ENGINEERING GUIDELINES FOR THE EVALUATION OF HYDROPOWER PROJECTS

CHAPTER 12 – WATER CONVEYANCE

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FEDERAL ENERGY REGULATORY COMMISSION
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TABLE OF CONTENTS

TABLE OF FIGURES

12-1 PURPOSE AND SCOPE

The purpose of this document is to provide guidance for the inspection, monitoring, and evaluation of the safety of water conveyance structures at hydropower projects. Failure of water conveyances can lead to loss of life, property damage, and environmental concerns, in addition to the loss of the intended function of the project.

This document is not intended to provide guidance on the design and analysis of water conveyance structures. For the planning and design of new water conveyance features, the following resources provide guidance:

<u>Penstocks</u>

AWWA C200-17: Steel Water Pipe - 6 in. (150 mm) and Larger

ASCE - Steel Penstocks, Manuals of Practice No. 79, 2nd Edition

<u>Canals</u>

USACE EM 1110-2-1601 - Hydraulic Design of Flood Control Channels

USACE EM 1110-2-1602 - Hydraulic Design of Reservoir Outlet Works

USACE EM 1110-2-1913 - Design and Construction of Levees

USACE EM 1110-2-2007 - Structural Design of Concrete Lined Flood Control Channels

USACE EM 1110-2-2104 - Strength Design for Reinforced Concrete Hydraulic Structures

USACE EM 1110-2-2502 - Retaining and Flood Walls

<u>Tunnels</u>

USACE EM 1110-2-2901 - Tunnels and Shafts in Rock

The above list is not exhaustive of design guidance.

12-2 CONVEYANCE TYPES

The following types of conveyances will be addressed in this chapter:

- Penstocks
- Power Canals
- Flumes
- Tunnels

Conveyances differ from dams in the fact that they typically traverse long distances. It is possible that a conveyance failure may go unnoticed by project personnel for a significant time. While each type of conveyance has specific failure modes and prudent defensive measures, a common theme is the need for project personnel to be able to identify a failure and be able to quickly take action to minimize the consequences of the failure. Typically this means closing the conveyance inlet, in some cases releasing water down a safe route, and if necessary, activating the Emergency Action Plan (EAP).

The consequences of a potential conveyance failure should be assessed by licensees, considered during the Potential Failure Modes Assessment (PFMA) of a project, and reviewed during FERC and Part 12D Independent Consultant inspections. If the consequences of failure are high, remote sensing is relied upon to detect a failure, and remote-controls are required to operate of gates and valves, the reliability of the control system and its associated flow control devices should be verified at a minimum by yearly testing. If operation of manual head gates or valves is required for consequence mitigation, their reliability to operate and the ability of the operator to access them during adverse conditions must be verified.

While dams are usually classified in whole as having either a high, significant, or low hazard potential, the majority of water conveyances may be mostly low hazard with limited areas of significant or high hazard potential. These areas should be identified, delineated, and defensive measures should focus on protecting these areas from failure or minimize the failure consequences. If there are habitable residences in the vicinity of the conveyance, and failure would have significant consequences, the failure of this conveyance should be included in the EAP.

All project PFMAs should consider failure of water conveyances. The Potential Failure Mode (PFM) examples provided for each type of conveyance in this chapter do not constitute an exhaustive list. All PFMs must be site specific. For explanation of a PFMA and PFMs, see Chapter 14 – Dam Safety Performance Monitoring Program.

The PFM classification will inform all licensees, owners, and inspectors of the degree of conveyance inspection and monitoring necessary. This guidance addresses conveyances that have failure consequences. All regulation is project specific. If there are reasons why deviation from this guideline is warranted, then deviation may be justified.

12-2.1 Penstocks

12-2.1.1 Typical Features

The great majority of penstocks at hydropower projects are steel. Older steel penstocks tend to be riveted plate, newer penstocks are typically spiral-wound welded plate.

A view of typical riveted penstocks is shown in Figure 1. When penstocks are above ground as these are, they are usually mounted on concrete or steel saddle supports.

Fig. 1. Steel penstocks.

Woodstave penstocks are also used at hydropower projects to a lesser extent. These are typically constructed of creosote treated wooden strips called staves ringed with steel bands. The bands are typically spaced at about 1 ft. or less. Wood stave penstocks are limited to low internal pressures. As can be seen in the picture below, they often leak profusely. This can result in saturation of the ground underneath them leading to support instability.

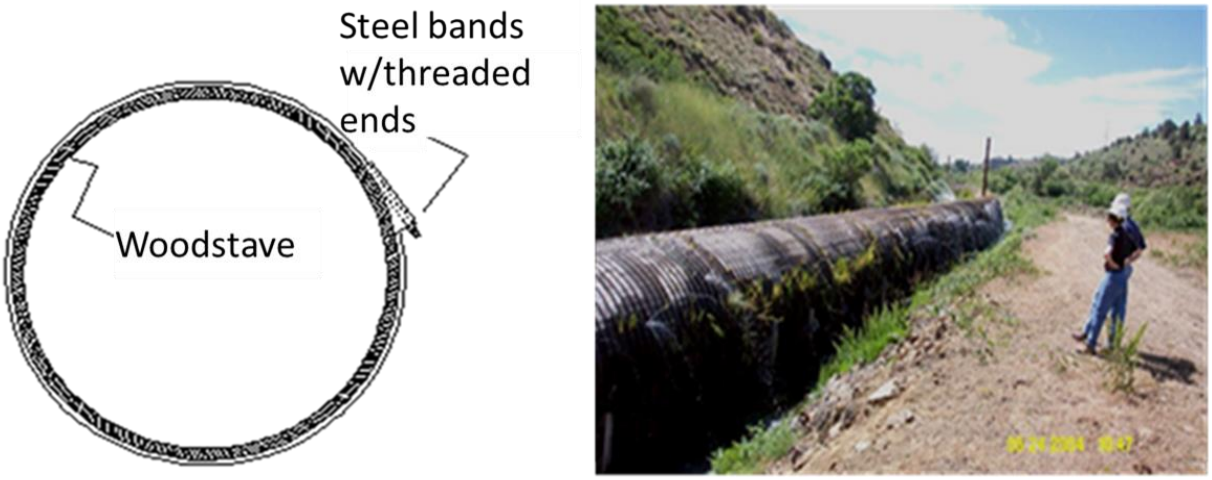

Fig. 2. Woodstave penstock.

While not common at FERC projects, fiberglass reinforced polymer (FRP) pipe are sometimes utilized for penstocks.

12-2.1.2 Failure Modes and Defensive Measures

<u>Failure Due to Excessive Internal Pressure</u>

Excessive internal pressures in penstocks typically occur after load rejection due to sudden valve/gate closure. The failure sequence of events is as follows:

1. Generator under load is suddenly disconnected from the power grid due to a circuit breaker trip or similar reason.
2. With the load disconnected, the generator begins to increase speed since the hydraulic forces driving the turbine are no longer resisted by electrical load. (This is sometimes called run away.)
3. The speed governor, which regulates turbine/generator speed by controlling valve/gate position of the turbine, quickly closes the valve/gate in response to the increase in machine speed.
4. The sudden valve/gate closure causes a temporary, but large pressure wave within the penstock, which is often referred to as water-hammer or transient pressure.
5. The large pressure increase causes high tensile stresses in the penstock shell and fails the penstock.
6. Water is released through the failed penstock until the intake gate is closed or until water in reservoir has drained to below the intake sill.

The pressures from closure can be calculated to evaluate the risk to the penstock. The amount of pressure increase is a function of the initial flow velocity (V_i), the valve/gate closure time (S), water mass density (ρ), length of penstock (L), and the wave speed in the pipe (a). The velocity versus time function for valve/gate closure is device specific, but closure is defined by the valve closure function depicted below, the pressure rise (P) can be expressed as follows:

$$S < \frac{2L}{a} \qquad P = a\rho V_i$$

$$S > \frac{2L}{a} \qquad P = \frac{1}{2} a\rho V_i \tan\left(\frac{\pi L}{Sa}\right)$$

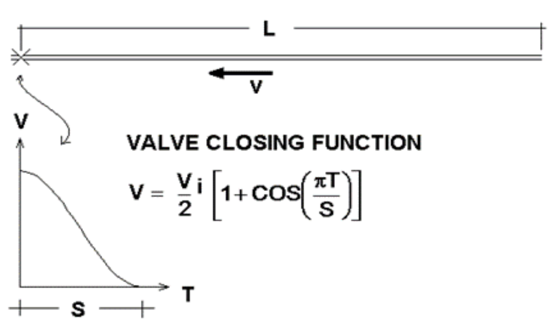

Fig. 3. Valve closing diagram.

The wave speed (a) is a function of water compressibility (k), water mass density (ρ), and radial pipe stiffness which is a function of pipe diameter (d), Young's modulus (E) and pipe thickness (t).

$$a = \sqrt{\frac{1}{\rho\left(\frac{1}{k} + \frac{d}{Et}\right)}}$$

Note that all values must be in consistent units.

Defensive measures

Surge tanks, which decrease the penstock length (L) from the valve to the surge tank instead of from the valve to the intake, reduce the effect of sudden valve/gate closure. Another method to reduce the effects of sudden closure, is to install a pressure relief valve that opens when the valve/gate closes. However, the best defense against this type of failure mode is to ensure that valve/gate closure times are long with respect to the ratio of the length of the penstock to the wave speed ($2L/a$).

Moreover, many power plants have hard physical limits on wicket gate closure speed, for example there may be a restrictor orifice in the supply line that feeds the wicket gate control ring ram.

The inspector should be familiar with the defensive measures employed at the project, and be satisfied that these devices are in working order.

Failure Due to Vacuum

This failure mode is quite common and is typically the result of a sudden closure of an upstream inlet gate or plugging of the inlet while operating, and the failure of the air venting system. Air vents are sometimes plugged with debris or ice. In most cases it takes very little vacuum to buckle a penstock (Figure 4), therefore sufficient air venting directly downstream of an upstream gate must be provided.

Fig. 4. Buckled steel penstock.

Defensive Measures

Venting of the penstock is important. It is recommended that penstocks have air valves at critical locations, but other methods such as standpipes can also be used to vent air. Both air valves and standpipes should be protected from freezing. The inspector should be satisfied that proper upstream air venting exists and that it is inspected and maintained by project personnel.

Failure Due to Corrosion

Steel penstocks, like all steel structures, are subject to corrosion. This is also true of the steel bands that clamp together wood stave penstocks. Corrosion can be a difficult problem if the penstock is buried because it is not visible, and because the surrounding soil may itself be corrosive. Gradual thinning of the penstock shell can lead to a sudden failure and can make the penstock more susceptible to failure from transient pressures.

Defensive Measure

The penstock shells should be evaluated for failure by testing the coating condition and for corrosion and shell thinning approximately every 10 years depending on the project. Projects that pose a hazard to the public may need more frequent testing than projects with low consequences.

Failure Due to Slope Instability

Penstocks often pass through mountainous areas with steep unstable slopes subject to landslides, rockfalls, mudslides, etc. Clearly if the slope that a penstock is sitting on (or buried in) slides, it will take the penstock with it. Penstock failures have also been caused by rockfalls. Large boulders tumbling down a steep slope hit the penstock and fail a section of it.

Defensive Measures

If a penstock traverses a long distance over unstable terrain, it may not be practical to attempt to stabilize the entire penstock corridor. In such cases the best defensive measure may be the ability to sense a penstock failure quickly and have the ability to close the upstream inlet. This will limit the amount of potential damage. There is a tremendous difference between a penstock failure that releases a limited volume of water over a short period of time, and one that discharges freely for hours or days. There are technologies available that will provide detection of a penstock failure. Pressure sensors in the powerhouse, combinations of flow meters or pitot tubes mounted in the penstock can all be configured to detect a loss of flow and trigger an inlet gate closure. Sophisticated systems incorporating flow meters at both ends of the penstock are capable of sensing leakage rates and can send a closure signal when a differential flow representing the leakage threshold is sensed.

The inspector should familiarize him/herself with whatever system a project has and question how it is tested. A common vulnerability of a penstock protection system is a telemetry line that runs alongside the penstock from the powerhouse up to the inlet. In the event of a failure, the telemetry line may be broken, making it impossible to remotely close the penstock. In addition to this problem, if the access road to the inlet is washed out by the failure, it may be difficult to access the inlet to manually close the gate.

Failure Due to Saddle Settlement or Deterioration

Penstocks that are supported by saddles can fail if the saddles are undermined by erosion. Saddles can also deteriorate due to freeze thaw damage.

Defensive Measures

Periodic inspection of the penstock and the support saddles should be completed.

Failure Due to Joint Rupture

Penstocks are typically equipped with joints that allow for expansion and contraction. A typical expansion/contraction joint detail is shown in Figure 5.

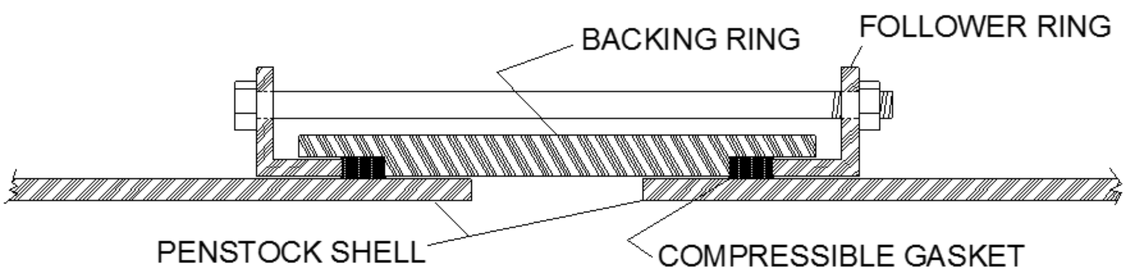

Fig. 5. Typical joint detail.

Expansion/contraction joints allow axial movement of the penstock shells. Since they cannot transmit axial stress, they should not be located in areas where high bending moments occur, such as at the midspan of a long section of pipe.

Some older penstocks under FERC jurisdiction have bellows expansion joints. Bellows joints are typically used on low pressure penstocks, in which the flexibility of the flanges is expected to accommodate the expansion and contraction that occurs within the penstock. This type of joint is subject to fatigue and therefore can be problematic.

Fig. 6. Failed bellows expansion joint.

Defensive Measures

As with all structures, joints are often the weak link and must be inspected routinely if the consequences of failure are severe.

12-2.1.3 Recommended Surveillance

12-2.1.3.1 Inspection

Above ground penstocks should be visually inspected at least once a year. Things to look for include:

- Leakage
- Missing rivets
- Misalignment due to differential settlement of supports
- Support undermining or degradation
- Loose or missing steel bands (Woodstave Penstocks)

As previously discussed, the ability of defensive measures to function properly should be verified at least on a yearly basis.

Depending on the potential hazard posed to the public, inspections should be done every 10 years to ascertain the extent of shell thinning due to erosion and corrosion. Ultrasonic shell thickness measurements should be recorded and evaluated.

In some cases, the penstock is inaccessible, which makes routine inspections difficult. Licensees/owners have begun to use drones to monitor inaccessible areas of penstocks. While this is a good tool, it may still be necessary to physically inspect the penstock.

12-2.1.3.2 Instrumentation

Usually, the only instrumentation employed at penstocks is internal pressure and flow sensors.

12-2.2 Power Canals

12-2.2.1 Typical Features

Power canals are typically parallel the river alignment downstream of the dam. A power canal's purpose is to provide diversion of water from a river or stream. The diversion provides the powerhouse with more operating head than would be possible if the powerhouse were located at the dam (Figure 7). Often, a power canal's failure would result in the release of water back into the river resulting in little or no life safety related consequence. However, the environmental consequences can be significant. Power canals that are contained by an embankment or canal wall, with water elevations in excess of the surrounding ground are a potential hazard. In such cases, it is possible to have a low hazard dam but a high or significant hazard power canal.

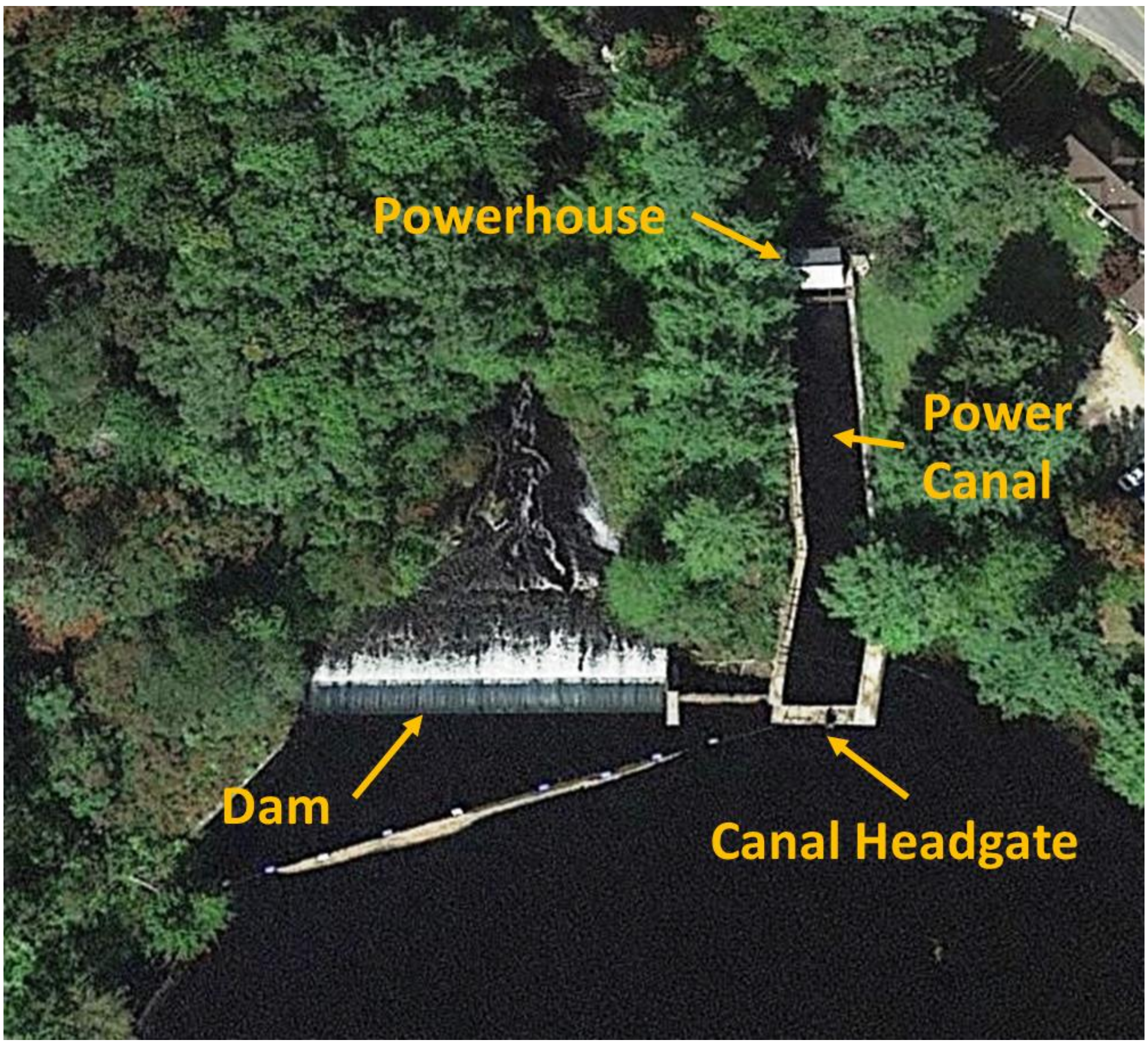

Fig. 7. Typical power canal layout (Powder Mill Pond, Google Earth).

The following photo depicts the failure of the Swift #2 Power Canal in 2002. The canal embankment (photo left side) failed due to piping into a rock fissure in the canal foundation. The hazard potential of elevated power canals can clearly be seen in this photo.

Fig. 8. Swift #2 Power Canal failure.

12-2.2.2 Failure Modes and Defensive Measures

Failure Due to Canal Wall/Embankment Overtopping

Overtopping can occur for many reasons for example:

In the case depicted below, embankment overtopping occurred as a result of a combination of high inflow through the upstream headgate structure and inflow from a stream that was a tributary to the power canal (Hatfield Project, Wisconsin, 1993).

Fig. 9. Hatfield power canal failure.

Another potential canal failure can be caused by load rejection. Typically, load rejection occurs at the powerhouse and the associated sudden valve closures will cause a surge wave up to a few feet high, which initiates at the downstream end of the canal and propagates upstream potentially overtopping the canal (Figure 10).

The following formula can be used for the surge wave height resulting from a sudden shutdown of a powerhouse at the end of a rectangular power canal:

$$\Delta H = V_i \sqrt{\frac{H}{g}}$$

Where:

ΔH = Surge wave height over and above normal flow depth
H = Normal flow depth
V_i = Initial canal flow velocity
g = Gravitational acceleration (32.2 ft/sec²)

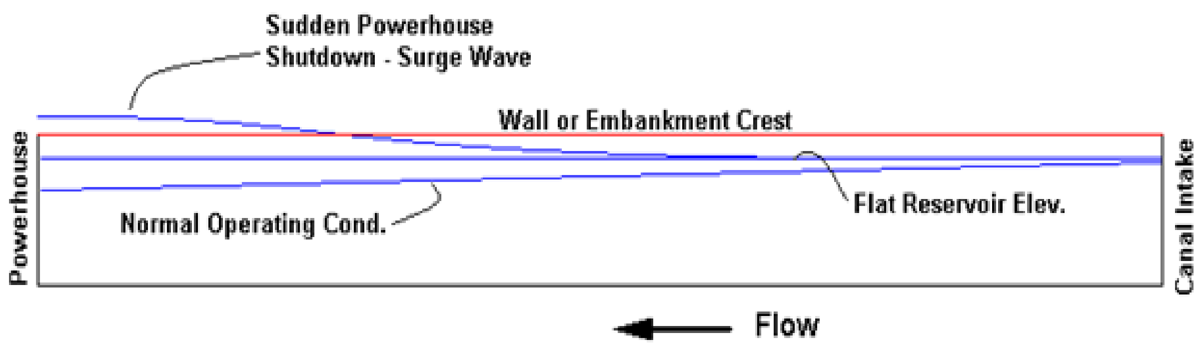

Fig. 10. Transient overtopping.

Defensive Measures

These examples of overtopping mechanism underscore the need to evaluate the sufficiency of canal freeboard under ALL conditions and not just the normal operating condition. Often the canal wall or embankment height is insufficient to contain extreme flood events. In addition, many canal embankments are quite long and may have areas of local settlement, meaning that the freeboard is less than what was intended.

Some canals have emergency overflow spillways that allow excess water to flow back into the river in a controlled manner. EM 1110-2-1602, *Hydraulic Design of Reservoir Outlet Works*, provides guidance for spillway design.

Canal Embankment Failure Due to Piping

Cause 1

Tree roots and animal dens provide initial flow paths, which can initiate piping failures in embankments. Many canal embankments are quite long and difficult to access in places. However, it is important to keep embankment slopes free of woody vegetation and burrowing animals.

Cause 2

Poorly constructed canal embankments can be under compacted in places. Some power canal embankments may have been constructed by side casting with little attention paid to placement or compaction of embankment material

Cause 3

Because of the length of many power canals, there may not have been an extensive foundation exploration and testing program prior to the canal's construction. It is likely that the canal passes over natural ground that has sand seems or rock joints or other features that could lead to a piping failure. Note the fissure that lead to the piping failure of the Swift #2 Power Canal embankment.

Fig. 11. Fissure at Swift #2 Power Canal.

Defensive Measure

The toes of canal embankments should be visually inspected to discover evidence of unusual seepage. This means that the toe of the embankment must be accessible for inspection. There must be vegetation control in place that keeps the embankment slope and toe area clear enough to be seen.

Canal Embankment Failure Due to Slope Instability

Power Canals exhibit all the classical slip circle failure modes that any water retaining embankment does, with the addition of deeper arcs due to the fact that they are often perched on a hillside as shown in Figure 12.

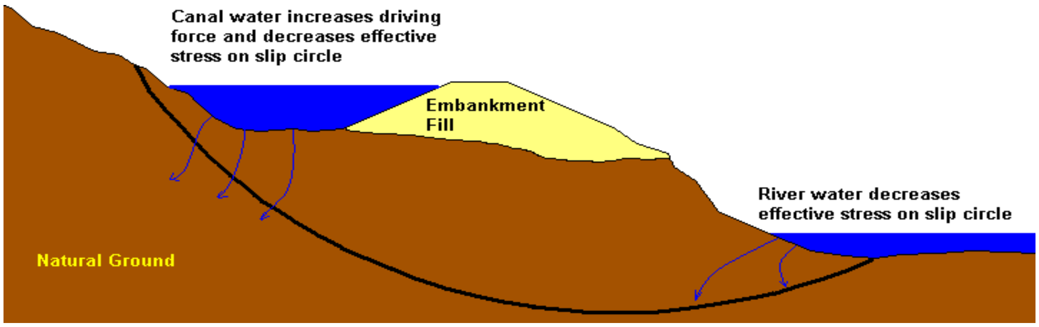

Fig. 12. Power canal stability considerations.

In addition, power canal embankments are subject to all the same concerns as any other water retaining embankments, such as internal erosion, sudden drawdown instability, seismic liquefaction, etc. For additional information for evaluating embankment dams, see Chapter 4 – Embankment Dams.

Defensive Measure

The consequences of failure of a canal must be well understood. Often the PFMA process is helpful for evaluating the consequences. Areas subject to potential instability with adverse failure consequences must be analyzed for slope stability. All relevant load cases must be considered including liquefaction if the canal is in a high seismic zone. Consult Chapter 4 of the Engineering Guidelines for how to evaluate canal embankments

Canal Failure Due to Landslides and Rockfalls

When canals are in areas of steep unstable slopes, rockfalls and landslides can damage or plug the canal as can be seen in Figure 13.

Fig. 13. Rock inside power canal.

Defensive Measure

As with penstocks, the best defensive measure for canals that are subject to landslides and rockfalls is the ability to detect the event and to act quickly to stop inflow. In addition, having a mechanism that can provide controlled release of the flow from the canal, such as a spillway or outlet, should be considered.

12-2.2.3 Recommended Surveillance

12-2.2.3.1 Inspection

Canals should be visually inspected over their full length at least quarterly by project personnel. High hazard sections with habitable structures subject to inundation by a failure should be inspected more often, and residents should be educated to be aware of adverse conditions and know how to report. As mentioned above, this means that the canal right of way must be sufficiently maintained and embankment slope/toe vegetation sufficiently controlled to make inspection possible.

If possible, canals should be dewatered on an interval appropriate to the identified potential failure mode and corresponding consequences to inspect the interior slopes for erosion, undercutting, or burrowing. Prior to dewatering any canal, the sudden drawdown condition should be evaluated (see Chapter 4 – Embankment Dams).

12-2.2.3.2 Instrumentation

In areas where canal embankments pose a high hazard, instrumentation appropriate to dam embankments may be appropriate for canals. In addition, it is important for project personnel to be alerted when failure is imminent or has taken place so that they can take appropriate action such as trigger the EAP, close headgates, etc. This means that canal water levels should be monitored. In the case where the canal is several miles long, it may be prudent to measure water levels at several locations. One question that should always be asked is: “Will project staff be aware of a failure soon enough to trigger the EAP?” Consideration should be given to automated public warning systems when human activation of the EAP cannot be done quickly enough.

12-2.3 Flumes

12-2.3.1 Typical Features

Flumes are basically elevated canals supported by some sort of structure (Figure 14). Since flumes are gravity flow conveyances with open tops, their sides can be overtopped. They can fail due to erosion of their foundations. Like penstocks, they are often in areas of high relief where landslides, mudslides and mass wasting can fail them.

Fig. 14. Typical flume.

Flumes are often supported by wooden railroad style trestles or steel bridge trusses. In addition to the failure modes discussed above, wooden flumes are also susceptible to fire, insects and wood rot.

Fig. 15. Failed flume.

12-2.3.2 Failure Modes and Defensive Measures

Flumes often cross valleys and drainages. The bents located in the flow path of the drainage course may be eroded during high flows, or the structure itself impacted by flowing debris during storm events or if debris flows occur.

In addition to failure modes and defensive measures already discussed for penstocks and canals, earthquake loading may be of special concern. A typical failure mode for flumes is depicted below.

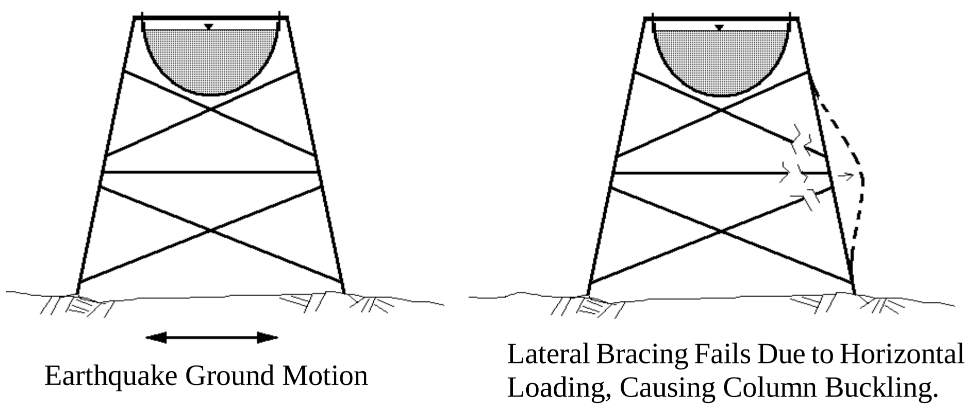

Fig. 16. Example of earthquake impact on the structural support for a flume.

Defensive Measures

Where failure of a flume poses a hazard, the flume should be evaluated for stability for all credible loading conditions including seismic if applicable.

12-2.3.3 Recommended Surveillance

12-2.3.3.1 Inspection

As with penstocks and canals, flumes should be visually inspected. The frequency of inspection is dependent on the consequences of failure. Typically yearly inspections should suffice. Flumes often traverse remote areas with rough topography or dense growth. Access throughout the flume alignment is necessary for inspection. The flume support foundations must be accessible.

12-2.3.3.2 Instrumentation

As with the other conveyances discussed, a remote flume failure must be detected by project personnel in a timely manner. In order to shut off flow and if necessary activate the EAP, the flume water elevation or flow must be measured continuously. An unusual drop in flow should trigger alarms and appropriate action to mitigate damage.

12-2.4 Tunnels

12-2.4.1 Typical Features

A typical power tunnel is depicted below. Tunnels are most often used in mountainous areas. Tunnels can be divided into two basic types, lined and unlined.

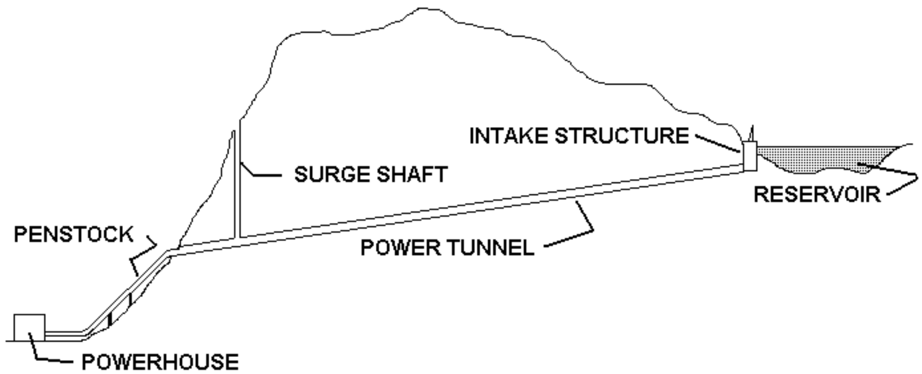

Fig. 17. Typical tunnel diagram.

12-2.4.2 Failure Modes and Defensive Measures

<u>Failure Due to Rock Joint Pressurization</u>

Figure 18 depicts the 1956 Schoellkopf Power Station failure (Niagara Falls). This rockslide was caused by unlined power tunnels, which allowed for pressurization of rock joints in the steep rock mass behind the powerhouse. The powerhouse was destroyed and one powerhouse worker was killed. This is an example of a failure mode that can plague power tunnels near their downstream ends.

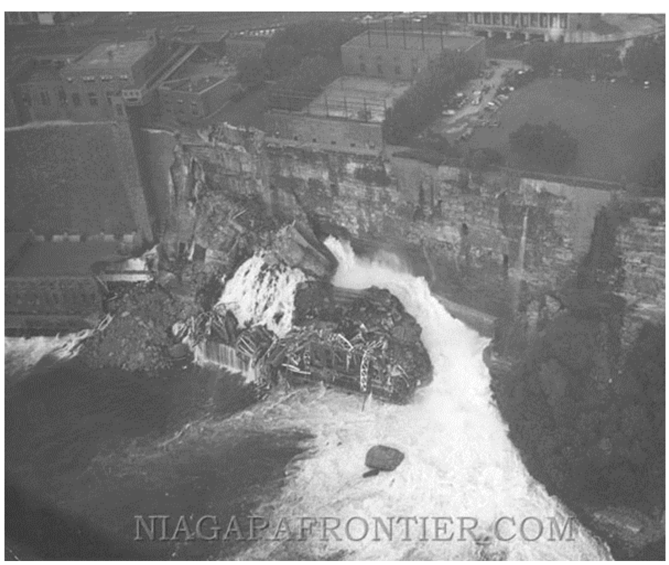

Fig. 18. Schoellkopf Power Station failure.

Figure 19 depicts the failure mechanism which was suspected in the Schoellkopf Power Station failure. If pressurized water from a tunnel can access open rock joints, an otherwise stable rock mass can become highly unstable. This is much more likely to happen if the tunnel is unlined.

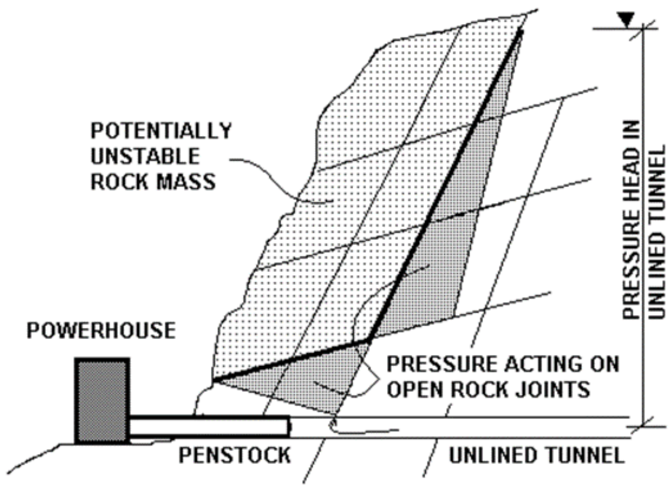

Fig. 19. Diagram of rock wedge at Schoellkopf.

Defensive Measures

The Schoellkopf Power Station failure occurred suddenly with almost no warning signs after 50 years of satisfactory performance. This suggests that monitoring techniques like piezometers, crack meters and surveys would not be very helpful. If the bluff geometry and joint pattern suggest a potential for instability and joint pressurization can occur, intercepting rock joints with drain holes around the circumference of the tunnel may be a prudent measure.

Note: Piezometers and crack meters are only beneficial if they happen to be in the right location. If the failure mode is not suspected, the instrumentation will in all probability not be in the right location to detect significant changes.

Failure Due to Vacuum or Low Internal Pressure

As with penstocks, if the internal pressure is significantly lower than external pressure, rock blocks can be dislodged into an unlined tunnel or buckle the tunnel liners. Often the surrounding hydrostatic pressure in rock joints or pervious soil can be quite high. Low interior pressure could be the result of a sudden closure of an upstream inlet gate or plugging of the inlet while operating, and the failure of the air venting system. Also, if the tunnel is dewatered too quickly the hydrostatic pressures surrounding the tunnel can result in failure of the tunnel walls.

Defensive Measures

It should be verified that proper upstream air venting exists and that it is inspected and maintained by project personnel. Also, if dewatering is planned, it should be done slowly under controlled conditions.

Failure Due to Rock Wedge Instability Produced by Seismic Load

If the tunnel has to function after an earthquake this issue should be considered.

12-2.4.3 Recommended Surveillance

12-2.4.3.1 Inspection

Dewatering of tunnels is not often done and can do more harm than good. Tunnel inspection should focus on the ability to shut off flow in an emergency. If the interior of a tunnel has to be inspected, a remotely operated vehicle should be considered.

12-2.4.3.2 Instrumentation

Tunnels can be instrumented with pressure and flow meters.