WIVENHOE DAM

RADIAL GATE TRUNNION BEARINGS

PEER REVIEW

MAY 2006

Glen Hobbs & Associates

SUMMARY

During an inspection of Wivenhoe Dam SunWater found that the seals on the radial gate trunnions had badly deteriorated. Sunwater subsequently prepared a number of reports on the seals and bearings with recommendations regarding further inspection and replacement.

SEQ Water engaged Glen Hobbs & Associates to peer review the SunWater reports, separately investigate the trunnion bearings and seals and make recommendations where appropriate; taking into account the practice of local and overseas authorities.

This Report concurs with SunWater's findings that the condition of the bearings is unknown and cannot be easily ascertained. To do so would involve dismantling a gate trunnion and removing a bearing. Such work is considered to be extremely expensive.

From a risk perspective, whilst bearing deterioration resulting in high trunnion friction may lead to either structural failure of the gate or components, or jamming of the gate, the loss of storage, could be mitigated through the installation of the bulkhead gate. However gate jam or failure during a flood event will result in the spillway capacity being reduced.

The Reports key findings are:

- The seals are in very poor condition and must be replaced
- There is no evidence to suggest that the bearings are deteriorating
- The ability of the gate structure, and trunnion housing and support, to withstand high trunnion bearing moment is unknown and should be

determined as a matter of urgency

- There are a number of examples overseas of high trunnion friction contributing to gate failure. However it is not the sole cause and it is usually associated with deficient structural design

This Report recommends that a risk based approach be adopted that involves:

- an analysis of the gate structures to determine the maximum value of trunnion bearing friction that can be withstood,
- strain gauging of a gate to determine a value of trunnion friction that is ‘typical’ for all gates, and
- if necessary and feasible, strengthening of the gates to withstand higher values of trunnion bearing friction.

Depending on the above findings and the feasibility of gate modification, new bearings may be required and ongoing periodic monitoring of trunnion friction may be necessary.

1. BACKGROUND

The radial gates have been in operation at Wivenhoe Dam for nearly 25 years. Recent inspections by SunWater found that a number of the seals on the trunnion bearing housings had failed and water had entered and collected in the housing.

Overseas experience has shown that high trunnion bearing friction when combined with structural deficiency of the spillway gate can result in gate failure

SEQWater are concerned that the operation of the radial gates may be compromised.

SunWater subsequently prepared a number of reports for SEQWater covering the various inspections and investigations that have been undertaken. The Reports have made a number of recommendations for further action.

SEQWater requested that Glen Hobbs & Associates (GH&A) peer review the reports and assessments that have been undertaken over the last two years on the radial gate trunnion bearings and provide advice regarding further action.

The scope of the review included the provision of recommendations regarding the management of the potential, current and future deterioration of the bearings.

2. INTRODUCTION

Wivenhoe Dam has five spillway gates designed by the former Queensland Water Resources Commission and installed in 1983.

The gates are radial type gates 16.6 m high by 12 m wide, and pivoted around a trunnion pin at each side. The gates are raised by rope hoist powered by hydraulically actuated winches.

The pins are of 320mm diameter. The trunnion bearings are a self lubricating bearing manufactured by the German company Elges (now INA-FAG, model No GE 320 DW).

Approximately four years ago it was observed that the seals had failed and water was accumulating in the bearing housing. SunWater were engaged to undertake an investigation and report with recommendations.

SunWater produced three Reports (Ref 1):

- Wivenhoe Dam; Report on Radial Gate Trunnion Bearings;
- Report: Fibre Optic Site Inspection, Radial Gate Trunnion Bearings, Wivenhoe Dam;
- Report commissioned by Sunwater: INTICO: Ultrasonic Thickness Survey of Radial Gate Trunnion Bearings;

SunWater made a number of recommendations including:

- Replacement of seals & provide a weather cover over the trunnion & provide anti-condensation heaters
- Undertake a further internal inspection after cleaning the inspection surfaces of grease

- Assess trunnion failure modes, risks & effects on gate operation
- Program gate trunnion bearing replacement, & review bearing housing & seal design

SunWater quoted a cost to supply the bearings in the order of $30,000 per gate.

Considering the difficult site conditions the actual cost of bearing replacement would be far in excess of this amount.

3. DISCUSSION OF SITE INSPECTION & GREASE ANALYSIS

Glen Hobbs of GH&A accompanied by Geoff Hales & Barton Maher of SEQWater, John Tibaldi of SunWater and the dam operations staff Doug Griggs & Jeff Elliott of Sun Water, inspected the site on the 13th February 2006.

Discussion with Dam Operations Staff

During the site inspection the dam operations staff reported that they have not observed any potential problems or abnormalities in the trunnion operation. This includes no abnormal noise or vibration.

Spare Bearings

A spare bearing is stored in the dam workshop (see Photos Appendix B). The bearing was dismantled and inspected. The bearing has a split outer ring clamped together with recessed head bolts. The bearing surfaces of the rings are coated with a Teflon fabric and the matching spherical bearing surface is chrome plated with a high quality finish. There are no seals to restrict the ingress of water or particles into the bearing surfaces, unlike modern bearings which have recessed seals fitted.

Gate Trunnion & Seals

The right hand trunnion of Gate Number 3 was inspected. On this trunnion the seal had completely failed and had been removed. The housing and support was in good condition with no evidence of movement. The seals were clearly deteriorated and they were no longer serving the purpose of excluding rain water and dust from the housing and therefore must be replaced. It was not possible to inspect the bearing due to the extremely limited space available, at best a grease sample was taken with a wire hook.

There was no evidence of water, it had probably already drained out.

With the upstream bulkhead gate in place the gate was partially opened. The gate opened smoothly and no jerky operation or noise was observed.

Vibration Data

Vibration monitoring of the trunnions has been carried out since 1996. The tests are done every six months during dry testing of the gates. The vibration is recorded with a hand held transducer on the trunnion hub. A brief visual scan of the results did not reveal any significant increase in trunnion vibration over the 10 year period since 1996.

The fact that no significant vibration was observed does not indicate that the bearings are in reasonable condition.

These observations support those of SunWater. SunWater observed ‘no significant changes’ over the period but commented that the vibration readings may not be a reliable indicator due to the low ‘rotation speed and range of motion’..

Hydraulic Hoist Pressure

The hydraulic hoist pressure has been recorded over a similar period to the hub vibration. Pressures are noted at random times during the gate raising operation.

A scan of results for all gates over the period did not show any trend with pressures remaining fairly constant. SunWater have also noted no change in hydraulic pressures over the period.

An increase in hydraulic pressure may indicate an increasing effort required to raise a gate, but this may be due to a variety of problems. .It is highly unlikely that the hydraulic pressure measurements would be sensitive enough to identify increasing trunnion friction which is a very low contributor to hydraulic effort and hence hydraulic hoist pressure. This assessment is supported by tests undertaken on a dam in Texas (Boyer et al, Ref 2).

Sampling & Analysis of Grease

It is clear from the report on the design of the gates 'Design of Crest Control Structures, Wivenhoe Dam, April 1995' (Cl 2.8.1) that lubrication of the bearings was not considered necessary, but it was decided to fill the cavity between the bearing housing and the pin with a lithium based grease 'as an aid to corrosion prevention'. The grease has also acted to retain foreign particles and corrosion products so it provides some indication of condition of the bearing and housing.

Six grease samples were taken by SunWater operations staff on the 27th February 2006 and forwarded to ALS Wear Check laboratories in Brisbane for analysis. (see Appendix A).

The samples were taken from:

Gate Four

Right Hand Bearing: Top & Bottom

Left Hand Bearing: Top & Bottom

Gate Three

Right Hand Bearing: Top & Bottom

The following conclusions can be made from the results of the analysis:

- There is minimal dust and grit contamination in the grease, this is indicated by the low values of aluminum (Al) and silicon (Si). Contamination can be air born dust or dust washed in by rain water.

- The high iron (Fe) content in the samples taken from the bottom of the trunnion housings indicates corrosion due to water ponding in the housing. The corrosion is probably minor.
  The low value of chromium (Cr), less than a measurable quantity, indicates that the chromed surface of the bearing has probably not deteriorated.
  Therefore the results indicate that there is corrosion of the carbon steel housing but probably nil or minimal corrosion of the exposed bearing surfaces.
- There are no large metallic components in the grease, indicating that wear of the metallic bearing surfaces is probably negligible, and there are no large particles of corrosion product.
  This is indicated by the PQ Index which is indicative of particle size, and relates to wear in the bearing. The PQ index should be considered along with the Fe value. The index value is in microns, the human eye cannot see a particle smaller than 40 microns.
  The fact that this PQ is low indicates that nil or minor wear has occurred, and corrosion is minor. The higher samples (123 & 188) for the lower part of the bearings is related to corrosion products. Wear is to be expected to be minimal considering the very small operational cycles of the trunnion bearings.
- Unfortunately the moisture content of the grease cannot be measured with this test.

Therefore the results of the grease sampling shows that the ingress of water due to the failure of the seals has resulted in corrosion of the forged steel housing but corrosion of the bearing surfaces is unlikely to have occurred.

4. REVIEW OF ULTRASONIC & BOROSCOPE INSPECTION REPORTS

Ultrasonics

Intico was engaged by SunWater in June 2004 to conduct an ultrasonic inspection of the housings to detect corrosion.

The report concludes that there is no corrosion on the internal surfaces of the trunnion housings. This contradicts the results of grease sampling which indicates corrosion. However it is likely that, based on the grease samples, corrosion is minor with surface corrosion only occurring; ultrasonic examination would not be sensitive enough to detect minor corrosion.
Therefore the ultrasonic results should be interpreted as indicating that no significant deterioration of the trunnion housings has occurred.

Boroscope

A fibre optic inspection of the bearings was undertaken by SunWater in September 2004.
The report states that the grease is contaminated and that ‘ it is clear that some corrosion has occurred on all the exposed faces of the bearing including the chromium coated inner spherical ring’.

However these findings contradict the grease analysis which shows the grease to be in reasonable condition with minimal contamination and no presence of chromium. A detectable level of chrome would be expected if the chromed steel surface had corroded.

Also it is very difficult to interpret from the boroscope photographs the contamination on the surfaces. For example the retaining collar (Item 3 Dwg 560) and ‘shaft sleeve’ (Retaining Ring Items 4 & 5 Dwg 560) are 316 grade stainless steel which will not corrode, yet from the photographs (Images 1 & 2) they appear to be in a similar condition to the chromed surface of the bearing. Therefore it cannot be definitively stated that bearing surfaces are corroded.

It is likely that the presence of grease has made a close inspection of the bearing surfaces difficult and given an appearance of corrosion.

The report recommends that the surfaces be cleaned and re-examined. However from recent discussion with the bearing manufacturer it is considered to be very difficult to achieve this in such an enclosed space. They could not recommend a suitable cleaning method; and the use of water or solvents to assist in grease removal could damage the Teflon bearing.

5. DISCUSSION WITH THE BEARING SUPPLIER

A meeting was held with INA-FAG's Alan Burt and Andreas Pieper, Manager Technical Division and Glen Hobbs and Ken Newton of Glen Hobbs & Associates on 3rd March.

Prior to recently coming to Australia, Andreas Pieper had extensive experience overseas with bearings for large dam gates & was closely associated with the development of some PTFE (Teflon) coated bearings for INA-FAG.

Burt and Pieper indicated that considering the infrequent operation of the Wivenhoe gates, the bearings, should normally have a life in excess of 50 years.

However the presence of water can result in the PTFE fabric absorbing water and swelling and the fabric losing its adhesion to the metal surface and breaking up. Particles of PTFE fabric will eventually work their way out of the bearing surface and collect in the housing. Also the porous nature of the chromed surface can result in corrosion of the carbon steel surface beneath it. These comments were also made by SunWater in their reports.

INA-FAG also indicated that grease should not be used for lubricating these bearings as it adversely affects the PTFE coating. However, they considered that as the grease was only applied to the outer surfaces of the bearing (as corrosion protection, see Design Report, Ref 3) it is unlikely to have come into contact with the PTFE and therefore will not be detrimental to the bearing performance.

In summary, they indicated that the condition of the bearings cannot be confidently predicted. If the water has affected the Teflon lining the bearing will deteriorate and friction will gradually increase.

6. CONSIDERATION OF THE EFFECTS OF BEARING DETERIORATION

As mentioned above deterioration of the PTFE will result in increasing friction. However particles of PTFE should remain between the bearing surfaces and the bearing would not suddenly fail through seizing. The progressive deterioration of a bearing can be monitored and quantified using techniques discussed later in this report. .

General Comments

High trunnion bearing friction can lead to:

- *An increase in hoist load.*
  The effect of increased trunnion friction is considered to be very low due to the large moment arm between the hoist point (cable attachment to gate) and the trunnion pin. The percentage of trunnion friction to the overall lifting load, based on the design bearing friction coefficient of 0.1, is less than 1%.
  An increase in the trunnion friction from 0.1 to 0.3 results in its contribution to the trunnion hoist load increasing to 1.5%. Such an increase should not have a detrimental effect on gate performance.
- *Gate failure*
  The trunnion bearing friction induces a moment in the arms and trunnion mount.
  If the arms are already close to their design limit then the compressive load in the arm combined with the trunnion moment can lead to buckling of the arm and subsequent gate failure. This has occurred at Folsom Dam in

California (Todd, Ref 4) and a dam in Malawi (Henning,Ref 5).

The design of the gate structure should be checked.
Also, as occurred on a dam in Norway (personal communication with Henning of Norconsult), the cyclic nature of the moment due to a gate regularly opening and closing can lead to fatigue of the structure.
The bearing moment into the trunnion mount should also be checked. A quick calculation shows that the bolts can withstand at least a 400% increase in bearing friction above the design value of 0.1. However the design of the trunnion pin attachment and support should be checked.

Wivenhoe Dam Design

In the report 'Design of Crest Control Structures, Wivenhoe Dam (Ref 3) Clause 2.8.1 states that:

> '*Typically, based on the bearing manufacturer's figures, the coefficient of friction will be less than 0.05 for the spherical plain bearing selected although a figure of 0.1 was used in design'*.

However it is not stated in the report that trunnion bearing friction was considered in the structural design of the gate. The gate design is based (Cl 2.2) on the US Army Corp of Engineers design (Manual EM1110-2-27020) but the date of the manual is not stated in the references; early manuals did not consider trunnion bearing friction in the structural design of a gate.

Nor is there any indication in the report as to what is a maximum acceptable figure for bearing friction.

Therefore the effect on the gates of increased friction cannot be determined without further analysis. Such an analysis should be undertaken as a matter of urgency.

Consideration of Risks Associated with Bearing Failure

If a bearings has been damaged then it is possible that friction will gradually increase in the bearing and the friction may increase to a level where damage to either the gate structure or trunnion support may occur.
The level at which damage may occur can only be determined through structural analysis and such a high level of friction may not be reached in the Wivenhoe bearings.

The gate failure scenarios are likely to be either:

- During initial opening the structure distorts or the trunnion attachment fails. This may be catastrophic (associated with buckling) like Folsom Dam or result in gate damage and possible jamming like the dam in Malawi.
- The hoist fails to generate enough torque to raise the gate, this is highly unlikely. Or the gate fails in a partially closed condition, again highly unlikely, as the torque from the gate weight and moment arm would far exceed the torque from the bearing friction.

The advantage of Wivenhoe Dam over the Folsom and Malawi Dams is the availability of the upstream bulkhead gate which can be lowered into flow. Therefore if a gate was to fail, or jam partially open, the bulkhead can be lowered into place under flow, minimizing loss of storage and allowing maintenance of the structure. At Folsom the storage level had to drop below the sill before work could commence.

However if failure was to occur in a flood event the radial gate may partially block the gate bay and restrict discharge.

7. EXPERIENCE OF OTHER AUTHORITIES

A brief survey was undertaken of the experience of other authorities both in Australia and overseas.

U.S.A.

Following the widely publicised failure of the radial gate at Folsom Dam in the USA, authorities world wide have investigated dams with potential trunnion bearing problems.

FERC

The US Federal Energy Regulatory Authority (FERC) has required dam owners to undertake various checks of their spillway gates including a structural check incorporating the moment due to trunnion bearing friction (see Tjoumas et al, Ref 6). A maximum value for the coefficient of bearing friction of 0.3 is assumed for structural analysis (Folsom Dam failed at a coefficient of 0.28)

The Grant County, Washington State

Has recently replaced the LUBRITE bushes on its large radial gates with a synthetic bearing material ORKOT (see photos in Appendix B). LUBRITE bushes are bronze journal bushes with hard lubricant slugs. Other contacts report unconfirmed problems with LUBRITE bushes.
Grant County have successfully used strain gauging to monitor bearing friction (R. Ellis, Ref 7).

United States Bureau of Reclamation (USBR)

The USBR (see discussion with P Hoffman, App A) has adopted a risk based approach. The spillway gates on 75 dams have been checked for buckling of the arms. Only 16 dams have warranted further investigation with some requiring stiffening of the arms in the vicinity of the trunnion.

Of all the dams checked P Hoffman indicated that Folsom was by far the worst with a slender gate construction and a very high trunnion moment largely due to the very large pin diameter (approx 800mm).
Therefore the USBR has strengthened gates to withstand high trunnion friction rather than by changing bearings to reduce friction.

The USBR has strain gauged 3 dams but does not use it as a monitoring tool.

Other US Authorities

A number of authorities are using laser beams to detect deflection and relate deflection to trunnion friction and allowable arm stresses.

Canada BC Hydro (see Email Appendix C)

They undertook a survey of their radial gates following the Folsom incident. BC Hydro adopted the approach that the 'condition of the trunnion bearings cannot be guaranteed over time and that ultimately it is the radial arms that are the limiting factor'. Where necessary arms were strengthened. They have strain gauged one gate but have not continued with ongoing monitoring.
They have no experience with plain spherical bearings.

Norway, Norconsult

Norconsult are a firm of consultants in Norway. They have strain gauged numerous gates on Norwegian dams and report a number of failures including at least one dam in Norway where the gate arm failed due to excessive friction. Also they reported a dam in Malawi Africa where the arm has distorted due to trunnion friction (see photos Appendix B).

It is not clear what type of bearing was used in these gates.

Norconsult also mentioned (personnel communication Appendix C) that on a dam in Norway, which has plain spherical bearings, the trunnion friction is monitored with strain gauging.

Australia

Some authorities with LUBRITE and spherical roller bearings have expressed concern over trunnion friction and are presently investigating it.
However there are no reports of trunnion friction causing problems or damage to dam gates or hoists.
No problems have been reported with plain spherical bearings.

8. DISCUSSION OF TECHNIQUES FOR CONDITION MONITORING OF BEARINGS

There are three methods that have been used to monitor trunnion friction.

Hoist Current

This method monitors the current drawn by the hoist motor during raising of the gate, an increase in current may mean an increase in trunnion friction or associated hoisting problems.

However this method has not been found to provide any reliable information on trunnion friction due to the minor contribution to hoist load and the high energy losses within the hoist and gate system (eg losses in gear trains, hydraulic drives, gate side seal etc).

Therefore it is not considered a reliable indicator of trunnion friction problems. (see Boyer et al).

Strain Gauging

Strain gauges are attached to the upper and lower fibres of one of the arms. The gauges measure strains due to water loading which is a compressive strain, and strains due to trunnion friction which is a cyclic compression and tensile strain (see Figure 1). During gate raising the upper fibres are in compression and the lower in tension; during lowering this pattern is reversed. The variation is an indicator of the strain induced by the bearing moment due to friction.

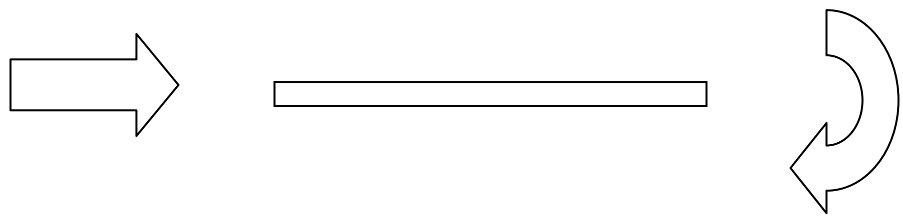

FIGURE 1
LOADS ON ARM BEAM

Strain gauging has been successfully used on radial gates in the USA, Canada, Japan and Norway. (Refer Shiogama et al, Ref 8 & Henning, Ref 5)
The technique requires attaching the gauges using adhesive or welding. Detection and recording equipment are required to interface with the strain gauges.
To gain a true indication of trunnion friction the gate should be operated under flow conditions. The gate is required to be opened only approximately 100 mm and lowered. This small degree of opening ensures that hydraulic load is constant through the travel. However if there is no water against the gate then an indication of friction can be obtained through gate operation under gate weight (as opening increases) and hoist cable load only. The test to be repeated to confirm results when there is sufficient water.
Regular checking of strain allows the bearing condition to be monitored. Inputting the strain results into the structural analysis allows the bearing friction to be determined. Also from the structural analysis the strain value that will result in structural failure can be determined. This strain value then sets the upper limit for bearing friction. Regular checking of bearing friction will allow the bearing condition to be monitored and bearing replacement to be predicted.

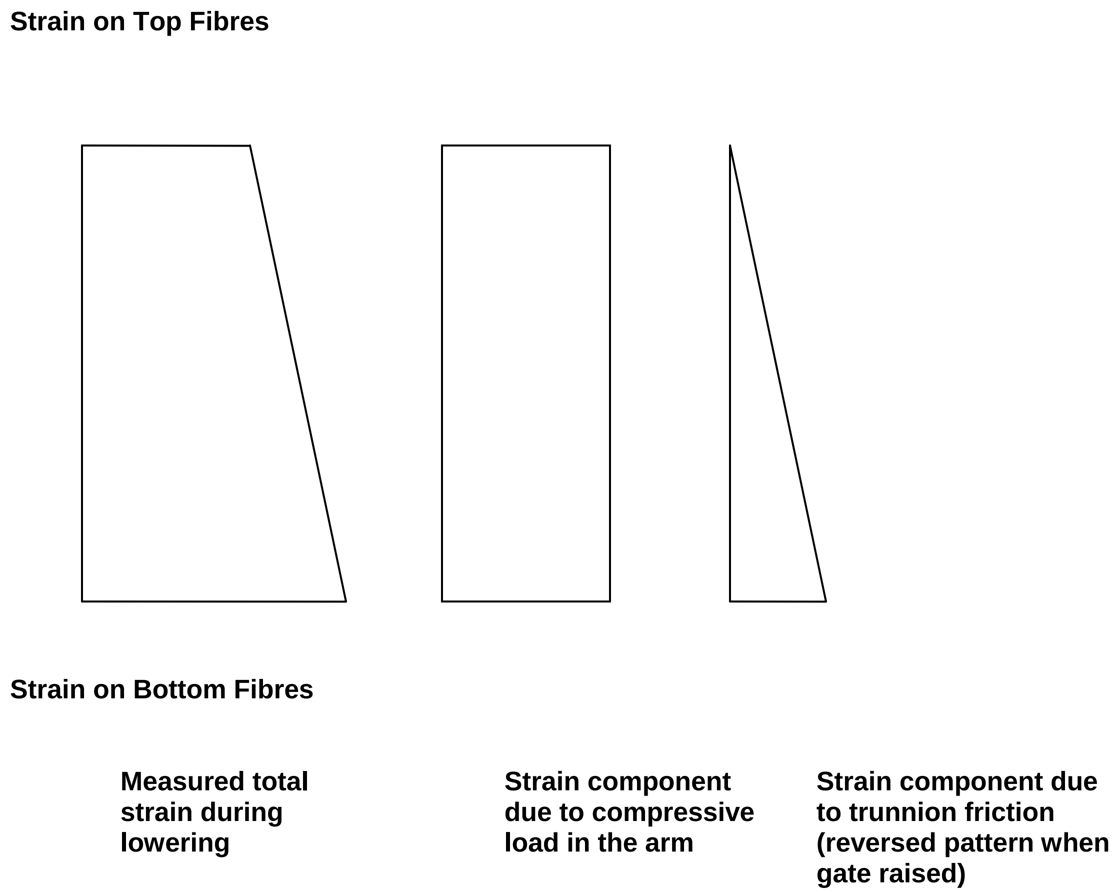

FIGURE 1
SHOWING MEASURED STRAIN FOR WATER LOAD & TRUNNION FRICTION MOMENT

Laser Deflection

This method detects the deflection of the gate arm. It involves attaching a laser to one of the gate arms pointing along the length of a gate arm and hitting a permanently mounted target. The deflection of the arm during raising and lowering is a direct indication of trunnion induced stress in the arm and hence trunnion friction.

This method requires safe access to the gate arms both for installation and monitoring. The laser is removed after testing, and can be repositioned at a later stage for repeating of the test, provided the target has not been adjusted.

9. CONCLUSIONS

The SunWater reports have rightly concluded that the bearings have possibly suffered degradation due to the ingress of water.
But the extent of the damage and the urgency for bearing replacement cannot be clearly established. A definitive assessment of bearing condition can only be obtained through the removal and disassembly of at least one bearing. Such an assessment would be extremely expensive considering the difficult procedure to remove a bearing from a Wivenhoe gate.

Bearing deterioration resulting in high trunnion friction may lead to either structural failure of the gate or components, or jamming of the gate. But loss of storage, through structural failure or gate jam in a partially opened position, could be stopped through the installation of the bulkhead gate. However gate jam or failure during a flood event will result in the spillway capacity being reduced.

Based on the review of the SunWater Reports and design report, site inspection and testing, grease analysis, and discussion with other authorities, it can be concluded that:

Bearing Condition

- The ingress of water has led to minor corrosion of the housing, the condition of the bearing surface is indeterminate but it is unlikely to be corroded
- Due to the ingress of water the PTFE low friction bearing surface may be damaged, but this cannot be determined. Although these plain spherical bearings may be in a deteriorated state they will not seize up.
- The presence of grease applied to the outside of the bearing is

unlikely to have had any detrimental effect on the bearing.

- The seals are in very poor condition and must be replaced. SunWater have provided a quote for a suitable replacement seal.

Structural Analysis

- During design of the gate structure, trunnion bearing moment was not specifically considered.
- The US FERC have adopted a maximum value for bearing friction of 0.3 and all gates should be capable of withstanding the trunnion moment induced by this friction value.
- The ability of the gate structure, and trunnion housing and support, to withstand high trunnion bearing moment is unknown and should be determined as a matter of urgency.

Overseas Experience

- There are a number of examples overseas of high trunnion friction contributing to gate failure. However it is not the sole cause and it is usually associated with deficient structural design.
- Some authorities have adopted a risk based approach and structurally checked or modified the gate to ensure that despite the possibility of high bearing friction the gate will not fail

Monitoring of Trunnion Friction

- There are a number of techniques available to monitor trunnion friction. Monitoring will allow the moment resulting from trunnion friction to be calculated.
- Regular monitoring will allow bearing replacement to be predicted.

Therefore, it is concluded that the condition of the bearings cannot be definitely determined without the expensive option of removing a typical bearing for inspection. However techniques are available to determine the bearing friction and guard against gate failure.

Two options are therefore available, either:

A. Replace the bearings with new ones. This is likely to be very expensive due to difficulties of working above the spillway and supporting the gate during bearing removal and replacement.

B. Adopt a risk based approach by assuming the trunnion bearing friction is high and ensuring that high friction will not result in gate failure, or at-least monitoring the bearing condition to check it does not get to a critical value.

10. RECOMMENDATIONS

The Risk based approached, Option B above, is recommended, with the following procedure:

A. Replace the seals with the type quoted by SunWater in their proposal of the 17th January.
B. Undertake a stress analysis of the gate arms, trunnion components and attachments to determine the susceptibility of the gate and connections to failure of the bearings and the value of trunnion friction that may result in failure.
   The analysis should consider the buckling of the arms under axial load and trunnion moment.
C. Strain gauge at least one arm, where water was clearly detected in the trunnion, to determine a typical value of trunnion friction. Ideally the gate should be subjected to hydrostatic head and operated under flow, but operation under dry conditions only, should provide an indication of trunnion friction..
D. Based on the outcomes of B and C above:
   a. If the structural analysis shows that the gate or trunnion components are susceptible to failure due to friction less than 0.3 then consider strengthening the gate as required. If this is impractical then consider replacing the bearings and/or instigating long term strain gauge monitoring.
   b. If the gate and components are able to withstand a high friction value in excess of 0.3, and friction is well below this value, then no modifications are required, but monitor trunnion friction say every 3-5 years. If there is no increasing trend then this period could be extended.

E. Reconsider the above recommendations if gate loading conditions or operational requirements change.

11. REFERENCES

Ref 1 SunWater Reports:

- Wivenhoe Dam; Report on Radial Gate Trunnion Bearings; April 2004
- Report: Fibre Optic Site Inspection, Radial Gate Trunnion Bearings, Wivenhoe Dam; September 2004
- Report commissioned by Sunwater: INTICO: Ultrasonic Thickness Survey of Radial Gate Trunnion Bearings; June 2004

Ref: 2: Tainter Gate Testing: A Holistic Approach; By Brad B. Boyer, Bennett B. Anderson & Stacy L. Jordan; Boyer Inc., Houston, Texas, USA

Ref: 3 Report on Wivenhoe Dam; Design of Crest Control Structures; By P Allen, Department of Primary Industries, April 1995

Ref: 4 Investigating the Spillway Gate Failure at Folsom Dam; By Robert Todd; Hydro Review February 1998

Ref: 5 Bearing Up Under the Strain; By F Henning, Water Power & Dam Construction August 2001

Ref: 6 Ensuring Tainter Gate Safety: FERC’s New Initiative; by C. Tjoumas et al; Hydro Review Sept 2001.

Ref: 7 Spillway Gate Repair Requires Innovation; R. Ellis; Hydro Review October 2002

Ref: 8 Friction Evaluation of In-Service Spillway Gate Bearing with One Year Gate Arm Strain Monitoring; By Yuzo Shiogama et el; HydroVision 2004

APPENDICES

A. RESULTS OF GREASE ANALYSIS

B. PHOTOS

C. CORRESPONDENCE

APPENDIX A

RESULTS OF GREASE ANALYSIS

WEAR CHECK

Grease

OIL AND EQUIPMENT CONDITION REPORT

UNIT NO.	RB Gate 4	**DATE SAMPLED**	27/02/06	**COMPARTMENT NAME**	Bottom Bearing
UNIT MAKE		**DATE RECEIVED**	02/03/06	**COMPARTMENT MAKE**	
UNIT MODEL		**DATE REPORTED**	06/03/06	**COMPARTMENT MODEL**	
UNIT SERIAL NO.				**COMPARTMENT SERIAL NO.**	
SYSTEM CAPACITY	Ltrs			**MACHINE LOCATION**	Wivenhoe

DATE SAMPLED		27/02/06
SAMPLE NO.		5902672
COMPONENT	Hrs	
MACHINE	Hrs	
OIL	Hrs	
OIL MAKE		Unidentified
OIL TYPE		Unidentified
OIL GRADE		?
OIL ADDED	Ltrs	
FILTER	Hrs	Not Applicable
OIL CHANGED		Not Changed
Metals (ppm)		
Aluminium (Al)		<10
Copper (Cu)		<10
Chromium (Cr)		<10
Iron (Fe)		60
Lead (Pb)		<10
Tin (Sn)		<10
Nickel (Ni)		<10
Contaminants / Additives (ppm)		
Silicon (Si)		<10
Boron (B)		<10
Sodium (Na)		<10
Potassium (K)		<10
Phosphorus (P)		140
Molybdenum (Mo)		10
Magnesium (Mg)		<10
Calcium (Ca)		40
Zinc (Zn)		70
Physical Tests		
PQ Index		< 10
		✓

UIN 68563

DIAGNOSIS

Current Sample :

Diagnosis not applicable. Sample dilution by 100. Limit of detection is 10 ppm.

Last Sample :

✓ NORMAL

LEGEND

- SEVERE
- ABNORMAL
- CAUTION
- NORMAL

WEAR CHECK

Grease

OIL AND EQUIPMENT CONDITION REPORT

UNIT NO.	RB Gate 3	DATE SAMPLED	27/02/06	COMPARTMENT NAME	Bearing Bottom
UNIT MAKE		DATE RECEIVED	02/03/06	COMPARTMENT MAKE	
UNIT MODEL		DATE REPORTED	06/03/06	COMPARTMENT MODEL	
UNIT SERIAL NO.				COMPARTMENT SERIAL NO.	
SYSTEM CAPACITY	Ltrs			MACHINE LOCATION	

DATE SAMPLED		27/02/06
SAMPLE NO.		5902678
COMPONENT	Hrs	
MACHINE	Hrs	
OIL	Hrs	
OIL MAKE		Unidentified
OIL TYPE		Unidentified
OIL GRADE		?
OIL ADDED	Ltrs	
FILTER	Hrs	Not Applicable
OIL CHANGED		Not Changed
Metals (ppm)		
Aluminium (Al)		10
Copper (Cu)		<10
Chromium (Cr)		<10
Iron (Fe)		200
Lead (Pb)		<10
Tin (Sn)		<10
Nickel (Ni)		<10
Contaminants / Additives (ppm)		
Silicon (Si)		10
Boron (B)		<10
Sodium (Na)		10
Potassium (K)		<10
Phosphorus (P)		160
Molybdenum (Mo)		20
Magnesium (Mg)		10
Calcium (Ca)		240
Zinc (Zn)		340
Physical Tests		
PQ Index		186

UIN 68568

DIAGNOSIS

Current Sample :

Diagnosis not applicable. Sample dilution by 100. Limit of detection is 10 ppm.

Last Sample :

NORMAL

LEGEND

SEVERE

ABNORMAL

CAUTION

NORMAL

WEAR CHECK

Grease

OIL AND EQUIPMENT CONDITION REPORT

UNIT NO.	RB Gate 3	DATE SAMPLED	27/02/06	COMPARTMENT NAME	Bearing Top
UNIT MAKE		DATE RECEIVED	02/03/06	COMPARTMENT MAKE	
UNIT MODEL		DATE REPORTED	06/03/06	COMPARTMENT MODEL	
UNIT SERIAL NO.				COMPARTMENT SERIAL NO.	
SYSTEM CAPACITY	Ltrs			MACHINE LOCATION	

DATE SAMPLED		27/02/06
SAMPLE NO.		5902671
COMPONENT	Hrs	
MACHINE	Hrs	
OIL	Hrs	
OIL MAKE		Unidentified
OIL TYPE		Unidentified
OIL GRADE		?
OIL ADDED	Ltrs	
FILTER	Hrs	Not Applicable
OIL CHANGED		Not Changed
Metals (ppm)		
Aluminium (Al)		10
Copper (Cu)		<10
Chromium (Cr)		<10
Iron (Fe)		30
Lead (Pb)		<10
Tin (Sn)		<10
Nickel (Ni)		<10
Contaminants / Additives (ppm)		
Silicon (Si)		20
Boron (B)		<10
Sodium (Na)		10
Potassium (K)		<10
Phosphorus (P)		170
Molybdenum (Mo)		60
Magnesium (Mg)		10
Calcium (Ca)		180
Zinc (Zn)		230
Physical Tests		
PQ Index		94

✓

UIN 68569

DIAGNOSIS

Current Sample :

Diagnosis not applicable. Sample dilution by 100. Limit of detection is 10 ppm.

Last Sample :

NORMAL

LEGEND

SEVERE

ABNORMAL

CAUTION

NORMAL

WEAR CHECK

Grease

OIL AND EQUIPMENT CONDITION REPORT

UNIT NO.	RB Gate 4	DATE SAMPLED	27/02/06	COMPARTMENT NAME	Top Bearing
UNIT MAKE		DATE RECEIVED	02/03/06	COMPARTMENT MAKE	
UNIT MODEL		DATE REPORTED	06/03/06	COMPARTMENT MODEL	
UNIT SERIAL NO.				COMPARTMENT SERIAL NO.	
SYSTEM CAPACITY	Ltrs			MACHINE LOCATION	Wivenhoe

DATE SAMPLED		27/02/06
SAMPLE NO.		5902675
COMPONENT	Hrs	
MACHINE	Hrs	
OIL	Hrs	
OIL MAKE		Unidentified
OIL TYPE		Unidentified
OIL GRADE		?
OIL ADDED	Ltrs	
FILTER	Hrs	Not Applicable
OIL CHANGED		
Metals (ppm)		
Aluminium (Al)		<10
Copper (Cu)		<10
Chromium (Cr)		<10
Iron (Fe)		10
Lead (Pb)		10
Tin (Sn)		<10
Nickel (Ni)		<10
Contaminants / Additives (ppm)		
Silicon (Si)		10
Boron (B)		<10
Sodium (Na)		20
Potassium (K)		<10
Phosphorus (P)		440
Molybdenum (Mo)		60
Magnesium (Mg)		<10
Calcium (Ca)		220
Zinc (Zn)		430
Physical Tests		
PQ Index		16

✓

UIN 6856A

DIAGNOSIS

Current Sample :
Diagnosis not applicable. Sample dilution by 100. Limit of detection is 10 ppm.

Last Sample :

NORMAL

LEGEND
SEVERE
ABNORMAL
CAUTION
NORMAL

WEAR CHECK

Grease

OIL AND EQUIPMENT CONDITION REPORT

UNIT NO.	LB Gate 4	DATE SAMPLED	27/02/06	COMPARTMENT NAME	Bearing Top
UNIT MAKE		DATE RECEIVED	02/03/06	COMPARTMENT MAKE	
UNIT MODEL		DATE REPORTED	06/03/06	COMPARTMENT MODEL	
UNIT SERIAL NO.				COMPARTMENT SERIAL NO.	
SYSTEM CAPACITY	Ltrs			MACHINE LOCATION	Wivenhoe

DATE SAMPLED		27/02/06
SAMPLE NO.		5902674
COMPONENT	Hrs	
MACHINE	Hrs	
OIL	Hrs	
OIL MAKE		Unidentified
OIL TYPE		Unidentified
OIL GRADE		?
OIL ADDED	Ltrs	
FILTER	Hrs	Not Applicable
OIL CHANGED		Not Changed
Metals (ppm)		
Aluminium (Al)		10
Copper (Cu)		<10
Chromium (Cr)		<1
Iron (Fe)		20
Lead (Pb)		<10
Tin (Sn)		<10
Nickel (Ni)		<10
Contaminants / Additives (ppm)		
Silicon (Si)		30
Boron (B)		<10
Sodium (Na)		20
Potassium (K)		<10
Phosphorus (P)		210
Molybdenum (Mo)		50
Magnesium (Mg)		<10
Calcium (Ca)		90
Zinc (Zn)		200
Physical Tests		
PQ Index		21
		✓

UIN 6856B

DIAGNOSIS

Current Sample :

Diagnosis not applicable. Sample dilution by 100. Limit of detection is 10 ppm.

Last Sample :

NORMAL

LEGEND

SEVERE

ABNORMAL

CAUTION

NORMAL

WEAR CHECK

Grease

OIL AND EQUIPMENT CONDITION REPORT

UNIT NO.	LB Gate 4	**DATE SAMPLED**	27/02/06	**COMPARTMENT NAME**	Bearing Bottom
UNIT MAKE		**DATE RECEIVED**	02/03/06	**COMPARTMENT MAKE**	
UNIT MODEL		**DATE REPORTED**	06/03/06	**COMPARTMENT MODEL**	
UNIT SERIAL NO.				**COMPARTMENT SERIAL NO.**	
SYSTEM CAPACITY	Ltrs			**MACHINE LOCATION**	Wivenhoe

DATE SAMPLED		27/02/06
SAMPLE NO.		5902670
COMPONENT	Hrs	
MACHINE	Hrs	
OIL	Hrs	
OIL MAKE		Unidentified
OIL TYPE		Unidentified
OIL GRADE		?
OIL ADDED	Ltrs	
FILTER	Hrs	Not Applicable
OIL CHANGED		Not Changed
Metals (ppm)		
Aluminium (Al)		10
Copper (Cu)		<10
Chromium (Cr)		<10
Iron (Fe)		620
Lead (Pb)		<10
Tin (Sn)		<10
Nickel (Ni)		<10
Contaminants / Additives (ppm)		
Silicon (Si)		30
Boron (B)		<10
Sodium (Na)		20
Potassium (K)		<10
Phosphorus (P)		160
Molybdenum (Mo)		80
Magnesium (Mg)		<10
Calcium (Ca)		160
Zinc (Zn)		150
Physical Tests		
PQ Index		123
		✓

UIN 68562

DIAGNOSIS

Current Sample :
Diagnosis not applicable. Sample dilution by 100. Limit of detection is 10 ppm.

Last Sample :

NORMAL

LEGEND
- SEVERE
- ABNORMAL
- CAUTION
- NORMAL

APPENDIX B

PHOTOGRAPHS

Wivenhoe Dam Bearings
(Photos 1 & 2)

Priest Rapids Dam Bearing Replacement
(Photos 3-6)

Trunnion Failures & Strain Gauging
Norway & Malawi
(Photos 7-9)

Photo 1
Wivenhoe Dam: Spare Bush, Assembled
Note protruding chromed surface of inner ring

Photo 2
Wivenhoe Dam: Spare Bush, Dismantled
Note Black PTFE coating on outer ring

Photo 3
Priest Rapids Dam Washington State USA

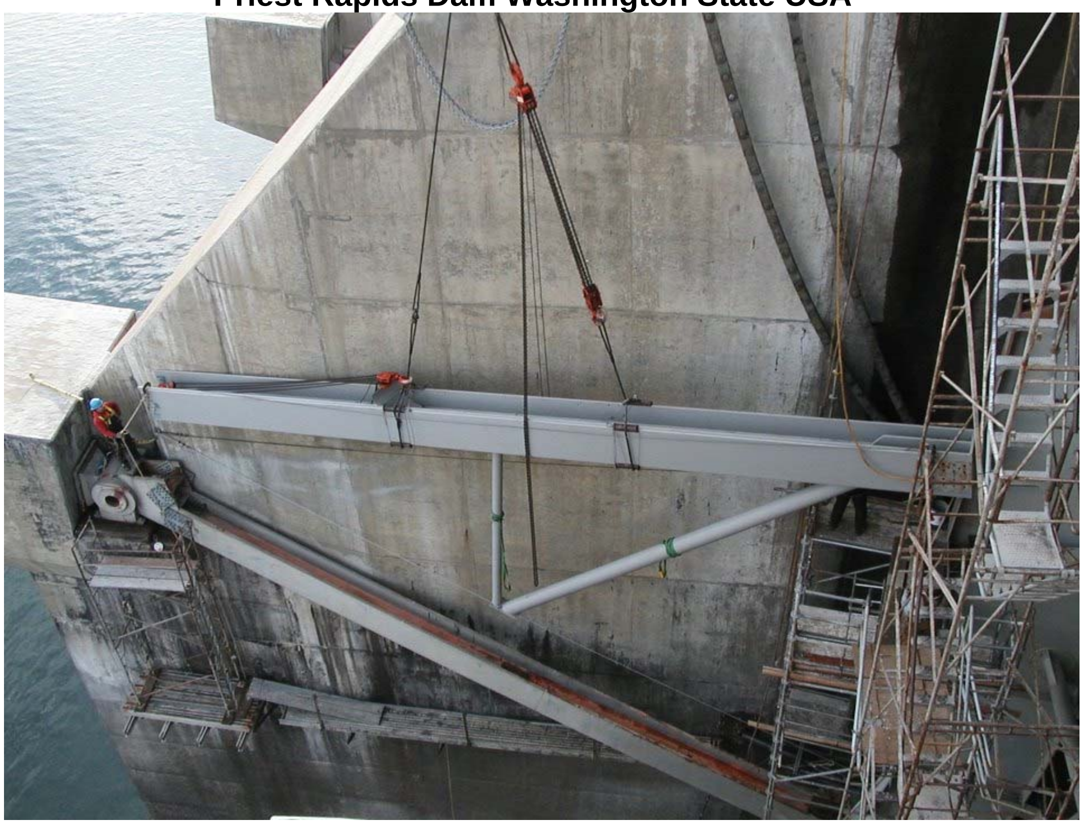

Photo 4
Priest Rapids Dam Washington State USA

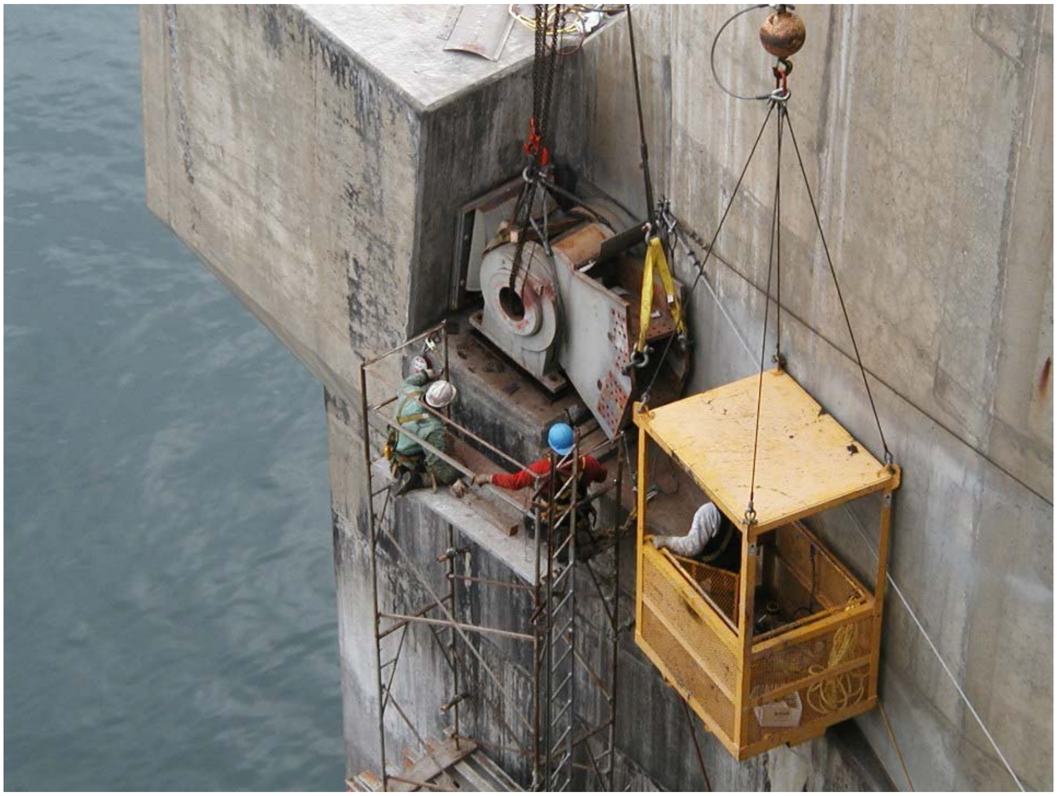

Photo 5
Priest Rapids Dam Washington State USA

Photo 6
Priest Rapids Dam Washington State USA
Deteriorated Lubrite Bush Replaced by ORKOT

Photo 7
Gate Failure: Ulefoss, Norway
Photo Supplied by H. Fosker of Norconsult, Norway

Photo 8
Gate Failure: Liwonde barrage, Malawi, Africa
Photo Supplied by H. Fosker of Norconsult, Norway

Photo 9
Strain Gauge Application, Norway
Photo Supplied by H. Fosker of Norconsult, Norway

APPENDIX C

CORRESPONDENCE & DISCUSSION

USA
- Bureau of Reclamation
- Grant County (Washington State)

Norway
- NorConsult

Canada
- BC Hydro

USA
Bureau of Reclamation (USBR)

Summary of Telephone Discussion with Peter Hoffman
United State Bureau of Reclamation, Denver Colorado, USA
Infrastructure Services Division, Hydraulic Equipment Section

Date: 3/5/06

He has analysed 75 USBR dams for potential problems with trunnion friction leading to gate failure.
The dams all have plain bronze bushes or self-lubrication Lubrite bushes.
Of those 75, 16 dams were found to be questionable requiring closer analysis.
His analysis was a simple approach that looked at the hydrostatic loads on the gate arms and determined the axial compression and the maximum allowable axial compression based on columns in accordance with AISC standards.
Gate arms where the loads approached the maximum allowable loads, were analysed in more detail.
It is interesting to note the gates on Folsom Dam far exceeded the stresses calculated for the other 74 dam gates.
Folsom dam
Following the investigation, the gates and bearings were retained. But an automatic lubrication system was installed (to operate each time the gates opened) and the arms were strengthened against buckling.
Strain Gauging
Three gates were strain gauged mainly to determine the trunnion friction, not as a monitoring technique. The gates were raised 150-300 mm and then lowered.
He has no experience with laser monitoring.
Remedial Work
The USBR has adopted a risk based approach with regard to trunnion friction.
They have identified the gates at risk and rather than replacing the bearings they have strengthened the arms.
The arms were strengthened by welding plate reinforcement near the trunnion end of the arms and extending for about 15% of the arm length. This significantly reduced the chance of the arms buckling.

USA
Priest Rapids Dam, Washington State

Summary of Telephone Discussions with David Moore & Raymond Ellis
Senior Civil Engineers,
Grant County Public Utility District
Date: 11th & 19th April 2006

During an inspection some years ago it was noticed that a number of the trunnion thrust washers were cracked. It was latter found that the cracking was due to pigeon excrement on the bearings leading to ammonia induced stress corrosion cracking.
The bearings get wet during flood discharges.
This lead to a replacement of the Lubrite bushes on the 22 radial gates (12m x 16m high, & 96 tonnes). Total cost around $4.2mil (AUD), or roughly $200,000/gate. The pins were 24-32 in dia. They replaced the bearings on one gate initially to develop the technique.
They trialed hoist motor current & power monitoring but found that it was not a good indicator of bearing condition.
Laser measurement was trialed but found to be difficult due to access and relating deflection to trunnion torque
Strain gauging was used to monitor friction. but it was very expensive.
Strain gauge measurements were taken before and after bearing replacement. It is not used as long term monitoring. The Lubrite friction value was 0.8-0.9, whereas Orkot was 0.6-0.7.
The bearings were replaced with Orkot which is a Teflon (PTFE) composite material. They found it swelled up and required some remedial work after installation.

NORWAY
Norconsult Consulting Engineers

Mr. Hobbs,
It is facinating that the paper has been read as far form Norway as it is possible to travel, but we have been there too. before my time our company planned dams and hydropowerplants in the Snowy Mountains.
The dam gate failures in question took place in USA (1), Norway(3) and Africa(1). I'm shure that I will be given permission to provide you with details about the incidents form the owners with the proper reference to your affiliation to the business. It is evident, however that all these five incidents were caused by increased trunnion friction.
We have performed strain gauge measurements of trunnion friction on more than 40 radial gates all over Norway and one in USA since 1998. Among these we have detected critical high friction in the trunnions of 5 gates, friction above nominal, but still not critical on approx 10 gates and 25 with nominal or lower friction. The smartness of the method is that we can detect the "rotten eggs in the basket" without braking them, or we can avoid dewatering and dismantling of fresh and sound trunnions.
On 3 newly comissioned gates, we have permanently installed strain gauges for monitoring purposes. Theese bearings are spherical plain bearings with PTFE film. Lundevann gates have non-metallic bearings.
You will find plenty of relevant information on our dam and hydro power plant activities on our web site, link below:
Please dont hesitate to contact us again for further information.
Regards,

Henning Føsker
[redacted]
Tel: [redacted]
Mobil:
Fax:
Privat:

www.norconsult.com

From: Glen Hobbs [redacted]
Sent: 28. mars 2006 14:15
To: Fosker, Henning
Subject: Radial Gate Trunnion Bearings

Dear Mr Fosker,
We are presently reviewing trunnion bearing performance at a number of large dams in Australia.
I was interested to read your paper titled : ' Strain Gauge Measurements of friction on Radial Dam Gate Bearings'
The article is most interesting.
You mentioned that at least five radial gate breakages in Norway & abroad are caused by bearing failure. Are you able to provide more information on these failures or provide details of contact persons I could chase up ?
Also could you please provide more details on the strain gauging process including:

- is the monitoring of bearings long-term; ie is it used as a maintenance indicator, and/or an indicator of potential bearing failure over a long period of time
- have you applied this to determining deterioration of low friction bearings such as spherical roller bearings and plain cylindrical PTFE coated bearings?
- have you installed strain gauges at other dams besides Lundevann Dam
- are you aware of water authorities in other countries strain gauging bearings
- what is the scope of the consultancy service that your organization provides to clients with regard to strain gauging of trunnions. Has your organization consulted to other clients on this type of work?

Thank you & regards
Glen Hobbs

Glen Hobbs & Associates P/L
[redacted]

CANADA
BC HYDRO

I was asked to respond to your enquiry below. After the Folsum Dam incident BC Hydro performed a review of all its radial gates. The review was not specific to the trunnion bearings but instead looked at the gate designs in general. Basically BC Hydro took the approach that the condition of the bearings can not be guaranteed over time and that ultimately it is the radial arms that are the limiting factor. In summary the review took the following steps.
1) An initial high level review of all gates. Gates were generally divided into 2 categories. Gates with arms fabricated out of standard beam sections and newer welded box girder designs. BC Hydro's view was that the newer box girder design would likely not be a problem.
2) A structural analysis was performed on all the gates fabricated out of standard beam sections. The objective was to determine the trunnion friction coefficient at which cause a structural problem (high stresses or buckling) during the opening of the gate.
3) Based on the above analysis the gates were further classified into gates where the friction coefficients that could lead to damage were likely too high to be realistic and ones that were in the realm of being possible.
4) The second category of gates were inspected and the analysis reviewed to make sure that it was representative. Of these gates some modifications were made to increase the arm stiffness. One gate also was modified to permit its self lubricated bearings to be greased (the concern was not so much that the bearing material was a problem but the the pin was not stainless steel and could be rusted).
5) Two gates designs in particular were highlighted as a concern as the pier walls appeared to be moving and there was concern about possible binding in the bearings. Remedial civil work was performed at one of these locations and this gate was strain gauged. In general any gate with beams with the bending weak axis horizontal (lower resistance to bending in the vertical direction) were the problem gates.

Regarding your specific questions below.
1) No ongoing monitoring or instrumentation is being done.
2) Other than routine inspections and maintenance (which includes greasing) I am not aware of any additional maintenance that was initiated after the Folsum Dam issue.
3) I haven't heard of these failures but would also be interested in finding out more. Do you have names of the sites? It's possible we might be able to dig up more information at our end.

Let me know if you have any more questions.

Chris Helston