

Cobb Dam Sinkholes

Bruce Walpole¹, Craig Scott²

TrustPower Ltd¹
Riley Consultants Ltd²

Monitoring and surveillance is crucial to managing the ongoing performance of dam structures. The true value of appropriate monitoring, surveillance and review processes is only realised when potential dam safety issues arise. TrustPower's civil safety monitoring and surveillance program includes nineteen hydro schemes throughout New Zealand and incorporates structures with Potential Impact Classifications (PIC) ranging from Low to High.

TrustPower promotes a continual improvement policy on its management of safety issues and conducts inspections on a regular basis. Routine and periodic independent inspections of the key components within a scheme are paramount to the viability of the safety management system. The importance and purpose of these inspections has recently been highlighted by the discovery of two sinkholes on the face of the earth dam associated with the Cobb hydro electric power scheme.

This paper provides an example of the need for continual monitoring and surveillance, vigilance of observations, good archiving systems and documentation. It discusses the broader issues surrounding the subsequent response processes to potential dam safety deficiencies, and the success (or otherwise) of investigative methods. It also highlights that an adequate dam safety compliance system has commercial value as there is a measurable reduction in dam performance uncertainty and hence greater efficiency in the speed at which accurate resolutions can be drawn.

Keywords: Dam safety, embankment, sinkholes, foundations, dam drainage, geophysical investigations.

Introduction

The Cobb dam is located inland of Takaka, on the Cobb river, on the northern tip of the South Island in New Zealand, within the Kahurangi National Park (Fig. 1). The dam was constructed in 1951-1956, and sits at the bottom of a glacial carved valley. It has the unique distinction of having the highest head of any hydro dam in NZ; 596m between the mean lake level, and the turbines located in the powerhouse.

In 2003 Cobb dam was incorporated into TrustPower's portfolio of hydro schemes and the dam became subject to civil inspection routines as part of TrustPower's dam safety monitoring and surveillance system.

During the course of a recent annual inspection a deficiency was identified.



Figure 1. Cobb dam location map

History

The Cobb Power scheme was initially constructed between 1937 and 1944 by the Hume (Cobb River) Electric Power Company Limited. Its ownership was transferred to the Public Works Department in 1940 (Blair 1994). For the first 10 years of operation, flows were simply diverted through the intake tunnel and into the penstocks, then down to the powerhouse located some 600m below (Fig. 2). Initially there was only a small artificial pond created by a low crib log weir diverting water through screens into the tunnel.

Construction of the current Cobb dam marked an important turning point in the history of New Zealand hydroelectric power schemes. It was the first to include a comprehensive seismic and magnetic survey of the foundations (Fisher 1946), and the first dam to incorporate a piezometer system for measurement of pore pressure (Jones 1955).

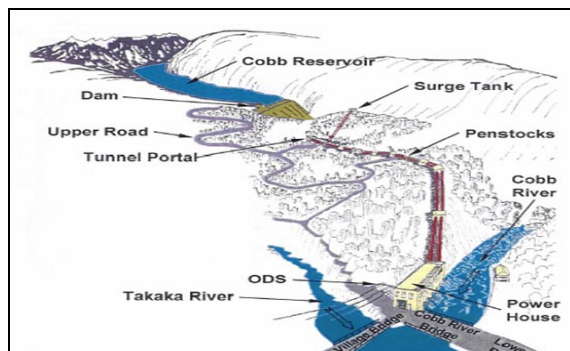


Figure 2. Current scheme layout

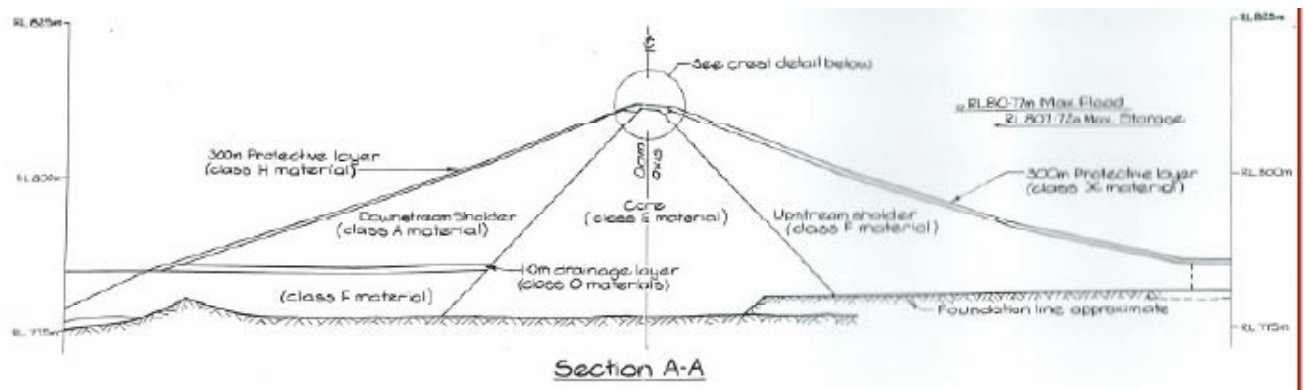


Figure 3. Typical cross section of the embankment

Dam Components

Cobb is a zoned earth and gravel embankment dam (Fig. 3) with a volume of 330,000 cubic metres. It is 34m high and 221m long. The reservoir volume when full is 30 million m³. The dam is a high potential impact category (PIC) structure.

The spillway is a concrete structure within the dam that discharges via four tunnels into two two-bay stilling basins. The spillway intake is divided into four sections. The spillway was constructed prior to the dam wall.

TrustPower monitoring and surveillance

Earth dams are prone to various types of failure and monitoring for signs of potential failure is a key part of TrustPower's monitoring and surveillance system. Regular monthly visual inspections incorporate numerous instrument readings by staff. Annual civil inspections supplement the monthly inspections and are attended by local TrustPower production staff, engineering staff from head office and independent engineering experts from Riley Consultants Ltd. This combination allows experts in civil safety to provide expertise and tuition while being informed of recent issues relevant to the scheme.

Identification of Deficiency

There have been no significant deficiency issues with the dam in its operational lifetime. Although there have long been damp patches on the face of the dam, the source of these damp patches has never been definitely determined. It is suspected that they are created by groundwater seepage from the abutments and steep valley hillsides above the dam, rather than lake seepage.

During the 2006/07 annual civil inspection staff noticed two significant sink holes on the downstream face of the dam wall (Fig. 4). The discovery was made during a walkover of the face of the dam, and although the local route march took staff relatively close to (10-15m) the depressions during routine

monitoring rounds, the angle of the slope and grass cover contributed to these sinkholes lying unnoticed until the annual civil inspection was undertaken. These sinkholes were shallow depressions, approximately 2.5 m square and less than 1 m deep (Fig. 5). The sinkholes were located approximately one third of the way down the dam face with one approx central and the second toward the left abutment.

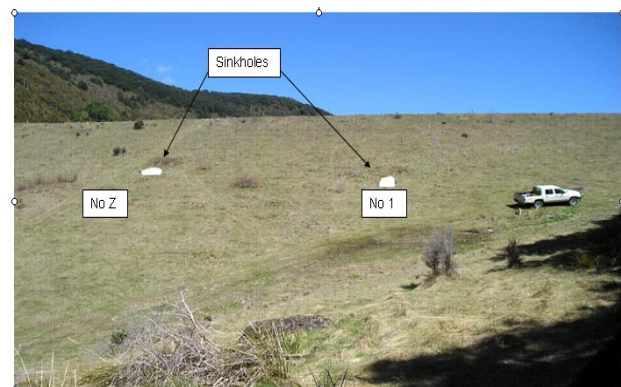


Figure 4. Location of sinkholes (note: route march sample point below truck)



Figure 5. Sinkhole size and depth at the surface.

Immediate incident response

A deficiency investigation programme was immediately formulated. This was broadly divided as follows:

Stage 1 : Immediate actions:

- Discuss antecedent conditions with staff;
- Completed detailed sinkhole inspections;
- Extensive search for further sinkholes;
- Measurement of location of holes;
- Gallery and drainage tunnel inspections;
- Inspect internal drainage system weir flows for sediment or other signs of damage;
- Sediment samples collected and traced;
- Intensify monitoring of flows and weirs;
- Notification of relevant parties;

Stage 2 : Document Review:

- Comprehensive documentation search for gallery and drainage drawings;
- Comprehensive documentation search for relevant dam construction reports;
- Accumulation of knowledge base in Tauranga, (TrustPower Ltd head office);
- Review of drainage flow data and piezometer levels;

Stage 3 : Physical Investigations:

- Internal inspection of shaft drainage points;
- Survey location of sinkholes;
- Ground penetrating radar for location of voids;
- Modelling of drainage system and layers in the dam;

Stage 4 : Future works:

- To be determined.

Stage 1 Immediate action findings

Discussion with staff

Station staff were closely questioned to ascertain if any unusual events had occurred on recent times that may have contributed to or initiated the features.

Antecedent Conditions

The Cobb reservoir has a significant storage range of approximately 14 m under normal operations. This means that when the storage is nearly empty the stored volume is only 10% of that at normal maximum operating level.

Lake levels were very low at the time, which was fortunate, but as a precaution spillway gates were operationally checked while the investigations continued. The lake level was 797.25 m, giving a volume of 7.5 million m³ compared to the possible 30 million m³ which could have been stored had the lake been full.

Earthquakes

Earthquakes are numerous in the Cobb region and discussions with local staff indicated a fairly recent

earthquake that may have provided the mechanism for settlement resulting in the surface depressions becoming evident. However, the seismic trips at the penstock tunnel portal were not triggered by the quake indicating the event was not severe locally.

A search of the GeoNet database for the locations and details of earthquakes that occurred around August/September 2006 showed that an earthquake of magnitude 5.2 (Richter Scale) at source occurred on the 11 September 2006 (Table 1) and was felt in the upper South Island and Wellington. This earthquake was one of only twelve events of M5.0 or larger to have occurred within 75 km of the dam since it was completed. It was one of the closest (epicentral distance 18 km) but occurred at a depth of 185 km.

Earthquake	Date	Time	Depth (km)	Magnitude
1	22-Aug-06	1:25	208	3.764
2	24-Aug-06	12:46	12	2.876
3	27-Aug-06	6:47	209	2.889
4	1-Sep-06	3:40	174	3.687
5	3-Sep-06	3:18	216	3.594
6	11-Sep-06	6:02	185	5.172

Table 1. Earthquakes centred near Cobb in late August and early September 2006.

Detailed sinkhole inspections

The sinkholes were nearly square depressions which had occurred relatively recently. One sinkhole had sufficient exposure for a small plant to establish itself on the vertical exposed scarp feature while the other sinkhole scarp was bare and fresh. The sinkholes were approx 30 cm deep and 2-2.5 m wide (Fig. 5). The edges had holes running into them 30 cm in depth. Long grass in places formed a mat over the failed zone. No water was present in or exiting the depressions.

Inspections were undertaken to ascertain if the process that led to the sinkholes was recent and had rapidly occurred or was part of a gradual process over the life of the dam.

It was judged that at this stage there was no indication of accelerating deterioration, seepage from the dam face or any other typical piping failure type indicator, aside from the surface settlement.

Inspection of drainage tunnels

Immediate investigations included inspections of the underground drainage galleries looking for evidence of material from the voids now at the dam surface. The drainage galleries are mostly concrete lined tunnels with few surface entry points.

No indications of large deposits of material were found apart from small gravel piles below one of the drop chutes. A fine black sand material found in the dewatering drive was traced back to the spillway gates which were well upstream of the location point

of the two sinkholes. This indicated that the sand was not from the sinkholes.

Stage 2 Document review findings

Drawing and documentation review

Comprehensive review of all available drawings and documentation quickly determined the most likely cause of the sinkholes was collapse associated with construction shafts. The area of the dam site was extensively investigated with drill holes, shafts and drives prior to and during construction. A number of the shafts and drives were left open to provide for access and drainage during construction. While many were backfilled at or before construction completion, several drives have remained open to the present day to provide access beneath the dam for monitoring and surveillance points.

The access drives and drainage tunnel drawings provided the most compelling evidence that the sinkholes were due to shaft backfill material settlement, and not a safety issue leading to a potential dam failure. Two construction shafts were shown to be in the near vicinity of the sinkholes and the size of the sinkholes matched shaft details.

Shaft 1

Shaft 1 (Fig. 6) was excavated in December 1944 to explore the underlying rock conditions on the true-left of the Cobb River. The shaft was 6' 6" by 3' 4" and was timber lined. A cross-drive was excavated beneath the Cobb River to connect this shaft with shaft 2. Fisher (1946) provides a detailed account of the geological and geophysical excavations undertaken until October 1946.

Shaft 1 extends from the ground surface to the cross-drive 30 m below. The shaft passes through the embankment fill (Class A downstream shoulder and Class G drainage material), and through in situ material consisting of moraine and river gravels. The blanket drain (Class G) was placed directly on the prepared dam foundation at a slope of 3.25:1.

Shaft 1 was due to be backfilled with Class F material after the completion of the foundation grouting but was left open until the end of construction as access for lining the cross-drive. Upon completion of the fill embankment, the base of shaft 1 in the cross-drive was to be filled with a concrete plug and the shaft backfilled with Class H material with compaction and the top 10' to 15' of timbering removed.

Shaft Z

Shaft Z was excavated as part of the earth dam drainage system, with four 3 inch diameter holes drilled at the top of the cross-drive to allow water to exit. This shaft was 8 ft by 8 ft and timber lined.

Unlike shaft 1, the dam fill material in this location sits directly on bedrock, with the blanket drain (Class G) placed on Class F material. This is due to

shaft Z being excavated into the original Cobb River, which was in the lowest point of the valley.

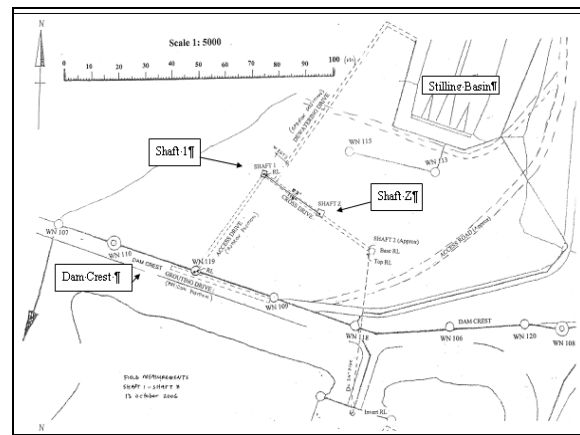


Figure 6. Location of shafts and sinkholes.

Construction photographs show shaft Z with timber shoring exiting the compacted earth. The photographs show the material surrounding the shaft being compacted. However it is possible that this material was not compacted to the same standard leaving some areas potentially erodible, or subject to differential settlement. Shaft Z was backfilled as for shaft 1.

Monitoring and Surveillance Review

Monitoring of drainage flows and standpipe readings was increased after identification of the sinkholes, to daily from monthly readings and station staff were placed on a 24hr scheme watch. Riley's staff undertook an immediate review of all monitoring and surveillance monitoring data. The dam monitored data includes:

- 16 weir flows.
- 9 standpipes.
- 4 visual inspection sites.

The data indicated all instruments were within their normal limits with the weir flow water running clear.

Sinkhole Investigations

A recent review of sinkholes in embankment dams noted thirty conditions and causes for the development of sinkholes (Jansen, 2000).

At least five of these conditions can be highlighted as potentially pertaining to those encountered on the Cobb dam face:

- 1) Segregation due to poor construction workmanship or migration of fines from gravel and cobbles.
- 2) Internal erosion across boundaries between zones with incompatible gradations.
- 3) Subsidence of backfill in exploratory shafts in the foundation.

- 4) Chimney sinks developed by successive arching and collapse of fill.
- 5) Settlement into cavities in the embankment left by decayed wood timbers, as in cut-off walls and construction trestles.

It is believed that a combination of these factors led to the development of the depressions in the Cobb dam face. The construction drawings indicate wood was used in the lining of the shafts. After 50 years with water and air voids present the timber is assumed to have degraded allowing spreading of shaft material.

Stage 3 Physical investigation findings

Ground penetrating radar

Physical investigations were deemed necessary to evaluate the desktop hypothesis that the sinkholes were due to construction shaft backfill settlement.

The investigation fieldwork centred on ground penetrating radar (GPR) and topographical survey, with the geophysics used to determine if cavities still existed at the shafts, and the topographical survey to confirm that the sinkhole locations were coincident with the shafts. GPR techniques have been successfully employed on confirming the presence of voids on embankment dams in the past (e.g. the 30m high Hardy Dam in Michigan (Silver *et al.* 1986)) and it was concluded that this technique would be appropriate for the present case. Subsurface Imaging Ltd were commissioned to undertake a full GPR survey of the entire downstream face of the dam, with particular focus around the sinkholes. Two

different sampling antennae were employed, including a 200 MHz high resolution antenna for shallow sampling up to 5 m, and a 35 MHz antenna for deeper sampling up to 20 m.

The geophysical survey identified the presence of possible large voids in or around shafts 1 and Z (Fig. 7).

A 3-D model of the dam structures and zoning was developed to help interpret the relationship of these targets with in situ material (Fig. 8). The targets all cluster around the shafts generally above the level of the blanket drain.

These void targets have been interpreted as either indicating the presence of dry granular material in the shafts, or the presence of air voids. Ongoing discussions with Subsurface Imaging Ltd have confirmed that the most likely interpretation of the target signatures is that they are consistent with air voids.

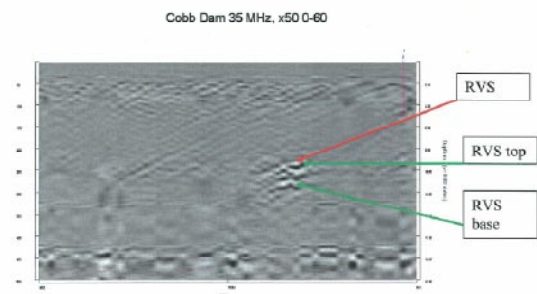


Figure 7. GPR data example of radar void signature approx 2-2.8m high

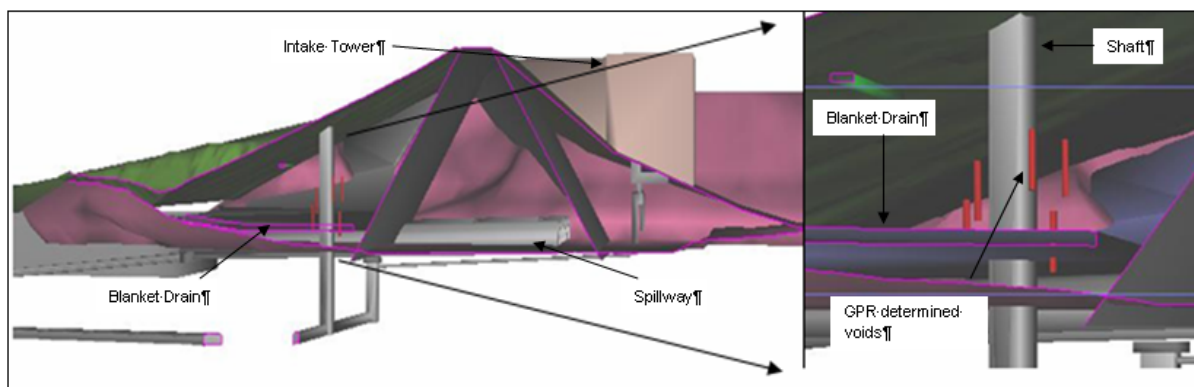


Figure 8. 3D model of dam cross section with close up view of GPR determined voids (red zones)

Review of dam material compatibility and internal stability

The Comprehensive Safety Review (CSR) undertaken by Damwatch in 2002 highlighted incompatibility between the zoned embankment materials and concluded that they do not meet modern design standards. Furthermore, the drainage

blanket material was never intended to be in contact with the Class H material used to backfill the shafts, although compatibility checks show that these two materials are, coincidentally, broadly compatible.

In addition, while there would have been some migration of fines due to water moving through the dam material, checks on internal stability and internal

erosion of the embankment show that for Class F, G and H materials it is unlikely that they are internally unstable (Fell *et al.* 2005).

Characteristics of the Class H material in the shafts suggest that this material is segregated. The maximum particle size of 150 mm, the low percentage of sand and fine gravels (25% finer than 4.75 mm), and the probable end-dumping from trucks and high lift heights are all typical precursors of segregated soils. Segregation of material may also have contributed to the internal movement of fine material, which has undoubtedly occurred as evident from a post-construction note from the site office to the Hydro Design office in Wellington about the need for monitoring discharge (of stones and muddy water) from the drainage holes in shaft Z (Cowie 1957).

The water in shaft Z drains to the cross-drive through four 3 inch holes. An inspection of these holes was undertaken during the site inspections and found that the first hole was blocked and the second hole had water seeping out. A long crowbar was inserted into the third hole with no resistance, indicating a large void immediately above the cross-drive, and when it was inserted into the fourth hole a small amount of fine gravel came out.

The void in shaft Z above the cross-drive was probably caused by the movement or removal of Class H material by water exiting the drain holes. It is inferred that, due to the probable segregation of the material, the finer fraction has been washed out of the drainage holes into the cross-drive until it has re-sealed. Prodding the material as discussed above induces flow of water and sediment through the holes. Arching of segregated large gravel has likely created a void above the cross-drive (Fig. 9).

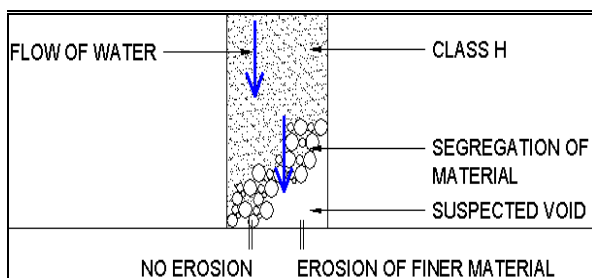


Figure 9. Schematic of Shaft Z showing segregation of material and loss of fines.

The flow path from shaft 1 to the cross-drive is unknown, but it is possible that a similar void exists above the concrete plug used to close the shaft at the base.

Where to now ?

A comprehensive safety review of the dam noted a number of key issues related to compatibility of dam zone materials. The sinkholes, initially a significant

concern, have been downgraded to an issue to be investigated in association with a full assessment of the dam's integrity.

Further Investigations

In the near future the following are proposed:

- CCTV inspection of drain holes in shaft Z to determine if the segregation and erosion cavities in the shaft base exist.
- Test pit sampling of the shaft backfill and crest materials to determine gradings and compatibility with surrounding materials.
- Installation of deformation survey markers to monitor settlement at the shafts.
- Commissioning of turbidity monitoring.
- Full geotechnical and geological data acquisition for the dam site.
- Dam zoning compatibility assessment and identification of key areas of risk.
- Dam stability assessment.

Remediation

With respect to the shafts several options are under consideration to treat the settlement:

- Enhanced Monitoring.
- Injection grouting of voids and shaft material.
- Forced settlement of material.
- Remove and replace shaft material.
- Replace surface material and level to adjoining surroundings.

The present consensus is that increased surveillance is appropriate at this time, as the inferred risks associated with the various other options are considered to outweigh the benefits until the cause of the settlement and exact nature of potential voids is determined. A comprehensive risk assessment has been proposed for the dam to test this option.

Conclusions

Several key conclusions from this unique event, the first of its kind on any TrustPower Ltd hydro scheme dams, are:

Trigger Earthquake

- An earthquake is likely to have triggered settlement of the shaft material that had not previously settled at the surface since commissioning of the dam approximately 50 years prior.

The Dam

- The sinkholes are not considered to be a dam safety issue and do not compromise the safety of the dam.
- The wooden lining of the shafts has likely deteriorated and contributed to void formation and settlement resulting in collapsed arches rising to the surface.
- Compaction of the shaft material will most likely continue to occur without remedial preventative action.
- Non invasive investigation techniques such as the GPR proved useful in assessing the cause of the shaft settlement.
- Modelling provides a good presentation tool in demonstrating the location of air voids in the backfilled construction shafts.
- Instrumentation did not play a part in locating the deficiency. Site visits are imperative in the dam monitoring and surveillance program.

General

- The monitoring and surveillance system based on NZSOLD guidelines used by TrustPower Ltd worked well. The several layers of independent inspections ensured the sinkholes were detected and assessed.
- Detailed inspections of civil components by appropriately trained staff external from site personnel are a critical component of a robust surveillance routine.
- Documents and drawings are key to assessing a safety issue. Availability of key information can be difficult to obtain.
- Having a hard copy of all documentation and drawing material at station sites proved very useful.
- Short chains of communication between dam owners and advisors, enhanced the understanding of the issue and allowed for quick authority to dewater the lake if needed.
- A high hazard dam of significant value was able to continue to operate without significant commercial ramifications due to the quick diagnosis of the deficiency.

Acknowledgements

We gratefully acknowledge the assistance of:

Gordon Fletcher and the staff at Cobb HEPS. Peter Lilley, TrustPower Engineering Manager, Steve Currie from Energy Surveys Ltd, Grant Roberts from Subsurface Imaging, and Stuart Read of GNS for providing an unpublished paper.

References

- Blair, A.K. 1994. The Cobb. The History of Cobb River Hydro-Electric Power Scheme. Nelson.
- Cowie, J.A. 1957. Cobb Power Project – Underground Galleries. Unpublished Letter to the Hydro Department
- Damwatch 2002. Cobb Dam and Penstocks Comprehensive Safety Review. Report to Natural Gas Limited.
- Fell, R.; MacGregor, P.; Stapledon, D.; Bell, G. 2005. Geotechnical Engineering of Dams. A.A. Balkema Publishers London.
- Fisher, W.M. 1946. Cobb River Power Scheme – Report on Investigations. Unpublished Public Works Department Memorandum.
- Galloway, J.H.H. (no date) Cobb Power Project: Earth Dam Design. Ministry of Works, New Zealand design office in Wellington
- Jansen, R.B. 2000. A review of sinkholes and related instrumentation at embankment dams. Twentieth International Congress on Large Dams (ICOLD) Beijing, pp.663-685.
- Jones, O.T. 1955. Construction of the Cobb Earth Dam, *New Zealand Engineering*, 10(11): 353-360.
- Silver, M.L.; Fisk, P.S.; Greenman, A. 1986. Grouting a sand dam. *Civil Engineering-ASCE*, 56(12): 34-36.