Maintenance and Testing of Post-Tensioned Anchors for Dams and Appurtenant Structures

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The use of permanent, load-monitorable post-tensioned, anchors for dam projects has been in place for approximately 35 years in Australia. Since then, over 30 large Australian dams have been strengthened using this technology, including the world record for anchor length (142 m - Canning Dam, WA) and size (91x15.7 mm strands - Wellington Dam, WA and Catugunya Dam, TAS).

In order to achieve the design life of 100 years expected of these anchors, an ongoing program of monitoring, testing and maintenance is required, to identify and rectify the initiation of corrosion or loss of pre-stress. Guidance for maintenance and testing regime for post-tensioned anchors in dams is provided in the ANCOLD Guidelines on Dam Safety Management (2003). The various conditions which may affect the performance of the anchor with time, such as anchor type, ground condition and loading fluctuations are not covered in the Guideline.

This paper reviews the implementation and results of anchor monitoring programs by Australian dam owners. The first part of this paper provides a summary of the testing and monitoring programs currently being implemented. The second part of the paper reviews the aggregated anchor load test results from a number of Australian dam owners, and identifies trends in anchor response over time following installation.

The paper aims to assess whether the recommended anchor testing regime proposed in ANCOLD (2003) is appropriate and cost effective, using evidence from recent load test data which has become available following the writing of the guideline. The lessons learnt from anchor maintenance programs will also be discussed.

Keywords: *post tension, re-stressable, ground anchors, monitoring, load testing, dams.*

Introduction

Post-tensioned permanent ground anchors (referred to as ground anchors in this paper) have been widely adopted in Australia as a means of stabilising concrete dams and appurtenant works. Ground anchors have generally been used to stabilise existing dams in order to achieve current industry standards for stability under earthquake or flood loading. Anchoring technology has advanced the past decades, mainly in the area of long-term corrosion protection. (Sinclair & Rodd, 2011) Ground anchors installed prior to the 1980s had their strands fully grouted and therefore the residual load in the anchors cannot be tested. Today in Australia and in many other nations, current good practice requires that all permanent ground anchors used on dams projects must be monitorable and testable.

The objectives of monitoring and testing ground anchors are:

- To confirm the anchor load is compatible with the design intent;
- To identify whether the ground or the anchor deforms with time (due to creep etc);
- To monitor state of the ground anchor, i.e. whether the anchors are still adequately protected against corrosion.

ANCOLD (2003) and DSC (2010) provide guidance on the frequency of testing of anchors, based on the Consequence Category of the dam. These two documents provide the only dam specific guidance on anchor monitoring that have been identified in the literature. This paper examines current practice in anchor monitoring by dam owners in Australia, and assesses the results of their testing to assess the appropriateness of the current guidelines.

The monitoring regime of the ground anchors in dams typically comprises periodic visual inspections, grease replacement and lift off testing.

General considerations for service behaviour monitoring for ground anchoring in dam structures

Ground anchor design load requirements

Ground anchors have typically been retrofitted to existing concrete dams or concrete spillway structures to improve the factor of safety for sliding or overturning under extreme floods and earthquakes. These anchors tend to be very large high capacity strand anchors. Other applications of ground anchors for appurtenant works include stabilisation of spillway training walls and to stabilise spillway piers. These anchors tend to have a much lower capacity, and comprise either strand or bar anchors.

The minimum working load (i.e. the design load) of an anchor is typically set at 60% of the Minimum Breaking Load (MBL), although a minimum working load as high as 65% MBL has been adopted. For the initial stressing of the anchor, the anchor typically has a target lock off of 7% to 10% of the MBL above the minimum working load, allowing approximately 10% load loss to occur prior to compromising the design load. As part of the installation process, the anchors are proof loaded to a load of 75% to 78% MBL. The primary purpose of the proof load is to confirm the bond strength of the fixed zone of the anchor.

For the service life of the anchors, the anchors should remain greater than the minimum working load and less than the maximum proof load. Typically, the service life of anchors for dams applications are specified as 100 years.

Strand anchors can be made re-stressable using a multi-strand jack by leaving sufficient strand length above the anchor head, however this is not typically undertaken. This allows the anchor load to be reinstated if excessive load loss has occurred. For re-stressing by monostrand jacking, the individual strands are gripped, extended and locked off. Alternatively, the entire anchor head is lifted, and shims are placed beneath the head to increase the extension on the anchor. There are concerns associated with the durability of the anchor following both types of re-stressing procedure, and the procedure is considered to be a “last resort”.

Existing monitoring guidelines

A number ground anchor standards have been developed, such as FIP (1996) (EU), PTI (2014) (US) and BS-8081 (2015) (UK). These standards all contain a section on the long term monitoring and testing of ground anchors. These standards are based on the original BS 8081 (1981), which was the first recognised standard on ground anchors and contains common philosophies in the monitoring requirements for permanent ground anchors. These standards have all been developed for a range of ground conditions, ranging from soils to hard rock. A review of guidelines produced by major dam safety authorities from countries outside of Australia did not identify any recommendations on monitoring of post-tensioned anchors.

A comparison between the monitoring programs recommended by a number of international ground anchoring standards is presented in Table 1 on the following page.

The frequency and number of tests recommended indicate a variety of approaches between standards, nevertheless indicate an underlying difference in philosophy for the monitoring requirements of ground anchors compared to ANCOLD (2003) and DSC (2010), namely:

- A focus on frequent testing early in the life of the anchor, with reduced testing into the life of the anchor, which is not considered in ANCOLD (2003) or DSC (2010);
- Typically recommend a lower percentage of anchors undergo testing than DSC (2010) and ANCOLD (2003);
- Differentiate the load monitoring based on whether for identification of corrosion or for determining ground movement;
- ANCOLD (2003) and DSC (2010) emphasise the consequences of failure as the primary variable in selecting frequency of testing, wherease the other standards recommend a testing frequency independent of consequences of failure.

It is noted that amongst all the various standards and guidelines, there is a greater emphasis placed on mechanical testing of anchor loads than on visual inspection of the anchor heads. The authors believe that this lack of emphasis on regular visual inspections is a serious omission; as the greatest threat to anchor performance is corrosion and this is likely to be identified with a detailed visual inspection. Littlejohn and Mothesille (2007) report case studies of a large number of anchor failures, and note the particular vulnerability of the anchor head to corrosion in modern anchors.

The next stage of the analysis of the accumulating database on which this paper is based; is to review the testing frequency guidelines with the aim of providing a deterministic basis for testing frequency based on considering such variables as anchor type, number of strands, foundation conditions and age as well as the Consequence Category of the dam.

Table 1 – Comparison between monitoring frequency guidelines

Source	Country	Recommended Monitoring Frequency
ANCOLD (2003) Table 5.3	Australia	Guide for "in service" dam monitoring frequencies Recommended monitoring for post tensioning: • Very low – N/A • Low – N/A • Significant – 10 yearly • High – 5 to 10 yearly • Extreme – 5 yearly Preferably all cables, but at least a significant representative sample to be monitored
DSC (2010)		The first Surveillance Report after anchor installation is to outline the results of recent load testing of ALL anchors, comparing performance against installation conditions and recommending future monitoring arrangements (e.g. number of tendons to be checked, frequency); and After this initial testing, the DSC requires a portion of anchors to be tested at five yearly intervals and reported in the next Surveillance Report for the dam along with recommendations for future monitoring. As a minimum, the DSC requires the following progressive sampling of anchors at five yearly intervals: • Extreme Consequence Category Dams – 50% • High Consequence Category Dams – 33% • Other Dams – 10%
AS4678(2002)		Appendix B – Ground Anchors - No discussion on monitoring requirements.
BS 8081:1981	UK	3-10% of anchorages are monitored for service behaviour on a given project. Monitoring commences at short intervals of 1-3 months and later at intervals of not greater than 2 years, depending on the results.
FIP (1996)	EU	Where the purpose of monitoring is the detection of corrosion, testing should be carried out at not greater than 6 month intervals for a period of 3 years and thereafter at long regular intervals of not greater than 5 years throughout the lift of the structure. At least 10% or three anchorages, whichever is the greater number, should be monitored on projects with less than 100 anchorages. On larger projects at least a further 5% of the excess over 100 should be monitored. Where the purpose of monitoring is limited solely to ascertain the effects of ground movements, it may be possible, where ground conditions are known to be uniform, to monitor fewer anchorages, e.g. 5% of the working anchorages, or three anchorages, whichever is the greater number.
PTI (2014)	US	As per FIP (1996)
BS 8081:2015	UK	When monitoring for corrosion, as per FIP (1996), however the percentage of anchors to be tested is not specified. Where the purpose of monitoring is the detection of ground movements, procedures should be designed to ascertain and record the pattern of the movements and should continue until they become negligible. In some cases, monitoring might be needed to ascertain ground movements in the early life of the structure and then to detect failures due to corrosion during its later life. In these cases, tests should commence at short intervals (typically 6 months) becoming gradually less frequent, until they are carried out at intervals not exceeding 5 years for the life of the structure. With additional note in Annex H1 Monitoring Related to the Nature of the Structure H.1.1 The consequences of the failure of the structures differ widely, independent of the value of the structure itself. For example, the collapse of even a small dam or bridge might lead to consequential damages far exceeding its own value. H.1.2 The nature of any monitoring ought to take these variations into account, with the highest standards of monitoring being accorded to those structures where the failure of a single anchor could lead to serious consequential damage.

For comparison, Table 2 provides the number of times an individual anchor would likely be tested during its service life based on ANCOLD (2003), DSC (2010) and FIP (1996) assuming the following:

- A 100-year service life
- The total number of anchors at the site is between 30 and 100
- Testing is distributed evenly amongst all of the anchors
- A "representative" number of anchors described in ANCOLD (2003) is taken as a minimum of 10% of the anchors (as per FIP (1996))

Table 2 Guideline comparison for number of load tests to be undertaken on an anchor over 100 year service

	Consequence Category				
	V. Low	**Low**	**Significant**	**High**	**Extreme**
ANCOLD (2003)	0	0	1 - 10	1 - 20	2 – 20
DSC (2010)	2			6.7	10
FIP (1996)	2.5 (with 60% probability of being tested once in first 3 years)				

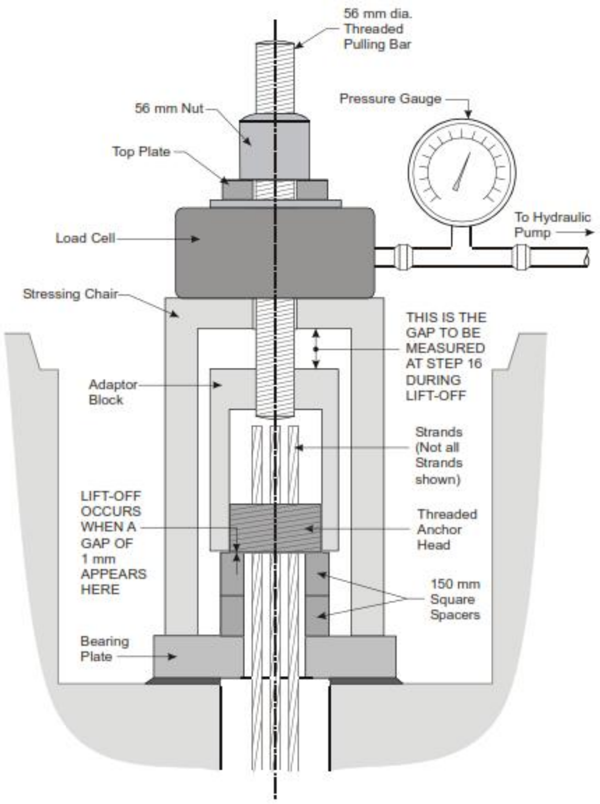
Table 2 indicates that for High and Extreme Consequence dams, ANCOLD (2003) and DSC (2010) typically require a far greater number of anchor tests to be carried out over their service life. It is noted that BS 8081 (2015), the most recent of the standards produced, has not specified the percentage of anchors to be tested.

Lift-Off testing

Definition

The purpose of a lift of test is to determine the residual load that the anchor is applying to the structure. Lift-off testing of anchors typically comprises installing a purpose built threaded load cell to the anchor head. The recorded pressure read off the gauge is then converted to the load, based on the calibrated relationship, to determine the residual anchor load.

Typical lift-off testing installations are shown in Figure 1.



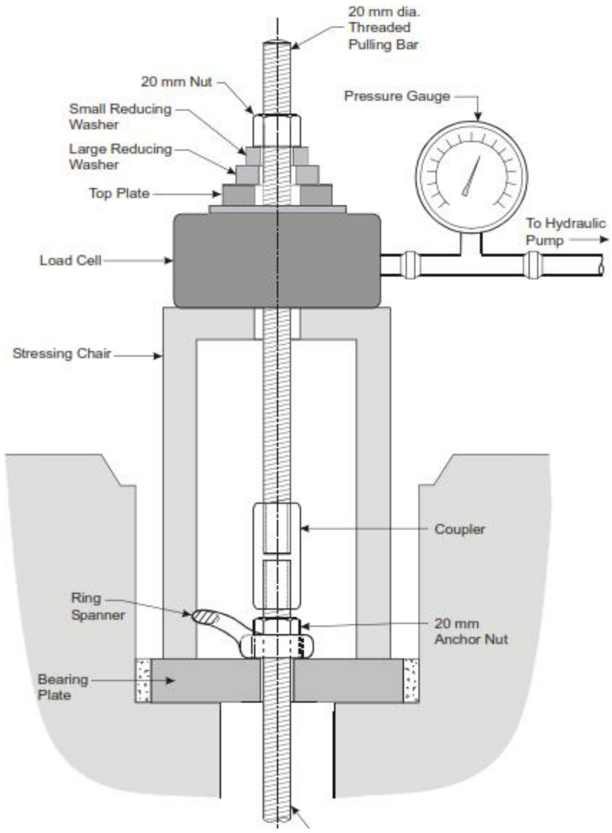


Figure 1 Example lift-off testing setup for strand anchor (left) and bar anchor (right)

Definition of "Lift-Off"

Theoretically, the lift-off load is the load is equal to the load that the anchor applies to the structure. If a force-extension relationship is plotted, lift-off should correspond with the point of inflection on the force-extension curve. Usual practice for measuring lift-off is to measure the extension using a feeler gauge to measure the gap that forms between the anchor head and the bearing plate (if possible in 4 locations around the head). For lift-off testing, load-extension is not typically plotted, and the extension signifying lift-off is taken to be approximately 0.1 to up to 1 mm. Lift-off for bar anchors is signified by the ability to turn the anchor nut. The impact of selection of lift-off extension has much greater significance for bar anchors and strand anchors with short free length than for longer strand anchors, as the load per unit of extension is much higher and therefore a 1 mm lift-off clearance is not considered an accurate means of determining lift-off. Even for strand anchors with longer free length this amount of lift off is considered to be excessive.

It is the authors' opinion that the practice of using a 0.1 mm feeler gauge inserted under the strand anchor head in 4 equally spaced locations around the circumference is adopted for strand anchors.

Accuracy of measurement of anchor loads

BS8081 (2015) lists the random factors that may influence the value of the prestressing load:

- Variations in successive indications of the same load-measuring equipment for the same load or pressure
- Errors arising from reading the scales of the load measuring equipment
- Variations in the internal friction of the jack and the anchor

Typically the uncertainty of the gauge reading specified for lift-off testing is +/-2%, which relates to a Class B system in AS2193 *Calibration and Classification of Force-Measuring Systems*. AS2193 requires calibration of diaphragm pressure gauges on a 6 monthly basis. Given the typical frequency of anchor testing carried out, this means that jack calibration is required every time that lift-off testing is carried out.

The reading error is based on inaccuracy from the resolution of the pressure gauge. AS2193 Class B systems require a minimum resolution of 100. Errors from reading the scales of the load measuring equipment can be expected to be <1%.

It is common practice to undertake a lift-off test twice for each anchor tested, to show repeatability of the result. For minor variations between successive lift-off results, the lift-off force is taken as the average of the two values.

Test results reporting

A universal template for reporting of ground anchor test results does not currently exist.

Littlejohn and Mothesille (2007) recommend items to include in an testing report, include:

- Anchor number, type and physical details
- Initial residual load immediately after lock-off
- Identification numbers and calibration reports for jacks, gauges and pumps
- Residual load in service (and lift-off movement, e.g. 1 mm if stressing is employed)
- Total change in load as a percentage increase or decrease of initial residual load

For ground anchor testing, it is also recommended to record other details which may be relevant to the assessmet of the anchor load, such as the reservoir level and temperature on the day of testing.

Alternative means of measuring load loss

The performance of anchors can be inferred from survey measurements of the entire structure. FIP (1996) recommends 'Where monitoring comprises geodetic measurements on the overall structure/ground/anchorage system or stress measurements within the structure, the programme should enable the role of the anchorages to be separated from other effects. The design of such a programme requires a detailed knowledge of the structure and should be derived by the designer of the structure.' On a more complex structure, a robust record and understanding of the many variables which may affect the survey results (foundation, concrete properties, state of internal and external temperatures, reservoir level etc.) is required to provide any reliable meaning on the anchor condition based on survey. Where the anchor load has a dominant bearing on the displacements of the structure (e.g. slender wall sections), measurement of the structure may provide a good indication of changes in the anchor load.

Resistivity and ultrasonic methods of testing have been trialled as methods of assessing anchor performance, however the results have not produced reliable indicators of anchor condition in dams, such as the recent trial at Meadowbank Dam (Topham *et al* 2015). This paper does not address these methods.

Visual inspections

The purpose of visual inspections is to check the external condition of the anchor and the condition of the corrosion protection systems such as the grease (volume and condition), anchor head threads, baseplate, anchor pocket drainage system, the gaskets, water-proof caps ("top-hat") and in some anchors, the pressure compensating system in the "top-hat".

It is the authors' recommendation that a very detailed visual inspection (based on a detailed checklist); with a comprehensive photographic record of every anchor head, is carried out every time that the anchor is monitored for load. In cases of High and Extreme Consequence Category dams, where access permits, a representative sample of anchors should be inspected on an annual basis and all anchors be inspected during the routine 5 yearly Dam Safety Inspections.

DSC (2010) recommend grease replacement on a 2-yearly basis. Littlejohn and Mothesille (2007) recommend replacement of the grease on a 5-yearly basis or grease sampling and testing of properties to check for compliance with the specification. It is the authors opinion that grease replacement (and other protection measures such as gaskets) should be undertaken each time an anchor undergoes load testing and whenever required as detected during routine visual inspections.

Anchor testing database

The database

The authors of this paper are currently compiling a database of ground anchor lift-off test results from a range of dam owners across Australia. This database is anticipated to provide valuable information in understanding the long term behaviour of anchors used to stabilise dams.

This dataset currently contains anchor test results from 23 anchored dams, which are owned by 10 different water authorities or councils. At the time of writing this paper, there are still several dams with key data that are anticipated to be added to this database.

The database currently comprises test results from a total of 1088 post-tensioned anchors, comprised of the following:

- 308 No. bar anchors
- 203 Strand anchors with between 2 and 25 strands
- 133 Strand anchors with between 26 and 50 strands
- 329 Strand anchors with between 51 and 65 strands
- 115 No. strand anchors with between 66 and 91 strands

Classification of ground anchors by size is summarised in Table 3. Most of the strand anchors comprise 15.2 mm dia. low-relaxation 7 wire strands with 250 kN Minimum Breaking Load (MBL). Bar anchors range from 20 mm to 56 mm diameter, with 38 mm diameter supergrade alloy steel bar being most common.

All ground anchors in the database are believed to have been installed with double corrosion protection (Class I Protection). However, detailing of the anchor head and installation methodologies have seen ongoing improvements since installation of anchors in the 1980s and 90s.

Table 3 Distribution of anchors in database by size

	2-25 strand anchors	**26-50 strand anchors**	**51-91 strand anchors**	**Bar anchors**
Total No. Anchors	209	197	443	385
Never tested	42	66	140	0
Tested once	167	131	303	385
Tested twice	91	126	242	163
Tested 3 or more times	68	254	2	24
Total No. tests	**326**	**511**	**547**	**572**

Preliminary results

Compilation, verification and analysis of the test data was still under way at the time of writing of this paper. Further work is required to interrogate the variables associated with stress change at each anchor in order to improve understanding of long term stress changes in anchors. This may allow improvements in the design and construction of ground anchors.

A few key preliminary plots have been included in this paper, to illustrate a number of points which have been identified.

Residual anchor loads

This plot provides an aggregated set of data showing the residual load performance of anchors in the database.

There is considerable scatter amongst the points. Further analysis is required to identify whether the variability is due to systematic and intrinsic error, as opposed to true variability in the anchor load performance. Ground anchors indicating a residual load below 60% MBL may no longer holding the design load.

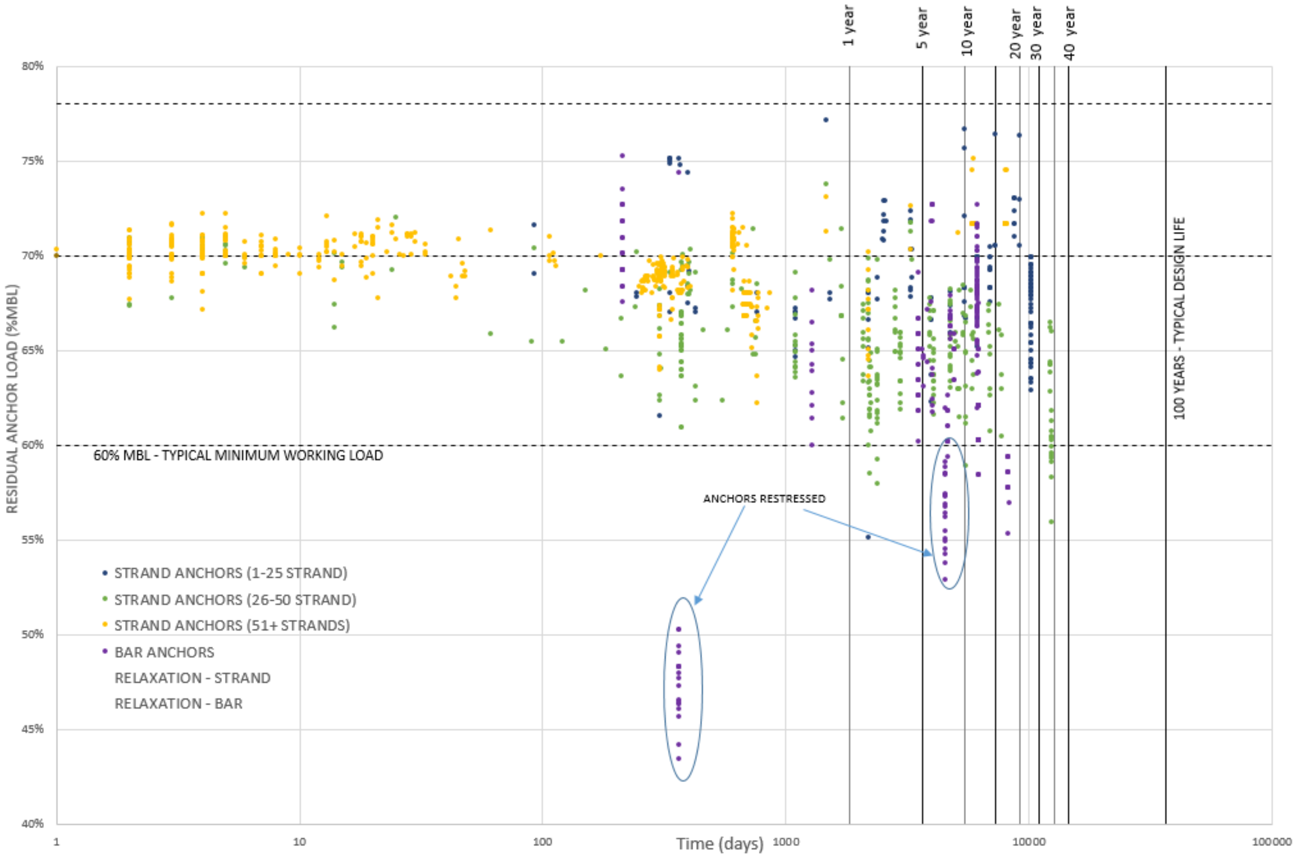


Figure 2 Residual anchor loads from lift-off testing

Rate of change in residual loads

Table 3 illustrates the rate of load change (ΔForce/Δtime) with units of %MBL/year plotted against time. The points were calculated based on the time and force increment between successive tests. The data is biased by anchors with a long period between the installation lift-off and the first lift-off test, which could often be 10 years or greater.

The rate of change due to stress relaxation for strand anchors has been plotted for comparison. The rate of relaxation has been based on the design relaxation, based on a lock-off load of 70%, as determined by AS3600 (2009), with a basic relaxation of 2% typical for strand anchors. The plot indicates that the rate of load loss is considerably greater than what would be estimated purely due to relaxation.

The plot indicates that the rate of stress loss in the initial months following initial lock-off is greatest in the initial months following initial lock-off.

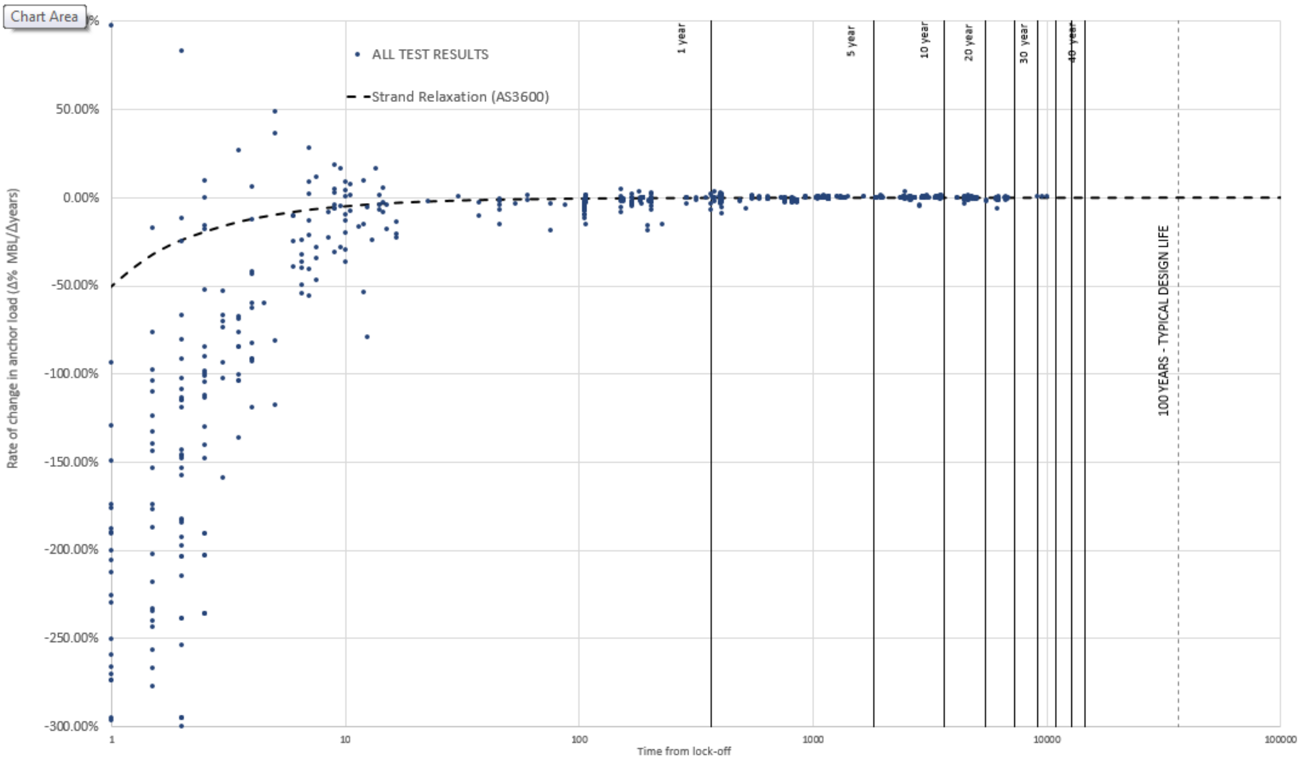


Figure 3 Rate of change of anchor load with time

Anchor failures

Failure of an anchor can take three forms, namely the loss of prestress, breakage, or, occasionally, over-tensioning above the maximum design prestress.

Failure due to relaxation of prestress

Based on the available dataset:

Approximately 3% of anchors tested have failed to retain the minimum working load of 60% MBL

For 3 dams which contained anchors with <60% MBL residual load, the stress loss appeared universal, i.e. the individual anchors did not appear to be outliers from the main set (133 total number anchors)

The remaining 6 dams which had anchors with <60% MBL residual load, the individual anchors tended to be outliers (43 total number anchors)

Approximately half of those anchors tested to have <60% MBL residual load have been restressed to date.
Additional investigation is required to determine whether the failing anchors that had outlying results displayed external signs to suggest their behaviour. This has a significant bearing on estimating the risk of testing a "representative" number of samples.

Failure due to breakage

Failure of a single 38 mm supergrade steel bar post-tensioned anchor occurred during lift off testing at Goulburn Weir 2009. Details of the investigation of the anchor failure are documented in Ross et al (2009). This case is the only instance of bar anchor failure occurring during testing identified in the database. There is no case in the database of a strands failing during lift-off testing. However there are a number of cases in which strands were broken during the proof loading phase.

However, the authors have identified several strand anchors with strands that have failed in situ between monitoring dates. The authors are of the opinion it will be possible to identify the most probable cause/s of these failures for the Dam Owners as the investigation into the failed anchor proceeds. Clearly, it would be in the interest of the profession and the Owners to conduct such investigations.

Several ground anchor testing regimes have limited the maximum lift off force tested to 60% of the MBL, as a means of reducing the risk of overstressing of the bars or strands. In order to gain a proper understand the behaviour of the anchors, the lift-off load is required.It is recommended that anchors are tested to lift off unless there is a good justification that there is a significant risk to testing personnel of the anchor failing during testing. In some instances, for example in the case of dams with Alkali Aggregate Reaction, the load in the anchor may be greater than the original lock off load. Experienced anchor testing personnel should be able to determine whether a corroded anchor can be tested safely.

Failure due to overstressing

No anchors in the current database have failed due to overstressing.

Conclusions and recommendations

Ground anchors provide an established and generally economical method to improve the stability of dams and appurtenant structures. However, without ongoing inspection and maintenance, ground anchors are vulnerable to corrosion damage. Without regular monitoring of anchor loads, the magnitude of anchor loading should not be relied upon.

At the time of preparation of this paper, the dataset shows that 3% of anchors installed since 1981 have undergone sufficient load loss to fall below the design working load. Further assessment is required to quantify the proportion of load loss may be attributed to accuracy of determining the load. Particular focus is required to understand the behaviour of outlying anchor test results, and whether there were external signs indicating their condition.

Once analysis of the database is complete, this will assist in identifying the presence of systemic deficiencies in the testing regimes. Additionally, this will assist in reviewing the current recommended frequency of testing of anchors. The preliminary data indicates that the rate of change in anchor loads is greatest in the initial months following installation. At this stage, it is recommended that lift-off testing of ground anchors approximately one year and five years after lock-off are likely to best indicators of the long-term behaviour of a ground anchor. On this basis, it would be prudent for an owner to perform lift-off tests of all the anchors at that frequency. Following these initial lift-off tests, the purpose of lift off testing is to identify changes in condition of the anchor, primarily load loss due to corrosion.

The preliminary data set suggests that load changes in the ground anchors significantly exceeds what would be estimated due purely to stress relaxation. Once the data set and analysis are complete, the authors anticipate this will provide additional insight into the long-term creep behaviour of anchored foundations; in particular whether particular design consideration should be given for anisotropic and/or low strength foundations (e.g. sedimentary) against more isotropic (e.g. granitic) foundations.

Testing and maintenance procedures for ground anchors for dams in Australia are currently not standardised. It is recommended that standardised methodologies are developed for both strand and bar anchors, which should be addressed in the next revision of the ANCOLD Dam Safety Management guideline. It is the authors hope that we will be able to present a more detailed assessment at ANCOLD 2017.

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