LANDSLIDE RISK MANAGEMENT AT BC HYDRO

Experience with Landslide monitoring and drainage
PRESENTATION OVERVIEW

1. BC Hydro - Overview

2. Landslide / Reservoir Slopes Program

3. Landslide Case Histories
   - Downie Slide
   - Dutchman’s Ridge
   - Revelstoke Dam

4. BC Hydro Experience – Lessons Learned
1. About BC Hydro

BC Hydro is a “Crown” (State-run) corporation, established in 1961, owned by the Province of British Columbia and regulated by the British Columbia Utilities Commission (BCUC), an independent body.

- one of North America’s leading providers of clean, renewable energy
- largest electric utility in British Columbia
- approximately 1.8 million customers
- serves about 95 per cent of the province’s population

Capacity

- 43 dam sites - 11,300 megawatts (MW) installed capacity
- 97% of generation based on clean, renewable hydroelectricity
- BC Hydro customers enjoy some of the world's lowest electricity rates

Transmission

- 18,600 kilometres of transmission lines
- 57,278 kilometres of distribution lines
BC HYDRO DAMS – GEOGRAPHIC CONTEXT

1. Aberfeldie Dam
2. Alouette Dam
3. Bear Creek Dam
4. Buntzen Dam
5. Cheakamus Dam
6. Clayton Falls Dam
7. Clowhom Dam
8. Comox Dam
10. Coursier Dam (decommissioned)
11. Duncan Dam
12. Elko Dam
13. Elliott Dam
14. Elsie Dam
15. Falls River Dam
16. Heber Diversion Dam
17. Hugh Keenleyside Dam
18. John Hart Dam
19. Jordan Diversion Dam
20. Kootenay Canal Dam
21. La Joie Dam
22. Ladore Dam
23. Mica Dam
24. Peace Canyon Dam
25. Puntledge Diversion Dam
26. Quinsam Diversion Dam
27. Quinsam Storage Dam
28. Revelstoke Dam (1985)
29. Ruskin Dam
30. Salmon River Diversion Dam
31. Seton Dam
32. Seven Mile Dam
33. Spillimacheen Dam
34. Stave Falls Dam
35. Strathcona Dam
36. Sugar Lake Dam
37. Terzaghi Dam
38. W.A.C. Bennett Dam
39. Wahleach Dam
40. Walter Hardman Dam
41. Whatshan Dam
42. Wilsey Dam
43. Site C - current
2. BC Hydro – Landslide Program

8 of 15 monitored landslides in this area
3. Upper Columbia - Landslide Factors

- Large topographic relief (3500 m+)
- Steep slopes (20° – 60°)
- Adverse geologic conditions (continuous structures: faults, foliation)
- Extensive precipitation 1500 – 2000 mm/yr
3. Landslide - Drainage Case Histories

- Dutchman’s Ridge
- Downie Slide
- Revelstoke Dam

All on west side of Columbia Valley.
All structurally controlled along foliation/shears.
Precedent for large, rapid rock slides (2 in last 200 yrs).
Moderate seismic zone (pga ~ 0.3 g).
DOWNIE SLIDE - OVERVIEW

- Identified 1950’s
- Extensively investigated (1965-present)
- 1.5 B m³ (9.5 km² x 250m deep)
Downie Slide – Key Dam Safety Issues

1. Landslide generated wave - Dam over-topping – dam breach

2. Reservoir blockage

3. Dam flooding (Mica)
Figure 1: Key physiographic features of Downie Slide; bounding scarps and steep bulging toe.

- Dam Approval linked to Downie Stabilization
- Extensive Public Consultation and review process
- Drainage selected
- “to more than offset filling of reservoir”
Downie Slide – Geologic Section

- Detailed geologic model required for drainage design

Drilling - Monitoring installed
- Geology  
  - Mica schist/gneiss; continuous structures
- Groundwater  
  - Multiple water levels
- Movement  
  - Slowly moving (3 to 200 mm/yr)
  - 20-25° downslope dip

(on 2 main surfaces)
Downie Slide – Drainage Program

- Adits - constructed using “Observational” approach (piezometers)
Downie Slide – Drainage Program

- Head scarp identified in the 1950s.
- 1.5 billion m³ of material.
- Slowly moving (3 to 200 mm/year).
- Drainage program from 1974 to 1982.
- Extensive Adit and Drainage System (ADAS) issues:
  - Overtopping wave
  - Reservoir blockage
  - Impact to reservoir users

Drainage Adit

- Adits primarily in slide mass.
- 2.45 km of adit.
- 24,000 m of drain holes.
Conventional drill and blast; “horseshoe” shape; extensively supported
1. Significant drainage effects – up to 100 m pressure reductions
2. Met initial objective but increasing pressure trends observed
3. Additional drainage required (2007-08)
1. Most piezometers encountered “perched” water levels
2. Water typically perched above the 2 active zones
3. Piezometers below slide base could indicate “dry” conditions
Slope displacement response to drainage, measured across lower slide plane:

1. Slight reduction following drainage (5 > 3 mm/yr)
2. Increase during reservoir filling (10 mm/yr)
3. Relatively consistent post reservoir fill (2 – 3 mm/yr)
Downie Slide – Summary

1. Groundwater levels reduced to below pre-reservoir levels

2. Displacement rates are similar or less than pre-reservoir conditions

3. Stability increased by ~ 7% (FOS)

4. Water License Requirement – must maintain system
BC HYDRO LANDSLIDES – Mica Dam

Mica Dam - 250 m high earthfill dam

The most upstream of 14 dams on Columbia River

Major upstream landslides
Dutchman’s Ridge Potential Slide

- Identified mid-1960’s (airphotos)
- 1969 drilling
- 30 M m³
- Physical wave model studies (50 m+ waves)
- Dam construction revised to accommodate slide waves
- Decision **not** to drain
Dutchman’s Ridge - Displacement

1. Pre-reservoir – negligible displacement detected

2. Reservoir filling (190 m) – initiated movements of 25 mm/yr

3. Slope displacement acceleration resulted in decision to further investigate

Slope displacement response to reservoir filling (pre-drainage)
Dutchman’s Ridge – Investigations

Geological Model (Updated):

- Well defined continuous basal sliding surface
- Depth of sliding – 75 to 150 m
- Movements of up to 200mm occurred during reservoir filling
- 115 M m3 (~4x original)

Analyses concluded:
- Raising of reservoir reduced stability by ~ 10%
- Large, first time slide possible
- Remediation preferred – drainage option selected
Dutchman’s Ridge Slide - Reservoir

- 1969 estimate of slide volume 30 M m³
- Post-reservoir re-evaluation (1982)
- Slide size reassessed 115 M m³
- Additional analyses (larger wave)
- Decision to install drainage system
Relevance of Dutchman’s Ridge – Aknes

Similarities:
- Size
- Geology
- Setting
- Landslide wave hazard
• Extensive monitoring system installed (350 measurement ports):
  ➢ To identify where water pressures could be drained
  ➢ To evaluate effectiveness of drainage system
Most drill holes showed “perched” water levels. Testing allowed optimum design of piezo installation.
Dutchman’s Ridge – Piezo Testing

Piezometric testing during drilling
Custom “through-the-drill-string” set up
Reliable – no issues with getting stuck
Data immediately available
982 m of Adit installed (1986-88); 20,000 m of drainholes
1. Large portions of potential slide fully drained.
2. Up to 100 m pressure drawdown – lasting effect.
Dutchman’s Ridge - Displacement

Inclinometer – Across Slide Base

Pre-drainage ~15 mm/yr

Post-drainage 0.5 mm/yr

Slope displacement response to drainage - rate reduced by > order of magnitude
Flow rates have reduced but pressures have remained “fully drained”
Dutchman’s Ridge – Compared to Downie

- Smaller slide mass - easier to effectively drain
- Single sliding plane (DMR) vs two + planes (Downie)
- Slightly better rock quality – less previous slide displacement
- Adit below slide in competent rock
- Nearly “fully” drained condition – effectively halted movements
Revelstoke Dam – Marble Shear Block

- 175 m high concrete gravity; with earthfill wing dam
- 1985 dam completion
- Slope instability on right bank (Marble Shear Block) 200,000 m$^3$
- Potential to undermine spillway; block tailrace
Marble Shear Block - Geology

1. Quartzite / Mica Gneiss
2. Persistent planes of weakness (foliation / shears) dipping down slope
3. Considerable groundwater

Risk Management
1. Risk to spillway / discharge facilities considered unacceptable
2. Drainage selected as remedial option
Marble Shear Block – Drainage

1. Spillway Structure
2. Sliding Plane
3. Adit (40 m long)
4. With ~1000 m of drainholes
1. Significant pressure reductions (up to 15 m) from drainage
2. Remedial effects are persisting over 15 years – lasting results
1. Minor displacement prior to drainage installation (2mm/yr)

2. Drainage 1998-99

3. Slope displacement effectively stopped following drainage
LANDSLIDE REMEDIATION THROUGH DRAINAGE

Lessons Learned – Summary:

1. Drainage has been effective – objectives achieved

- Dewatering /depressurizing
- Displacement reduced/stopped
- Improved stability (5-10% FOS)
LANDSLIDE REMEDIATION THROUGH DRAINAGE

Lessons Learned – Summary:

2. Well positioned monitoring system required (plan/evaluate)

Need to understand where water is located. Detailed site investigation and monitoring required. Needs to be installed before drainage.
LANDSLIDE REMEDIATION THROUGH DRAINAGE

Lessons Learned – Summary:

3. Well positioned monitoring system required (plan/evaluate)

1. Need to conduct *in situ* testing during drilling to understand where water is located –
2. Identifies perched zones and downhole gradients that are otherwise missed
3. Allows planning for permanent piezometric monitoring.
4. Use of multi-port type piezometers highly effective (i.e. “Westbay” type).
LANDSLIDE REMEDIATION THROUGH DRAINAGE

Lessons Learned – Summary:

4. Drainage response typically confined to treated area only
LANDSLIDE REMEDIATION THROUGH DRAINAGE

Lessons Learned – Summary:

5. Plan for maintenance – successful results come from long-term commitment

- Lighting, ventilation, power supply
- Drainhole replacement (cleaning ineffective)
- Requirement to install additional monitoring
- Rock support
LANDSLIDE REMEDIATION THROUGH DRAINAGE

Questions / Discussion?
BRITISH COLUMBIA – NORWEGIAN CONTEXT

British Columbia
944,735 sq. km
1900 km long
505 km wide
Mountainous
Lots of snow
Lots of fjords
3% of population of Norwegian descent

Norway
304,282 sq. km
1347 km long
304 km wide
Mountainous
Lots of snow
Lots of fjords