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Total engineering geology and hydropower development in the Coast Mountains, British Columbia, Canada

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ABSTRACT

The Coast Mountains of British Columbia exhibit features typical of alpine glaciation; steep bedrock bluffs, layers of glacial till or glaciolacustrine sediments on the valley floors and glaciofluvial / kame terrace melt water landforms on the valley shoulders. This already complicated geomorphic model is further complicated by near surface weathering, downhill solifluction and quaternary colluvial / alluvial processes that produce a number of different landforms and, therefore, engineering soil units. The "total engineering geology" approach to investigation, design and construction is used to characterise the geotechnics of a number of hydropower projects undertaken in the region. The investigations for these projects were undertaken in phases with each phase defining the scope, methodology and areas of interest for the next. This methodology maximises the efficiency and quality of the data collected by defining an initial geological / geotechnical model that is continually challenged and refined throughout the life of the project. Engineering geological issues such as geohazards (avalanche, mass movement, liquefaction and floods) are also discussed.

1 INTRODUCTION

The premise of the "total engineering geology" approach to site characterisation is that the ground conditions at any site are a product of their complete geological and geomorphological history. The engineering performance of a site is also dependant on the influence of any engineered works on that site's complete geological and geomorphological history (Fookes et al 2000).

This paper describes the application of the "total engineering geology" approach to run-of-river hydropower projects in the Coast Mountains, British Columbia. It provides a summary of the geological and geomorphological history of the Coast Mountains, the strategy of investigation, the engineering geological information collected and the hazards identified. The central theme of the paper is the development and continual refinement of the geological / geotechnical model throughout the project life and the value that this adds in the project decision making process. Engineered solutions to geotechnical issues are able to be identified and implemented at the correct time in the project's revenue stream.

2 HYDROPOWER DEVELOPMENT IN THE COAST MOUNTAINS

The Coastal Mountains are an unbroken chain of rugged mountains that run the length of British Columbia, Canada. This chain of mountains has provided British Columbia with the catchment, storage (dam, snow and glacial) and topography to ensure a vast supply of clean energy and legacy infrastructure. As with most of the developed world, however, this legacy infrastructure is at or near capacity and the province's energy provider (BC Hydro) is investing in renewable and socially responsible energy projects. An ever increasing number of these projects are run-of-river hydropower schemes.

Run-of-river projects are dramatically different in design, appearance and environmental impact from conventional hydropower projects. There are two main differences. First, there is no water storage other than the limited amount required to submerge the intake pipe. Second, there is no alteration of downstream flows, since all diverted water is returned to the stream below the powerhouse. A typical run-of-river project consists of the following: an intake structure at which water is diverted, a pipeline (or penstock) through which water travels down slope, a powerhouse, and a tailrace where the water is returned to the stream.

3 GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

3.1 Physiography

The Cascadia subduction zone is a very long sloping fault that stretches from mid-Vancouver Island to Northern California and separates the Juan de Fuca and North America plates. The Coast Mountains are more than 100 million years old and were created by compression, heating and uplift associated with the Cascadia subduction zone (Figure 1). They comprise Cretaceous age quartz diorite and granodiorite rocks with moderately spaced and tight orthogonal stress and exfoliation stress relief fractures (Journey and Monger 1994).

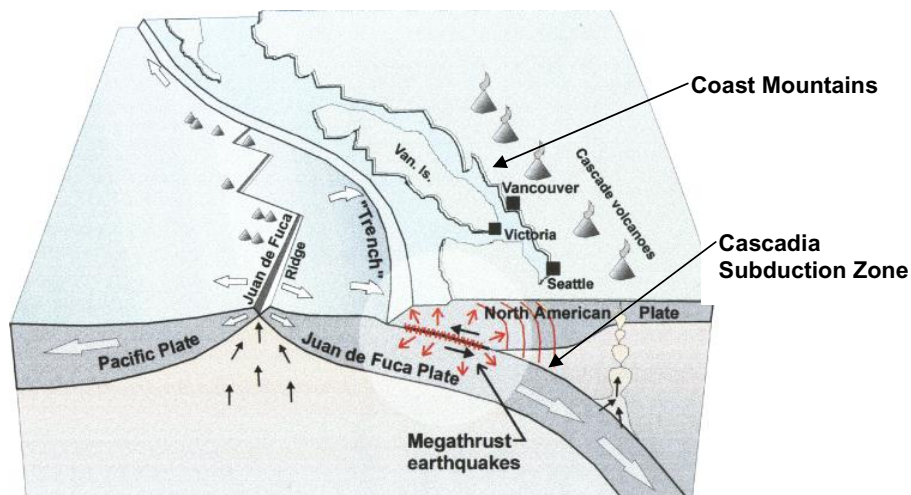


Figure 1: British Columbian tectonic assemblage (Hyndman et al 1996)

During the Pleistocene, the land was heavily loaded with ice and the areas near the coast were submerged below sea level. The uplands have matterhorn (arret) forms produced by well-developed cirque glaciation and the peaks and ridges below about 2000m elevation are rounded and subdued by the effects of ice-sheet erosion. Valley walls have been steepened and spurs truncated, resulting in typical U-shaped profiles and numerous talus and scree-block slopes. The slopes below 1400m are heavily forested and scenic features of glacial origin, such as cirques, hanging valleys and over-steepened slopes, are common.

3.2 Glaciation and surficial geology

The surficial geology of the Coast Mountains is characterised by the multiple episodes of glaciation and deglaciation that occurred during the Pleistocene. In particular, it is the most recent cycle of glaciation that has produced the current landscape. Outwash and ice-proximal sediments consist of a complex of materials that range from till to glacial fluvial, glacial lacustrine and outwash sediments.

Following deglaciation, fluvial and mass wasting processes redistributed glacial sediments to their present day distribution. Today, the Coast Mountains exhibit features typical of alpine glaciation; a layer of glacial till blanketing the valley, colluvium (including talus) originating from soil and exposed rock at higher elevations, glacial-fluvial and kame terrace melt water landforms on the valley shoulders and alluvial deposits accumulating in the valley bottoms. This geomorphic model is further complicated by near surface weathering, downhill solifluction and mass wasting producing a number of different landforms and engineering soil units (Bichler et al 2002).

4 DEVELOPMENT AND APPLICATION OF THE ENGINEERING GEOLOGY MODEL

The run-of-river hydropower projects the authors were involved in were undertaken in an Engineered Procured Construct (EPC) environment. The "total engineering geology" approach was

very effective in this project delivery mode as the engineering geologist / geotechnical engineer could influence significant project decisions for a relatively modest time and capital investment.

4.1 Engineering geology model development - staged assessment

The central theme of the "total engineering geology" approach is that the geological / geotechnical model is continually refined throughout design and construction; either as the design evolves or as more ground is opened up during construction. Value is added at each stage of inspection or investigation and each subsequent stage is designed to resolve outstanding issues identified earlier (i.e. each stage of investigation defines the scope, methodology and areas of interest of the next). Figure 2 presents a summary of the project methodology and the objectives for each stage of investigation / assessment.

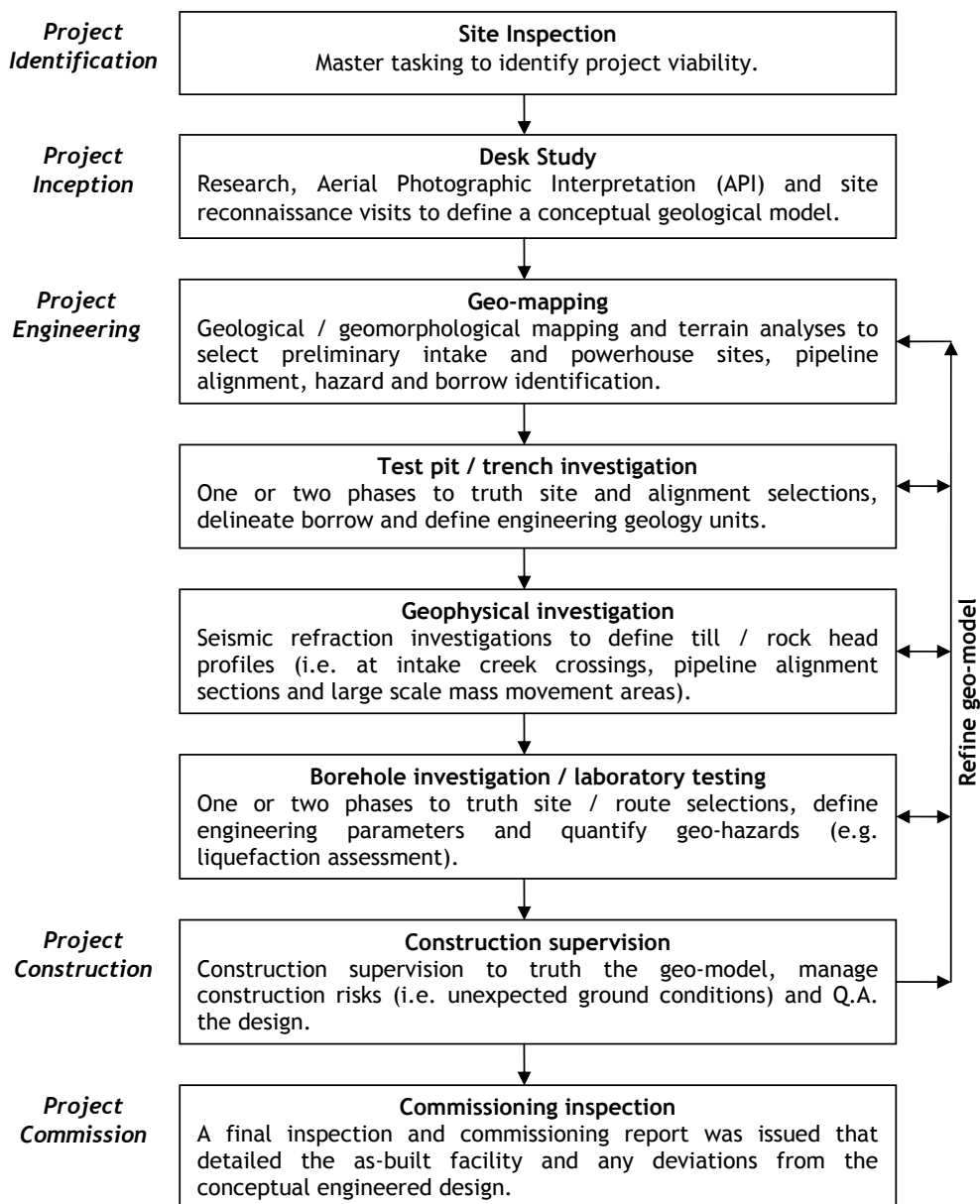


Figure 2: Total engineering geology project methodology - hydropower investigations

As stated in Fookes et al (2000) and Baynes et al (2005), geological and geomorphological mapping is a critical aspect of the total engineering geology approach. The authors also found that, in terms of cost benefit, it was the most economical

4.2 Engineering geology model application - design and construction

The function of the engineering geology model is to baseline the geological and geotechnical information for each engineering geology unit. This information was presented as a "reference condition" that defined a unit's origin, stratigraphic position, material description, engineering description and anticipated engineering performance. Reference conditions provided the baseline geotechnical data required to design the project.

Specific design and construction objectives for run-of-river hydropower projects were defined as follows:

- Identify intake weir and powerhouse sites. Variables include foundation conditions, geo-hazards and hydraulics.
- Design hydraulic structures (earth embankment dams, intake/powerhouse flood protection and penstock stream crossings).
- Optimise penstock alignment. Variables include hydraulics, vertical and horizontal alignment, geo-hazards, penstock restraint and constructability.
- Design cut / fill batters (intake-weir structure, penstock route and powerhouse tailrace).
- Identify and reduce geo-risk (mass movement, hydraulic and seismic hazards).
- Identify and quantify construction materials.
- Supervise construction to truth the engineering geology model.

4.3 Engineering geology model application - reporting

As the engineering geology model was continually refined throughout the projects lives, reference conditions were not finalised until the end of construction. In order to facilitate the transfer of information to allied engineering disciplines, geotechnical design and construction data was presented as follows:

4.3.1 Design Basis Report

Information derived from the desk study, API and preliminary site inspections was presented in the Design Basis Report (DBR). This report contained the site tectonic, geological and physiological setting in addition to climatic, hydrologic and pre-feasibility engineering designs. The DBR contained the initial engineering / geotechnical model for the sites.

4.3.2 Geo-mapping and intrusive investigations

Extensive geological / geomorphological mapping and terrain analyses (Howes and Kenk 1997 methods) of the intake, penstock route and powerhouse were undertaken. Mapping methodologies, maps and implications for design were presented in a terrain analysis report.

The results of the geophysical, test pit, borehole and laboratory testing investigations were presented in a factual report. The factual report elaborated further on the engineering geology model provided in the DBR and reference conditions for each engineering geological unit were defined. The factual report was a live document that went through a number of revisions as each investigation stage better characterised the site.

4.3.3 Specialist Reports

Specialist design reports were produced for specific structures requiring analysis and design. Design reports were produced for the powerhouse, intake weir and penstock. Specialist reports or memos were also produced during the design and construction supervision stages to proof the engineering geology model and provide engineered solutions to anomalous conditions. Examples include mass movement stabilisation requirements, penstock liquefaction risk assessments and penstock flood protection designs.

5 GEOLOGICAL / GEOTECHNICAL HAZARDS

Geological and geotechnical hazards are high risk areas for any project. One of the primary engineering aims of these projects was to identify and reduce these risks. Geological and geotechnical hazards are described below:

5.1 Mass movement hazards

Slope instability was prevalent in the oversteepened glaciated terrain. Mass movement hazards included the following:

- Shallow translational failures: common on poorly developed shallow soils overlying steep bedrock slopes. This type of instability was widespread in glaciated and fluvial terraced terrains, particularly where undercut by stream erosion. Regressive translational failures were identified to be a high risk element and, therefore, penstock alignments were located away from oversteepened creek banks or identified failures (active or relict).
- Rock falls: common on oversteepened bedrock slopes in glaciated terrains. Evidence of rock falls were observed along many of the proposed penstock routes and critical structures were located outside of any rockfall impact or runout zones.
- Debris flows / cones: this type of instability is also common in glaciated terrain. Risk reduction techniques comprised setting the vertical alignment at a depth below that of the debris flow scour depth. Critical elements of infrastructure were either located outside of debris flow risk areas or protected by riprap deflection barriers.

5.2 Hydraulic hazards

Hydraulic hazards were significant in the project areas as the rivers and creeks are characterised by high gradients and energy regimes. Hydraulic hazards included the following:

- Gully Erosion: deeply incised erosive creek beds were often associated with debris and avalanche flow areas. Significant gullies were stabilised with keyed-in engineered riprap.
- Flood: highly destructive flash flooding events are common in the Coast Mountains, particularly during the spring freshet. Individual flood assessments were undertaken for the intake weir, powerhouse and any substantial stream crossings in order to design adequate flood protection measures. These measures typically included riprap protection and, where possible, channel modification.
- Sediment transport: sediment and drainage control measures such as silt fences, hay bales and settling ponds were utilised during construction to prevent excess stream turbidity.

5.3 Seismic and other hazards

Other hazards included the following:

- Seismicity: the southern Coast Mountains are situated in a region where the level of seismic activity has, historically, been low. There is, however, potential for large earthquakes within south-western B.C.; these can be either crustal earthquakes within the continental North American Plate or earthquakes associated with the Cascadia subduction zone (Adams et al 1990). A seismicity assessment was undertaken for each project. The design basis earthquake for each site was used in the design of hydraulic and non-hydraulic earth embankments, intake structure retaining walls and powerhouse foundations.
- Liquefaction: normally to slightly over-consolidated glacial fluvial, kame terrace, recent alluvial and colluvial sediments were often encountered along the penstock alignment and at a number of the powerhouse sites. Where saturated and forming structural foundations, these sediments represented a hazard. Critical elements of infrastructure were sited outside of these zones.
- Snow Avalanches: avalanche tracks were readily identifiable during the API and site inspection stages. Critical elements of infrastructure were sited outside of these zones.
- Problem Soils: soft/loose colluvial soils presented potential bearing capacity and / or stability hazards. Geo-mapping and intrusive investigations delineated problem soils and a cost benefit analysis was undertaken to evaluate the feasibility of alignment change or ground improvement.

6 CONCLUSIONS

This paper describes the application of the “total engineering geology” approach to quantifying the geotechnics and hazards of a number of run-of-river hydropower projects in the Coast Mountains of British Columbia, Canada. The Coast Mountains are characterised by complicated and variable

glacial terrain that has been significantly modified by quaternary processes. This produces a highly variable and complicated engineering geology model and a challenging set of geo-hazards.

The premise of the paper is that the engineering geology model is continually developed and refined throughout the project life. Value is added at each stage of investigation with each subsequent stage being scoped to resolve outstanding design and construction issues. The "total engineering geology" approach provided the authors with a systematic methodology of investigation and design that added considerable value in defining the site conditions, identifying and mitigating geo-hazards, but most significantly, in influencing project decisions at the correct time in the design schedule and project revenue stream. The "total engineering geology" approach allowed the authors to more ably present the potential cost/benefit of significant project decisions to the client.

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