MATERIAL SELECTION FOR PENSTOCKS

by J.L. Gordon and D.G. Murray

When designing a penstock to carry water from an intake to a powerhouse, engineers must choose from a multiplicity of materials and material strengths. The most suitable material is selected to form the penstock to meet the unique site characteristics. For high head penstocks, steel is the only material that should be used, but the required steel strength must be determined. At lower heads, wire wound wood stave, banded wood stave, fiberglass, plastic, concrete and mild steel can all be used. This article discusses how to economically select penstock material and addresses the advantages and disadvantages of using various materials.

Transporting water from an intake to a powerhouse appears to be a simple task. After all, water pipes are common items, and thousands of miles of pipe in the U.S. and Canada supply potable water, or feed hydropower plants. However, determining the most economical arrangement for a penstock is not such a simple task. It is our opinion that consultants do not always make the final selection; very often it is made by the contractor bidding on the job.

For example, suppose a consultant designs a penstock 4 feet in diameter, 400 feet long, with the head varying from 30 feet at the intake to about 150 feet at the powerhouse. Mild steel could be specified with a yield strength in the range of 30,000 to 40,000 psi; the thickness would then be calculated and weld quality control would be based on the ASME boiler and pressure vessel code. Tenders would be called, and fabricators would bid on the work. However, the low bid could offer pipe supplied from a mill that can provide a few hundred feet of 48-inch spiral welded gas pipe built to American Petroleum Institute (API) specifications, by adding the required length to a production run for another order. This pipe would be entirely acceptable, provided it met minimum thickness and strength requirements. The consultant should write an end product performance specification, and let the contractor do the detailed design work, keeping in mind that hydraulic considerations will rarely influence material selection, since differences in friction factors are negligible and hydraulic transient differences will be insignificant when based on the same diameter and penstock length.

J.L. Gordon is a vice-president of the Hydraulic Resources Division, Monenco Consultants Limited. D.G. Murray is a senior supervising engineer in the Civil Engineering Department, Monenco Consultants Limited.

Large and High Head Penstocks

The foregoing example was simplified to illustrate a problem that becomes much more complex with larger and high head penstocks. The most common material for such penstocks is steel, although on occasion, steel-banded wood staves can be used where the head is not excessive. If high head steel penstocks are selected, the consultant must decide whether to use welded joints or mechanical couplings; use mild steel, intermediate strength steel, or high strength quenched and tempered steel; use a surface or buried penstock; or use a surface penstock with anchors and expansion joints or a design that eliminates expansion joints.

In this case, some of the decisions must be made by the consultant, but others should be left to the contractor. The following guidelines may help to determine whether the consultant or the contractor is responsible for certain decisions.

JOINTS. We prefer using welded joints wherever possible, because they are much less expensive than mechanical joints. However, an exception is for gently-sloping, soft terrain, where it is difficult to find suitable foundations for large concrete anchor blocks. The consultant should make this decision.

STEEL STRENGTH. Determining steel strength is one decision that should be left to the contractor. The consultant could easily design and detail the penstock, but he would have to select the steel plate, perhaps using several strengths of steel as the head increased. On the other hand, the contractor could decide to use higher strength (more expensive) steel to limit the thickness to what can be accommodated by his shop rollers, or use lower strength (less expensive) steel for economy. Therefore, the consultant should write a specification permitting the contractor to select the steel and undertake the detailed design.

SURFACE OR BURIED PENSTOCK. The consultant should decide whether to use a surface or a buried penstock. Factors influencing the decision include the nature of the ground, the ambient temperature and environmental requirements.

If the penstock can be buried with a minimum of rock excavation, this is usually the most economical solution. Expansion joints and concrete anchors can be eliminated, the sand-gravel backfill provides natural insulation and maintenance painting of the exterior surface is not required. (However, painting and wrapping to protect the exterior from corrosion must be done carefully, and close inspection is required during installation to ensure that the protective coating is not damaged.) Other major advantages are that the pipe can be buried and forgotten, and that the pipe can follow natural ground contours with a minimum of excavation. Steep mountainous terrain, near-surface rock and sidehills with deep stream gulleys are major factors affecting the cost of a buried penstock.

From an environmental standpoint, a major benefit of buried penstock is that the ground can be returned to its original state, so that the pipe does not form a barrier to the passage of wildlife.

The use of pipeline steel manufactured to API specifications should be considered, particularly for longer penstocks. However, it is not economical for steel mills to change roller spacing and plate benders for runs of less than about one-half mile of a given diameter and plate thickness.

Two types of penstocks can be built above ground: one uses expansion joints; the other does not.

The most common type, an expansion-jointed penstock, is built in straight or near straight lines, with concrete anchor blocks at bends and an expansion joint between each set of anchors. Between the anchors, the penstock should be supported with ring girders on rockers (see Figure 1).

The anchor blocks are designed to take thrust from the penstock, plus the friction forces caused by expansion and contraction. Where the anchor block is cast around a relatively straight section of penstock, at a bend of only a few degrees, steel thrust collars may be needed to transfer the penstock thrust forces into the concrete anchor.

The concrete anchor usually contains nominal surface reinforcement to distribute cracking, and no consideration is given to the transfer of internal bursting stresses to the concrete. To avoid spalling at the ends where the pipe emerges from the anchor, a strip of compressible material, about one-half inch thick by three inches long, is wrapped around the pipe to accommodate the local rim bending forces. Concrete is then poured against the compressible material.

Although it is not required, rock should be used for anchor foundations. The same stability and sliding criteria used for the dam are normally applied to the anchor, and earthquake-induced forces should be combined with normal waterhammer, since an earthquake will cause a controlled unit shut down triggered by the turbine shaft vibration detector.

However, in rare cases, the nature of the ground is such that anchors at some bends may require a large volume of concrete, which is very expensive. In such a situation, an alternative design can be used where every second anchor block is eliminated, along with all expansion joints. The alternate bends are left free to move, providing for expansion and contraction caused

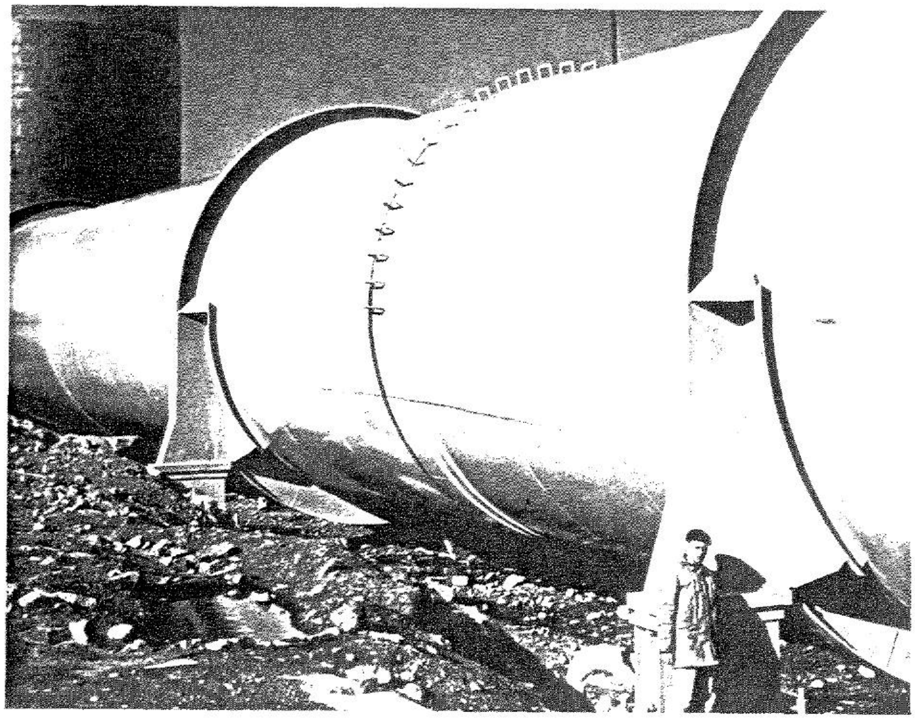

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FIGURE 1: Large ring girder on rocker supports mild steel penstock in Hart Jaune, Labrador. The penstock is 20 feet in diameter and 574 feet long. Note the expansion joint in the center with ladder rungs to facilitate inspection and maintenance.

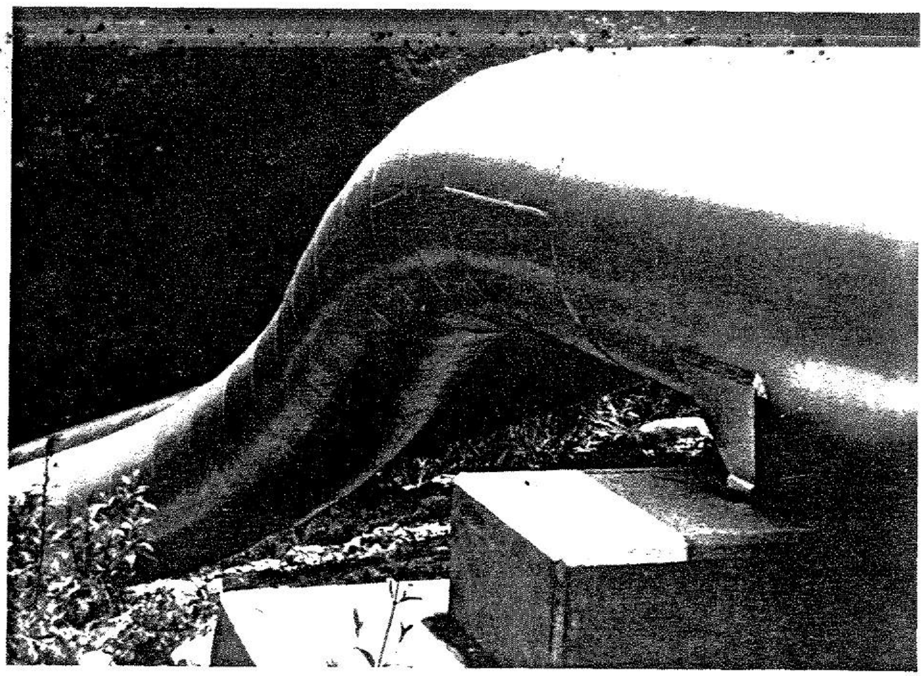

FIGURE 2: Free bend on the penstock in Santa Isabel, Bolivia. Note saddle support, which provides freedom of movement in two directions. At this bend, the 45-inch diameter penstock turns through a vertical angle of 20 degrees and a horizontal angle of 42 degrees. Design head for the penstock, including 25 percent waterhammer, is 3,570 feet.

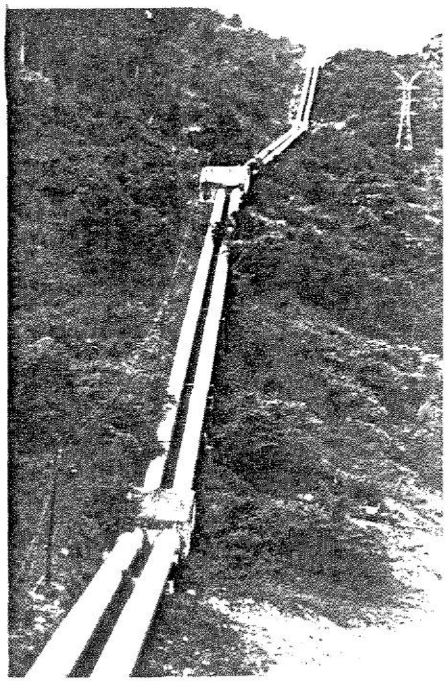

FIGURE 3: Small saddle supported and concrete anchored steel penstocks, Maskeliya Oya Stage II, Sri Lanka. The diameter is 5 feet; the length of the penstock is 5,904 feet. Note the access manholes and the expansion joints located immediately downstream of each anchor.

by temperature changes (see Figure 2). Between the free bend and the concrete anchor, the penstock is supported on saddles, and those near the bend are designed to provide freedom of movement in both lateral and longitudinal directions. In this case, the consultant should clearly outline the complex design method in the specification, but must leave the detailed design of the pipe to the contractor.

Small and Low Head Penstocks

For small and low head penstocks, mild steel is usually adequate, and a consultant should be able to detail all work. However, the choice of material may evolve from selecting steel quality, to deciding whether to use other materials such as fiberglass, plastic, wood or concrete. Therefore, the consultant should leave this decision to the contractor. The consultant should confine his work to writing an end product specification that covers all permissible materials.

For large and high head penstocks, one of the first decisions the consultant must make is the selection of a buried or surface design, since this affects the use of the various materials. The factors which affect this selection for small and low head penstocks are the same as for high head penstocks.

For a surface penstock, steel or wood staves could be used. If the penstock is buried, the choice of materials includes steel, wood staves (steel-banded or wire wound), fiberglass, plastic and concrete.

SURFACE STEEL. Surface steel represents the conventional choice in a concrete anchor-expansion-jointed configuration with simple saddle supports (see Figure 3). The saddle supports provide a contact arc of 120 degrees to 150 degrees with the pipe, and sometimes have a steel insert with a grease or graphite impregnated pad to reduce friction. On some of the more simple installations, the pipe is simply covered with a few layers of roofing felt impregnated with tar, against which the concrete saddle is cast, with the pipe on temporary supports in its final position. As well as being watertight, steel has long life and is maintenance-free, requiring only occasional painting. Disadvantages include extensive grade preparation to achieve straight runs between anchors, extensive concrete requirements for anchors and saddles, and insulation in cold regions.

SURFACE WOOD. Pressure-creosoted wood stave, steel-banded pipe is an alternative that can be used in diameters up to 18 feet and heads of up to 160 feet, increasing to a head of 400 feet.

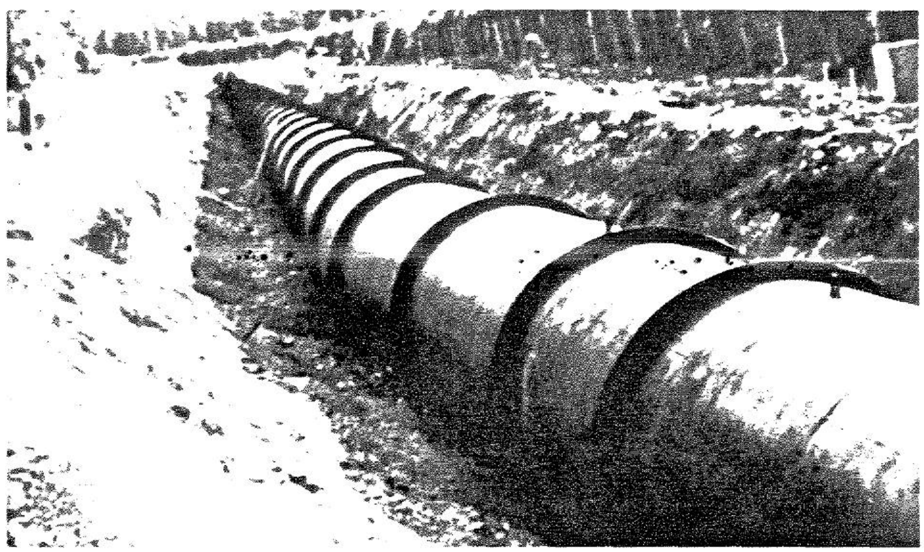

FIGURE 5: This 1,870 foot, 102-inch diameter buried steel penstock in Cascade, Alberta, replaced a surface wood stave penstock. Note the stiffeners and the second wood stave penstock on right. Penstocks provide water to a two unit powerplant. Adjacent wood penstock will be replaced with a buried steel penstock. Power development is in a national park, where buried penstocks are preferred.

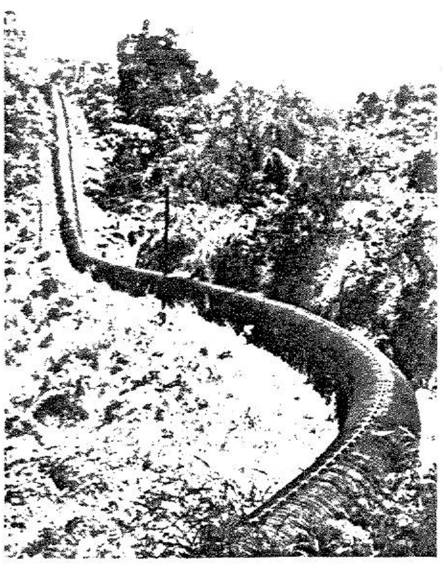

FIGURE 4: The woodstave pipeline in Maggotty, Jamaica, is shown at the location of the inverted syphon leading to the surge tank. The pipeline diameter is 66 inches and is 5,317 feet long. At the bottom of the syphon there is a 6-inch valve for dewatering, and the surge tank functions as an air vent during pipe filling. Note how the pipe follows the ground with a minimum of grade preparation.

with five feet in diameter. The advantages include the ability to follow ground contours, reducing grade cut-fill quantities (see Figure 4); flexibility to conform to ground settlement; no requirement of expansion joints; and no necessity for concrete and insulation. Simple erection is possible with unskilled labor, and it is easy to repair if subjected to accidental vacuum conditions, i.e., if the tongue and groove joint between the staves fails, a few staves pop inward, and the vacuum is alleviated. Disadvantages include leakage, particularly during filling operations; maintenance such as spray coating with tar every five years; undergrowth control, particularly in the damp areas below the pipe; and a relatively short life of 30 to 40 years. Another disadvantage is that a wood stave pipe must always have a valve at the downstream end to keep the pipe full of water to prevent dry-out during turbine maintenance.

BURIED STEEL. Buried steel is the conventional choice, because it is watertight, requires no maintenance and has long life (see Figure 5). Its major disadvantages are that it requires skilled welders and heavy equipment for erection. Exterior protection must be carefully applied to avoid corrosion.

BURIED WOOD. The main advantages of buried wood include that unskilled labor is used for erection; the only erection equipment needed are trucks to transport the material; and, in confined areas, the penstock grade can be used as the access road for erection. Disadvantages include leakage, which causes surface softness; the expense of repairing any large leaks; and the necessity for a downstream valve. For diameters below 2-½ feet, wire wound (machine-banded) pipe is an alternative, and is available in heads up to 400 feet (see Figure 6); however, plastic pipe for such small sizes is frequently used.

BURIED FIBERGLASS. Although fiberglass is becoming a more common pipe material, it still falls into the "exotic" category because of its rarity. It can only be used underground, because of its high coefficient of expansion and its degradation by ultraviolet light (see Figure 7). The main advantages are its light weight and the use of unskilled labor for erection. Disadvantages include that it is brittle; rocks and cobbles must not come in contact with the exterior coating; and the joint system should not rely on the use of epoxies or resins applied at the site.

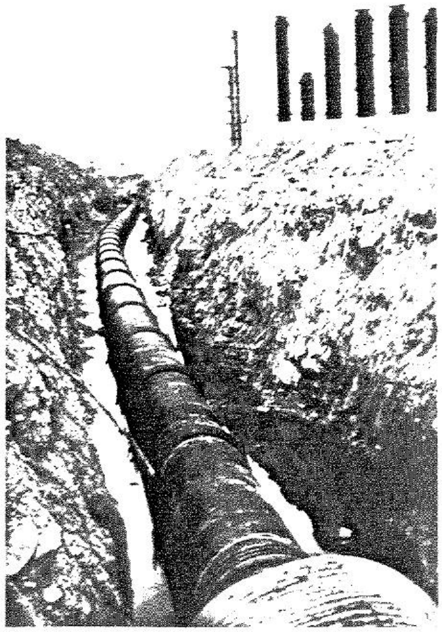

FIGURE 6: Shown is a wire wound wood stave pipeline located in MacAskill Brook, Nova Scotia. This 30-inch diameter, 9,500-foot long, 126-foot maximum design head pipe was placed in a trench and buried. The pipe was supplied in 8-foot lengths with collar connections.

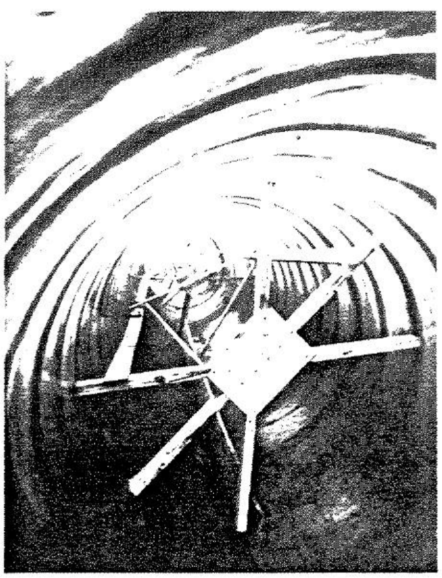

FIGURE 7: Interior view of fiberglass penstock, showing spiders for support during installation. Located in Morris, Newfoundland, the penstock is 66 inches in diameter, 805 feet long, and design head is 95 feet, plus 25 percent waterhammer.

BURIED PLASTIC. Pipe manufactured from petroleum compounds (polyethylene) is now available in diameters up to about 44 inches, and heads of up to about 140 feet, increasing to a head of 184 feet for smaller 32-inch inside diameter pipe. Therefore, plastic can be used on smaller projects (see Figure 8). These limits can be increased somewhat for special orders when the length of pipe exceeds 1,000 feet. Plastic is lightweight, watertight, has high flexibility and is easy to install.

Buried fiberglass and plastic pipelines are generally installed with a minimum cover of three feet over the crown of the pipeline, which provides added protection to the pipeline in case vehicles cross over it. In addition, for flexible pipelines, an excavated trench is required so that the springline of the pipeline is at or below ground level. This provides the required sidewall support that the flexible pipeline materials require to achieve their necessary strength characteristics. Flexible pipelines also require carefully graded backfill material free from large stones or rocks that could puncture the pipeline shell. The use of a gravel or other similar sandy material is generally recommended because of ease in placing and compacting around the pipeline haunches.

BURIED CONCRETE. It is possible to build a pre-fabricated and pre-stressed concrete penstock at the site, but this is likely to be expensive. A more conventional solution is to use standard concrete pipe. There are two types of concrete pipe: one uses high tensile wire to pre-stress the pipe; the other uses steel reinforcement (see Figure 9). Both types have an interior steel jacket to prevent leaks, and use rubber gasket bell and spigot joints. The concrete pipes are commonly used for water supply mains, and are available for heads up to about 200 feet in the smaller sizes, and for diameters up to about 12 feet. Due to the weight of such pipe, its use is confined to areas close to the manufacturing plant. Concrete pipe is robust and has long life. However, these advantages are counteracted by the disadvantages of heavy weight, high transport cost and site access requirements for heavy equipment.

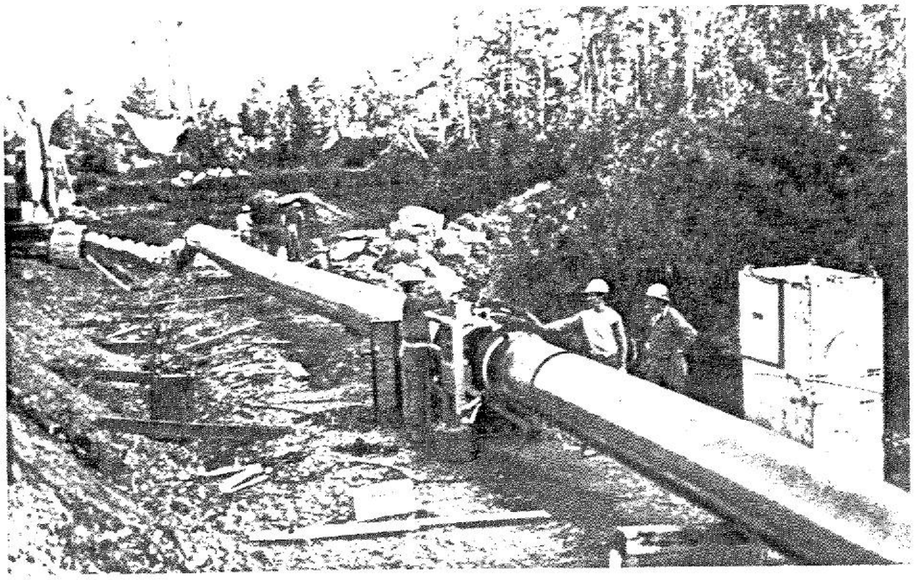

FIGURE 8: In New Richmond, Quebec, 28-inch internal diameter PVC pipeline was fuse-welded on-site. Five 50-foot long pipe sections were fuse-welded at the storage area before being towed into place along a prepared trench. Each 250-foot pipe section was then fuse-welded to the preceding pipeline section. Flexible pipeline was used at a stream crossing (top left of photo).

FIGURE 9: Buried concrete pipe located in Goat Creek, Alberta. This 2,200-foot long, 24-inch diameter pipe forms part of a pumping plant where local groundwater is pumped into the Spray power canal.

Hydraulics and Stress

It is evident that the consultant must produce a clear specification for the penstock design, and the most important criteria are the waterhammer conditions and the corresponding allowable stress in the penstock shell. The subject is complex, so references are provided at the end of this article for readers interested in penstock design. To summarize, however, there should be two values for the design of waterhammer conditions: normal and emergency.

Normal waterhammer occurs whenever the unit shuts down under governor control; this should be at least 25 percent over static water pressure (SWP), and not more than 50 percent over SWP. For high head penstocks connected to impulse (Pelton) units, normal waterhammer should be 25 percent over SWP, since the needle valves can be closed slowly while the fast acting deflectors limit speed rise. For reaction units, normal waterhammer will range between 25 and 50 percent over SWP depending on the governor time constants.

Emergency waterhammer, which one hopes never occurs, should be at least 100 percent over SWP. This condition can only be caused by a malfunction of the turbine controls, such as rapid closure of some wicket gates or needle valves, or, more commonly, by a harmonic vibration of a valve seal or governor control cable.

For each of these waterhammer conditions, a corresponding allowable stress should be specified for the penstock material.

For steel, this stress should be specified as a function of both the yield strength and the ultimate tensile strength. For normal waterhammer, the maximum combined steel stress should be the lower of 60 percent of yield or 38 percent of ultimate tensile strength. For emergency waterhammer, the maximum combined steel stress should be the lower of 96 percent of yield or 61 percent of ultimate tensile strength.

For plastic and fiberglass penstocks, there is a much larger margin of safety between the normal design pressure and rupture pressure. Therefore, a design based on the normal waterhammer pressure only is adequate, with the emergency waterhammer pressure allowed to encroach on the factor of safety; however, this approach should be checked with the pipe manufacturer.

If these criteria are followed, a balanced design should be attained, since there is a maximum 60 percent increase in design pressure (from 125 percent to 200 percent of SWP) from normal to emergency waterhammer condition, and a corresponding 60 percent increase in the allowable stresses (60 percent to 96 percent and 38 percent to 61 percent). Which of the two waterhammer conditions governs design depends on the penstock profile.

For negative waterhammer, the penstock grade should be selected so that the top of the pipe is at least one-half diameter below the lowest negative surge line, preferably 1.5 diameters below. When the pipe is only about one diameter below the negative surge line, it will start to "breathe" on every surge. This is caused by insufficient internal pressure to keep the pipe round, and the pipe will sag into an oval shape. If the pipe is supported on concrete saddles, and the "breathing" is almost continuous because of a low hydraulic gradient just above the top of the pipe, the metal will fatigue, and longitudinal fatigue cracks will appear above each saddle, eventually causing pipe failure.

If the pipe is fitted with discharge valves at the low points and air vent valves at the high points, it can follow the ground level up and down slopes, provided that it is always below the minimum hydraulic gradient.

Site Construction Work

A consultant is faced with several alternatives in site work. These include specifying supply of the pipe, with erection by the general contractor; supply of the pipe and a nominated subcontractor to the general contractor; or supply and erection by the general contractor.

It is important to avoid split responsibility for the finished product. For example, there can be endless arguments over who is responsible for repair of a joint leak — the supply contractor because of faulty manufacture; or the erection contractor because of improper installation.

For large penstocks, where the diameter exceeds rail transport limits of about 16 feet, the manufacturer should establish a site shop to weld plate into pipe cans of a length between 24 and 64 feet, which are then transported to the penstock grade. For smaller diameters, the manufacturer has the choice of either shop fabrication into cans (perhaps nesting these for shipment) or, alternatively, bending plate in his shop for shipment to a site welding facility. Site space, power and accommodation will be needed.

Based on our experience, separate supply and erection contractors should be avoided. There are too many problems with divided responsibility, coordination of manufacture and erection, and repair of defects before acceptance.

For large penstocks, the preferred method is for the manufacturer to erect the pipe as a nominated sub-contractor to the general contractor. The general contractor usually charges a small fee for this arrangement to cover the cost of providing working space and coordinating his grade preparation, concrete work and backfill operation with the penstock contractor.

For smaller penstocks, the preferred method is to have the general contractor select the pipe manufacturer, perhaps from a list of approved subcontractors provided by the consultant. However, on a small project, breaking the work down into smaller packages can limit contractor interest, which can lead in turn to higher costs.

Pressure Testing

Always pressure test! The only question is — at what pressure? It is extremely expensive and also impractical to pressure test for waterhammer pressures because the pipe has to be sectioned, test heads added, temporary anchors installed, high pressure pumps connected and a water supply provided. Instead, the pipe should be tested at static water pressure after completion of erection. For a surface penstock, leaks (mainly at expansion joints) will be evident immediately. For a buried penstock, leaks at mechanical joints may occur; therefore, joint areas should be left open, free from backfill, until the pressure test is completed.

Conclusion

The consultant should refrain from detailed design of a penstock and should only provide the route, pipe diameter, and configuration (buried or surface). He should write an end-product specification that allows the bidders to select material and perform the detailed design and, thus, avoid divided responsibility for the finished product.

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Mr. Gordon graduated from Aberdeen University in 1952 with a degree in civil engineering. He has worked on all phases of hydropower project design, from reconnaissance through feasibility reports to detailed design. He has authored or co-authored more than 40 technical papers, and is a registered engineer in Quebec and Alberta. Mr. Gordon can be reached at P.O. Box 6088, Station A, Montreal, Canada, H3C 3Z8, (514) 286-3653.

Mr. Murray graduated from the University of Saskatchewan in 1970 with a degree in civil engineering. Since receiving his master's degree in 1973, he has worked on the hydraulics of water supply, irrigation and hydropower projects. He has authored or co-authored more than 10 technical papers, and is a registered engineer in Quebec and Newfoundland. Mr. Murray can be reached at P.O. Box 6088, Station A, Montreal, Canada H3C 3Z8. (514) 286-3789.