Advice from an experienced hydro engineer.

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***Abstract* - A few thoughts for prospective hydro engineers from an old hand.**

***Index Terms*—Design, Hydro.**

I. INTRODUCTION

First, I must thank Dr. Bryan Karney for the invitation to address this class. It is an honor, and an opportunity to pass on some wisdom gained from over 55 years working on hydro developments both in Canada and overseas. I was fortunate to start my engineering studies at Aberdeen University where hydraulic model work was being undertaken for several North of Scotland Hydro projects, and later I worked for Montreal Engineering which had contracts to both design and operate hydro plants in Canada and Bolivia. The work was interesting, challenging, and at times quite exciting.

What is unique about hydro engineering is that every hydro facility is different. No cookie-cutter designs copied from the previous project are possible. Changing topography and foundation conditions guarantee that there will be challenges on every job, so you will never be bored, and this is what kept me interested in hydro throughout my working life. And don't let anyone tell you that hydro is an old and mature industry, with no new developments.

There are new dams such as concrete-faced rock fills, and their use in high dams has resulted in unexpected cracking due to the concrete face sliding down and being compressed by the narrower valley abutment rock, producing long vertical compression cracks at about the center of the dam. The problem was not anticipated, so now attempts are being made to undertake finite element modeling of the structure, a very difficult task due to the various materials within the dam – how does one model the interface between rock and concrete?

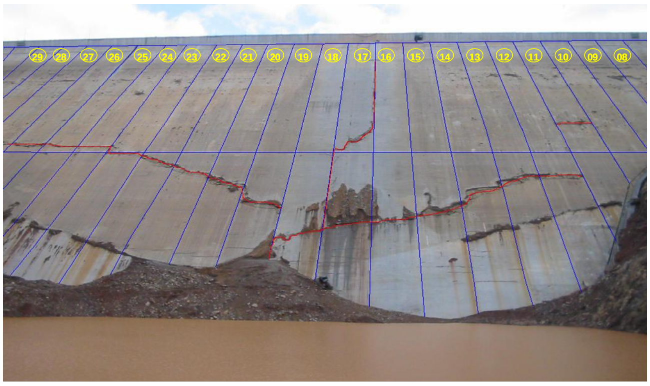

Figure 1 – Photo of cracking pattern at a high concrete-faced rockfill dam in Brazil. Source - A. Marulanda.

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Another challenge is rock stability, and occasionally there are major problems, resulting in demolition of plants and equipment. Rock mechanics presents an on-going challenge, particularly in hydro-fracturing, the result of excessive water pressure within rock faults, causing the rock mass to move. Recently this caused a large underground powerhouse in Canada to move slightly, something that I vigorously disputed and thought it was a physical impossibility, until I was shown photos of cracks in the concrete structure.

Figure 2 – photo of destruction of the Santa Rosa powerhouse in Bolivia from a large rock fall.

The heart of every hydro plant is the turbine. There are about 30 different types currently commercially available, and more are being developed, particularly for ultra-low heads. The selection of the appropriate type for a particular installation is a challenge, and occasionally mistakes are made, resulting in excessive cavitation and destruction of the turbine. Now all designs are made with the help of computational fluid dynamics, programs which require massive computer power, and only recently has it been possible to model the entire turbine from spiral case inlet to draft tube outlet. Previously three programs had to be used, one for the casing and guide vanes, another for the turbine runner, and finally one for the draft tube.

On the electrical side, the advances in equipment control technology are so rapid, that the concepts used in the previous hydro plant are obsolete in the next. I recently met a retired professor of electrical engineering who mentioned that in one year, he had to change his lecture notes three times, due to the rapid advances being made. On every project, I advise my clients that although I am not an electrical engineer, I can mention that major problems will likely be encountered due to a lack of compatible communication between sensor and computer, and the logic of the controls, often resulting in delays on commissioning. The only projects where this is not a problem are those of Hydro Quebec, where the utility undertakes all control design and installation work.

Figure 3 – impulse unit cavitation and erosion.

So with this short introduction, I will move on with some concrete advice, pun intended.

II. Check your Facts

Before I started studies at Aberdeen University in 1948, I obtained a summer job as an intern with the Aberdeen Harbor Board. One of my tasks was to help with a survey of the bay at the harbor mouth for a hydraulic model at Aberdeen University. For about 2 weeks we steamed out on a tugboat, the pilot would take readings on one sextant, Rob, the harbor engineer on another and a seaman would drop a plum-line to measure the water depth. My job was to shout out “mark” when the pilot advised we were in position and all were ready.

Figure 4 – Aberdeen harbor from Google Earth.

We had been doing this for several days, until we had a storm come through with high winds and waves. Nevertheless, the pilot decided to go out, and we worked as best we could. However, I noted that the seaman was always shouting out “6 fathoms”, even with readings taken at the top of a wave, and at the bottom of a wave. Since the waves were about 10ft high, I thought this strange, so went down on deck and asked the seaman why the readings were all 6 fathoms, he replied “cause that’s all the line I got” – problem solved, and a lesson learned – keep your eyes open and check all instruments. We had to redo all areas where the survey indicated a depth of 6 fathoms, this time with a 10 fathom line.

Figure 5 – wave impact on new eastern groin at Aberdeen harbor, built from model study data. Source – Google E.

A few months later, when at university, our class was shown the harbor model, the wave machine, and what they were trying to model - an extension of the breakwaters and a new eastern groin to reduce wave heights inside the harbor. However the professor mentioned that their first task was to calibrate the model to see if it could replicate existing conditions, before proceeding with changes. He indicated that they had spent many months trying to get the model to work without success; it just would not replicate the existing wave pattern within the harbor during a storm. He had eventually concluded that there must be something wrong with the survey of the harbor mouth, and had asked for a re-survey, the work we had been doing. I then mentioned my experience with the “6 fathom line” and he was astounded to learn that the re-survey could have been wrong again.

III. Don’t be Afraid of a Difficult Assignment

After I had been with Montreal Engineering for 5 years, I was promoted to the position of a Project Engineer.

My first assignment was the detailed design of the complicated 6MW Maggotty River project in Jamaica. It included almost every type of structure used in a hydro plant, including a small concrete weir, a low level sluice, a low level outlet, a gathering tube intake (very rare), a concrete pipe, a steel pipe bridge over the Maggoty River, a long wood-stave pipeline with an inverted siphon, a surge tank, a steel penstock and finally a concrete powerhouse with a vertical axis Francis turbine equipped with a relief valve. The conduit hydraulics posed a major problem, and I suspect this was why I was selected for the task.

Figure 6 – view of Maggoty weir and intake structure.

Harland Engineering in Scotland had been awarded a water-to-wire contract for the supply of all powerhouse equipment, (turbine, relief valve, generator, controls, switchgear, crane and pumps) except for the turbine governor, to be supplied by Woodward in the U.S.A. The contracts had been awarded before I was appointed to the job, and made no mention of the hydraulic issues. I quickly found out that Harland did not know how to integrate the design of the relief valve with the turbine and governor, so I took on this task without fully realizing the implications. I designed the complex interconnection using a step-by-step process developed by G. R. Rich in his book “Hydraulic Transients”. The mathematics required guessing the answer first, and then working out the answer over about 15 steps, to see if your guess agreed with the answer. If not, you had to guess again and repeat the iteration process. The task required about 2 months of intensive work, and can now be accomplished in seconds with a computer. I found that I was the only one in the office who understood what I was trying to do, so I was on my own. The manufacturers also did not understand the process, but all was clarified when the plant was commissioned.

When I arrived at Kingston, I was met by Mr. E. Mais, the operations Vice-President of Jamaica Public Service with whom I had exchanged many long letters explaining the complex hydraulics of the powerplant, since we had to install a two-speed governor, a first for Woodward. Also we had to convert the air vent pipe at the top of the inverted siphon to a surge tank, to reduce the pressure surges in the pipeline. When I arrived at the powerhouse, I spent the first two days just looking at the governor and reading the operating manual.

The governor was a new design for the manufacturer. It had two speeds, a rapid movement to 15% gate to obtain a quick breakaway on the thrust bearing, and afterwards a very slow opening rate of over 60 seconds to limit waterhammer. For closure on detection of a fault, the movement was rapid, in less than 10 seconds, while the relief valve opened at the same time. Normal closure was in 60 seconds, and the relief valve did not open. The operating schematic was very complex, covering a large drawing showing how the relief valve, speed ball-head, pilot valves, valves, dashpots and servomotors all interacted with one another through pipes, levers, rods and wires. I wish I had kept a copy. We started dry tests to see if the relief valve opened to the required calculated position on closure of the turbine wicket gates. Unfortunately, the valve did not open to the correct position at intermediate positions, despite simulation of all controls in the "wet" position.

A review of the control schematics indicated that the shape of a stainless steel cam in the relief valve controls must be at fault. The cam rotated through about 90 degrees as the wicket gates moved to full open. As the cam rotated, a small roller lifted to move a pilot valve, which controlled the relief valve servomotor, to a position corresponding to the required relief valve opening. I tried rotating the cam on the shaft, but to no avail. The shape of the roller surface on the cam had to be modified to include an indent at about the half load position. Discussing the problem with the turbine erector, it was decided to substitute a pine wood cam, to be shaped by trial and error. We then used a file to shape the cam to the required profile based on numerous dry tests. For the wet tests, a hard mahogany cam was substituted, cut to 2mm. above the pine wood profile, leaving some wood for final shaping.

The wet tests proceeded cautiously, with the pressure gauges marked with red tape at the design waterhammer pressure limits. Pressure gauges were also installed at the quarter points up the length of the penstock. They were not the recording type, so we had inspectors sitting on the pipe, carefully watching the gauges to see if the needle flipped past the red line. Load rejection tests were undertaken at 5% gate increments, and progressed very slowly since someone had to walk up the penstock to obtain the gauge readings after every test. The mahogany cam was carefully filed down until pressures were all within design limits. The turbine erector then used the mahogany cam to shape two steel cams cut from discarded checker plating. Both were tested and finally shaped with a grinder. One was returned to the manufacturer as a model for a stainless cam, installed a few months later.

Figure 7 – Maggotty relief valve discharge.

The plant is still operating, and in January of this year, I received a phone call from a consultant to advise that they were in the process of installing a new larger penstock, and adding another unit to the powerhouse, so I warned them about the project hydraulics.

IV. Write Papers and Attend Conferences

I have always encouraged engineers to write papers and attend conferences. At the latter, networking is very important, the more information you exchange, the greater the chance of encountering someone who has had similar experience from which you can benefit, as this incident will illustrate.

I had been working as a reviewer of a medium sized hydro plant, and was looking at the water to wire contractor’s second design for a 40MW vertical axis Francis turbine-generator. Comments on the first design had been accepted by the contractor, and appropriate revisions made, except for one comment on the generator rotor, where a flat steel disc was still proposed as the connection between the generator shaft and the rotor poles. I had questioned the selection of a disc to support the rotor poles in the first design, based on a lack of precedent, and a suspicion that there would be severe vibration problems arising from the lack of rigidity between shaft and rotor poles. Vibrations in the disc could be induced by turbulent flow through the runner at part gate openings, perhaps enhanced by harmonic interaction with vibrations emanating from the space between the runner and turbine headcover. I had no mathematical means to support my suspicions, so all I could do was ask the contractor to provide a precedent for the design.

The contractor did provided several precedents, but all were for horizontal axis units, falling into two categories. One was for high-speed generators of less than about 10MW capacity connected to diesel units. The other category was more appropriate, being for large slow-speed horizontal axis bulb units. All the generators had disc plates between the shaft and the generator rotor. The steel discs had a thickness ranging up to about 8cm. According to the contractor, the generators had been in operation without incident for several years. This data appeared to provide adequate precedent, but I was still hesitant to approve the design concept, pointing out that there was a vast difference in the forces acting on the disc in a horizontal and vertical generator. However, in a water to wire contract, the final design decision is entirely within the jurisdiction of the contractor, and the Owner was reluctant to reject the design, since it would provide an open invitation to the contractor to submit a claim for a substantial extra.

Figure 8 – at CDA conference site visit to the Hydro Quebec Grande-Mere powerplant, October 2006.

A few weeks later, I was attending an international hydro conference, and met Peter, an engineer from New Zealand. Over a convivial repast, I mentioned the problem with the generator design, omitting details which could identify the project. Much to my surprise, Peter immediately mentioned his experience with a similar design on a 60MW vertical axis Francis unit which had been provided with a generator with a disc-supported rotor. I was quite incredulous when Peter proceeded to open his wallet and extract a small piece of paper on which he had listed in minute handwriting, all the pertinent details about the projects on which he had worked. The data included name, head, capacity, unit speed, dam type, spill capacity and so forth. After about 2 years operation, the New Zealand rotor disc was examined in detail, and hairline fatigue cracks were discovered around the periphery, at the junction with the rotor pole support section. The cracks were gouged out and repaired by welding. A year later, another inspection revealed further cracking requiring more repairs and the rotor disc was replaced with a standard very stiff "spider" section fabricated from large wide-flange steel sections.

I obtained data on the project and passed it on to the contractor, pointing out that the generator had been manufactured by a company recently purchased by the contractor, and therefore all data on the unit and the repairs must be in the subsidiaries files. About a month later, a new generator design was submitted by the contractor, with a standard spider design based on the use of wide-flange steel sections. I asked the contractor why, with the negative experience with disc rotors obtained by the subsidiary, the contractor insisted that the disc design was acceptable. The reply was to the effect that the subsidiaries file retrieval system was manual and not compatible with the contractor's new computer-based drawing retrieval system, and hence the experience was not readily available to the designers.

Networking at the conference had paid off handsomely, and illustrates the prime advantage of attending conferences. In these days of cut-backs, downsizing and budget reductions, one of the first cost cutting measures usually introduced is a reduction in conference attendance. The value of networking is often overlooked, and never taken into account – to the detriment of the utility or consulting engineer.

V. BE PREPARED TO TRAVEL

Most hydro developments are in remote areas, so travel is a necessity. One of my more exotic trips was to the Amazon jungle, where I was asked to look at a possible hydro site found by the local engineer operating a large suction dredge working on the Yolosani River, a tributary of the Beni, and owned by the South American Gold Company. After flying to La Paz and settling in at the Crillon Hotel, I met Nick, a young engineer who would be coming with me to the jungle. Next day we went up to the airport and reported in at the Lloyd Aero Boliviano counter. The clerk advised that the flight had been cancelled since the mountain pass was fogged in. And how did they know, by just looking out the window to the mountains on the horizon to the far North.

Figure 9 – Author and Nick on mules, Yolosani valley.

Finally the fog cleared and we departed. Going through the pass, it looked as if the wings were almost touching the mountains. After landing on a narrow grass strip, we walked over to the camp and were shown to our bungalow. The mining engineer, Julio, pointed out the cookhouse and his office, and asked us over for a brief meeting before lunch. At the meeting, we went over our itinerary for the next few days.

Two days later, we departed for the dam site, far up-river. Apart from me, our party included Julio, Nick, a couple of Indian helpers, and an Indian guide carrying an ancient blunderbuss! Except for the guide, we were all mounted on mules. I found out that the blunderbuss was loaded, so I kept well clear of the guide. We did not seem to have any supplies, apart from coffee and a couple of tins of peaches. Food was not needed as I was to find out. After several hours travel we came to a small village of about 15 thatched-roof dwellings. We entered one, the local restaurant for travelers and ordered lunch. There was only one item on the menu, “arroz con pollo” - chicken with rice. We were taken out back, to select our chickens, lunch was certainly fresh, and tasted delicious.

At the next village there was an overnight rest stop, in a large thatched-roof building with no walls. We slung out hammocks from the posts, and again had our chicken meal for dinner.

Figure 10 – jungle motel, author and Nick.

At the village, we were taken over to visit the local store, operated by a German still hiding from the Gestapo. All his transactions were in gold, and he had a large collection of mason jars full of gold dust, lining the wall behind the counter. I asked him if he was not afraid of being robbed, and he replied that there was only one path out to the end of the road, a week’s journey on a mule, so any robber would not get far.

Next morning we had a breakfast of fried eggs and bananas. The abundance of banana trees explained the lack of provisions. We could pluck bananas off the trees as we traveled by on mules, and I found that there were three species, one suitable for eating, another for boiling, and another for frying. However, there was one tree we had to avoid, as explained by our guide. It had a symbiotic relationship with red fire ants, the ants being poised on the upper branches, waiting for an animal to pass below, and would descend in a cloud of ants onto the animal. Depending on the animal’s size, between 50 and 100 bites were fatal. For humans, 25 bites would make you severely sick. The guide would spot the tree, and pound the ground with his stick, a signal to the ants that there was something below, they would fall in a cloud, the guide would shout to the next 3 persons on the trail to gallop through before another wave of ants were ready. The mules were well aware of the procedure, and this was the only time they could be persuaded to move at a gallop. We waited a few minutes, and the guide would then pound the ground again, and the process was repeated until all passed.

Figure 11 – coffee time in a small clearing.

About 10.00am we stopped for coffee in a clearing and I sat down on a stump. I had only been sitting for a few seconds, when the two Indian helpers ran over, grabbed my arms, and forcefully jerked me off the stump. Apparently I had sat down on a fire ant tree stump, and the ants were swarming all over my trousers. Fortunately, they were flicked off before any could bite, so I learned another lesson of life in the jungle.

We continued on, stopping again at a village for lunch. In the evening, we slung the hammocks which had a rain cover and mosquito net, from some trees and we were soon quite comfortable. Dinner was fried bananas and tinned peaches.

Early the next day we arrived at the river, and I had a good look at the proposed site for the dam. However, it proved quite unsuitable for a small powerplant, since the flood flow was very large, the spillway would be expensive, rendering the site uneconomic. So it was back to camp, whereupon Julio announced that they had a large balsa wood raft waiting just downstream, which would take us back in about 3 hours. Arriving at the river bank, we stripped down to our underwear, and stowed all belongings in waterproof bags made of flour sacks impregnated with locally obtained gum from rubber treas. They proved to be completely waterproof, and the ride back was wild, especially through the rapids, where we were often completely submerged. Approaching one particularly ferocious rapid, Julio advised us to hang on tightly, since the rapids were called “Quita Calzon” – underwear stripper! The two Indian helpers were expert rafters, and managed to get us all back without overturning the raft. Quite an experience!

Figure 12 – rafting across the Yolosani River.

Back at camp, I told Julio what we needed was a stream with a high head, instead of the low head Yolosani river site. He knew of such a stream nearby, about three hours walk through the jungle. We looked it over, it seemed suitable, and I gave the surveyor instructions for mapping the area, expecting this to take several months of cutting survey lines through the dense jungle. After that, I flew back to Montreal. So I was surprised to receive a detailed map of the site only a few weeks later. We developed a design, estimated the cost, and issued a report. Three months later we got a letter from South American Gold apologizing for the mapping, it was not correct. Apparently, the surveyor, realizing the enormity of the work involved in cutting survey lines through the jungle, decided to sit on a rock in the middle of the river, and make a free-hand drawing of the topography!

VI. Question your advisors

On many hydro projects, it is now usual to have a team of advisors, commonly known as a "Review board". We learned to always question their advice. In 1969 we started work on the North Saskatchewan River Bighorn dam in Alberta. It had a very difficult foundation condition with a deep buried valley in-filled with pervious gravel. It was only due to the recent invention of specialized excavation equipment in Italy, that construction of the dam was possible. This new equipment was used to construct a 0.75m wide vertical concrete wall through pervious alluvial gravels down to impervious rock, later connected to the dam's earth core at the top of the wall.

Figure 13 – three excavators inside cut-off wall hoarding. All work undertaken in winter.

We had two geotechnical consultants on the project, but unfortunately one passed away shortly after we began work, a great loss. He was replaced with Dr. Arthur Casagrande, of Harvard University, whom I got to know very well.

Dr. Casagrande made a fundamental change to the dam design, joining the impervious core in the main dam to the cofferdam core with a horizontal layer of clay, to engage a short upstream cofferdam blanket to increase the seepage path by a considerable margin. It proved to be the detail which saved the dam from a possible disastrous washout. Work on the cut-off wall was undertaken by specialist contractors, and the low bidder was from Italy. The wall was constructed inside a gigantic plastic building in winter, with heat provided by propane burners. In fact it was so warm inside the building that the Italian workers joked that they should have brought over some grape vines.

Quality control of the concrete being poured into the wall proved to be almost impossible. The problem was the stability of the trench wall, with small local sloughs during concreting causing gaps in the concrete, which were filled with pervious wall material. The volume of concrete in each wall panel was carefully calculated, but this data was of no use, since the volume of a slough into the wall would match the volume of concrete replacing the sloughed material.

When the dam was filled, seepage was much larger than expected, and the end result was a leaky wall, just what we were trying to avoid. We had to add a gravel toe to the downstream side to contain the seepage. From a study of the foundation pressures, we found that the concrete wall in the pervious foundation gravel must have a flaw, resulting in the increased seepage. The wall was the deepest ever built at the time, so we were pushing the design envelope considerably. However, the seepage was contained with the gravel toe and now is decreasing due to fine silt in the reservoir from glacial rock flour providing an impervious coating to the river bed.

Figure 14 – Bighorn Dam, showing downstream toe.

Current construction methods call for grouting of the foundation adjacent to the wall, prior to wall trench excavation to improve wall stability and eliminate sloughing. However, this technique about doubles the cost, but seepage through the wall is almost eliminated. When Bighorn was constructed, grouting to such depths was not possible, so we had no choice.

All meetings with our consultants were held at the site, and Dr. Casagrande would fly from Boston to Montreal, stay overnight, and we would fly out early the next morning to Calgary, rent a car, and drive past Banff to the site, a very picturesque journey. Dr. Casagrande was such an eminent engineer that his opinions were never questioned. He mentioned this to me when returning from a trip to the site.

He opened the conversation with the remark that he enjoyed working with the Montreal Engineering team at site. I thanked him for the compliment, and asked why. He replied that we always questioned his opinions, and often the resulting discussion improved the design by some change in details. Apparently on all other projects – and he was involved in many – his remarks were never questioned, and implemented without further discussion, so he had to be very cautious before expressing any opinion, and act as his own critic! On Bighorn, he was not afraid to express an opinion he had not thoroughly investigated, knowing that we would look at it from all angles to see if it would work as expected. I was heartened to hear that our approach to consultants was vindicated - always question their opinions!

VII. Don't panic during stressful times

After the success of Maggotty, I was asked to work on the Brazeau development, by far the largest hydro plant ever built by Calgary Power. In fact, for about 4 months after it started in 1965, it had the largest powered hydro turbines in the world at 210,000HP and 250,000HP. Currently, the record for turbine size is over 1,000,000HP at Three Gorges in China.

We pushed the envelope on the design, unfortunately in one case, a bit too far. We had a geotechnical consultant who had undertaken many design assignments for Calgary Power and was deemed infallible. He had presented his design concept for the intake which rested on over-consolidated glacial till containing discontinuous sand lenses, at a meeting in Montreal attended by our principles and myself, and later sent his report.

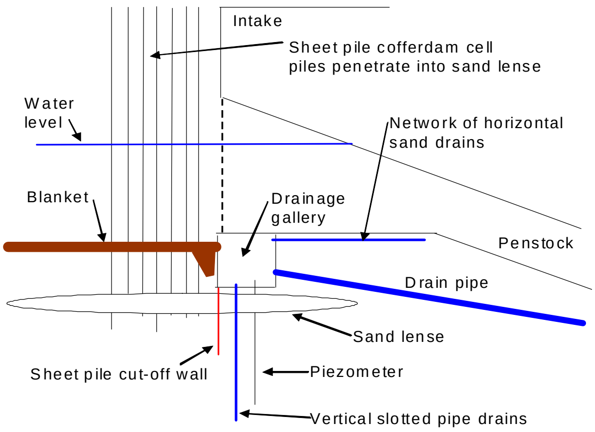

Figure 15 – Schematic Brazeau intake drains.

However, when I saw the report and details of the design for the intake foundation, I was worried about the complexity to such an extent, that I wrote a 2-page memorandum to our Chief Civil Engineer, expressing my concerns. I was worried by the size of a 0.45m drain from the intake, very large for seepage flows. I could not put my finger on what was troubling about the design, which included an impervious blanket, a sheet-pile wall, vertical slotted plastic drain pipes, and a drainage gallery below the intake. Several piezometers were included to measure the uplift pressure at levels in the glacial till below the intake. My instinct said something was definitely wrong. In my memo, I discussed the risks in the design and ended by requesting another meeting with our geotechnical consultant. I was advised that I could not question the consultant's designs, so no meeting and my memo ended up in the waste paper basket, but I kept my copy.

Figure 16 – intake before dewatering. Note circular sheet steel pile cofferdam on left of intake, reservoir ½ full.

However, I was so worried that I requested Frank, the site resident engineer to carefully monitor the water pressure under the intake, a simple task, since the piezometers were accessible by a vertical 100ft ladder down to the gallery. I also provided a chart showing safe, unsafe and disaster uplift water pressures, with a note saying that I had to be advised of the measured pressures on a daily basis. As the work progressed, all went well. I had been inspecting the construction work about every three months, flying out to Edmonton, renting a car, and driving to the site. The daily pressure readings at the intake showed no change, and all seemed well.

Figure 17 – Brazeau Intake perched above powerhouse.

In November 1964 I went to site to commission the first unit, and was met at the airport by a very worried Frank. He told me that over the past few hours, the water pressure under the intake had started to increase rapidly, was now over the safe level, and if it continued at the same rate, it would reach the disaster pressure in only 19 hours.

The reservoir in front of the intake was only at half level, a precaution very fortunately proposed by Frank months previously, when he understood my concerns. However, there was no way to evacuate the water except through the turbine, still not ready to operate since the thrust bearing was being installed, and the task would not be completed for another few days. During our discussions on the long drive back to the site, we arrived at a plan to pass water through the turbine by tying down the generator to prevent the unit from rotating, and opening the wicket gates, something never tried in the past.

At site we had a meeting with the contractor, and the turbine erector Hans Jensen from Dominion Engineering. We initiated the plan after Frank and I had signed documents taking over control of the project and absolving the contractor and the turbine manufacturer of any responsibility and damages. The construction camp near the powerhouse was evacuated, and because of the danger, the only staff remaining on site was the contractor's superintendent, Frank and one of his engineers, a volunteer from the survey crew to read the pressure gauges, Hans, the plant's chief operator Bill Maxwell from Calgary Power and myself.

Hans was instructed to stop bearing installation and tie down the 157MW generator by attaching wire ropes from the generator spider to any fixed point in the powerhouse. Within two hours the generator was laced with rope and secure. You had to climb through the ropes to access the turbine pit, and I didn't think the generator would rotate under any circumstances, since Hans and Bill had done such a good job. The wicket gates were opened to 6% and a close watch was kept on water level in the gallery and flow in the drain. After about three hours, and near midnight, it became evident that the battle was being lost, and that the wicket gates would have to be opened further. After some discussion, and over the vociferous objections of Hans, the wicket gates were opened to 11%. By this time the noise and vibration within the powerhouse was indescribable - expected, since something like 20,000 horsepower of energy was being dissipated through the stationary turbine! The effect on the rate of water level rise in the gallery was immediate, and it peaked within 0.3m of the gallery roof before subsiding. Within a few more hours the headpond was empty, and the crisis was over.

What had gone wrong. A detailed examination of the headpond upstream of the intake revealed a watertight blanket. However, the rate of water inflow to the gallery indicated that there must have been a direct connection to the horizontal sand lenses within the foundation till adjacent to the intake. Eventually, the investigation concentrated on the sheet steel piles beside the intake, where it was found that there was just enough flow area within the interlocks to conduct water down to the sand lenses, through and below the perimeter sheet steel piling and into the gallery. Water could flow into the pile interlocks through the vertical steel slots where the steel to steel contact was discontinuous. The remedial work included welding closed all the vertical interlock slots from 3m below grade to 1m above maximum water level, the addition of a bentonite beneficiated blanket contact with the sheet steel piling to 3m below grade to improve impermeability, and a float operated alarm in the drainage gallery. The repairs proved successful and operate without further incident.

A few years ago I was asked to participate in a panel discussion on emergency actions during a dam failure. All the other panel members spoke about committees and action approvals, consultations with the head office and so forth. When I spoke, I summarized the measures taken during the Brazeau failure, without identifying the project, noting the need for immediate actions, sufficient authority to command resources, the ability to take responsibility for the work and someone willing to step in front to direct work without having to refer back to any other offices. This was possible at Brazeau due to the close relationship between consultant and client. It is certainly not possible today with numerous agencies responsible for various safety issues, overlapping jurisdictions, and the inability to assume unquestioned command. Who would be foolish enough today to say to Hans, the turbine erector, "we just have to do it. I will type out a paper absolving Dominion Engineering of all responsibility, you can read it over the phone to Percy Soicher (his superior in Montreal) and we can both sign it".

VIII. EMBRACE NEW TECHNOLOGY

As we all know, technology is advancing rapidly. When I started working in 1952, all we had was a slide rule, drafting table, T-square and a few triangles for drawing. And if more accuracy was required than could be provided by the slide rule, then you used tables of 4-digit or books of 8-digit logarithms. Communication was by snail-mail, telephone or telegram. In fact, the calculating tools had not changed much over the past 300 years, since the slide rule was invented in 17th century after William Oughtred developed the logarithm mathematical principles in 1614.

Figure 18 – engineering tools, 1952.

Now, there is a multiplicity of tools, ranging from fax machines to computers and laser printers. Communication is instantaneous anywhere in the world with satellite phones, and almost every engineer carries a cell phone or Blackberry. Computation accuracy is to about 12 decimal places, and computers can undertake long complex calculations within a few seconds. But, and this is significant, many years ago, mentors were available, and most consulting companies trained their new junior engineers. Also, most Canadian hydro developments were described in detail in the Energy Journal (ASCE) or the Engineering Journal (EIC) or in the Transactions of the CEA. Hence there was a remarkable fund of information available on hydro developments, and junior engineers quickly learned how to design projects.

Unfortunately, none of aforementioned publications exist today. In fact, it is difficult to obtain permission from utilities to publish data, particularly powerplant drawings due to safety concerns, and many prohibit publication of cost data due to competitive issues in the current unregulated hydro market. So junior engineers have to find mentors, preferably within the company, and if such are unavailable, an arrangement with an external mentor should be developed.

However, back to technology. What I have learned is that you should never use a computer program unless it has been tested and proved reliable. This incident involved a relief valve on a turbine similar to that at Maggotty.

The water-to-wire equipment contract was awarded to a turbine manufacturer who advised that he was familiar with relief valves, and had a computer program which could solve the waterhammer problems associated with integration of the relief valve and turbine. Waterhammer was to be limited to +/- 25%, but with the computer program, the manufacturer advised that more precise control of the relief valve could be attained, limiting pipe waterhammer to within +/- 15%. Calculations of waterhammer at 25%, 50%, 75% and full load rejection were produced on a graphical trace of pressure versus time, and indicated that waterhammer was indeed within the range claimed by the manufacturer.

The manufacturer's brochures included photos of relief valves, but what we failed to realize, was that they were old, and that the engineers who had worked on their design had long since retired.

Figure 19 – repaired woodstave penstock.

On commissioning the equipment, the wood stave penstock collapsed on the first test. A detailed inspection of the installation indicated that there was no position detection device on the valve, no indented cam, and the relief valve had opened to the full open position on the first small part-load test rejection. Discussions with the manufacturer revealed that the hydraulics of the relief valve had been subcontracted to a graduate in mathematics who had written a waterhammer program. A copy of the program was obtained and perused it in detail, where it was found that, in addition to the lack of valve motion data, there were also no inputs for valve or turbine characteristics. A meeting with the waterhammer programmer was arranged.

At the meeting the programmer sat down at the computer, entered the data, and produced the waterhammer-time profile for a full load rejection. The exercise was repeated with a 50% load rejection, and the graphical output was found to be identical in shape to that for the previous calculation. This is known to be a physical impossibility, since the stage-discharge characteristics of turbine and valve are very different, particularly at the half-open positions, where a half-open relief valve will discharge more than a half-open turbine. The programmer was asked how the relief valve knew that with a 50% load rejection, the valve should only open to about 45%, a question which puzzled the programmer. Further discussion elicited the response "Oh, with a half load you must use a half sized relief valve", end of discussion and problem solved. The programmer, with a degree in mathematics, had no concept of the engineering involved, and the manufacturer was not aware of this, hence the lack of a valve position sensor and a means of limiting relief valve opening.

Figure 20 – turbine and generator.

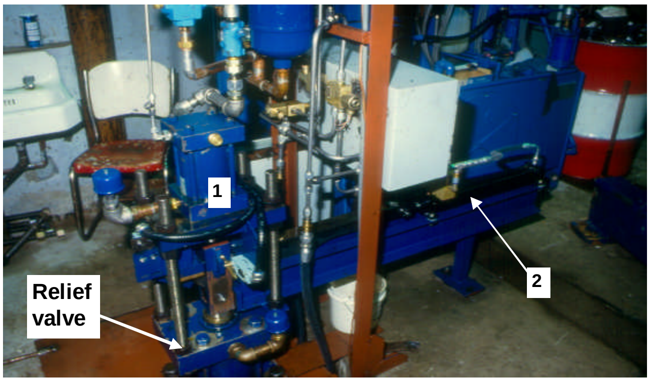

Figure 21 – relief valve and controls. 1. Valve servomotor. 2. Black indented slider added after accident, moved by wicket gate operating ring, prevents valve opening excessively on partial load-off.

The repair was expensive and included an indented slide positioner to physically limit relief valve opening based on the extent of wicket gate opening at start of load rejection, all at the manufacturer's cost. Commissioning was delayed by several months. As for the collapsed wood stave penstock, it was repaired with the original staves and some spares at minimal cost. So, always test new computer programs!

IX. Conclusions

Hydro engineering is a fascinating science, one where the economies of scale are very evident. Small micro-hydro developments using micro-turbine runners (Figure 22), cost more per kW than large developments using large runners as illustrated in Figure 23. However, the similarity between the runners is clearly evident, so that experience gained on small hydro projects can be applied to large projects.

Figure 22 – small 14-bucket Francis runner, 100mm throat diameter, 8.95kW, 18.3m head, flow 61.3l/s. Manufactured by Rodney-Hunt, England.

Figure 23 – last large Francis runner manufactured in Canada, for Tarbela, Pakistan. 7,150mm throat diameter, 440MW, 135.6m head, 90.9rpm. Manufactured by Sulzer in Montreal, factory now closed.

Calculating the stream flow for a small site is very similar to the calculations required for a large site. In fact, it is easier for the larger site since more time and money will be made available. Similarly, experience gained in designing small intakes and powerplants can be extrapolated to larger facilities. This is a major advantage for young engineers, in that it is possible to start working on very interesting small projects, where ingenuity is needed to keep costs to a minimum, and gradually work up to the larger projects.

I would therefore suggest that any young engineer considering a hydro career, should first obtain experience with a small hydro consultant, followed by a few years on a hydro site, preferably with a large contractor, after which a decision is needed. There are three options, (1) return to university to obtain a doctorate in a specialty such as soil or rock mechanics, (2) become a generalist and work for a small consultant, moving later to a larger consultant, or (3) continue to work in the field, either for a contractor or a large utility.

Note that I have not mentioned working for a consultant on site. Most hydro site work is now supervised by the contractor on "design-build" contracts, or by the utility on unit price contracts. Site work by a consultant is confined to a site representative to maintain liaison between the design office and the field work. This is why it is almost impossible to obtain site experience while working for a consultant, an unfortunate situation. Construction experience is essential for any design engineer in the industry; it is the only way to learn what is important, and how hydro structures are built.

Also, document your experience, preferably by keeping copies of reports and important drawings. I once had to ask one of my senior engineers to move to another office for a few years to supervise the design of a large hydro project. He readily consented, provided I agreed to accept the cost of moving his files – stored in 17 document storage boxes! He had been with the company for over 35 years, and had kept a copy of all his drawings and reports. I immediately realized that they would be a valuable reference at the new office, so we accepted the cost. Now such storage can be easily maintained with a small dedicated external hard drive.

And produce papers. This is the best way to be noticed in the industry, so that prospective employers will come looking for you, instead of you looking for them!

Finally, I would like to put in a plug for a new Canadian digital hydro journal. As mentioned previously, there is no journal dedicated to hydro developments in Canada, and with the upsurge in hydro activity, I think one should be started. To keep costs to a minimum, it could be administered by a group of volunteer editors, papers would be submitted in final print form in a format similar to that used for this article, and the only cost would be that for the host web computer. Any suggestions?

X. Biography

Jim Gordon graduated from Aberdeen University in 1952 with a first class honors degree in Civil Engineering and commenced work with Montreal Engineering. During the time he was the Chief Design Engineer for 6 hydro projects which received awards "for excellence in design" by the Association of Consulting Engineers of Canada. He has worked in 15 countries, and for 9 years he was the Vice-President Hydro, retiring in 1990. Since then, he has practiced as a private consultant, providing advice to consultants and hydro utilities on design, cost, mechanical equipment selection, and has served on many review boards. He was awarded the Rickey Medal by the American Society of Civil Engineers, and the Distinguished Service Award by the Canadian Electrical Association. He has authored or co-authored 84 papers covering a wide range of subjects, from vortices at intakes, to turbine cavitation and generator inertia. He has been an invited speaker at 26 seminars, and is the author of 43 "Lessons learned" articles published by HRW (Hydro Review Worldwide).