Stability issues at Intake UD

A. ROWLAND, Black & Veatch, Redhill, UK
Dr C.F. WAN, Black & Veatch, Hong Kong

SYNOPSIS. Intake UD in the New Territories of Hong Kong diverts water from a rocky stream into a tunnel system feeding into High Island Reservoir. The majority of the diversion structure is a siphon weir with a height of 9m above downstream ground level. The structure is constructed predominantly of mass concrete with reinforcement provided only in the siphon inlets and hood.

During a routine inspection, staff of the Water Supplies Department (WSD) noted relative movement of adjacent siphon blocks and horizontal cracking of the upstream face. The evidence was completely consistent with a stability failure at mid-height of the structure. However, stability analyses showed that the factors of safety for all load conditions were adequate and in line with normal design criteria.

The structure was designed with a hearting of 'Class C' concrete and 0.76m thick skin of 'Class B' concrete. Stability analyses for the skin concrete, assuming that it had separated from the hearting concrete, showed that the factors of safety reduced to only a little above unity for some possible loading conditions.

Investigations are still continuing but the preliminary conclusions may have implications for larger gravity dams of composite construction.

INTRODUCTION

High Island Reservoir was formed in the early 1970s by the construction of dams across each end of a sea channel separating High Island from the mainland in the eastern part of the New Territories in Hong Kong. It has a relatively small direct catchment area for the size of reservoir and the direct run-off is supplemented by supplies gathered from adjacent indirect catchments by a system of intakes and tunnels, including intake UD which is the subject of this paper.

Managing Dams: Challenges in a Time of Change. Thomas Telford, London, 2010

DESCRIPTION OF INTAKE UD

Intake UD is located on the Hau Tong Kai River and comprises a weir across the river which diverts flows into a feeder tunnel through a portal in the right abutment.

The weir structure, see Figure 1, is formed of three overflow units, each 6.706m wide, with abutment walls on each side. Each overflow unit has three siphon outlets 1.829m wide and 0.914m high. The siphons have an air regulating structure cantilevered from the front face of the overflow monolith. The hood of the siphons continues down to a sealing basin at the downstream toe. The structure stands about 5.6m and 9.0m high above the stream bed level on the upstream and downstream sides respectively.

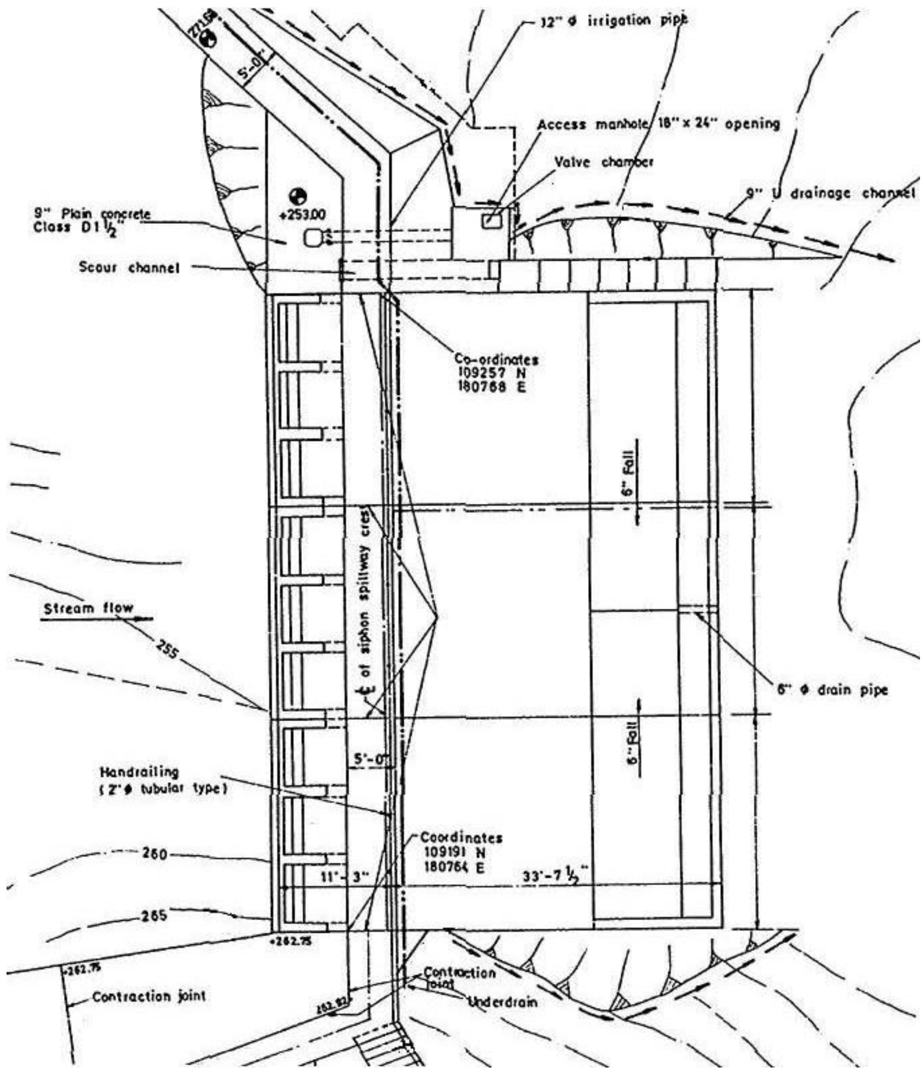

Figure 1. Plan of Intake UD

The body of the weir is a mass concrete gravity structure founded on rock. The foundation at the upstream edge is shown on the drawings as 0.9m below ground level, which is assumed also to have been the rock level in the stream bed. There is a 1.5m wide concrete cut-off below the upstream edge of the foundation. A drain is provided on the downstream side of the cut-off just below the foundation level of the structure. The foundation steps down about 4m to the underside of the 1.5m thick base of the sealing basin. The thickness of concrete on the downstream face of the gravity structure is a minimum of 1.5m.

The section in Figure 2, reproduced from record drawings, shows a hearting of Class C1½ concrete and a 0.75 m thick skin of Class B1½ concrete. However, it is by no means certain that the contractor would have chosen this form of construction and he may have constructed the whole gravity structure in Class B1½ concrete. Unless proven otherwise by further investigations, it will be assumed that there are two zones of concrete of different strengths.

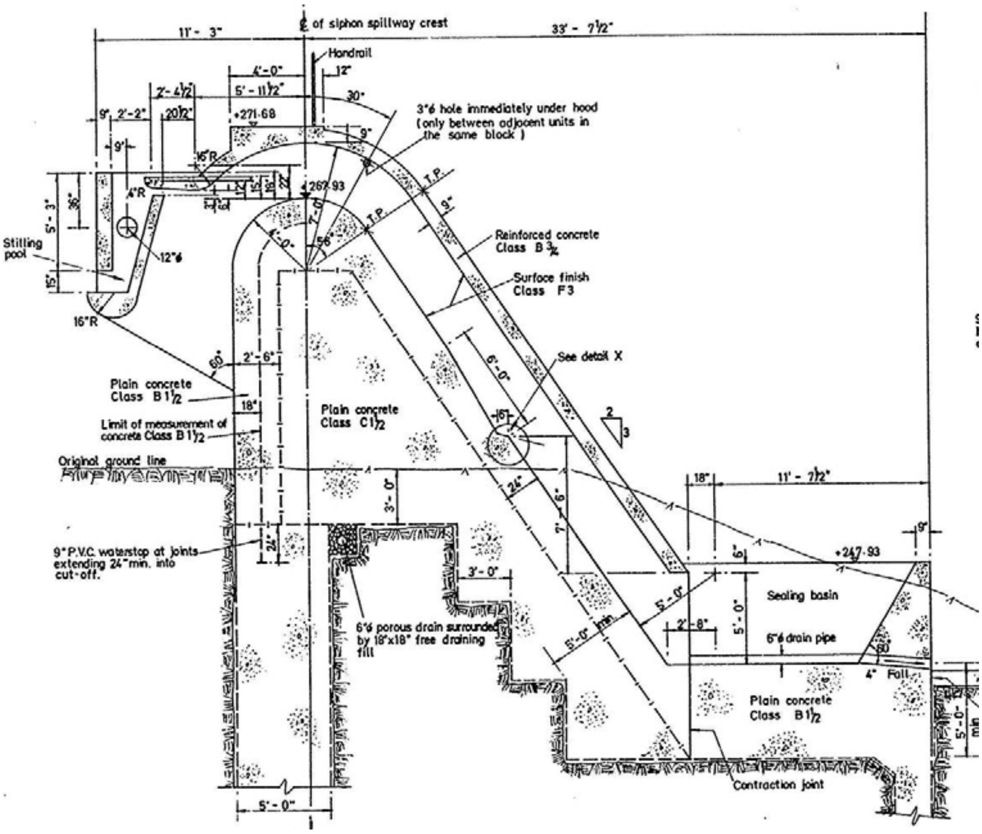

Figure 2. Cross section of Intake UD siphons

The reinforced concrete air regulating inlet structure projects 2.21m from the face of the gravity structure. The lowest point of contact of the side walls of the inlet is 4.35m below the top of the structure, which is 3.2m below the top of the gravity section. The side walls and hood of the discharge portion of the siphon units are also constructed of reinforced concrete.

THE PROBLEM

During an inspection of the structure in 2006 a crack was observed in the upstream face of the gravity weir, just below the springing point of the cantilevered side wall of the inlet structure. As can be seen in the photographs, the crack is continuous across the front of all three blocks, but is widest in the left hand block. There is also cracking in the adjacent wing wall just above the penstock that can be seen in the photograph.

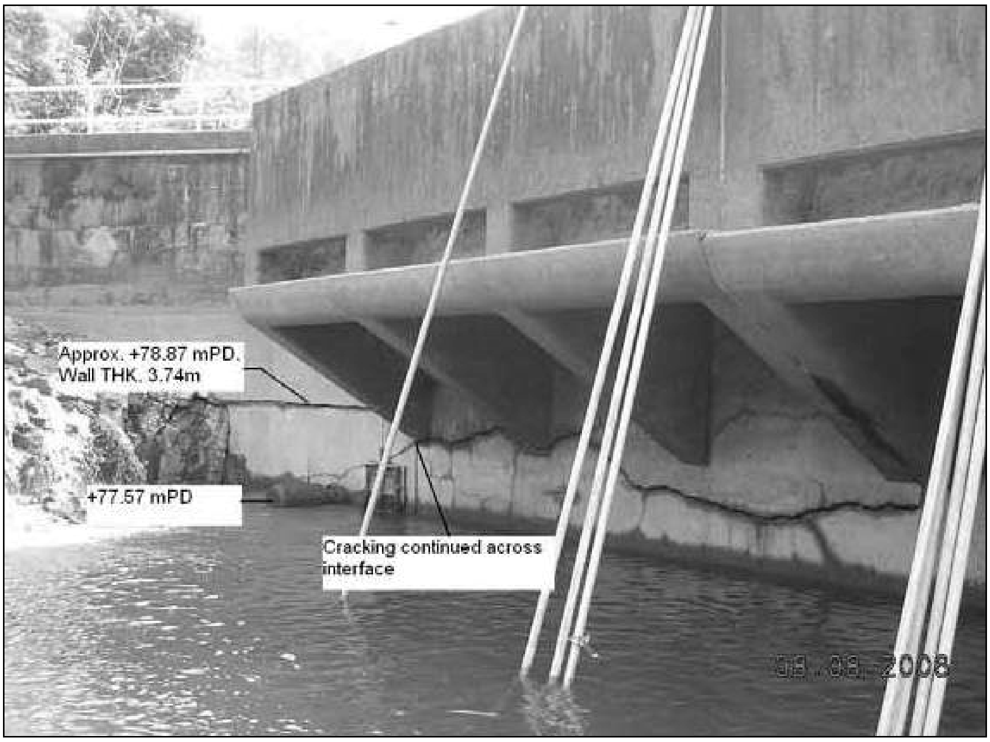

Plate 1. Left end of siphon unit and left abutment wall

Apart from the major horizontal crack across the whole length of the three siphon blocks, random cracks, probably caused by shrinkage, were observed on the upstream face of the blocks (Plate 2).

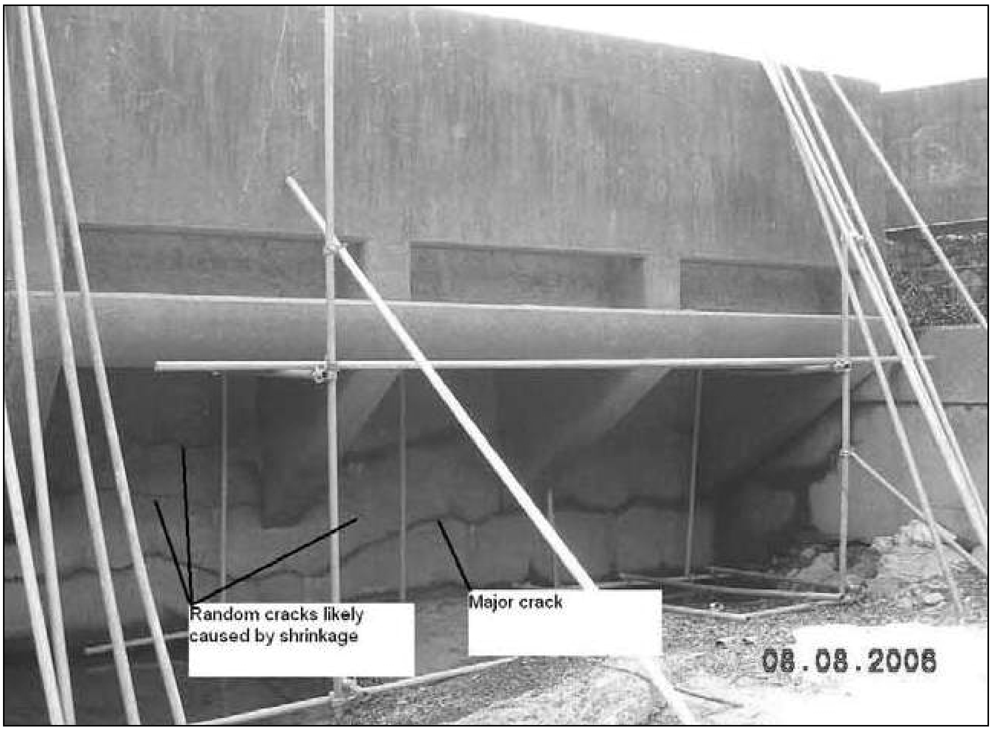

Plate 2. Right end of siphon unit

WSD arranged for 10 cores to be taken from the concrete on the line of the crack to investigate its depth. The cores indicated that the crack extends up to 700mm from the face of the concrete. Monitoring of the displacements has shown that there is no continuing movement.

There is very clear movement of the top of the units relative to each other and to the abutment walls, consistent with upward movement of the upstream side of the structure. The amount that the structure has lifted appears to be roughly consistent with, but perhaps slightly greater than, the width of the main crack:

- left unit relative to left abutment wall 30mm
- left unit relative to centre unit 20mm
- right unit relative to centre unit 20mm
- right unit relative to right abutment wall 10mm

There appears to be no displacement of the end wall of the sealing basin or of the downstream side of the siphon hoods, although comparison across the joints was made difficult by vegetation growing in the joints. No cracking could be seen in the siphon hoods or in the exposed concrete surfaces of the air regulator inlets. Inside the siphon barrels there has been extensive random cracking of the concrete, which is thought to be due to shrinkage in the unreinforced parts of the structure.

The wide crack on the upstream face does not appear to have developed along any lift joints or cold joints. The crack is approximately horizontal and continues through the entire length of each of the three siphon blocks. The crack is at approximately + 78.33 mPD immediately below the walls supporting the hood. There was an obvious tilting of the upper part of the left most siphon block towards the downstream side, and the crack at the upstream face was the widest (> 10mm) compared to the cracks in the other two siphon blocks. The location and nature of the cracks indicated a stability failure of the upper part of the siphon blocks.

STABILITY ANALYSIS

Approach

Because the major crack is located at approximately + 78.33 mPD, the stability analysis was carried out for the section of the siphon block above that level only.

The stability analysis was carried out in 3 steps:

- Step 1 assumed that there was no initial cracking in the siphon block before loads were applied. The siphon block was then checked for stability against horizontal shear failure, overturning and bearing failure for water levels above the top of the hood at + 82.808 mPD.
- Step 2 assumed that a horizontal crack had developed at + 78.33 mPD through the thickness of the outer concrete on the upstream side of the section to a depth of 0.762m (assumed thickness of the outer concrete). Full uplift pressure was assumed to act along the depth of the crack.
- Step 3 assumed that the outer concrete was separated from the inner concrete above the analysis level at + 78.33 mPD from location P1 to location P5. Full uplift pressure was applied along the separation.

The following major assumptions were also made in the above stability analyses:

- The effect of tailwater was neglected;
- The weight of water above the top of the hood was neglected if the water level was higher than the crest level;

- The hood and the dividing walls supporting the hood contribute no moment of resistance or shear resistance and were treated only as dead loads;
- Suction equivalent to a negative water head of 6.3m was applied along the ogee crest for high water levels when the siphons are in action;
- The weight of water within the barrel was considered.

<u>Step 1</u>
The assumed failure surface for the analyses in Step 1 and Step 2 is shown in Figure 3.

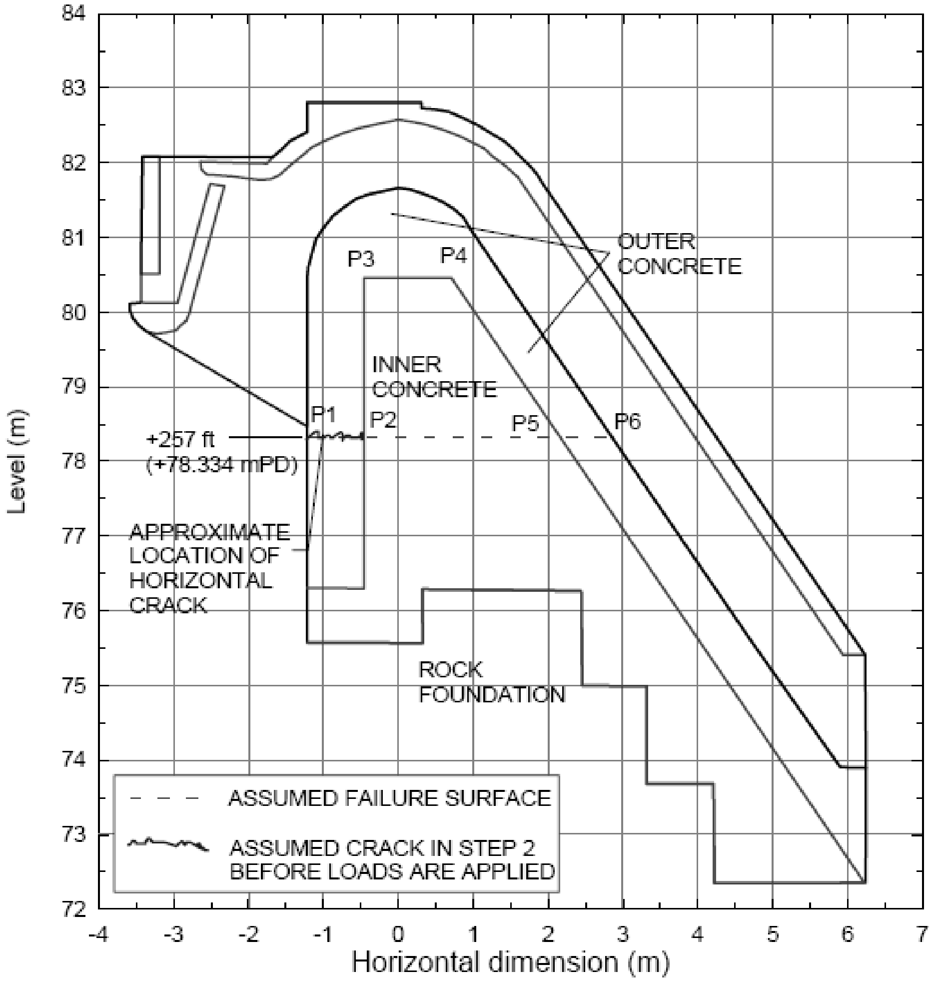

Figure 3. Failure surface for Steps 1 and 2

The analyses reveal that minor tension begins to develop at the upstream face at the analysis level when water level rises above + 83.1 mPD (c.f. top of hood at + 82.808 mPD). If the stress is high enough to initiate tensile cracking at the upstream face, increase of uplift pressure along the crack and stress redistribution will lead to reduction in the Factors of Safety (FoSs) against shear failure, overturning or bearing failure at the downstream toe at the analysis level.

While the FoSs for shear failure and bearing failure remain very high at all water levels up to +83.8 mPD, the FoS against overturning about the downstream toe at location P6 will become only marginally greater than unity when water level is at about +83.8 mPD, about 1m above the top of the hood. In other words, the siphon section would only be at the verge of overturning if the water level should rise to this unlikely level.

The tensile stress at the upstream face remains quite low (less than 34.5 kPa) at a high water level of + 83.8 mPD. The chance of tensile cracking in the concrete due to the applied dead loads and hydraulic loads should, therefore, be very low, as good quality plain concrete can easily withstand a tension of 500 kPa without cracking.

Step 2
Full hydrostatic pressure in an upward direction has been assumed acting along the crack at + 78.334 mPD at the upstream face of the siphon block. The initial depth of the crack before loads are applied is 0.762m (2.5 ft), which is the assumed thickness of the outer concrete.

Results of the analysis in Step 2 indicate that the increase in the initial uplift pressure due to the crack only reduces the FoSs slightly at low water levels, when the applied hydraulic loads are not high enough to cause cracking further than through the 0.762m thick skin concrete. At water levels higher than + 83.3 mPD, the FoSs obtained are the same as those obtained in Step 1.

Step 3
The assumed failure surface for the analyses in Step 3 is shown in Figure 4. Analyses in Step 3 assumed that the outer concrete of the siphon block was detached from the inner concrete along points P1, P2, P3, P4 and P5. Full uplift pressure was assumed to develop along the separation before other loads were applied.

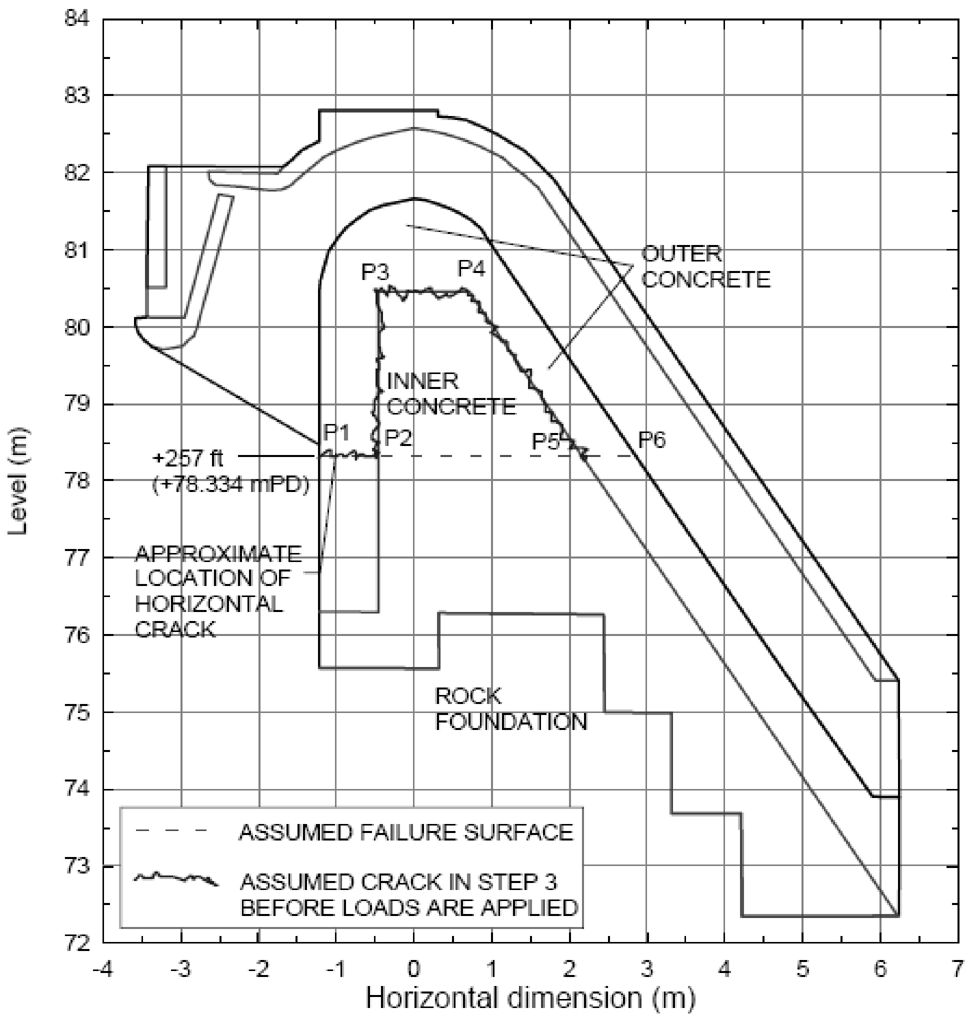

Figure 4. Failure surface for Step 3

Due to the assumed detachment of the outer concrete from the inner concrete, the weight of the inner concrete core was not taken into account when assessing the FoS against overturning about point P6. Results of the stability analyses indicate that the FoS against overturning is significantly reduced when compared with the results of analyses carried out in Step 1 and Step 2, and is reduced to unity when the water level reaches about +83.3 mPD (about 0.5m above the top of the siphon hood). At about the same water level, detachment of the outer concrete from the inner concrete will extend beyond point P5, resulting in even higher uplift pressure than estimated.

The FoS against shear failure along a plane at elevation + 78.33 mPD remains very high for a water level up to + 83.3 mPD, as the shear resistance of the inner concrete is taken into account in the stability analysis.

The structure cannot fail by shear along this level without a failure through the inner concrete core.

CONCLUSIONS

The major crack at the upstream face of the siphon section does not seem to have initiated along any plane of weakness such as a lift joint or cold joint.

There have been no major extreme events, such as earthquake or floods resulting in flows passing over the top of the siphon hoods.

The stability analyses reveal that the chance of the observed cracking and movement of the structure being caused by dead loads and hydraulic loads is low, unless there were pre-existing cracks. This is because the tensile stresses at the upstream face of siphon block would be too low to initiate tensile cracking in good quality concrete even if the water level rises to 1m above the top of the hood.

The presence of other relative minor random cracks at the upstream face of the structure suggests that initial cracking in the outer concrete might have occurred due to concrete shrinkage or thermal expansion/contraction. The difference in the stiffness between the reinforced hood and dividing walls and the unreinforced outer concrete of the gravity ogee section mass concrete ogee section might have aided the cracking process.

Once cracks were initiated by differential shrinkage, water could penetrate into the mass concrete section. The increase in pore/uplift pressure within the mass concrete section together with the hydraulic loads during high water level might have separated the outer concrete from the inner concrete, causing further increase in uplift pressure and increased overturning moment.

A moderate overtopping (about 0.5m above the top of the siphon hood) would have induced high enough overturning moments to widen the crack at the upstream face and tilt the upper part of the siphon section. It is possible, but not proven, that a flood level at the top of the siphon hood may have established the right conditions for the movement to initiate.