Slope Stabilization of a Section of the Welland Canal

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Outline of Presentation

- History and Background
- Site Description and Subsurface Conditions
- Ground and Structure Movement Summaries
- Remedial Measures
- Analysis and Design Criteria
- Performance
- Construction
History and Background

- Constructed from 1913 to 1933
- Marginal stability and slope failures
- Movement and repairs to main pier foundations
- West bank and west main pier of Bridge 4 focus of presentation
Canal Excavation History

- Started in 1913 with 2H:1V cut slopes
- East bank failed in 1917
- Flatten slopes to 3H:1V
- West bank failed in 1921 near Bridge 4
  - Buried 85 ton shovel
- More failures between 1922 and 1924
- Widening (berm profile) in 1925 and 1926
- Several slides between 1928 and 1933 in vicinity of Bridge 4
Canal Excavation History (cont)

- Canal deepened 0.6 m in 1957
- More slope failures – stabilized by rockfill toe berms
- In 1989 upper banks cut back and Bridge 4 lengthened
- In 1996 significant slope movement observed in SI during dewatering
- In 1999 slope failure immediately north of Bridge 4
Bridge 4 History

- Important transportation link
- Clear span of 60 m with total length of 190 m
- Timber pile foundation
  - 1913 to 1926 construction
  - failure in 1917 (east pier moved 3 m)
  - east pier foundation reconstructed by 1920
  - 1926 additional piles driven to support new double-leaf bascule bridge
  - caused west main pier to move
  - jacked piles to refusal
Bridge 4 History (cont)

- Bridge structure construction 1927 to 1928
- In 2000 bascule jaws binding and substantial wear
- Estimated movement (closure) of 30 mm
- Bridge superstructure in satisfactory condition
Bridge 4: circa 1930 - 1940
Canal Operation

Season from April to December

Drained every few years in off-season or as required for maintenance
Geotechnical Investigation

Field:
- 20 sampled boreholes & field vanes
- 25 CPTs
- 5 PMTs
- 5 slope indicators

Laboratory:
- index and classification
- oedometer
- triaxial
- direct shear
Site Stratigraphy

- 6 m sand and gravel (upper banks)
- 20 m soft to stiff silty clay
- 2 m very stiff clayey silt
- 5 m very dense sandy silt till
- shale bedrock – Queenston Formation
  - upper 1 m weathered
Silty Clay Deposit

- undrained shear strength: 20 to 60 kPa
- water content: 20 to 42 %
- liquid limits: 33 to 47
- plasticity index: 15 to 25
- OCR: 1.3 to 1.9
  - weakened zones: 15 kPa close to bridge
- \( \frac{S_u}{\sigma_p} \): 0.19 - 0.30
- effective friction angle: 22 to 26°
- effective cohesion: 20 to 0 kPa
- Cone Factor \( (N_k) = 19 \)
Silty Clay Weak Zones

- Within silty clay exist pre-shear (weakened) zones as a result of past slope failures / ground movement
- Confined to within lower bank above base of canal
- No deep weakened zones
Stability Analysis

- Slope/W – Morgenstern-Price

- Back Analysis:
  - original construction
  - 1999 failure (lower bank)
  - localized lower bank (weakened zones)

- Canal bank only marginally stable at low canal level

- Design Analysis:
  - lower bank (with wall) stability
  - overall bank stability
### Summary of Stability Analyses

<table>
<thead>
<tr>
<th>CASE</th>
<th>FS</th>
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<tbody>
<tr>
<td>Original</td>
<td>2H:1V</td>
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<tr>
<td></td>
<td>≤ 1.0</td>
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<td></td>
<td>3H:1V</td>
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<td></td>
<td>1.38 canal filled</td>
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<tr>
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<td>1.15 canal empty</td>
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<tr>
<td>January 1999 Failure</td>
<td>&gt;2 (average undisturbed strength Su = 45 kPa)</td>
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<tr>
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<td>&gt;1.6 (lower bound Su = 35 kPa)</td>
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<tr>
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<td>1.0 (Su = 15 to 20 kPa - close to remoulded)</td>
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Slope Indicator Readings

- Monitored ground and pier structure movements since 1986
- Slope moved laterally by as much as 230 mm as a result of cycles in operational canal water levels
- Pier movement essentially elastic
  - Permanent plastic deformation of 3 mm to 6 mm in 15 years
- Pier movement due to ground movement adjacent to pier
West Bank Movements

History of Slope Indicators 52 and 53
6 m depth

Profile of Slope Indicator 52
Pre and Post 1999 Slope Failure

1999 Slope Failure

East (towards canal)
West Pier Movements

History of Slope Indicator 64
6 m depth

Response of Slope Indicator 64
after 1999 Bank Failure
Possible Remedial Measures

- Minimize number of canal dewatering cycles
- Soil Reinforcement:
  - micro-piles on both sides adjacent to west main pier
    - 600 piles 20 m long
    - $2.5 M
- Structural Wall:
  - anchored caisson wall on both sides adjacent to west main pier
    - 100 m total length: 30 m deep
    - $2.7 M
Conceptual Plan – Scheme 1
Pile Reinforced Soil and Slope Regrading
Reach 2 Feasibility Study, Welland Canal
Conceptual Plan – Caisson Wall – Scheme 3
Reach 2 Feasibility Study, Welland Canal
Figure 8 – Plan view of Caisson Wall System.
Caisson Wall

- 54 m on north side and 69 m on south side of Bridge 4
- 1.07 m diameter – 159 piles in total
- H-piles at 1.5 m spacing to top of weathered bedrock – 80 piles in total
- Filler piles to 15 m depth (≥ 3 m below observed weakened zones) – 79 piles in total
Caisson Wall (cont)

- Designed to be “stiff”:
  - maximum deflection of 15 mm at top of wall and 3 mm at base of canal
- Anchorage Caissons at 3 m spacing
  - total of 41 caissons, 1.22 m diameter
  - placed to top of fresh bedrock
Earth Pressures on Wall

- Conventional analysis
- Wall friction considered
- Both short- and long-term conditions analysed
- Canal in dewatered state basis of design
- Undrained condition governed design
  - lower net lateral pressure
  - representative of repeated canal dewatering cycles
Earth Pressures on Wall (cont)

Lateral Net-Pressure Diagram

- Pressure (kPa)
- Elevation (m)
- Net Pressure - short term (kPa)
- Net Pressure - long term (kPa)

- Caisson wall
- Ground surface
- Groundwater level
- Silty Clay
- Clayey Silt
- Sandy Silt (Till)
- Bedrock
Anchors

- Anchored into shale bedrock
- Approximately 40 m free length (FREEL)
- 6 m bond length in shale bedrock (BONDL)
- Allowable bond stress:
  - 350 kPa in shale bedrock
- Anchor load of:
  - 600 kN – proof tests
  - 900 kN for performance tests
Anchors (cont)

- All anchors satisfied performance specification:
  - elongation: > 60% of elastic elongation of FREEL
  - < 100% of elastic elongation of (FREEL + 0.5x BONDL)
  - creep not exceed 2 mm during final time log cycle
Anchors (cont)

- Measured elongation
- Theoretical min elongation
- Theoretical max elongation

Graph showing elongation (mm) versus load (kN).
Tieback Pile and Caisson Wall Performance

- Lateral movement monitored during anchor testing

- At 900 kN (150% design load):
  - tieback pile moved 17 mm to 27 mm (westward)
  - Tieback pile movement to 8 m depth
  - top of caisson wall moved 4 mm (westward)
  - movement to 8 m depth
Tieback Pile and Caisson Wall Performance (cont)

- At 600 kN (design load) after 5 days
  - tieback pile rebounded 2 mm
  - top of caisson wall moved additional 2 mm westward (6 mm)

- After 9 months caisson wall net westward movement (± 3 mm)
History of SI-52 and SI-53 at 6 m Depth
History of SI-64 at 6 m Depth (East-West Direction)
History of SI-64 at 6 m Depth (North - South Direction)
SI-64 Profile for Complete Canal Dewatering Cycles
Construction Highlights

- Constructed between November 2001 and February 2002
  - Total cost of CAN $2.4 Million
  - Canal dewatered December 2001 for maintenance
  - Wall portion completed prior to dewatering to minimize risk of bank / pier movement

Anchorage Caissons south of Bridge

- Construction carried out along west bank
  - No disruption to Canal operations
  - Equipment not placed on lower slope where shear strengths as low as 15 kPa exist
  - Toe berms along lower slope maintained

- Lower slope in front of wall regraded after wall in place to improve stability
Project Participants

- **SLSMC (Seaway):** Owner
  - Mike Whittington, P.Eng.
  - Rudy Lee, P.Eng.

- **Golder Associates:** Prime Consultant
  - Dennis Becker, P.Eng.
  - Dan Breeze, P.Eng.
  - Andrew Walker, P.Eng.

- **Isherwood Associates:** Caisson Wall Design
  - Nadir Ansari, P.Eng.
Project Participants (cont)

- Delcan Corporation: Bridge Structure
  - Tim Wright, P.Eng.

- Deep Foundations Contractors Inc.: Contractor
  - Bill Starke, P.Eng.
  - Ross Maltman, P.Eng.
  - Ken Dawson
  - Edward Kolakowski