Pipeline

Hydro-Electric Penstock Design

by Jerry Ostermeier

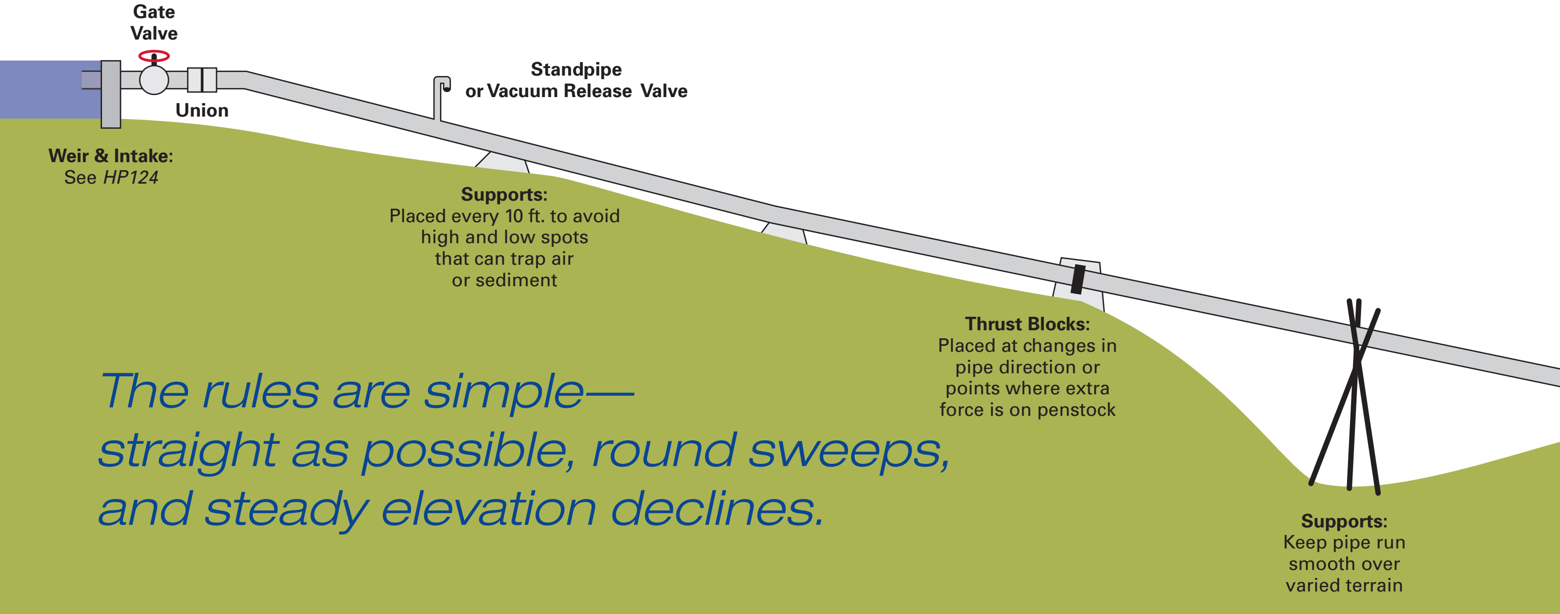
If you want to extract every last bit of energy from your microhydro system, three main components are critical to optimal performance—intakes, penstocks, and turbine selection. Intake options were covered in *HP124*, along with various methods of diverting water from the source. Here, we'll talk about best practices for penstocks, which channel the water from the intake to the microhydro turbine, building up pressure along the way.

In many ways, the penstock (pipeline) is the most important part of your hydro-electric installation. It's the "engine" in your system. Trying to cut corners on this design element can cost you in performance. And poorly installed penstocks can give you trouble, instead of what you're really after—maximum *energy* generation.

Intake and top section of penstock with standpipe vent.

Pipe Types & Pressure Ratings

Almost any type of pipe will work as a penstock, at least to some degree. The most common types are white polyvinyl chloride (PVC) and "poly pipe" (black polyethylene, PE; or high-density polyethylene, HDPE), which come in several pressure ratings. Common drainpipe is thin-walled and not rated for pressure. Though it can accommodate up to about 30 feet of head if you are careful opening and closing valves, drainpipe is not normally a recommended choice.



The rules are simple—straight as possible, round sweeps, and steady elevation declines.

In selecting pipe with the correct pressure rating, be sure to allow an extra 40% above the static water pressure in the pipe. For example, with 200 feet of head, the static pressure is about 87 pounds per square inch (psi). Multiply that by 1.4 (140%) to reach the needed pipe pressure rating of 122 psi. To compute the static pressure for the proposed penstock (in psi), divide the total head (in feet) by 2.3.

To save on penstock costs, a system can use pipes of increasingly higher pressure ratings as it gets closer to the bottom of the run, where pressure is highest. In that case, calculate the pipe pressure ratings for different total heads as you move down the pipeline.

Some hydro installers will disagree, but my strong preference for penstocks is to use PVC pipe in 20-foot lengths with a bell end for gluing lengths together. Splices used for other pipe types are not reliable at high pressure or for unrestrained pipe movement. Thin-wall poly pipe comes in a long roll and can be easy to use, especially if your penstock has to weave through trees and over rocks to the turbine, and if you can complete the entire run without splices. Thick-wall poly pipe requires special butt-welding equipment. The welds will leave a bead on the inside of the pipe that will affect flow. In our area, the critters tend to like chewing on poly pipe, but in other parts of the country, they seem to have a taste for the white PVC.

Aluminum pipe can be easy to get in agricultural areas but generally should only be used for pressures up to about 125 psi. It should not be buried unless treated to deal with the acidity in soils. Steel will handle very high pressure but should also not be buried, since it will rust out over time. Common PE poly pipe and HDPE have pressure ratings around 80 psi. They are available at even higher pressure ratings but can be hard to get in larger sizes.

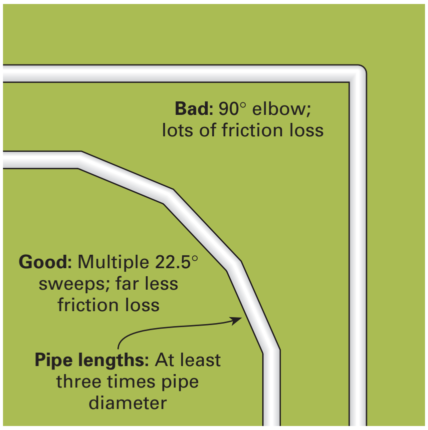
Dealing with Losses

Aluminum, steel, and poly pipe have comparatively high friction loss (resistance to flow), so it is important to factor this loss into sizing—which can play a part in system cost. As with different types of electrical wire, every pipe type has different resistance to flow based on the roughness of the walls. Also like wire, the diameter of the pipe determines the resistance to flow and how much flow the penstock can handle. In very high-head situations, steel pipe might be the only pipe capable of handling the high pressures.

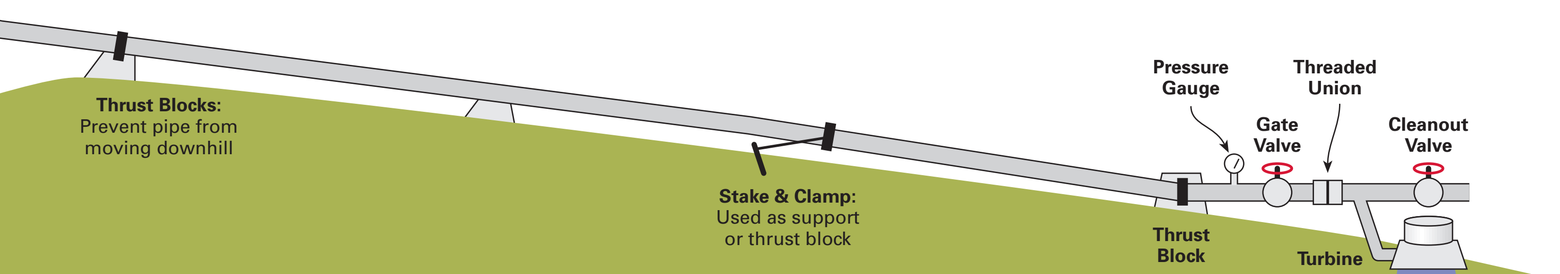
Pipe friction-loss tables for each pipe material will tell you how much flow a particular pipe size can handle. Then, by comparing prices, you can determine if changing pipe diameter or material type is worthwhile. Steel and aluminum pipes generally have double or more the resistance of PVC, and the larger sizes tend to make it prohibitively expensive for use in small systems.

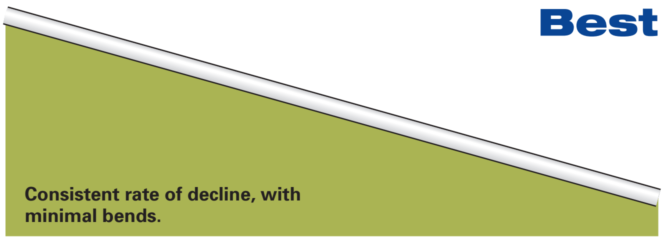
Friction-loss tables are commonly used for hydro penstock sizing (visit www.homepower.com/penstocktables), but precise friction-loss calculations can become complicated because they deal with velocity, pressure rise, critical time, and pressure wave velocity—frankly, it can become a physics exercise. But more simplified pipe sizing "rules" can address all the factors adequately. The following rules are for typical PVC schedule-40 pipe with runs of 300 to 1,200 feet. Short,

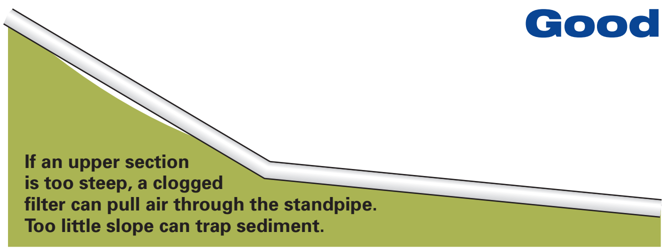
Round the Bend

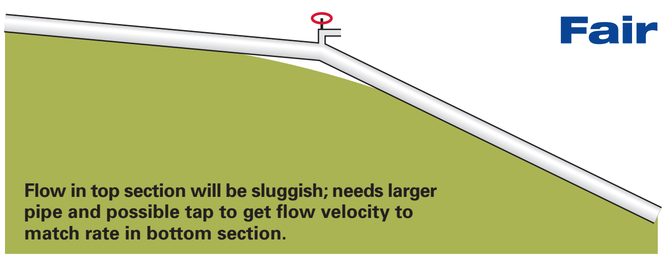


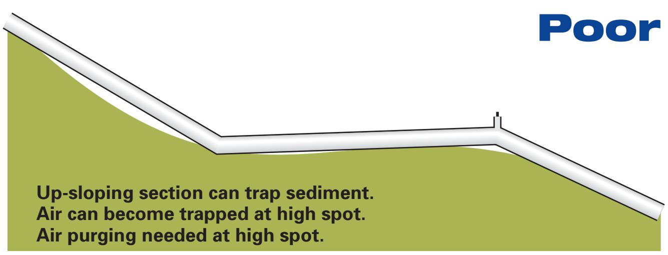
Choose your pipe type based on head, flow, run length, and your budget.











straight pipe runs can exceed these max flow rates a little—longer pipe runs need to be reduced.

- Up to 7 gpm can use 1-in. pipe (300 ft. of static head or higher)
- Up to 15 gpm can use 1.25-in. pipe (250 ft. of static head or higher)
- Up to 25 gpm can use 1.5-in. pipe (200 ft. of static head or higher)
- Up to 45 gpm can use 2-in. pipe (any head)
- Up to 75 gpm can use 2.5-in. pipe (any head)
- Up to 110 gpm can use 3-in. pipe (any head)
- Up to 190 gpm can use 4-in. pipe (any head)
- Up to 300 gpm can use 5-in. pipe (any head)
- Up to 430 gpm can use 6-in. pipe (any head)

The "rules" list is based on rounded estimates. If you are pushing the envelope within a pipe size, it is usually better to go bigger. This strategy will almost always improve system performance. The same holds true for long pipe runs. Bigger pipe will make more power available to your hydro plant at the bottom end of the penstock.

Web Link: For more information on determining pipe and fitting friction loss, go to www.homepower.com/penstocktables

Penstock Protection

Poly pipe is well known for being chewed on by rats, raccoons, and bear, to name just a few—but PVC has been attacked too. On the other hand, poly pipe can sometimes be better than harder-shelled pipe types because it is relatively freeze-tolerant and can be a little tougher for laying over treacherous terrain. Buried pipe offers more protection from toothsome critters, freezing, and falling trees, and more stability to handle pipeline movement.

If you are burying the penstock, the recommended trench depth is 2 feet for pipe up to 4 inches in diameter. Bury larger pipe at least 2.5 to 3 feet deep. Also be sure to check average frost depth in your area. Although moving water generally won't freeze in most climates, snafus—such as blocked nozzles in the turbine—can stop the flow of water and lead to freezing during a cold snap.

The trench bed should be free of sharp rocks that can damage the pipe. A layer of sand or pea gravel under the pipe works great. The trench should not curve beyond the

Supporting the penstock with brackets and cables helps keep the run smooth and prevents pipe movement.

Valves & Vents: Microhydro Relief

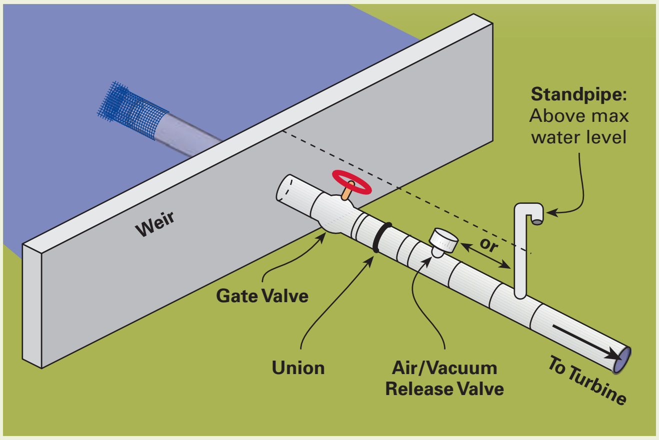
Placing a valve between the intake's pipe and the main penstock can be quite handy when you need to shut down a hydro system for maintenance or freezing weather. Any type of valve, other than a plastic slide-gate, will work. I usually place a union close-coupled just below the gate valve, so I can clear pebbles or other debris that might accumulate in the cavity at the bottom of the valve and prevent the valve from closing completely.

Sometimes, instead of adding a valve, the connector between the penstock and the intake pipe, such as a rubber compression union, can be removed to keep water out of a penstock. This is not only a hassle and slower than a valve but also problematic if the pipeline has to be shut down in a hurry. Some systems may use a rubber hose to connect the two pipes. In this case, it is important to make sure that the hose is suction-rated and has wire coil molded into the rubber to prevent collapse. A screw-apart union or a compression splice can also work to keep water out of the penstock.

At the turbine, consider using a gate valve for the main shutoff—especially for high-head systems. Compared to a ball valve, they operate slower, reducing the risk of water hammer—an effect caused by stopping a flow of water too quickly. There's a lot of kinetic energy in water flowing down a pipe, and gradually slowing the flow to a stop will avoid the high pressures that can break or weaken a pipe and its joints. A ball or vane valve can be a better choice on lower-head applications because they create less turbulence at their typically higher-flow rates. Regardless of your system type, this rule is paramount: Be careful to shut the main valve at the turbine slowly to avoid water hammer.

Venting also should be included in any design, especially in a system that has an upper shutoff valve, because there is a chance that the intake screen could become blocked enough to collapse the penstock. The down-pipe movement of water can create tremendous suction in the pipe if its flow is stopped from above. At 200 feet of head, a pipe has greater risk of collapsing from suction than breaking from water hammer when a turbine shutoff valve is suddenly closed.

A manual valve works as an air–vacuum release.



Top-of-penstock components.

The diagram above shows an automatic air-vacuum-operated release valve. If a vacuum occurs, the valve lets the penstock drain without damage. Penstocks 4 inches and smaller should use a 1/2-inch or larger valve. Larger pipe should have a valve sized no less than one-sixteenth the diameter of the penstock.

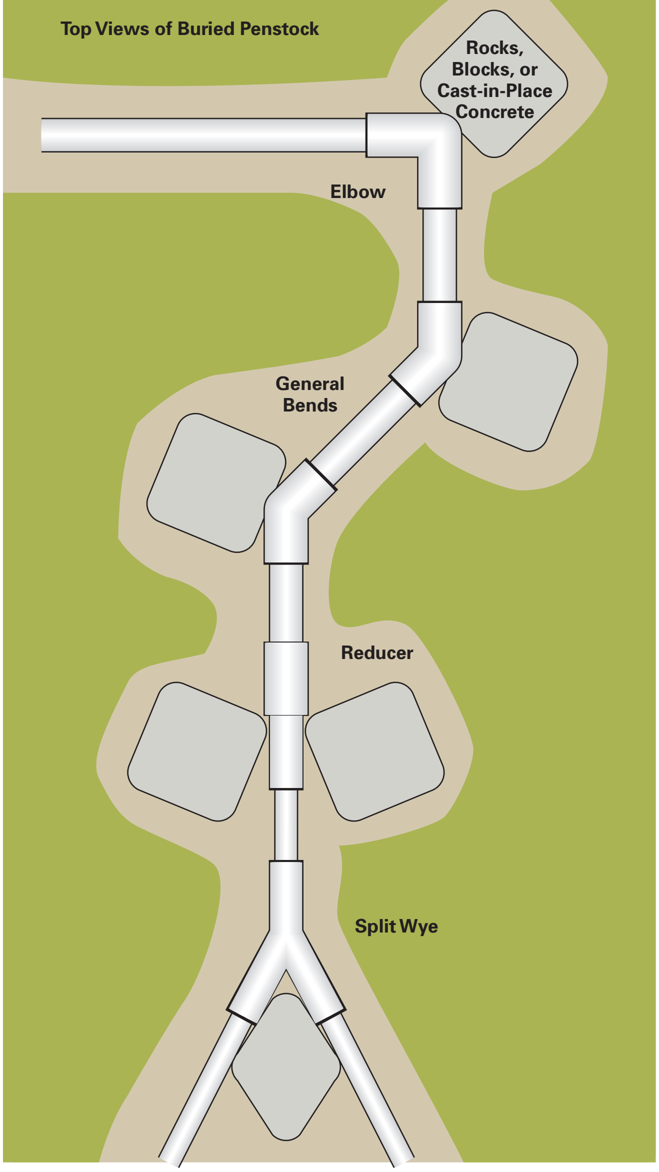
Another method for suction relief uses a standpipe, which must be placed below the valve to the penstock and extend above the maximum level of the water source at the diversion. This keeps the penstock open to the atmosphere above the water level. Be sure to place the standpipe far enough down the penstock so that the system will have enough suction to draw through the intake instead of sucking air down the standpipe.

A standpipe can also help purge from the penstock any air bubbles mixed in with the water that result from turbulence in the intake area. Spring-loaded and manual vents are also available. Avoid the floating ball type because they tend to open when they shouldn't, sucking air at higher-flow rates or in the event of partially obstructed intake filters. Air trapped at any high points in the pipeline can slow or stop water, decreasing or even stopping turbine output. At low heads (32 feet or less), this is not usually a problem, but air in the penstock can also lead to premature bearing failure in the turbine, or even damage the runner, when an on–off repeated pulse set up by water–airspace repetitions acts like little hammer blows hitting the runner. The higher the head and the bigger the airspace, the greater the blow to the turbine.

Another air-removal method is to use permanently installed manual valves to bleed the air from the high spots when the penstock is full but not flowing. Some hydro system owners will simply thread a screw into the penstock at the high points, and occasionally back the screw out to bleed any accumulated air.

The bottom of the system should always include a drain valve for draining all piping or bypassing the hydro plant. In cold climates, the unburied end of the penstock, valves, and hydro manifold are susceptible to freeze damage if the flow is stopped, so it is critical to keep the drains or bypass open if freezing weather is imminent. This applies to all nozzles on the hydro—not just the ones that are currently "on." Re-jet the nozzles if necessary to be able to open them all. If you can't, it is better to shut the whole thing down and drain everything. Not paying attention to this can cost you several hundred dollars in freeze damage.

Thrust Blocking



A penstock, heavy with water, should be anchored at the turbine to keep from moving downhill. How much anchoring is necessary is calculated in the same manner as any other thrust blocking. In areas with very steep terrain, there may be no way to apply thrust blocking in the normal manner. Instead, the pipe can be anchored with wire rope by attaching one end to the hillside's rocks or trees and the other end to the pipe, and then, using turnbuckles for adjustment.

Lower Penstock & Hydro Connection

Connecting the turbine to the penstock usually involves correcting the angle of the downhill pipe run to match the turbine's angle, which is usually zero. You can change the angle with a king nipple (similar to a hose barb) and a short, high-pressure piece of rubber hose, or you can use two 22.5-degree elbows that can make any correction up to 45 degrees. Correction may be unnecessary for hydro turbines that have a gang manifold at the end of the penstock or use valves and hoses to feed the individual nozzles. Some manifolds are hard-plumbed, and will likely need an angle correction where they meet the penstock. A cleanout valve at the end of the manifold may also be helpful for draining or flushing leaves and trapped sediment.

The most visually impressive installations have the pipe exiting the ground at a 22.5-degree or 45-degree angle inside a shed or protected area that houses the hydro turbine. If you keep your turbine out of the weather, it will last longer and need less service, especially the wound-field models.

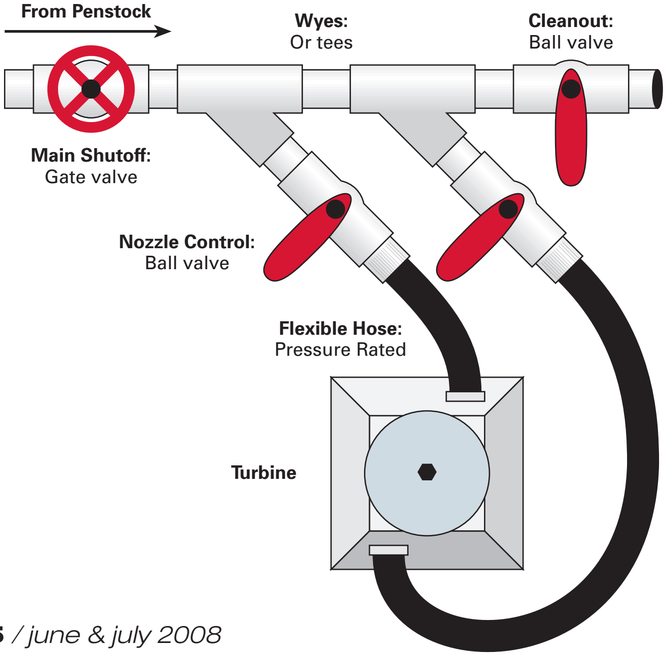
Hydro Mounting & Tail Race

Since most turbines are meant to discharge water out the bottom, it's important to design your system so the "waste" water can move away freely. In constructing a turbine mount, be sure that the cutout is not smaller than the turbine's tail-water opening. A cutout that is too small will deflect water back into the runner and reduce the system's performance.

recommendations for the particular pipe being laid in it, or else the pipe could break or distort to the point of flow restriction.

Water weight and normal vibrations from water moving through the pipe can cause the pipes to move. Where a change in flow direction occurs, like at an elbow, powerful forces can break or separate connections. "Thrust blocking" at the bends in the system prevents that pipe movement. Blocking is usually unnecessary for 3-inch or smaller pipe that is buried in most soils. The illustration above shows recommended thrust blocks for different bends commonly found in penstocks. For pipes up to 5 inches, it is prudent to dig a little deeper at the critical points, build a makeshift form, and pour concrete over the entire corner. Though the concrete does a good job at keeping the pipe in place, it also can make pipe replacement or repairs difficult later on. For larger pipe and high-flow situations, the size of the thrust block must be calculated precisely. (see "Calculating Thrust-Block Size" sidebar).

At the Turbine



Calculating Thrust-Block Size

Preventing pipe thrust from harming a penstock is critical to a successful hydro installation. Here is a sample thrust-block design calculation for a 45-degree bend in the penstock. This case assumes that a 4-inch pipe under 87 psi of pressure is buried in medium, clay-type soil.

Determine pipeline thrust. From the "Pipe Fitting Thrust" table, the factor is 12.4 lbs./psi for a 4-inch pipe and a 45° elbow.

Calculate the total thrust at the fitting. 12.4 lbs./psi x 87 psi working pressure = 1,078.8 lbs. of thrust

Determine soil load strength. From the "Soil Load Strength" table, the soil load strength is 2,000 lbs. per sq. ft.

Calculate the size of the thrust block. 1,078.8 lbs. ÷ 2,000 lbs. per sq. ft. = 0.54 sq. ft. of thrust-block surface area

The computation means that 0.54 square feet of blocking is necessary to hold the bend against the medium clay-type soil. Concrete is usually poured over the pipe fitting, filling the area against the undisturbed trench sides for thrust blocking.

For unburied pipe or pipe in soft soils with little resistance to movement, thrust blocking needs to rely on mass instead of the area resting against trench wall. Here is an example calculation of thrust block weight for a 6-inch pipe at 139 psi with 8 degrees of deflection:

Determine the thrust factor. From the "Side Thrust" table, 6-inch pipe has 61 lbs. of thrust per 100 psi per degree of deflection.

Calculate the amount of thrust. 0.61 lbs./psi x 8° x 139 psi = 678 lbs.

This means that there needs to be 678 pounds of mass (usually poured concrete) to keep this penstock from moving at the bend.

A chunk of concrete, cast in place, acts as a thrust block for a small change in direction of this penstock.

Pipe Fitting Thrust

Pipe Size (In.)	Thrust (Lbs./psi) Tee	90° Elbow	45° Elbow	22.5° Elbow
1.5	2.94	4.16	2.25	1.15
2.0	4.56	6.45	3.50	1.80
2.5	6.65	9.40	5.10	2.60
3.0	9.80	13.90	7.50	3.80
4.0	16.20	23.00	12.40	6.30
5.0	24.70	35.00	19.00	9.70
6.0	35.00	49.00	27.00	14.00
8.0	59.00	84.00	45.00	23.00
10.0	92.00	130.00	70.00	36.00
12.0	129.00	182.00	99.00	50.00

Soil Load Strength

Soil Type	Safe Bearing Load (Lbs./Sq. Ft.)
Shale	10,000
Cemented sand & gravel; hard to pick	4,000
Good mix compact soil	3,000
Clay—medium	2,000
Clay—soft	1,000

Side Thrust

Pipe Size (In.)	Thrust Factor*
1.5	5
2.0	8
2.5	12
3.0	17
4.0	28
5.0	43
6.0	61
8.0	103
10.0	160
12.0	225

*Lbs. per 100 psi per degree deflection

Although the most common mount is a simple, 2- by 4-foot plywood, structure, built close to the water source, the most durable mounting platforms are sturdy plates on permanent concrete structures with the tail or waste water exiting the bottom or side, either into a wide opening or a drain pipe. The drainpipe needs to be at least twice the diameter of the supply pipe, with a reasonably steep downward slope. An air vent in the tailbox will help prevent the tail water from sucking on the water running through the hydro, creating a power loss on an impulse turbine. The vent also removes pressure so that water won't find its way into the front bearing, which can lead to a bearing failure in some hydro turbines.

Another popular hydro mounting method uses a modified 55-gallon metal drum, with the turbine fastened to the drum top with bolts. The bottom third of the drum is secured into the creek bank with concrete or by loading the drum with rocks. The middle third has a hole drilled out, which allows water discharge. These drums will usually last about 10 to 15 years before they rust out.

Alternatively, an up-ended culvert pipe that is 24 inches or larger can be used, though fabricating a top will be more difficult. My preferred top is a high-density polyethylene sheet at least 1/2-inch thick. This special-order item is more expensive, yet longer lasting, than plywood.

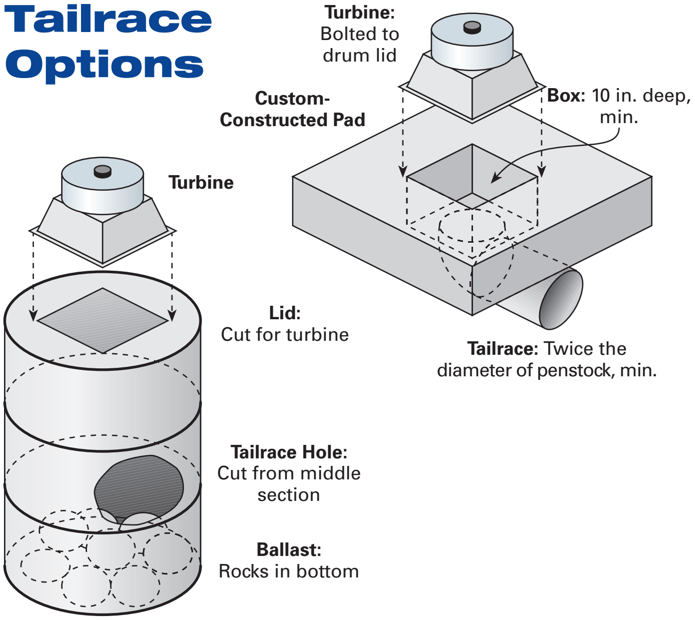
Mounts can have more elaborate masonry spillways or even drains that feed to a decorative water feature in the yard. Other times, the tail water can be used for a secondary purpose, such as filling a pond or irrigating a garden. Let your imagination be your guide, but remember that once you have extracted the energy for making electricity, the water will not be pressurized for other uses and gravity needs to take the water away freely.

The final consideration for hydro mounting is protection for electrical portions of the control panel. Though rain needs to be kept out, the unit should not be so well sealed that condensation becomes a problem. A roofed, three-walled structure for the turbine works great. One side is left open for easy access to the hydro plant. Although most permanent-magnet turbines are built for outdoor operation, they will last longer if protected from the elements. In terms of human resilience—an all-important factor to enable turbine maintenance—having a shelter makes repairs, flushing the penstock, and cleaning the turbine jets much more tolerable.

The components at the bottom: Thrust block, coupler, pressure gauge, cleanout valve, nozzle valves, turbine, and tailrace.

Courtesy www.microhydropower.com

Tailrace Options



Best Penstock Practices

For penstocks, the rules are simple—straight-as-possible, round sweeps, and steady elevation declines. Unfortunately, that's usually easier said than done. Often times, site constraints make it necessary to break or bend the rules. You should do what you have to do, but know that your system will be more vulnerable to performance and maintenance issues. Any low spots in the pipeline, for example, could become sediment traps that will occasionally need to be blown out by opening the pipe at the bottom and letting it run full volume. High spots in the penstock will create air pockets that will need to be bled. Finally, any bend in the pipeline will mean greater resistance to flow and reduce the energy available.

Include a pressure gauge in the pipe on the uphill side of the lower shutoff valve to help diagnose problems. A higher-than-normal reading usually indicates a plugged jet. A lower-than-normal reading can mean that the pipe or filter screen is plugged, or that there is not enough water available to the penstock. A pulsating gauge indicates turbulence, usually caused by running a higher flow rate than the penstock is designed for, which can result from installation errors, such as too many bends or an uphill run somewhere.

Select the right pipe, anchor it well, and keep it straight and simple. Follow these rules, and the penstock "engine" will serve you and your turbine well—and get the most energy out of your hydro system. And be sure to check out the next installment, where we'll take a look at the electrical and wiring aspects of your hydro system.

Access

Jerry Ostermeier (altpower@grantspass.com) owns Alternative Power & Machine in Grants Pass, Oregon (541-476-8916 • www.apmhydro.com). He has been designing and installing microhydro and off-grid power systems since 1979. He also manufactures a user-friendly residential-scale microhydro turbine.