WATERPOWER XII

SMALL HYDRO WORKSHOP

Salt Lake City, Utah USA, July 9, 2001

DISSERTATION ON SITE DEVELOPMENT AND COSTS

By

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1. Introduction.

Many entrepreneurs approach small hydro development as a license to print money. Fuel is free, and the market is assured, with little or no competition. Yes, with the right combination of circumstances, the plant can be very profitable, but in many cases, there are significant problems encountered during construction, and quite often the equipment does not perform as expected.

In this workshop, we will try to outline the pitfalls to be avoided, and provide some guidelines on approaches to the design and construction process. But first, two anecdotes to illustrate what can happen with different approaches to the design and construction process.

2. Case studies – good and bad, lessons learned.

Case 1. Disaster Rapids.

This site was developed by a partnership with no engineering experience. The site required the construction of a small concrete dam with stoplog and gated spillway, and a powerhouse with 2 horizontal axis "S" units, to produce about 18MW at about 10m. head. Bids were solicited for engineering, the water to wire equipment, and construction. In all cases the contracts were awarded to the low bidder.

What happened?

Design concept.

The layout developed included a long stoplog spillway, to be operated by a rented mobile crane, and one small spill gate equipped with a hydraulic hoist. The mobile crane was located far from the site and rarely available when needed, resulting in at least one incident where the spring flood overtopped the dam. Eventually hoists were added to several of the stoplog openings.

When the spill gate was operated, the adjacent portion of the dam vibrated severely due to a lack of rigidity. The dam was designed with an upstream 45-degree sloping face with thin 0.3m. buttresses. Mass concrete was added to improve rigidity.

In winter, ice immobilized the stoplogs, as expected. However, the northerly flowing river thawed early in the south, resulting in water overflowing the ice, and arriving at the dam with frozen logs in place. Heaters were added to some of the stoplog openings.

The powerhouse was built into the dam, with the upstream wall of the powerhouse forming the downstream face of the short intake. The horizontal axis "S" unit has anchors for the upstream guide and thrust bearing holding the shaft built into the upstream powerhouse wall. On filling the headpond, the wall deflected, causing the bearing to move out of alignment. An investigation indicated that the wall lacked rigidity, mainly due to a too short supporting pier between the units.

The unit was realigned with a full headpond, and the bearing continues to deflect by a small amount as the headpond level varies.

The headgate cannot close against flow, since it is a slide bulkhead operated by a mobile crane. The draft tube gate is designed to close against flow, but has not been tested.

Construction.

The cofferdam failed twice, flooding the powerhouse and destroying the access road bridge.

The contractor declared bankruptcy.

One of the generator rotors was dropped about 2m. onto the repair bay floor when the mobile crane operator had to release the load due to failure of the earth embankment under the crane.

The sump pump plugged with debris and the powerhouse flooded for a third time, with all electromechanical equipment in place. Commissioning was delayed to dry out the generators.

The powerhouse walls were so porous that 2 months were spent grouting the voids.

Commissioning was about a year late, and cost exceeded the budget.

Post mortem analysis. The design contract was awarded to the low bidder who had little or no experience in hydro work, and the same could be said for the contractor. The Owners adopted a “hands off” approach during construction, indicating to the two contractors and consultant that they should arrange their own meetings to resolve construction issues. The project was sold shortly after commissioning, and the new owners spent several millions of dollars upgrading the development.

Case 2. Sunshine River.

A retired power line contractor, who had worked for many years around small hydro plants, developed this site. The site was at an existing dam, requiring the addition of a short intake canal, intake, buried steel penstock to a powerhouse enclosing one horizontal axis “S” unit developing about 6MW at 8m. head. Bids were negotiated for the water to wire equipment. The detailed design was undertaken by an industrial engineer and a draftsman known to the Owner, with guidance provided by an engineer with extensive hydro experience. The Owner undertook project management from an office at the site. A contractor who had worked with the Owner in the past carried out the civil work.

What happened?

Design concept.

The layout had been developed by the Owner over many years, with due consideration of construction costs. For example, the site was peppered with drill holes to locate the rock surface, so that rock excavation was minimal. Powerhouse layout was entrusted to the water to wire contractor, with some input from the hydro engineer and the Owner, who added an office and washroom facilities.

The hydro engineer guided penstock and intake design. At the Owner’s request, the penstock was sized conservatively, to reduce hydraulic losses.

Construction.

Construction proceeded with no untoward incident. A geotechnical engineer was engaged to advise on excavation slope stability around the penstock. During construction there was close discussion of the issues with all parties. For example, when foundation rock at the powerhouse was found to be some 0.4m. lower than expected, the whole powerhouse was lowered, increasing submergence on the unit, and increasing turbine output marginally.

During commissioning, there were some anxious moments when losses across the trashracks were about 6 times higher than calculated – due to some filter fabric from the demolished cofferdam becoming lodged against the racks and impeding flow. The project was completed on time and well within budget.

Post mortem analysis. There was no formal bidding process for the work. Instead, the Owner negotiated all contracts in a fair manner. With the exception of the detailed design engineer, all parties had hydro experience. The Owner, who benefited from his previous experience as a contractor, closely managed the project and spent a considerable time at the site.

Lessons learned.

- ☐ Select only experienced engineers and contractors. If the design engineer does not have sufficient experience in small hydro work, engage an experienced senior hydro engineer to provide guidance.

- ☐ Keep the design team small, able to make decisions quickly.

- ☐ Undertake at least some site foundation investigations. A clear understanding of the foundation conditions will allow the contractor to reduce the bid price.

- ☐ Appoint one entity to be the project manager, either the Owner, if there is sufficient experience, or if not, the construction contractor.

- ☐ Have the design engineer work for and with the contractor, so that designs can be optimized for both function and cost.

- ☐ Include a contingency fund in the budget to cover any unforeseen expenses – and expect to use this fund.

3. Site selection considerations.

As hydro sites are developed, the availability of undeveloped sites is reduced. This is obvious, but unrecognized by many developers. Also, since the first sites to be developed are the most economic, the remaining sites become more expensive. A ballpark cost for a new site can be obtained from the following formula:

$$\text{Cost} = k \times (\text{kW} / h^{0.3})^{0.82} \qquad (1)$$

Where k = a factor obtained from the data for a similar adjacent site.
kW = installed capacity.
h = developed head in meters.
Cost = cost of the site, excluding access road and transmission.

Small hydro sites are relatively expensive, compared to larger sites. To overcome this disadvantage small hydro sites should possess some attractive features. If the power market is for a utility, the site should include an existing dam, and adjacent road and transmission line. The one exception to this is a small high head site where the dam is little more than a low weir across the stream. If the market is an isolated community or industrial plant where power currently is provided by diesel, then a much higher cost can be justified, and a site without a dam can be economic. Other desirable features are obvious, such as the higher the head, the more attractive the site. Also, the conduit length to head ratio is important. If this exceeds about 6 to 8, an expensive surge tank or relief valve on the turbine may be necessary.

4. Desirable dam spillway features.

Small hydro operators can rarely afford the luxury of a manned spillway. Hence the only cost effective and reliable type of control is a simple overflow weir. This leads to two alternative dam layouts:-

1. An embankment dam, with an adjacent low weir overflow spillway built into either a rock abutment, or an adjacent saddle. Use the rock excavated for the spillway in the dam.

2. A concrete or roller-compacted concrete dam with either automatic rubber dam crest control, or a simple overflow weir.

Compensation water could be provided by either a valve or pipe through the dam. An alternative is a coreless rock fill dam where seepage provides compensation flow.

5. Intake.

Keep the design as simple as possible, but include provisions for maintenance. Trachracks, slots for timber stoplogs, a gate capable of being lowered without power against flow, and an air vent, large enough to provide access to the pipe or penstock are all needed.

Downstream sealing gates are preferred. These are installed in their own gate well upstream of the air vent, and are not affected by an operating error resulting in an explosive ejection of a mixture of compressed air and water from the pipe. (See HRW Oct. 96, page 52) Upstream sealing gates are installed in a combined gate-air vent well, and could be ejected during an operating error.

Keep the air vent house well separated from the hoist house. The air house will be demolished during an explosive ejection of air/water, as has happened at several intakes.

There are two formulae, which can be used to simplify intake cost assessment.

Weight of steel racks = $68 \times A^{1.21}$ kg. ------------------------ -------------------------------- (2)

Intake concrete volume = $15 \times Q$ cubic meters. -- (3)

Where A = Rack area in square meters.
Q = Intake design flow in cubic meters per second.

It is important to have an intake gate capable of closure against full turbine runaway flow, with no power being available at the hoist. Except where there is a turbine valve, the gate provides the second line of defense on flow control, in case of governor failure. The usual type of gate installed under such circumstances, is a roller gate on a wire rope hoist, with drop closure controlled by a fan brake. Some developments omit the hoist and brake, with emergency closure initiated by cutting the rope, and operating the gate with a mobile crane hoist. However, experience with such installations has indicated that a hoist was eventually installed, since the cost of renting the crane was proving to be excessive.

6. Pipeline and surge tank.

Obviously, the shorter the pipeline and penstock the better. Most developments have a conduit length to developed head ratio of 3 to 6. Anything higher than about 7 may require a surge tank or relief valve attached to the turbine. A relief valve will add about 25% to the turbine cost. A surge tank is even more expensive. A ballpark cost of a surge tank can be obtained as follows:-

1. Locate the tank about three times the head upstream of the powerhouse. The ground at this location will be the level of the surge tank tee.

2. Assume the tank riser to be the same diameter as the upstream pipeline.
3. Assume that the tank will have a diameter three times the pipe diameter.
4. Assume that the top of the tank is 3 meters above flood level.
5. Assume that the bottom of the tank is 4 meters below low supply level.
6. Calculate the volume of the tank (V), excluding the riser.
7. Determine the distance between the mid-height of the tank, excluding the riser, to the tee junction between riser and pipe at ground level = H.

The weight of steel in the tank can then be obtained from the following formula. (HRW Sept. 98, page 26)

$$\text{Weight} = 4.02 \times V^{0.91} \times H^{1.06} \text{ kg.} \quad (4)$$

Where V = Tank volume, excluding riser, in cubic meters.
H = Tank height from mid-tank to tee, in meters.

8. Multiply the steel weight by about three times the cost of structural steel installed in a building.

The least expensive pipe is a buried design, which has the added benefit of natural insulation. Provide corrosion protection, and forget about maintenance. Some designers use anchor blocks at bends in a buried pipe. In most instances these are not required. Use a large radius bend, and the forces at the bend will be taken by the backfill. Where the pipe is on a steep grade, use low strength slurry concrete to support the pipe under the bottom quarter, where compaction of the backfill is difficult.

7. Powerhouse.

In many small hydro developments, there are minimal provisions for equipment maintenance. Some plants have been built without an access door to the equipment floor, and in others there is barely room to squeeze around the turbine-generator. This is a serious omission, and adds to the cost of maintenance. As with all electromechanical equipment, maintenance is a necessity, and becomes more onerous as the equipment ages. Minimal requirements would be:-

- The ability to back a pickup truck into the powerhouse and offload an oil drum.
- The provision of a small repair bay, with sufficient space to work on a component.
- A crane in the powerhouse with at least a motor hoist and manual travel.

It is recognized that a micro-hydro plant of less than 100kW capacity could omit the second and third requirements. However, as the size of the turbine-generator increases, provisions for maintenance need to be improved, since delays in completing maintenance will cause significant losses in revenue. Even a rubber tired small 3-ton hoist mounted on an I-beam significantly improves ease of maintenance.

Again, there are several formulae, which can be used to simplify the cost assessment.

$$\text{Powerhouse concrete volume} = 140 \times d^{2.4} \times (N + 0.5) \text{ cubic meters.} \quad (5)$$

$$\text{Powerhouse superstructure steel weight} = 2.6 \times (N + 0.5) \times C^{0.38} \times d^{1.14} \text{ tones} \quad (6)$$

$$\text{Turbine throat diameter} = d = 0.482 \times Q^{0.45} \text{ meters.} \quad (7)$$

$$\text{Generator rotor weight} = C = R \times (MVA)^{0.74} / n^{0.37} \text{ tones.} \quad (8)$$

Where C = Powerhouse crane capacity in metric tones.
d = Turbine throat diameter in meters.
MVA = Generator rating.
N = Number of units.

n = Generator speed, rpm.
Q = Turbine rated flow in cubic meters per second.
R = Generator rotor weight quality factor.
= 50 for utility grade generators.
= 40 for motors operated as generators.

One aspect often overlooked in a small powerhouse is ventilation during summer. A generator produces significant heat and this has to be vented. Where the ambient temperature is high, air ducts to and from the generator are a necessity.

8. Powerplant equipment.

The turbine-generator is the "heart" of the hydro facility. As such, it is not wise to economize on this equipment. There is a wide variation in the quality of generating equipment available today, and as with any electromechanical equipment, increasing quality is matched by increasing price, and efficiency. Manufacturers fall into two broad categories. There are about a half-dozen major manufacturers at the forefront of the technology, who maintain hydraulic laboratories and complex computational fluid dynamics (CFD) programs. These programs are continually updated as more experience is obtained with their new operating turbines, and with the latest hydraulic laboratory data. The second set of manufacturers are small, do not have access to laboratories, and their CFD programs are relatively simple with wide spaced nodes describing the water passages. The result is a difference of 1 to 3 percentage points in peak turbine efficiency.

The major manufacturers have entered the small turbine market with sophisticated designs and equipment which costs about 50% more than the same equipment from a small manufacturer. This is where a detailed analysis of the lifetime cost and revenue is needed. Very often the higher efficiency and reliability of equipment from a major manufacturer will justify the higher price.

9. Construction contracts.

Prior to about 1985, all hydro construction contracts were based on payment of unit prices for excavation and concrete etc. A consultant working for the Owner undertook design, site geotechnical investigations and construction supervision. This unit price (UP) form of payment allowed for variations in the quantities since the precise elevation of the foundation rock, and even the detailed design of the structures was not known at time of tendering. After 1985, the lump sum (LS) cost contract was introduced, with the design undertaken by a consultant working for a contractor. Site geotechnical investigations were limited and often neglected. Now all small hydro work is undertaken under such contracts. A LS contract transfers all the risk associated with site unknowns to the contractor, and the contractor who makes the most optimistic assessment of the unknowns ends up with the lowest price and is usually awarded the contract. This, of course, is a recipe for problems with the contract.

Based on Canadian anecdotal evidence, about half of LS small hydro contracts result in litigation at the end of the contract. The causes are various, such as:-

- Insufficient foundation investigation, resulting in a tunnel boring machine running out of rock.
- Sand lenses in an abutment, causing a washout of the dam on headpond filling.
- Construction of a buried steel penstock with no corrosion protection.
- The use of a pipe with insufficient wall thickness, which collapsed on backfilling.
- Powerhouse designed with a right-angled bend in the penstock, just upstream of the turbine.
- A powerhouse designed with insufficient rigidity.

On the other hand, litigation after completion of UP contracts was only about one in twenty. Nevertheless, there are several advantages to the use of a LS contract. By far, the major advantage is a large reduction in the up-front expenditures required prior to contract tender – foundation investigations and tender drawings/specifications are reduced to a bare minimum. In effect, about 75% of these costs are transferred to the bidding contractors and design-build contractor. Other advantages are:-

- The project cost is known with a higher degree of accuracy prior to start of construction.
- Site survey work to calculate quantities for payment of unit prices is eliminated.
- The consultant works closely with the contractor to optimize designs.

Against these advantages, there are some disadvantages, such as:-

- Design quality can be compromised – and this is a major concern.
- Resolution of claims based on insufficient site data is difficult.
- The generating equipment may not be optimized to the site.

To overcome these disadvantages, the site owner should:-

- Pre-qualify all consultants, construction contractors, and W/W equipment contractors.

- Call for bids and award a separate water to wire contract for the W/W equipment prior to calling for construction bids, and advising the construction bidders to include support to the equipment contractor during installation.

- Prepare a more detailed specification for the design and construction work, particularly for electrical instrumentation required to interface with the Owner's existing SCADA equipment.

- Accept some responsibility for changed foundation and subsurface conditions, and be prepared to negotiate reasonable claims.

- Tie progress payments to completion of easily identifiable events such as award of contract, establishment of site office, completion of powerplant excavation, diversion of river, and so forth.

The pre-qualification of bidders eliminates the difficulty of having to eliminate a low bidder, after the bidder has spent a considerable sum of money on bid preparation. Also, contractors are more interested in bidding if the tender is restricted to 3 or 4 pre-qualified contractors.

By calling for W/W equipment bids, the Owner will be able to analyze the benefits of variations in efficiency and price, an option not available if the W/W equipment forms part of the contractor's price.

Specifications for interfacing with SCADA equipment are extremely important. All manufacturers have proprietary SCADA programs, which do not interface with different Owner's SCADA. This will require the specification of manufacturer and even model number for all SCADA instrumentation.

If the construction cost increases above the contractor's allowance for unforeseen costs, due to changed foundation or subsurface conditions, a claim can be expected. If the claim is not resolved during construction, the contractor can be expected to start economizing on both design and construction to the detriment of quality, and start litigation to recover the extra cost.

The contractor requires a steady series of progress payments to defray construction costs. These payments, in a UP contract, would be based on the work quantities. With no measurement of quantities in a LS contract, another method of assessing progress and payment is needed. By selecting a series of events from the construction schedule, on completion of which, payment would be made, it is possible to set up a method of payment in the specifications, to approximately match the contractor's expenses. Some 10% of the progress payments would be retained for payment on commissioning. Allow contractors to modify the value of these progress payments in the bid, and expect to negotiate some modification to the payment schedule if it appears that the contractor is requesting too much up-front money. A large payment – say 15% - on contract award, could be supported by a bank guarantee from the bidder, and a percentage deducted from progress payments until payments are more in line with expenditures.

10. Engineering designs.

Consulting engineers can provide two classes of design work, one a documented design, and the other a non-documented design. All large hydro work for major utilities, and where funding is provided by international banks, is usually undertaken with a documented design. This includes:-

- A detailed feasibility study and extensive geotechnical site investigations.
- Design transmittal documents for all components and structures, describing how the part will be designed and to what standards.
- Detailed specifications for all equipment and construction procedures.
- Copies of all design calculations.
- Drawings for all structures, updated to "as built" on completion of construction.
- Analysis of all bids, with recommendations on contract award.
- An operating manual, containing copies of all manufacturer's drawings.
- A completion report.

The execution of such extensive work is time consuming and expensive. Statistics kept by the author have shown that the engineering man-hours required for the design office work, excluding any site work, can be estimated with the following formula:-

$$\text{Man-hours} = T \times (MW / h^{0.3})^{0.54} \text{ hours.} \quad (9)$$

Where T = 21,000 for a documented design.
T = 8,300 for a non-documented design.

In other words, a non-documented design can be undertaken for about 40% of the cost of a documented design. A non-documented design is undertaken in a LS contract, and only includes:-

- Brief specifications for the equipment not included in the W/W contract.
- Drawings of all structures, with minimal details.
- Unbound copies of manufacturer's drawings.

For many Owners of small hydro plants, this extent of work is entirely satisfactory. Such Owners are only concerned with the end product, and not interested in details of the project. However, some Owners need to know more about how the project was built, and should specify in the construction bid documents the desired extent of drawings and equipment specifications to be provided, particularly the provision of "as built" drawings. Another factor is that once the design-build contract is signed, there can be no further changes to the work - any attempts by the Owner's engineers to change even a minor detail will result in a claim for extra money, and even time added to the schedule to design the change.

For many large utilities, the paucity of information about the LS contracted project, and the inability to participate in the design process, is just not acceptable, and for this reason a preference is retained for UP contracts. However, some large utilities are now thinking of using LS contracts on smaller projects, where the plant capacity is less than about 100MW.

11. Maintenance requirements.

Some Owners do not realize that a hydro plant requires regular maintenance. Just set up the computer remote controls and lock the door! Site visits with a proud Owner to a remote and locked but operating plant tend to support this impression. Often, the extent of maintenance is not recognized until after the project is commissioned. A small hydro plant added to a drop structure on a western irrigation canal provided a graphic illustration of an unexpected maintenance requirement. The plant shut down on low penstock water pressure the day after commissioning, due to trashracks plugged with tumbleweed. Apparently, the tumbleweed rolled across the prairie until it dropped into the canal, where it was swept downstream onto the racks. An automatic trash cleaner was installed.

Provisions for maintenance should include:-

- Easy access to all equipment, particularly to turbine bearings.
- Provision to lift all gates suspended in water, to deck level.
- Inward opening high level windows for access to replace broken glass and cleaning.
- Access openings as large as possible into all tunnels.
- Access to all rock roofs and walls for scaling, rock bolt and wire mesh replacement.
- Access to all vertical shafts, particularly to unlined shafts containing equipment.
- Assess to the crest and downstream toes of all dams, particularly embankment dams.

Equipment access is very important. Currently there is a trend to use vertical shaft, close-coupled turbine-generator units. Often this design restricts access to the turbine guide bearing. Provision for easy access should be part of such a design. If access is difficult, maintenance will be neglected. Also, try to include "sky-hooks", - inverted U-bolts embedded in the concrete ceiling above ancillary equipment, to facilitate lifting and removing the component for maintenance.

Add 150mm diameter holes through concrete floors beside all columns, to provide a route for future control and power cables – an inspection of a powerhouse, 10 years after commissioning, where this feature had been provided, indicated that over half were in use.

Many gates have wire rope hoists. Where the gate is suspended in water, the wire rope rusts at water level and eventually fails. Inspections are needed about every 5 years, and for this the gate has to be lifted to deck level. With severe rusting, or if the water is aggressive, stainless steel ropes are preferred.

Window glass replacement problems are routinely overlooked. High windows are usually broken by bird impact. It is a simple matter of specifying inward opening windows, particularly for intake and spillway gate hoist houses where exterior access is often extremely difficult.

All unlined rock tunnels need maintenance, and this usually requires powered equipment. A 2.5m. diameter access door is a minimum requirement. Concreting the tunnel invert, although very expensive, will greatly simplify maintenance. A rough rock invert will preclude the use of powered equipment and will add considerably to maintenance costs. A lifetime cost analysis should be undertaken.

Rock roofs deteriorate with time, and need maintenance. Wire mesh needs to be emptied of fallen rock and replaced. Access to the roof of underground tailrace surge chambers is often overlooked, and becomes impossible during plant operation. Provisions for access should be built into the design.

All shafts in rock incur seepage. Equipment in shafts, such as elevator rails, piping and structural steel holding power cables rusts and needs regular painting. Safe access for such maintenance work must be provided and built into the design.

Embankment dams need to be monitored and maintained. A renowned geotechnical engineer, who has participated in many dam safety inspections, recently remarked that "25 years ago I would have said that embankment dams were maintenance-free. Now I believe that embankment dams require more maintenance than concrete dams". Large truck access to the toe is a requirement to facilitate repairs to the downstream slope, or perhaps the addition of material to stabilize seepage. Crest access is needed to repair rip-rap and local settlement.

12. Conclusion.

The author hopes that this brief overview of lessons learned during a 50-year career in hydro design will be of use to the reader. Any questions are welcome, and if there are further questions after conclusion of this workshop, the author can be reached at by e-mail at - jim-gordon@sympatico.ca