Smaller Hydro, Higher Risk

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***Abstract*—Small or large Hydropower plant design, construction and operation are complex tasks. Thousands of details must be well conceived and executed, and carefully coordinated for a project to achieve safe and economical operation that can be judged a social, technical and environmental success. Any hydroelectric installation, as a rule, should be designed using several stages. At each stage, all project documentation should be reviewed by independent reviewers selected and nominated by official authorities. Reducing the amount of analyses, without justification, or worse yet, neglecting the design procedures puts the project at risk. A collaborative effort at reducing this risk is thus advocated.**

***Index Terms*--Hydro power, Review, Risk, Runaway, Small hydro, Large plants, Guidelines, Project stages**

I. INTRODUCTION

The growth of both electricity demand and subsequent production and supply, and particularly the related interest in hydropower, is of world wide scope and significance. It is a growth and interest that shows no sign of decreasing or letting up [11], [12], [15], [21].

And yet there is also no doubt that hydropower plant design, construction and operation are complex tasks. Such an undertaking requires, among other things, competent environmental and hydrological assessments, careful planning and design, visionary financing, long-sighted political planning, demanding construction and supervision, painstaking commissioning and trouble shooting, and meticulous operation and control. Tens of thousands of details must be accurate, well conceived and executed, and carefully coordinated for a project to achieve safe and economical operation that can be judged a social, technical and environmental success. Yet, when only a few of these myriad details are overlooked, under-estimated or improperly linked to each other, great complications can quickly arise. It has not been uncommon to have major investments in hydro projects to under-perform and forced to run at much lower than design loads due to failures in the review process, particularly associated with the poorly understood issues of system hydraulics. The purpose of this paper is to review such issues and bring them strongly to the attention of the larger energy community.

For large-scale projects, even minor performance improvements deserve consideration during development and testing. Similarly, when a system is expanded and up-rated, since most of the investment is justified by the performance improvements alone, these improvements must be predicted and verified with accuracy. The effectiveness of incentives for performance achievement has many examples to date.

Yet small developers are seldom as well equipped, financed or experienced as those working on larger units. As a result, they are liable to face greater risks and complications. Special standards to provide comprehensive rules and guidelines for smaller units and new developers would largely alleviate some of the inherent, yet avoidable risk. The issues and concerns associated with developing special manuals for hydroelectric plants, particularly smaller plants, should be effectively engaged and controlled by a public committee or task force, including possible solutions. The main purpose is to protect the owners from unqualified designers, manufacturers, managers and other complications and thus to avert avoidable risks and expenses during operation [10].

These problems are perhaps further magnified by the use of computers and readily available programs. Overall, the practice of professional engineering has become increasingly reliant on computers, and engineers use many programs that incorporate technical principles for design and simulation. Ultimately these programs are used as tools for baseline installations and in some cases their applicability can be seriously questioned. Invariably, such programs are based upon assumptions, limitations, interpretations and judgments on engineering criteria that were made by or on behalf of an engineer when the program was first developed. Therefore, it is often difficult to determine, simply by using a program or studying its manual, the inherent assumptions, coding algorithms employed and their limitations. When using computer programs to assist in this work, engineers should not only be aware of the engineering principles and incorporated assumptions but must independently verify the results and are thus responsible for the interpretation and correct application of the analyses the programs provide [2], [21].

II. HYDRO DEVELOPMENT

Any hydroelectric installation, as a rule, should be designed using the following stages:

(i) Feasibility study,
(ii) General design,
(iii) Detailed design (after bidding),
(iv) Commissioning and running - in process,
(v) Trouble-shooting investigations, and
(vi) Reconstruction, redesign, adjustment or enlargement.

Ideally, all project documentation should be reviewed at each critical stage by independent reviewers selected and nominated by official authorities. Short-changing the analyses, without justification, or worse yet, neglecting any design stage or its associated review, puts the project at risk. At stake here is the economical and efficient functioning of the whole project; taking short cuts can lead – and indeed has often led – to large-scale problems. The point here is that the design team, the project documentation, and the review process all play an interconnected role in anticipating and resolving difficulties before they are implemented in the field, and thus solving them when they are relatively simply addressed [6], [7], [8], [10].

There is no single hydroelectric project running through the commissioning and trial operation without troubleshooting; thus a higher degree of review and documentation through project stages could pinpoint problems earlier and more effectively than later. Furthermore, this process, while costing only a small premium, would decrease troubleshooting and maintenance costs over the project's life time.

III. MULTIDISCIPLINARY TRANSFER OF EXPERIENCE AND KNOWLEDGE

The continuity of experience has been largely lost in Canada and most parts of the world due to the slow pace of implementation. Canada has had more than 100 years of experience in the electricity sector but individual areas have lost valuable knowledge that accrued during this period. However, poorly coordinated transfer of practical and theoretical experience appears to be root cause of this loss. The consequences are an unstable market and investment climate, accidents, inefficiency and troubleshooting (of the same problems), which have all shown up regularly in recent years, will continue to occur if appropriate steps are not taken. The organized multidisciplinary transfer of experience is a priority task to be undertaken by the universities and electricity sector in Ontario and Canada; it is urgent that decisions to address this be made now. There is a clear need to plan, finance and implement various long-term initiatives.

One of the greatest tasks facing the electricity sector in Ontario is the design of new generators and the urgent rehabilitation of existing units. Yet there are too few engineers with extensive experience and too few project managers who know how to cultivate the right skills from the market place.

IV. HYDRAULIC TRANSIENTS

As in electrical system, transients in hydraulic networks and infrastructure can become critical constraints during design and operation. Vibrations produce the highest pressures in the waterways and associated conduits. They cause critical stresses in the overall hydraulic and mechanical structure and therefore cannot be neglected during design. This aspect is independent of the size of the conduits or hydraulic machinery and is thus recommended for all installations including mini and small Hydro [3], [4], [5], [6], [8], [9]. The costs associated with cavitation, transient conditions, vibrations and stress analysis for mini, small and big hydroelectric plants are often quite comparable in absolute terms; however, the relative cost as a fraction of the total investment is obviously much greater. Bigger plants usually entail such costs less than one percent of the total whereas smaller installations may well see these costs as being nearly equal to overall initial expenses.

The pressures stemming from private sector design and accounting are certainly now upon us in a big way. The result is a rapid movement to minimal staff or no site staff. Extensive use of numerical simulation for the performance of hydraulic machinery is remarkable these days, but a shortage of qualified specialists and engineers is often aggravated as a result. New staff, whose number will have to grow again in the light of initiatives, will rely on these new guidelines and upon up-to-date standards and technical literature.

Small hydro power plants often suffer from the same problems as the large ones. The analyses of transient regimes are actually more complicated, due to complex boundary conditions. Despite this, there is a general tendency to decrease the design costs and to simplify analysis.

Thus, in general, the smaller the hydroelectric plant, the higher the risk of having troubles as the result of reduced project costs. Saving money by reducing reviewing costs further increases the risk.

V. RISK AND RUNAWAY PROTECTION

In designing a hydraulic machine unit, the runaway operating condition has to be considered. The balance between safety and costs for manufacturing components and maintenance must be recognized and allowed for. Excluding small size units, all generator motors are at risk at full runaway. Kovalev N.N. [5] discuses the issue as follows:

"Turbine and generator must withstand the effects of full runaway speed for a short time, as stipulated in the delivery specifications of the order. According to the experience of Soviet hydro plants, actual runaway occurs only very seldom. In all known instances of runaway, no serious damage was found when the unit was stopped. In plants with automatic regulation, out of twelve instances of runaway, four occurred during the governor-adjustment period, and eight during normal operation; the unit was shut down by the governor itself in five instances. By statistical analysis, Gidroproekt found the probability of runaway occurring to be once every 24 years. The analysis covered 450 hydro units for a period of five years (1954-1958)."

Kovalev reports that instances of runaway in European hydroelectric plants were rare and were usually associated with distributor valve problems during turbine start up. Except for one instance in Finland, damage was not observed. However, considerable damage was associated with several instances of runaway in the U. S. A.

The general guideline Kovalev provides is that large low-head turbines, irrespective of location or make, should always equipped with runaway-protection devices.

Of concern though is the experience that all existing protective devices receive the control impulse only after a significant time lag, starting to act only when the runner rotates already at 160% to 170% of its normal speed. Isolation gates are only closed once the runner has reached full runaway speed.

Counter measures depend on the application. Assuming that runaway is likely occurring, the distributor may be used in conjunction with additional protective devices; the runner should be designed to withstand this condition but this requires a heavier and stronger unit. An individual servomotor for each guide vane might be justified in such cases. This servomotor would be the final-control element of the governor under normal conditions, and would shut down the unit at runaway if connected to the emergency control-valve.

On the contrary, assuming that runaway is unlikely, Koralev argues that “special protective devices could be omitted so as not to complicate the turbine, only the normal governor equipment with a stand-by pressure source being installed. The rotor can thus be designed to withstand smaller runaway speeds. Possible damage due to runaway will be considered accidental, and will be compensated for by the savings obtained through the more economical design.”

The second alternative is economically preferable, since the probability of runaway occurrence is small enough that the damage and repair costs are less than the savings obtained by eliminating the costly protective devices. Quantitative analysis of such issues can be made only by means of dedicated and tailored calculations.

Thus, for Kaplan turbines having a runner diameter of 6 to 10 m the distributor can be used for protection, assuming that an emergency pressure activation mechanism is provided, and that the control impulse is given immediately after rejection should the distributor fail to close.

The unit should therefore be designed to withstand short full runaway speed for short durations, and head gates should be provided together with means for changing the shear pins while the turbine is running.

For Kaplan turbines with runner diameters from 3 to 5 m, Koralev argues that “it is possible to adjust the blades to mid-position for runaway protection in addition to the emergency shutdown control-valve.

The protection against runaway Raabe J. [9] discuss in similar way and these conditions are so important that we quote at length

“Contrary to practice with thermal turbo generators, the hydro turbo set in general has to withstand the runaway speed of its turbine. This is a multiple (1,4 to 3,3) of the rated speed, depending on the design. The first safety precaution is the speed governor of the set (if any at all). At least each set has an emergency shutdown device for the case a certain overspeed (about 1,3 of the rated one) is surpassed.

Since the closing time of gates is limited by water hammer-induced pressure surge in the penstock, the set may reach rather high overspeed during emergency shutdown. When this device fails, e.g., by jamming, the then unloaded set may attain its runaway speed.

As a general rule, it may be stated, that sophisticated devices for avoiding runaway (such as jet deflectors in impulse turbines or braking runner blades swinging out in axial turbines) are impracticable and not reliable in larger sets.

In micro power stations runaway may be the state in which the set passes the time between its working periods. In such plants the peripheral blade speed may be small, so as to experience long idling period instead of runaway, useful to ensure the lubrication of bearings.

Sometimes in double regulated Kaplan turbines the runner servomotor may be short-circuited by an overspeed-actuated valve. Thereafter, the blades can follow their inbuilt opening tendency to ensure the lowest possible runaway speed. This implies that the outermost components of the alternator rotor like the poles are overstrained so as to need rewinding. But the core of the set has to withstand runaway until the bulkheads are inserted.

In smaller units with step up gear for the alternator the latter may be protected against runaway by loosening the clutch then used to attach the gear casing to the ground. Remember that any gear needs a connection to the foundations so as to lead the difference in torque between the input and output shaft into the ground. When this connection is interrupted, the gear functions as a coupling. Thereby the alternator rotor is protected against runaway speed. Such a device has been proved successfully in the bulb turbine at Ossbergshausen on Agger, West Germany.

The high head pump-turbine sets at Silz in Tyrol, Austria, of the Sellrain scheme are an exceptional example of the situation that the lowest critical speed falls short of the runaway speed. Here, a thickening of the shaft sufficient to raise the critical speed above the runaway speed would have required the use of rather expensive material in the alternator rotor because of the resulting increased diameter. In such a case, care must be taken, that under all imaginable operations the runaway speed never coincides with the critical speed. The latter is only passed during running down or speeding up.

In two recently built sets with Isogyre pump-turbines, Grimsel, Switzerland, and Malta, upper stage, Austria, the lowest critical speed falls short of runaway speed. This may be a reasonable practice, if the runaway speed deviates from the lowest critical speed under all possible modes of operation.

However, for the Malta set this is not assured, as the sets operate with a large variation in head and runaway speed so as to need, by the way, also a change pole alternator. Hence the critical speed occasionally may coincide with the runaway speed. In this case all the emergency shutdown devices, like governor, overspeed governor, valves and gates must operate safely.

In Pejovic [18] it is argued that the low specific speed, high head pump-turbine "S" form instabilities in the runaway zone, which is close to normal operation, first discovered by computer simulations done at “Energoporojekt,” Belgrade by the team of engineers designing the Pumped-Storage Plant, Bajina Basta (Fig. 1), and in 1976 published by Pejovic et al. [17]. The peaks of pressure fluctuations exceeded 900 m, the design penstock pressure head. Therefore, the governing and protective system had been changed to prevent parallel runaway of both units minimising the risk of a catastrophic accident. The problem was solved if any of the four protective devices respond in all critical transients. If not, the pressure transient peaks would exceed the design limit of 900 m pressure head. Both wicket gates and penstock spherical valves were constructed to prevent runaway in these dangerous unstable transient operating points [18].

In this example the client’s designers identified the dangerous phenomenon. The manufacturer verified this instability and the control system were altered to prevent two units simultaneous runaway catastrophic case. Probability that four protecting devices – two spherical valves and two guide vanes fail to close is very small. But the risk is still present as the archive does not have the drawings, booklets and manuals.

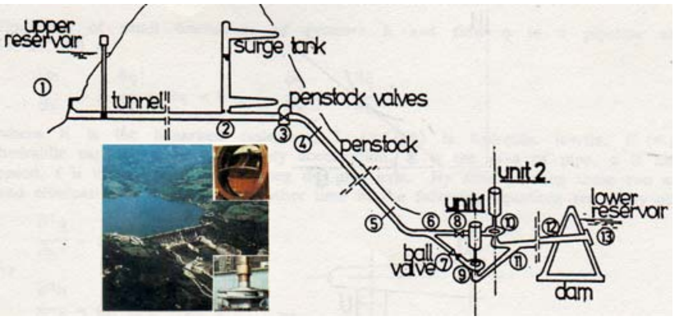

Fig. 1 Bajina Basta pumped-storage plant; two pump-turbines each 315 MW output and pump discharge 51 m^3/s at speed 428.6 rpm; head 600 m.

VI. LAYOUT AND METHODOLOGY

To illustrate the possible causes and origins of specific systems, several cases studies are introduced. The goal is to simply illustrate the range of issues and challenges that so quickly arise in practice, and is not intended to apportion fault or blame on any party or developer. Rather, it is presented to advocate a renewal of collaborative ties and a sharing of expertise across the field. In all cases, the role of the design process, its connection to operation, and the specific role hydraulics (and particularly transients) will be illustrated, and comments are made about the possible value and role of the review process. Space limitations prohibit doing justice to the details of these designs.

The Fig. **2** portrays sixteen bulb turbines each rated at 28 MW, but has large vibrations at high heads starting at the rated head. To reduce investments, the turbine diameter was decreased and the speed of rotation raised flow velocity, increasing vibrations. After 20 years of operation, shaft failure occurred (Fig. 3), and frequently runner blades cracks had to be repaired.

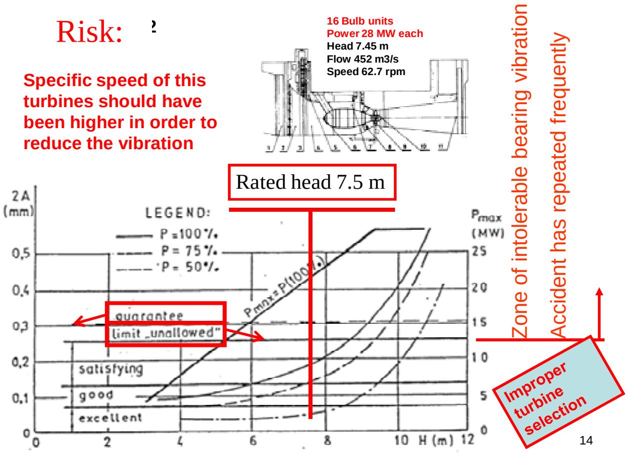

Fig. 2 Sixteen units each 28 MW

A detailed and quantitative analysis should be made for reconstruction, redesign, and adjustment, considering the balance between manufacture and maintenance costs.

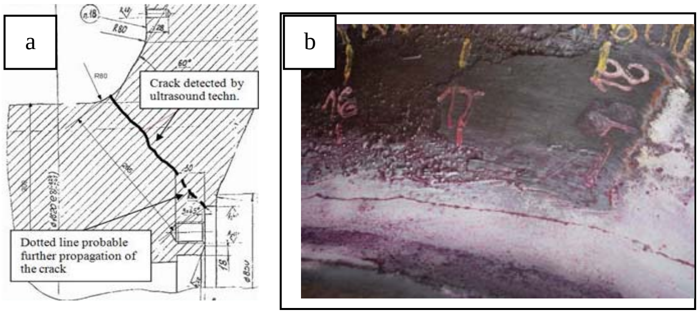

Fig. 3 Horizontal shaft crack; b Shaft to flange transition radius; Damaged protective coating and shaft material crack along the perimeter

The second plant is a big 2000 MW underground structure with eight equal turbines having long tailrace tunnels (Fig. 4). An air injection system designed to prevent the rejoining of the separated water columns in the draft tubes occurring in most transient regimes. Sufficient air must be injected from the beginning of transient behaviour, until the new steady operating conditions stabilize. The draft tube flap gate is carefully designed for the severe vibrations and transient pressure surges. The vortex core should be aerated to extend the life time of the turbines. If having had chance to decide, the submergence would have been increased to prevent reverse waterhammer, and air injected to suppress draft tube vortex core excitations [1], [13], [14], [15], [19], [20].

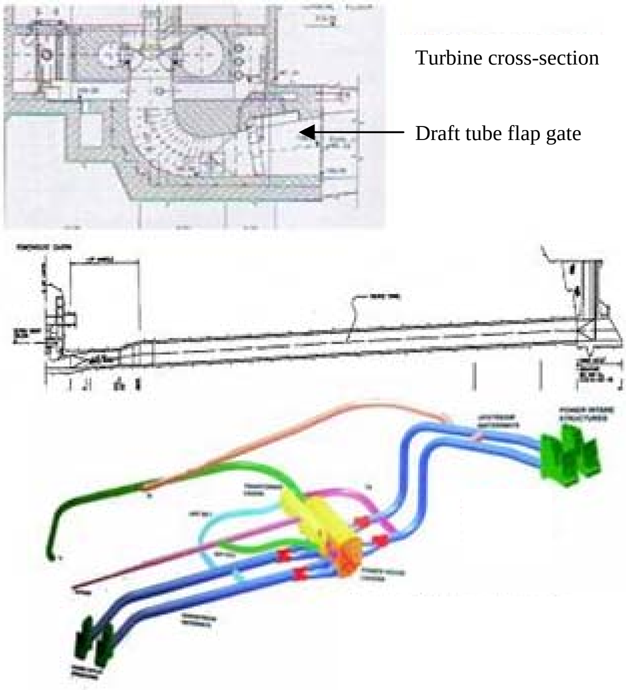

Fig. 4 Power plant under construction; eight unit each 259 MW

The third example is a medium 120 MW plant (**Fig. 5**) under construction. Here model tests of the waterways were deemed extremely helpful to verify and increase the hydraulic smoothness in the approaching flow.

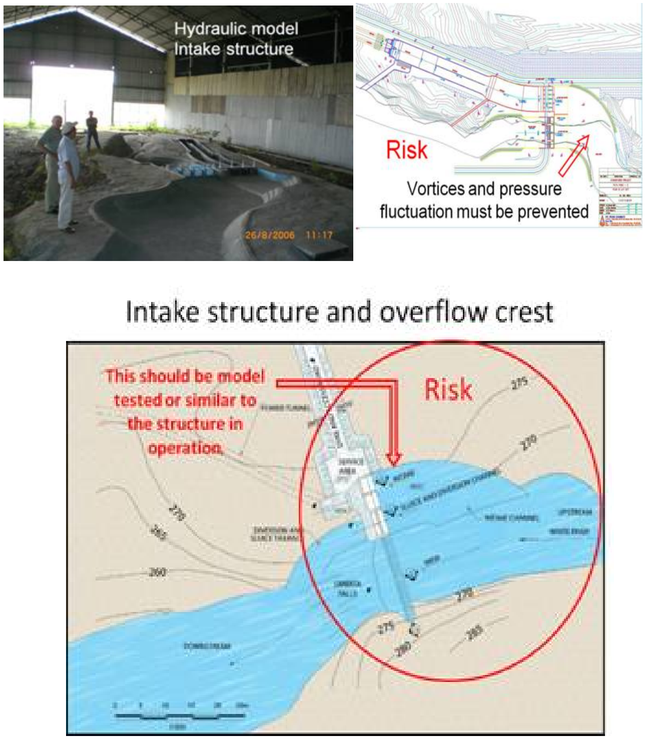

Fig. 5 Powerplant: 3 units each producing 65 MW by verifying important hydraulic model testing

Fig. 6 shows a plant with four turbines and four insufficiently submerged pump-turbines. Based on the available data describing troubles, sources listed in the figure identified and a bid was submitted. The final solution is unknown as the bid failed.

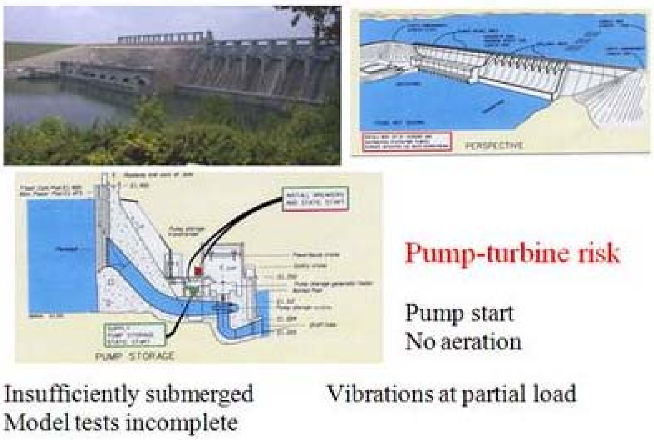

Fig. 6 Four turbines each 78 MW and four pump-turbines each 76 MW

The next example is a small 20 MW plant (Fig. 7) under construction which could be at risk. Based on figures and data origiannlly posted on internet the cause might be high head, big diameter, bulb unit sensitivity to vibrations and/or bend disturbing the inflow into the turbine. We are lead to believe that designers have verified and corrected all issues, highlighting again the value and role of a review process.

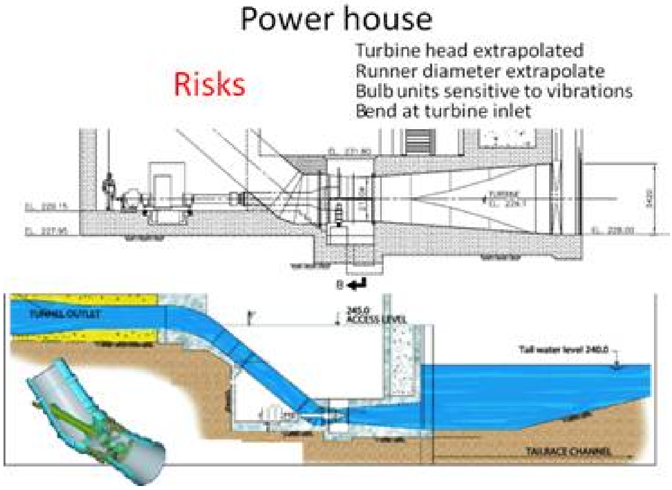

Fig. 7 Small powerplant under construction: two units each 10 MW. Hydraulic constraints must be verified.

And finally Fig. 8 shows a small powerplant under construction which has two units, each rated at 10 MW. The intake structure as yet needs to be verified on the model if the layout has not yet been verified on a similar plant in operation. Data and drawings are replicated from the internet.

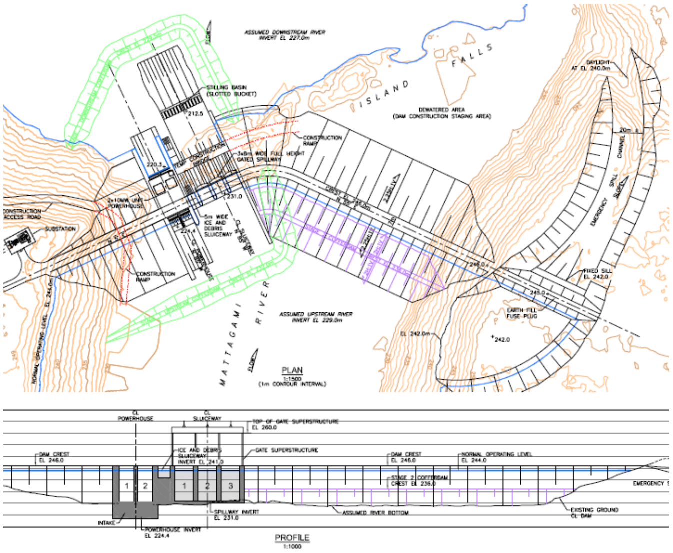

Fig. 8 Small power plant under construction: two units each 10 MW. Hydraulic should be verified.

VII. Conclusions

As has been illustrated from the above case examples, troubleshooting of both large and small hydro installations will almost certainly occur in the field and would thus require experts to provide solutions. Many of these problems, particularly for mini-hydro, are due to incompatible approaches to the design as opposed to large installations. The design at Bajina Basta was a large one and the error was caught due to the review process. Such a process is thus encouraged for smaller installations, perhaps with the aid of codes or guidelines for standard, contemporary or replicable design.

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IX. BIOGRAPHIES

Dr. Stanislav Pejovic was born in Belgrade, Serbia and received his Ph.D. Degree from University of Belgrade. At the Department of Mechanical Engineering he served various positions, and was full professor until 1998. Since 2002 he is teaching at the University of Toronto and Ryerson University, Toronto. He has also lectured on specialized subjects related to energy, thermodynamics, physics, fluid mechanics, design of power plants and hydraulic transient analysis (waterhammer, vibrations, hydraulic vibrations, stability, resonance in technical systems and human blood vessels) as the visiting Professor at the University of Singapore, Hong Kong, Sarajevo and Skoplje, Nis, to name a few. He specializes in design, construction, commissioning, maintenance, troubleshooting and review of electric plants, hydraulic systems, pumps and turbines as well as the complex systems of thermal and nuclear plants. He has designed 27 power plants, 3 test rigs, a number of pumped storage plants and pumping systems; successfully completed hydraulic transient and vibration analysis for 31 large hydraulic machines and systems; developed model acceptance tests of 11 rotating (turbo) machines, field tests of 12, and acceptance tests of 7 power plants an has led numerous final field tests as Chief Engineer. He published 20 textbooks and monographs, as well as over 140 technical papers. He is the author of several books on vibrations, hydraulic transients, and a co-author of: "The Guide to Hydropower Mechanical Design", prepared by ASME Hydro Power Technical Committee, 1996 (new edition is under review), as well as "Guidelines to Hydraulic Transient Analysis", 1992; and 1987. He has acted as consulting engineer on design, construction, on-site and model tests of power plants and computer simulation of transient and hydraulic vibration of many systems. At "Energoprojekt", Belgrade, he designed and tested the highest, at the time, (600 m) head Pumped-Storage Power Plant "Bajina Basta", and a number of other electric power plants and pumping systems; designed the second phase for four small plants "Vlasina" having five units rated at 13 to 16 MW and the pump plant "Lisina" pumping into "Vlasina" storage. He has been involved in troubleshooting in US, Canada, and Iran, and is a licensed Professional Engineer in the Province of Ontario.

Dr. Bryan W Karney is a Professor of Civil Engineer and Chair of the Division of Environmental Engineering at the University of Toronto, where he has worked since 1987. Dr Karney has spoken and written widely on subjects related to water resource systems, energy issues, hydrology, climate change, engineering education and ethics. He was Associate Editor for the ASCE's J of Hydraulic Engineering from 1993 to 2005.

Qinfen Zhang, P.Eng. has been working in hydropower and hydraulic engineering both in China and in Canada for more than 15 years. Specialized in transient analysis and hydraulic design, and published a number of research papers in relevant areas.

Gaurav Kumar is a Research Associate in the Division of Environmental Engineering at the University of Toronto. His primary research focus is on educational, engineering and investment issues in energy supply mix, energy market and storage technologies, and environmental considerations in the context of energy. He is also actively involved with studies on pumped storage and evaluations of its impacts for Ontario.