially lined spillways with no provision for energy dissipation can be constructed in durable, lowly stressed rock with R.Q.D. generally greater than 75% and erodible seams generally absent. Full energy dissipators are required in rock with R.Q.D. generally less than 50% and erodible seams generally present.

1. INTRODUCTION

This paper deals with one aspect of spillway geology, rock scour resistance and the need to provide concrete lining and energy dissipation structures downstream of the spillway crest. Complete or even partial omission of these structures, where possible will result in a major cost saving and significantly improve the economics of the dam project. Fourteen dam spillways designed or operated by the Water Resources Commission of New South Wales have been studied with respect to the geological, topographic and operational factors which influence the type of terminal structure provided.

2. GEOLOGICAL ROCK MASS PROPERTIES

The scour resistance of a rock mass is determined by the following properties:

2.1 Durability.

Rocks which disintegrate on exposure (e.g. some shales, siltstones and tuffs) must be considered erodible.

2.2 Weathering.

In particular, the presence of erodible seams and joint fillings, which are more critical than the overall degree of weathering of the rock material.

2.3 Rock Quality Designation (R.Q.D.) and Fracture Frequency.

These reflect joint block size, one of the most important factors influencing erodibility of rock. Some sites exhibit variable rock conditions which must be carefully assessed before an unlined or partially lined spillway design can be accepted. For example, at Windamere spillway some exploratory drill cores show R.Q.D. of 75-100% while other cores show R.Q.D. generally less than 50%. The design of this spillway accepts that major zones of potentially erodible rock are likely to occur in the spillway and that, although nominally unlined, a significant amount of dental concrete may be required to protect these zones from erosion. The low operational frequency of the Windamere spillway (once in 6 years, on average) was an additional factor in the decision to adopt this design.

2.4 Aperture and Persistence of Joint Planes In Situ.

Numerous, widely open, persistent joints greatly predispose a rock mass to scour. Aperture and persistence of joints cannot be determined from drill core.

It is possible for two rock masses to yield similar rock quality parameters from drill cores when they are, in fact, very different (e.g. Glennies Creek and Glenlyon spillways, Fig.1). At Glennies Creek the joints were at least slightly open and very extensive (persistence greater than 10 m). In contrast, at Glenlyon the joints were minor in character and generally tight; systems of major, extensive joint planes being largely absent. The difference in aperture of the joints in situ had been indicated by water pressure testing of the original exploratory drill holes (permeability at spillway floor level 3-5 Lugeons at Glennies Creek compared with 0-3 Lugeons at Glenlyon. Apart from Glenlyon, the unlined and partially lined spillways in Fig. 1 generally had joints with high persistence.

2.5 Number and Orientation of Joint Sets.

Except under very severe conditions, such as those existing in the Copeton and Burrinjuck spillways, it is probable that the orientation of tight, unweathered joints will not be a critical factor in determining rock scour resistance while the orientation of open, weathered and erodible joints may be of great significance, particularly in rock masses with a small number of joint sets, (up to 3). In more highly jointed rock with 4 or more sets joint orientation is likely to be less important.

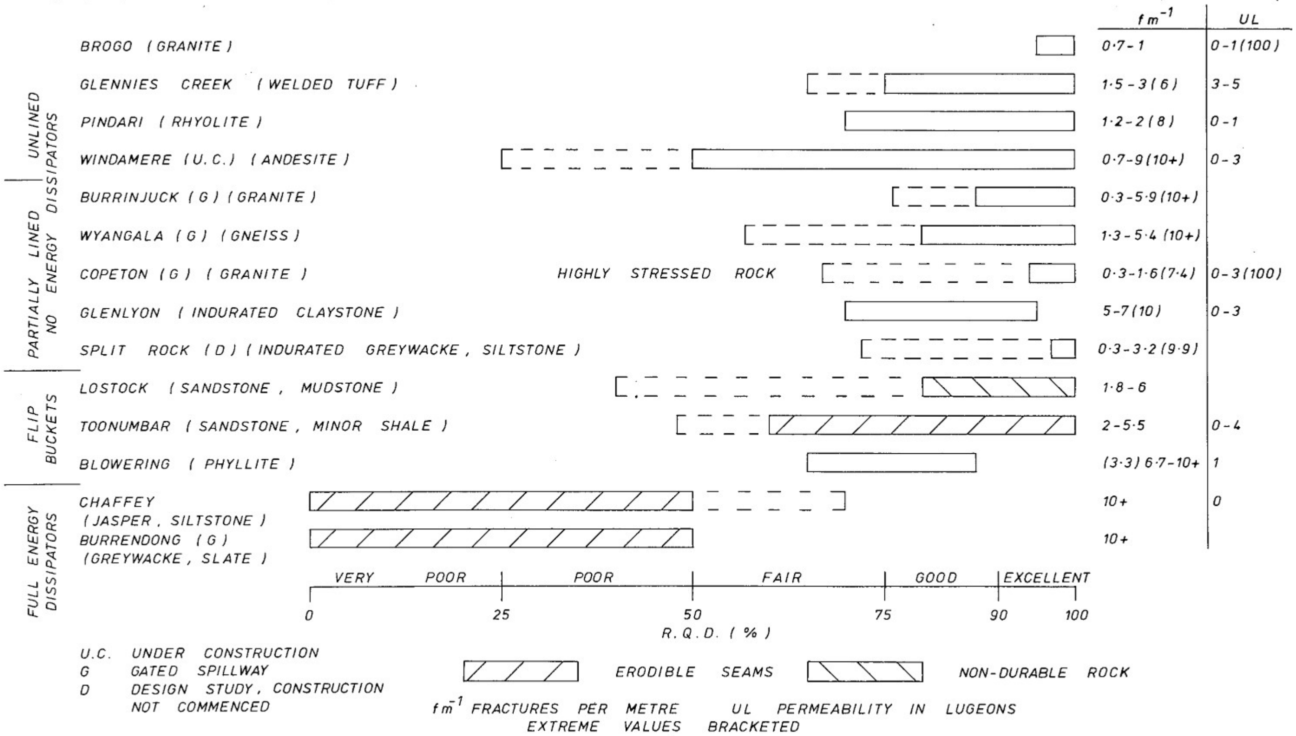


Figure 1 Geological conditions at downstream end of concrete lining

Unfavourably oriented joints will be those that strike about normal to the water flow and dip steeply downstream, thereby favouring the development of a near vertical face, unconfined on the downstream side. Such a vertical face, whether produced by the geological structure or by the site topography, will greatly assist in the removal of joint blocks. If such a face cannot develop, due to flat topography or the absence of suitably oriented geological structures, the rock mass will be much more confined, particularly in the downstream direction, and scour of rock much less likely.

The most unfavourable combination of joint sets and topography is where water flow can remove joint blocks simply by sliding on one set of joints or along the line of intersection of two joint sets without having to perform the additional work of lifting joint blocks up dip.

2.6 In Situ Rock Stress.

The scour experienced in the Copeton spillway (Bowling and Woodward, 1979 and Thomson and Woodward, 1980) showed that high, in situ, compressive stress in the near surface rock can result in massive erosion of an apparently scour resistant rock mass.

2.7 Uniformity of Geological Conditions.

Some spillways, e.g. Pindari, Brogo, Glenlyon and Glennies Creek, are located in very uniform geological conditions with one rock type which does not show any great variation in degree of weathering. Such uniform geological conditions are likely to provide a much more scour resistant rock mass than would a highly variable site.

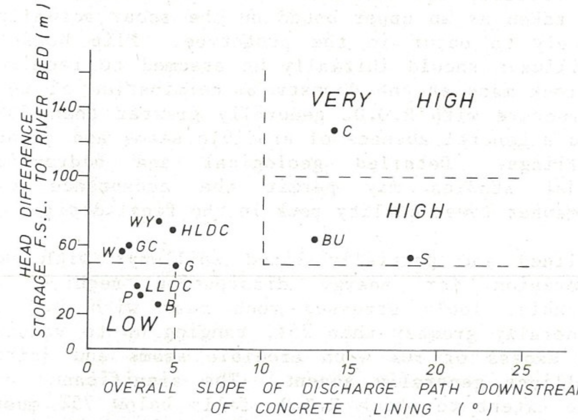
Data shown in Fig. 1 refer to rock conditions existing at the downstream end of the concrete lined section of fourteen dam spillways designed or operated by the Water Resources Commission of New South Wales. The solid bars indicate the range of the majority of R.Q.D. values in exploratory drill cores. The dashed bars indicate, in general terms, the range of extreme (usually lower) R.Q.D. values, in most cases indicative of localised zones of lower quality rock.

3. TOPOGRAPHIC AND DESIGN FACTORS IN ESTIMATING POTENTIAL SCOUR

The potential for spillway scour is a function of flow velocity, the theoretical flow velocity at any point being determined by the head drop from the reservoir level to that point (actual velocity will be less because of friction losses which depend on the roughness and slope of the discharge path).

For unlined or partially lined spillways the head drop to the downstream end of the concrete lining (h_1) is therefore a measure of the scour potential at this critical point. Typical values of h_1 (gated spillway 25 m; ungated spillway 7 m; unlined spillway 0.5 m) show the severe conditions existing in partially lined, gated spillways. The potential for scour within the spillway excavation will depend not only on h_1 but also on the head drop to the downstream end of the excavation (h_2), the slope of the excavation floor ($\emptyset_1$) and the length of unprotected rock in the floor of the spillway excavation downstream of the concrete lining (L). A high scour potential is indicated by large values of h_1, h_2, $\emptyset_1$, and small values of L. Downstream of the excavation some scour of soil and highly weathered rock is inevitable. Scour here is of less immediate concern but, in the long term, could migrate upstream and approach the concrete chute. The potential for scour in this area depends on the head drop from the storage to the river bed below the spillway (h_3) and the slope of the discharge path downstream of the excavation (ϕ_2).

Fig. 2 is a plot of h_3 against the overall slope downstream of the concrete lining, ϕ_3 giving a measure of the "ultimate" scour potential of a spillway site. High scour potential can be arbitarily associated with ϕ_3 greater than 10° and h_3 greater than 50 m, while spillways with h_3 greater than 100 m (high head spillways) have a very high scour potential. Similarly low scour potential can be arbitarily associated with ϕ_3 less than 5° and h_3 less than 50 m.



B	Brogo	LLDC	Copeton Low Level Diversion Cut
BU	Burrinjuck	P	Pindari
C	Copeton	S	Split Rock
G	Glenlyon	W	Windamere
GC	Glennies Creek	WY	Wyangala
HLDC	Copeton High Level Diversion Cut		

Figure 2 Ultimate scour potential of unlined and partially lined spillways

Fig. 2 will not necessarily predict scour due to local geological or topographic variations along the discharge path. In particular, any locally steep section of the discharge path or highly erodible geological feature could be the site for significant local scour.

4. OPERATIONAL PARAMETERS OF SPILLWAYS

The likelihood of potential scour actually occurring is determined by geological properties of the rock mass and by operational parameters of the spillway discharge such as unit discharge, unit power, frequency of operation and spill duration.

Fig. 3 is a plot of unit discharge at design flood against h_3. The unit discharge refers to the narrowest portion of the spillway excavation. The theoretical unit power at the downstream end of the discharge path, also shown is based on the assumptions that the spillway discharge undergoes no dispersion or concentration on leaving the spillway excavation and there are no friction losses. In most spillways the tendency would be for the spillway discharge to disperse on leaving the excavation thus drastically reducing the unit discharge and unit power at the downstream end of the discharge path. However, if the spillway discharges into a gully the flow may concentrate rather than disperse resulting in an increase in the unit discharge and unit power in the river bed.

Glennies Creek spillway (unit power less than 20,000 kW m^{-1}) has little likelihood of developing a major scour problem while spillways such as Burrinjuck and Copeton (unit power greater than 100,000 kW m^{-1}) have a much greater likelihood of significant scour.

The spill duration and frequency of operation are important since these factors respectively influence the amount of rock that may be scoured during any one flood event and the time likely to be available for remedial works to be carried out before the spillway is again called upon to pass a flood. A spillway whose frequency of operation is once a year or more often presents a much greater likelihood of scour problems than a spillway with a frequency of operation of once in 5 years or less often.

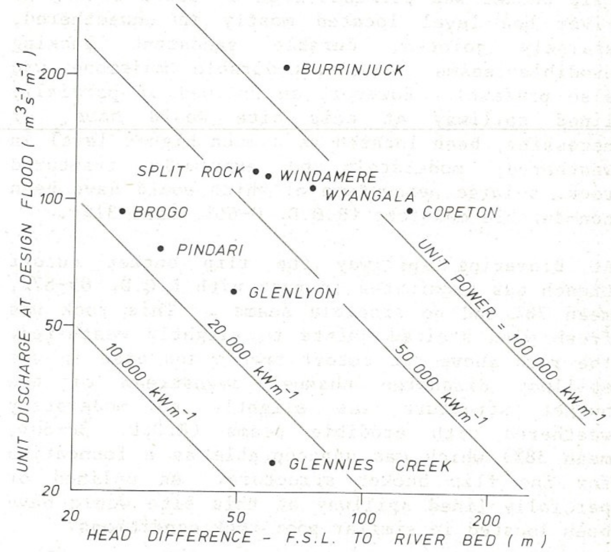


Figure 3 Unit power of unlined and partially lined spillways at river bed during design flood

5. SPILLWAY PERFORMANCE

Of the nine unlined and partially lined spillways in Fig. 1 five have operated and two (Copeton and Burrinjuck) have experienced significant scour problems. Brogo, Pindari and Wyangala spillways have passed unit discharges of 12.5, 30.4 and 13.6 $m^3 s^{-1} m^{-1}$ respectively without significant scour. The Pindari discharge was 40% of the design flood outflow (compared to 13% at Brogo and Wyangala).

During a major flood in 1974 the Burrinjuck northern spillway experienced a unit discharge of 102 $m^3 s^{-1} m^{-1}$ (49% of design flood outflow) resulting in scour that destroyed a penstock to a downstream power station.

At Copeton initial scour along an existing gully produced a notch like channel which had the effect of concentrating a virgin stress of 15-20 MPa by a factor of three resulting in upward buckling failure of unweathered granite. Copeton

Dam also possessed two temporary hydraulic structures, the Low Level and High Level Diversion Cuts (L.L.D.C. and H.L.D.C. respectively). The L.L.D.C. was located in coarse grained granite (R.Q.D. 90%, range 82-99%) and passed a unit discharge of 72.5 $m^3 s^{-1} m^{-1}$ without scour. The H.L.D.C. while located mainly in coarse grained granite, was notable for a major, vertical dolerite dyke, about 10 m wide which occupied a central, longitudinal position in the floor of the cut. The H.L.D.C. experienced a unit discharge of 17.2 $m^3 s^{-1} m^{-1}$ which resulted in dramatic scour of this dolerite dyke (R.Q.D. 51%) which only halted when the discharge through the H.L.D.C. ceased. The granite enclosing the dyke (R.Q.D. 90%) suffered no scour. Permeability of the dolerite dyke was 5-6 Lugeons.

The rock conditions shown in Fig. 1 for flip bucket spillways are not necessarily those that were judged inadequate for an unlined or partially lined spillway at the same site. This is well illustrated by Lostock spillway where the flip bucket was terminated in a cutoff trench at river bed level located mostly in unweathered, sparsely jointed, durable sandstone lacking erodible seams (some non-durable mudstone was also present). However, an unlined or partially lined spillway at this site would have, of necessity, been located at a much higher level in weathered, moderately to extremely fractured rock, a large percentage of which would have been non-durable mudstone (R.Q.D. 0-66%, mean 31%).

At Blowering spillway the flip bucket cutoff trench was terminated in rock with R.Q.D. 65-87%, mean 78% and no erodible seams . This rock was fresh with stained joints to slightly weathered. The rock above the cutoff trench and also in the spillway discharge channel downstream of the bucket structure was slightly to moderately weathered with erodible seams (R.Q.D. 30-60%, mean 38%) which was unacceptable as a foundation for the flip bucket structure. An unlined or partially lined spillway at this site would have been located in similar poor rock conditions.

The rock in the Toonumbar spillway is more scour resistant than suggested by the data in Fig. 1. At Toonumbar generally massive sandstone contained some thin, horizontal beds of erodible shale. Water flow could not directly attack the shale beds (protected by overlying, sparsely jointed sandstone) which, because of their horizontal orientation, did not significantly reduce the scour resistance of the rock mass.

Lostock, Blowering and Toonumbar spillways have passed unit discharges of 4.3, 14.4 and 8.1 $m^3s^{-1}m^{-1}$ respectively (11-14% of design flood outflow). These spillways have performed satisfactorily although at Blowering the unlined discharge channel excavated in alluvium has been eroded into a 120 m diameter scour hole and, downstream of the bucket, spillway discharges have scoured up to 5.5 m depth of rock locally.

Burrendong spillway has performed satisfactorily in passing a unit discharge of 12.2 $m^3s^{-1}m^{-1}$ (9% of design flood outflow). The other spillways in Fig. 1 have not operated to date.

6. DISCUSSION

The data in Fig. 1 suggest the following correlation between rock mass properties and type of spillway terminal structure.

Spillways with full energy dissipators such as Chaffey (hydraulic jump stilling basin) and Burrendong (submerged roller bucket dissipator) are required in rock with R.Q.D. generally less than 50% and erodible seams and joint fillings generally present. Scour patterns in full energy dissipators can be studied in a hydraulic model with a moveable bed material. Flip bucket spillways should also be tested in this manner using a bed material scaled to represent the actual joint block size in the prototype. Such tests, in effect, assume that the spillway rock is erodible and the scour patterns obtained can be taken as an upper bound on the scour actually likely to occur in the prototype. Flip bucket spillways should initially be assumed to require a rock mass at the downstream termination of the structure with R.Q.D. generally greater than 50% and a general absence of erodible seams and joint fillings. Detailed geological and hydraulic model studies may permit the acceptance of somewhat lower quality rock in the final design.

Unlined and partially lined spillways with no provision for energy dissipation require a durable, lowly stressed rock mass with R.Q.D. generally greater than 75%, ranging up to values in excess of 90% with erodible seams and joint fillings generally absent. The significance of the extent to which R.Q.D. falls below 75% must be assessed for each spillway individually. R.Q.D. marginally below 75% (say down to 70%) is not a cause for concern. However, numerous R.Q.D. values down to 50% do indicate the presence of significant zones of lower quality rock whose possible effects on the successful operation of the spillway need to be carefully considered. The provision of a short concrete lined chute is indicated in the case of gated spillways, where other engineering structures such as a road bridge are founded on the spillway crest or where the rock mass fracture frequency is generally greater than 4 f m^{-1}. If the joints are also significantly open (permeability generally greater than 5 Lugeons) the rock mass should be considered potentially erodible, particularly in spillways with high scour potential, large h_1 or large $\emptyset_1$.

The spillways in Fig. 1 mostly belong to a group with the following characteristics:

(i) the spillway will operate frequently. This implies that, on average, the spillway can be expected to operate about once in 5 years or more often. This excludes emergency type spillways whose frequency of operation is about once in 100 years.

(ii) the spillway is of moderate head only, that is, the total vertical fall from the reservoir level to the river bed below the spillway is less than 100 m. This excludes high head spillways such as Copeton (head drop 130 m).

(iii) the maximum unit discharge of the spillway, under design flood conditions, is moderate, that is, about 100 $m^3 s^{-1} m^{-1}$ or less. This excludes spillways such as Burrinjuck (unit discharge 210 $m^3 s^{-1} m^{-1}$).

Emergency spillways are often constructed as unlined cuttings in soil (possibly vegetated). When such a spillway operates scour is inevitable, the main design concern being to ensure that the duration of the spill will not be long enough for gullying back into the storage and breaching of the reservoir to occur. Similar considerations can also be applied to rock cut spillways, e.g. L is maximised to ensure that any scour will not have sufficient time to migrate upstream, undercut the storage control sill and result in an uncontrolled release from the storage.

At Copeton rock failure under high in situ stress was the cause of the scour problem. In the absence of high stress it is likely that the spillway would have performed satisfactorily. At Burrinjuck there is no doubt that the very high unit discharge experienced was responsible for major scour. This scour did not, however pose any threat to the dam or the spillway control structure and was only significant in engineering terms because of the vunerable location of the power station penstock.

Spillways with high to very high scour potential combined with severe design flood discharge conditions (i.e. maximum unit discharge significantly in excess of 100 m^3 s^{-1} m^{-1} and/or unit power, at the river bed, in excess of 100,000 kW m^{-1}) are most at risk from scour and should have rock at the end of the concrete chute with R.Q.D. generally greater than 90% and no erodible seams. Such spillways should avoid additional unfavourable conditions such as siting the spillway so that it will discharge into an existing gully which runs directly up into the spillway excavation (i.e. the spillway should be sited to ensure that the flow disperses rather than concentrates on leaving the excavation). Particular care should be taken to fully investigate the possible effects of geological and topographic features on performance during the siting and design of these spillways.

Flow velocity and unit power are greatest at the river bed so scour tends to commence here and migrate upstream with time. However, it is the rock at the downstream end of the concrete lining which is the final defence against damage to the spillway control structure. An extensive, gently sloping bench of scour resistant rock (large L, small $\emptyset_1$) downstream of the concrete lining of a partially lined spillway offers excellent protection against undermining of the concrete chute even though major scour may still occur downstream of the spillway excavation. (L can be maximised by siting the spillway crest as far as possible towards the upstream end of the spillway excavation). At some sites however, a steeply sloping excavation floor may be located in higher quality rock than would a gently sloping floor and a choice would then have to be made as to which alternative offered the greatest protection against scour.

The suggested correlation between rock mass properties and type of spillway terminal structure will have to be applied within the limitations imposed by site topography and economics although it is possible for the apparent cost advantage of a particular spillway design or location to very quickly disappear if a major scour problem does develop and expensive remedial works are required. The geological criteria given above are aimed at ensuring the safety of the spillway control structure but erosion can have other undesirable effects such as the deposition of scour debris in the river bed below the spillway even when no threat to the control structure exists.

7. CONCLUSIONS

A study of fourteen dam spillways designed or operated by the Water Resources Commission of New South Wales suggests the following correlation between type of spillway terminal structure and site geology.

TERMINAL STRUCTURE	R.Q.D.(%)	ERODIBLE SEAMS
Full Energy Dissipator	<50	YES
Flip Bucket	>50	NO
Unlined or Partially Lined		
- moderate conditions	>75)Durable,)Lowly)Stressed)Rock	NO
- severe conditions	>90)	NO

Unlined rock cut spillways are usually associated with a rock mass fracture frequency generally less than 4 f m^{-1}. Circumstances requiring the provision of a short concrete lined chute downstream of the control structure are:

(i) gated spillways

(ii) other engineering structures such as a road bridge founded on the spillway crest

(iii) rock mass fracture frequency generally greater than 4 f m^{-1}. Open jointed rock (permeability generally greater than 5 Lugeons) is potentially erodible.

In situ rock stress levels should be assessed at any site for an unlined or partially lined spillway to prevent a repetition of the Copeton spillway scour problem.

8. ACKNOWLEDGMENTS

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9. REFERENCES

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