Slope Stabilization of a Section of the Welland Canal

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Outline of Presentation

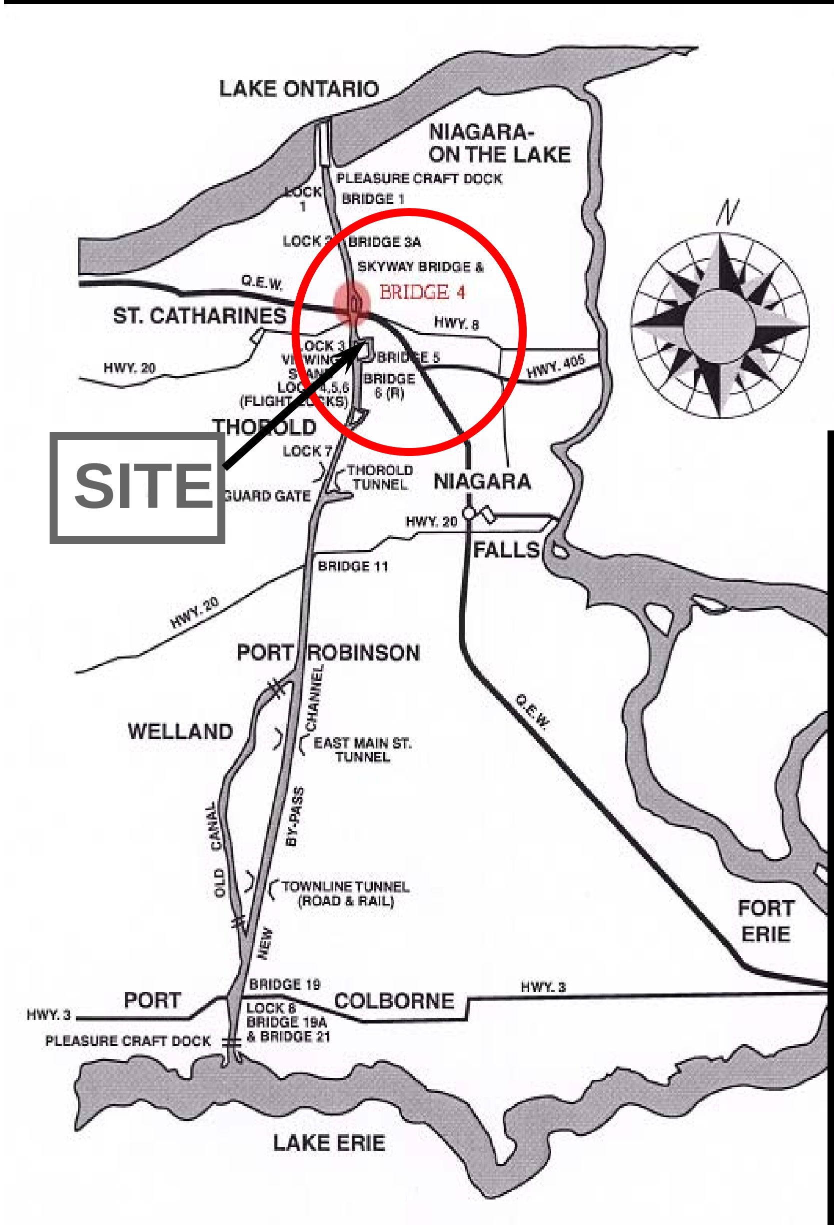
- History and Background
- Site Description and Subsurface Conditions
- Ground and Structure Movement Summaries
- Remedial Measures
- Analysis and Design Criteria
- Performance
- Construction


CANADIAN MINER

Map


CANADA
NORTH
Lake Superior
Welland
Canal
St. Lawrence River
Lake Michigan
Lake
Huron
Lake Ontario
Lake Erie
UNITED
STATES
Atlantic Ocean

Site Location

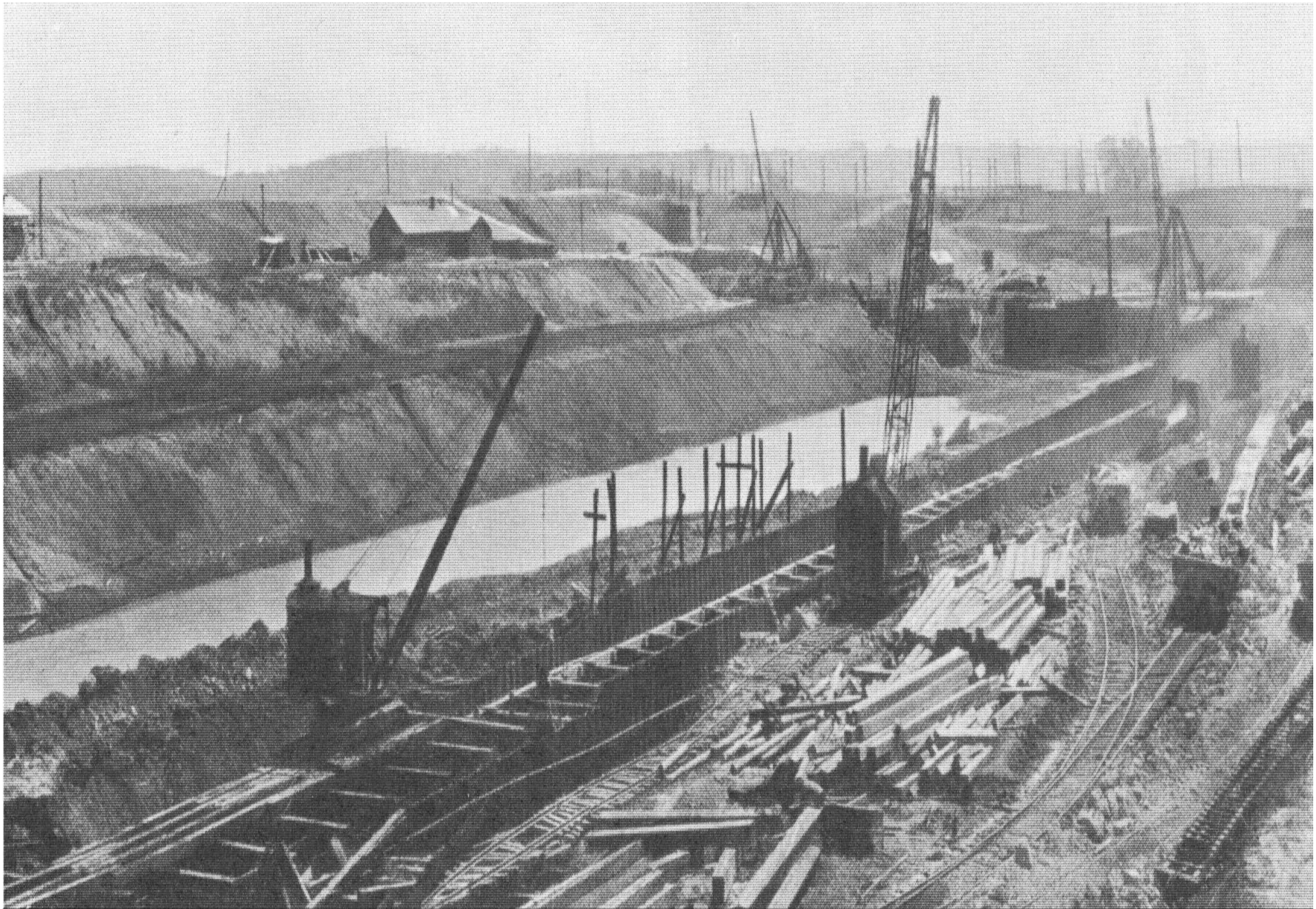


History and Background

- 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



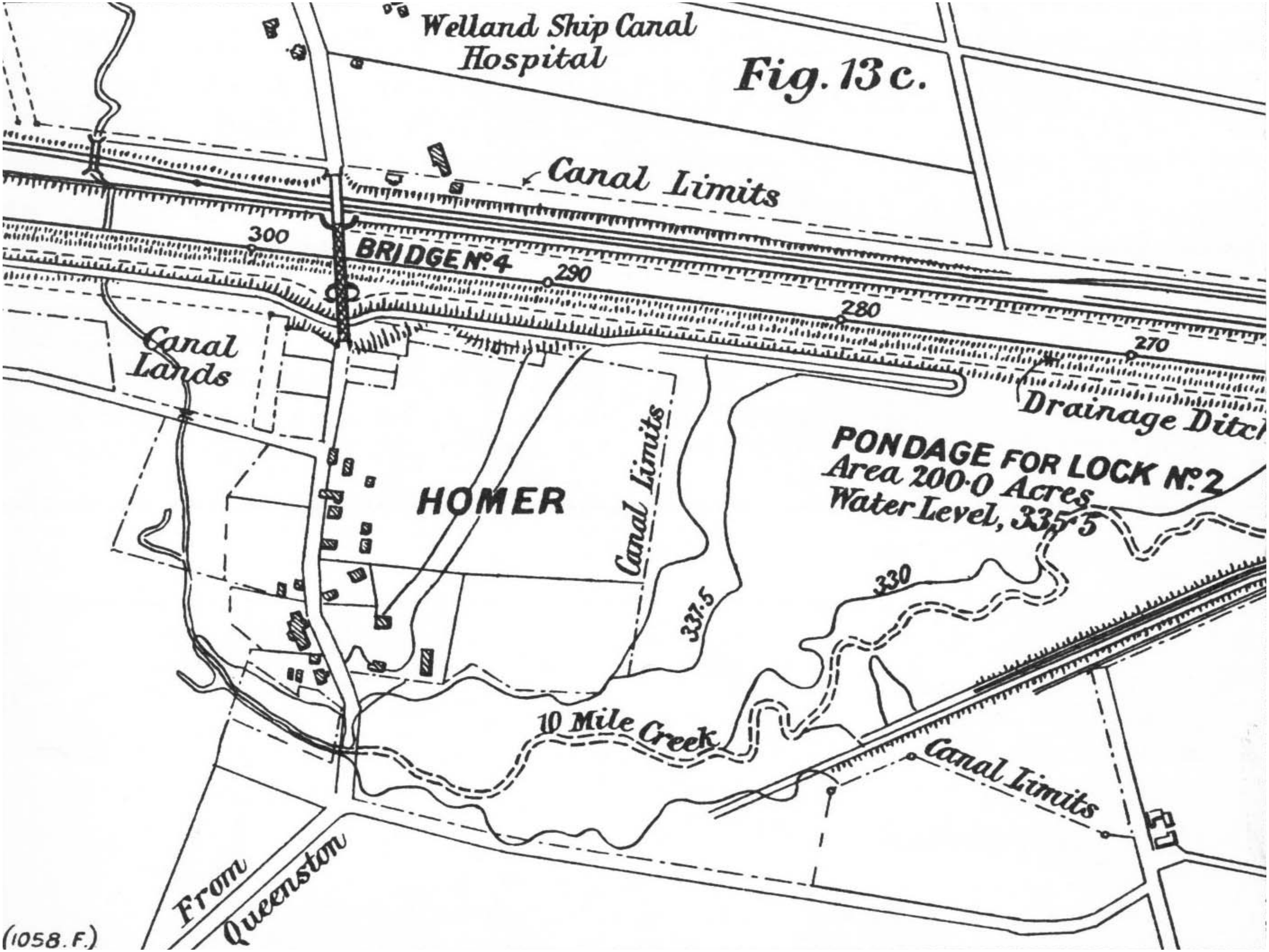


Fig. 13 c.

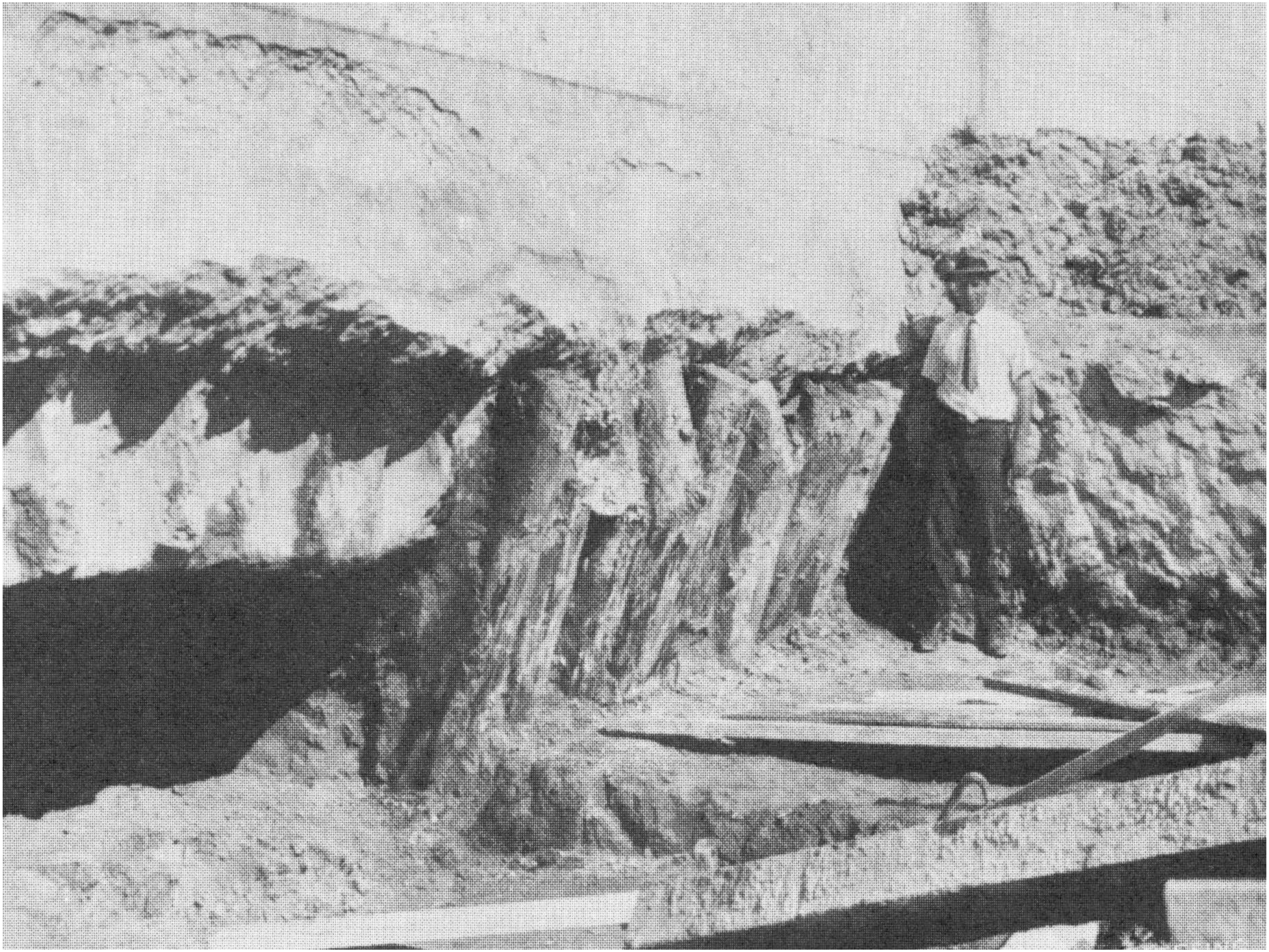
(1058. F.)

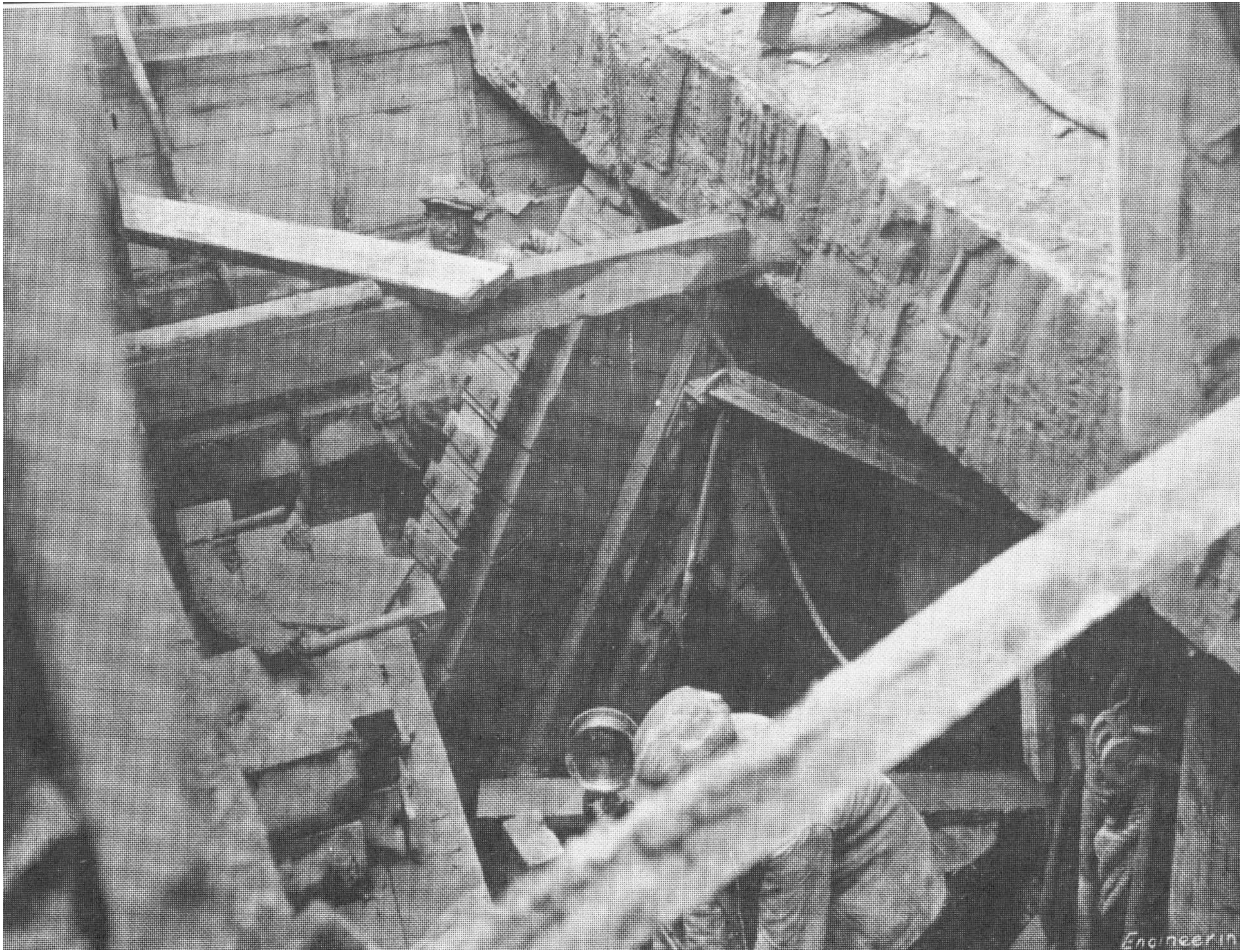
Canal Excavation History (cont)

- 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

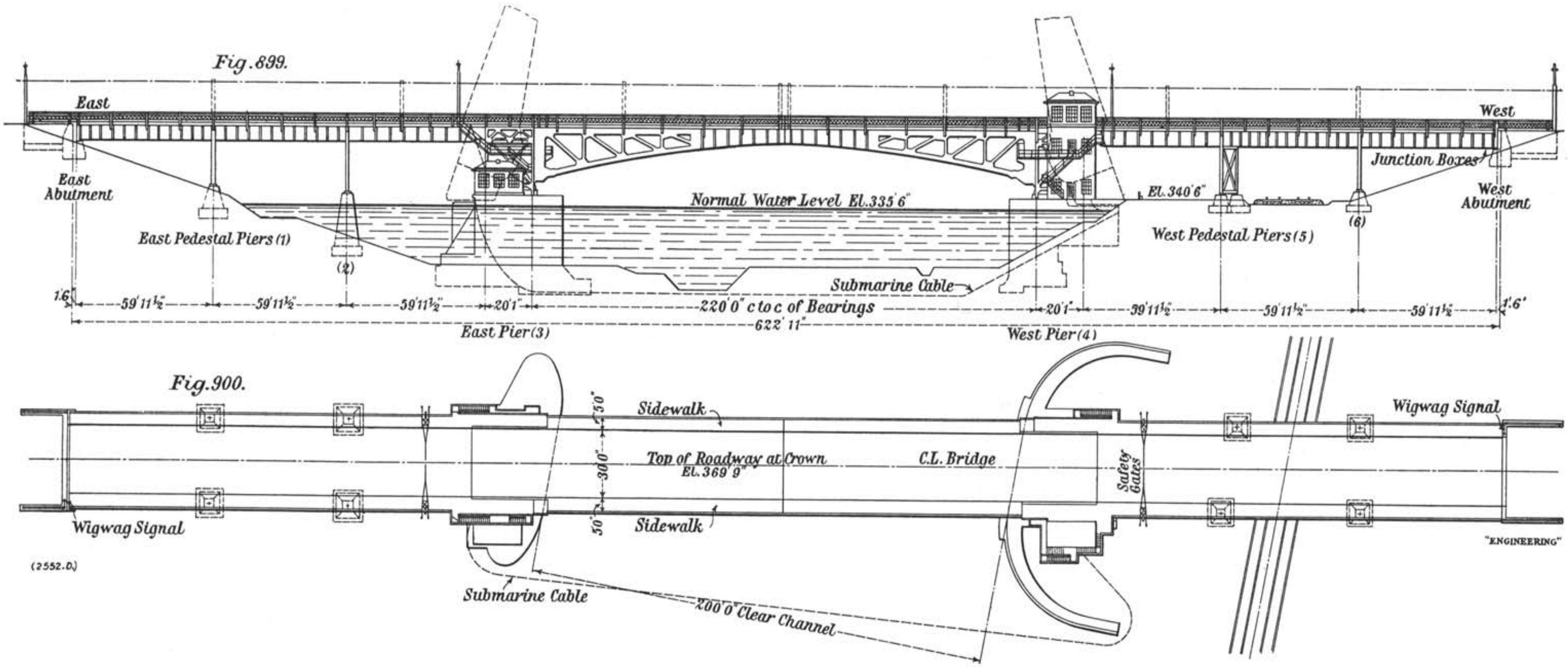



Engineering

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

East West



Bridge 4

West

East

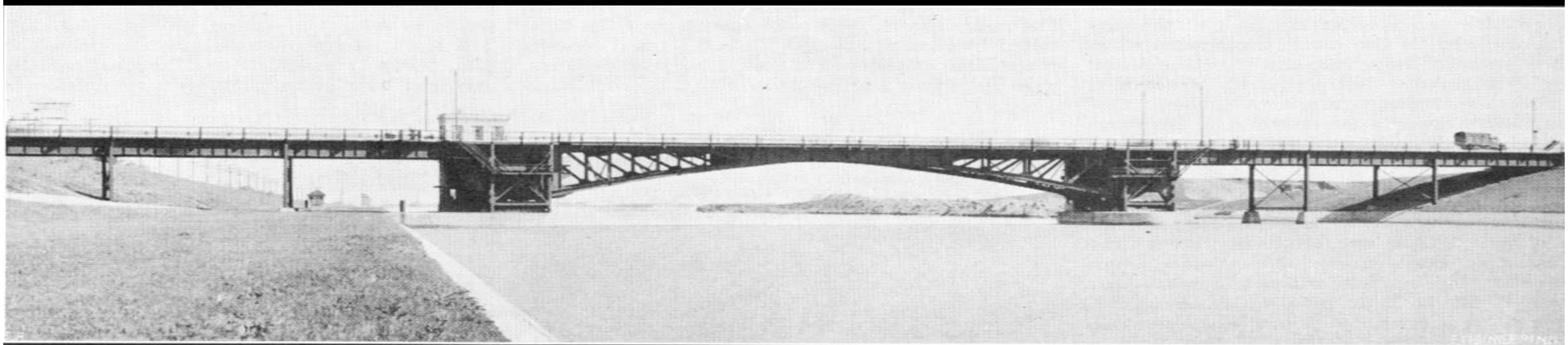


Fig. 925. Bridge No. 4; Closed.

Bridge 4: circa 1930 - 1940

West

East

Bridge 4: 2001

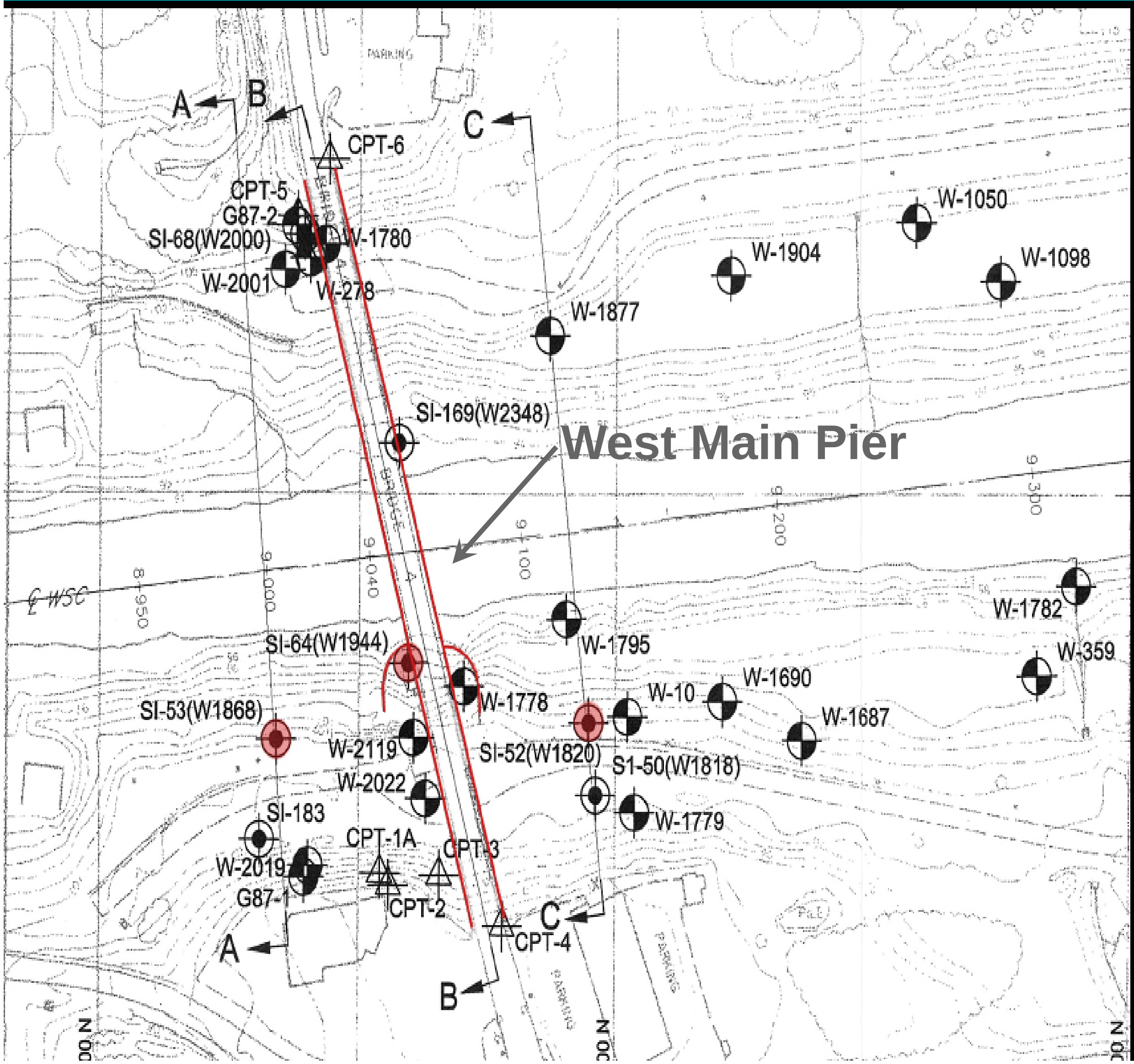
Main East Pier - Bridge 4: 2003

Canal Operation

Season from April to December

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

Geotechnical Investigation



Field:

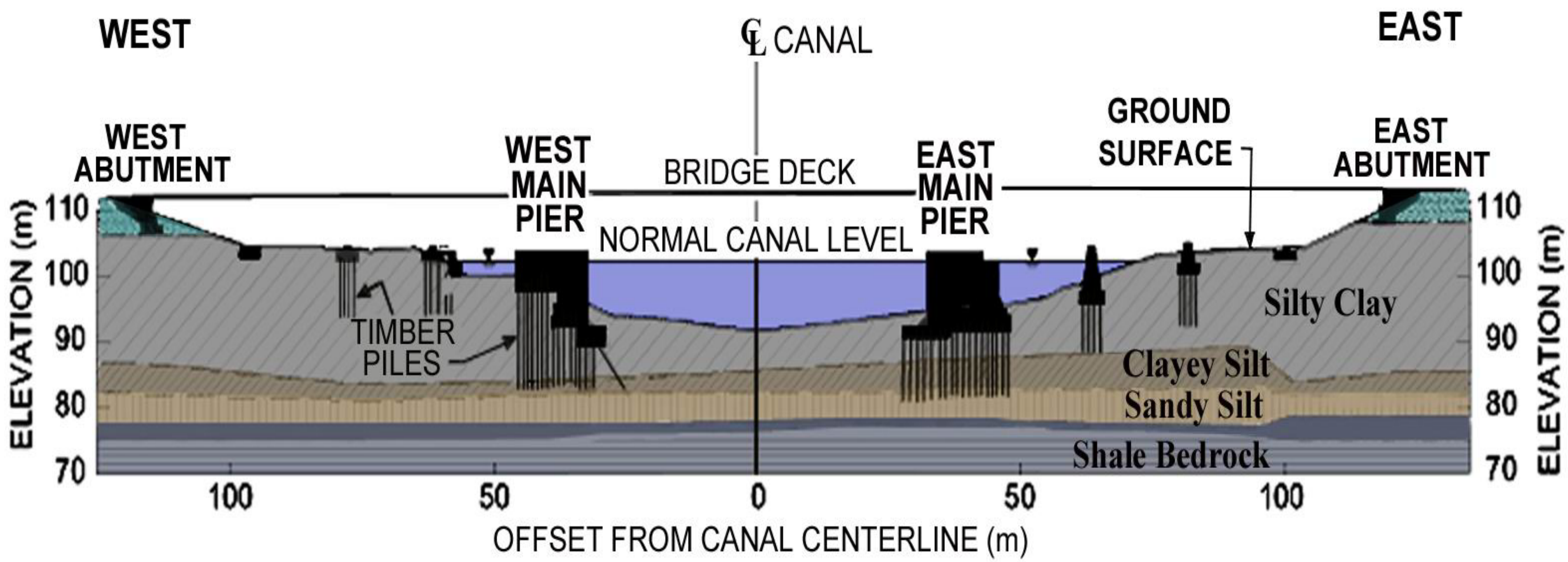
- 20 sampled boreholes & field vanes
- 25 CPTs
- 5 PMTs
- 5 slope indicators

Laboratory:

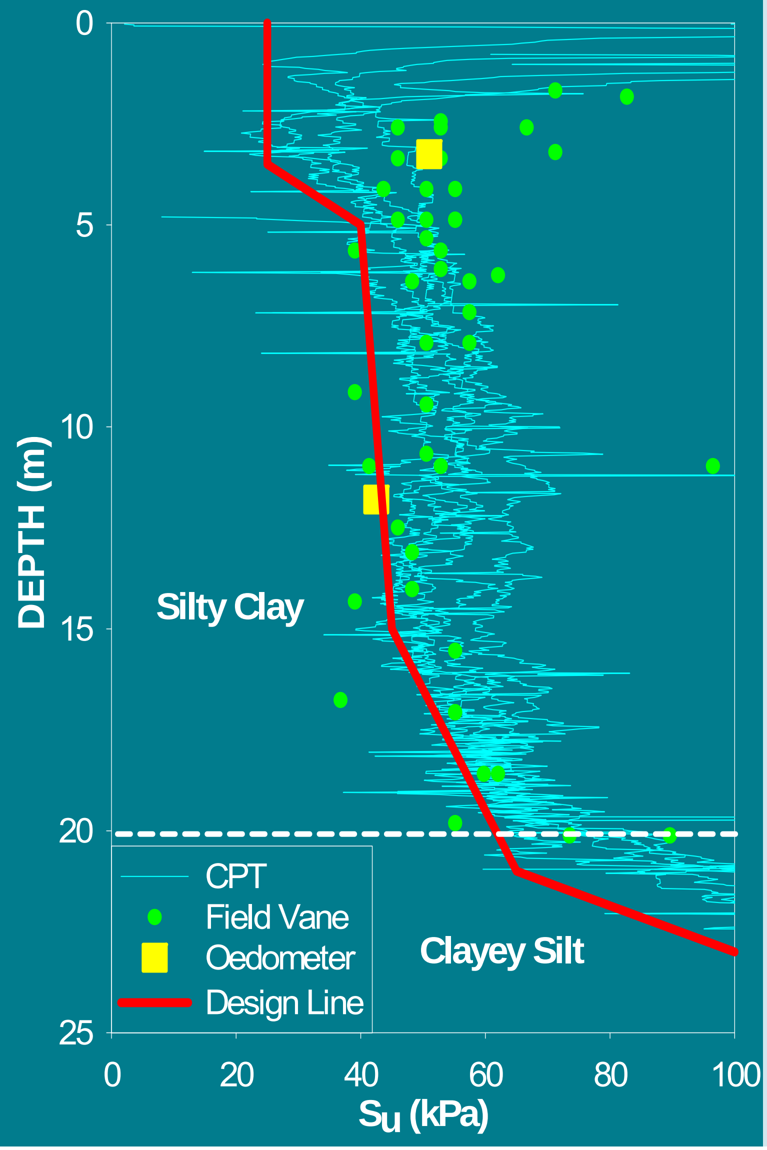
- index and classification
- oedometer
- triaxial
- direct shear

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
- $Su/\sigma_p{}^1$: 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

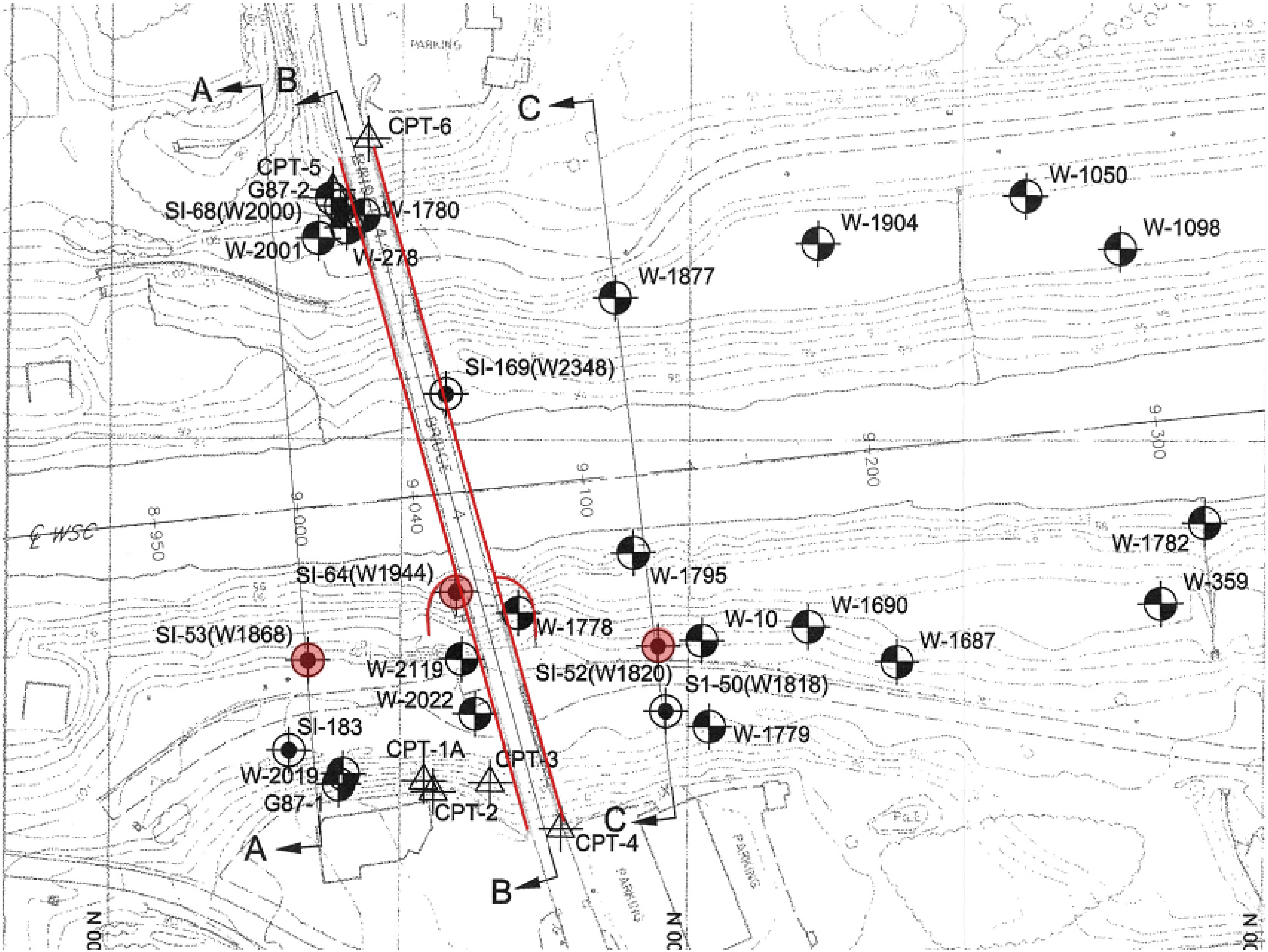
- Slope/W – Morgenstern-Price
- Back Analysis:
  - original construction
  - 1999 failure (lower bank)
  - localized lower bank (weakened zones)
- Canal bank only marginally stable at low canal level
- Design Analysis:
  - lower bank (with wall) stability
  - overall bank stability

Summary of Stability Analyses

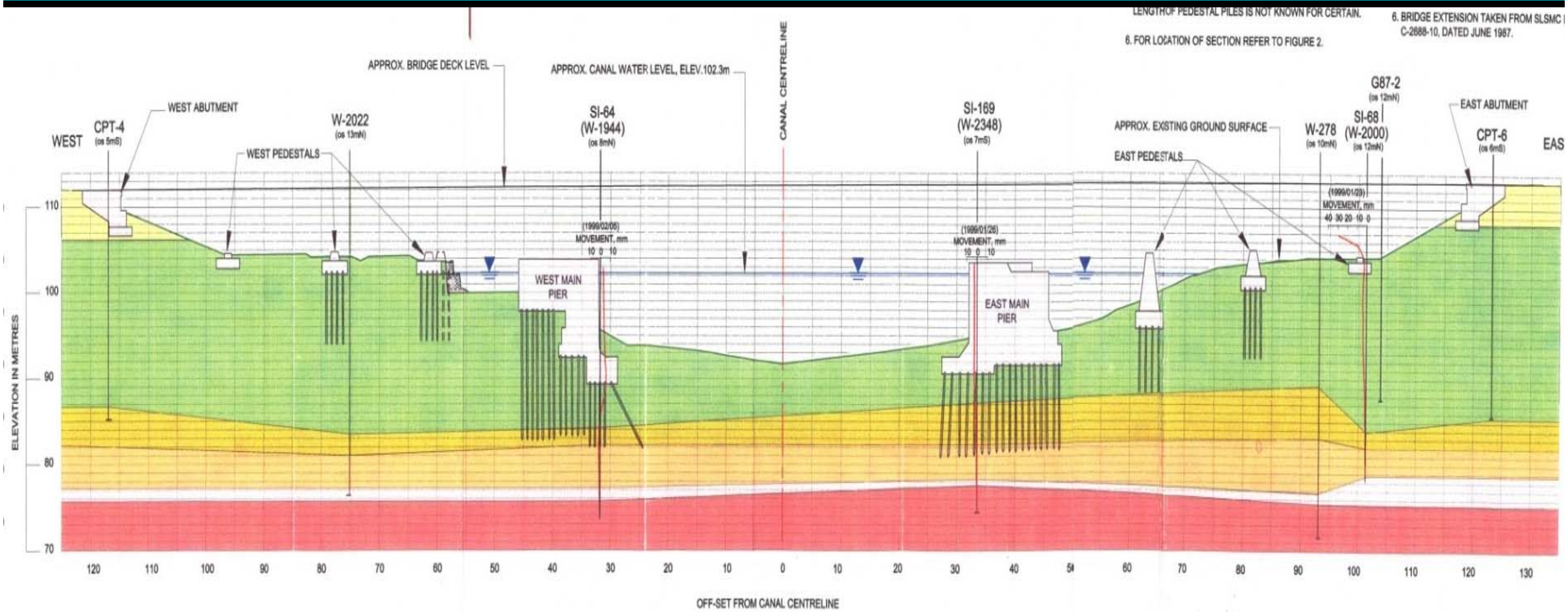
CASE		FS
Original	2H:1V	≤ 1.0
	3H:1V	1.38 canal filled
		1.15 canal empty
January 1999 Failure		>2 (average undisturbed strength Su = 45 kPa)
		>1.6 (lower bound Su = 35 kPa)
		1.0 (Su= 15 to 20 kPa - close to remoulded)

Slope Indicator Readings

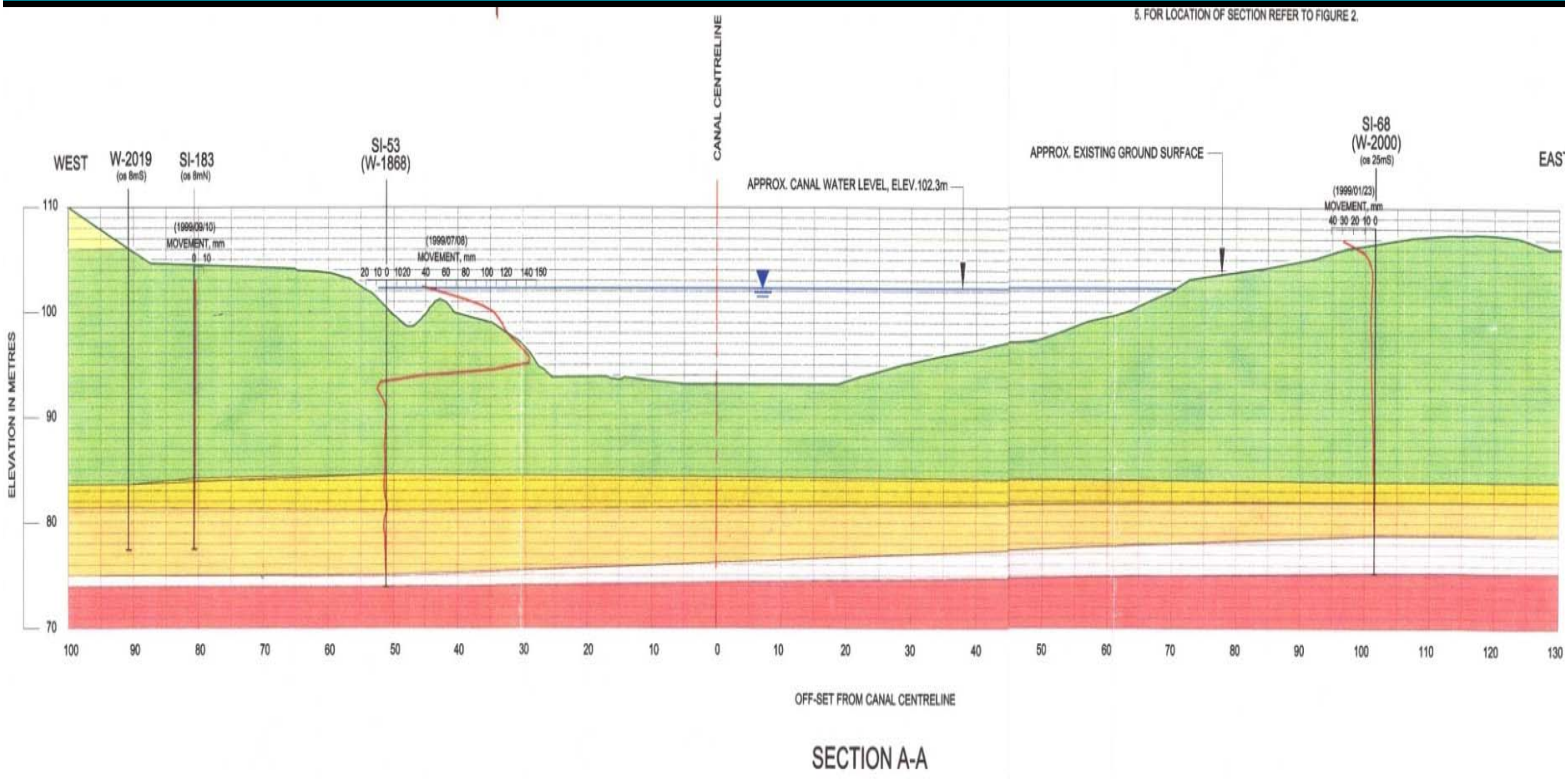
- Monitored ground and pier structure movements since 1986
- Slope moved laterally by as much as 230 mm as a result of cycles in operational canal water levels
- Pier movement essentially elastic
    - Permanent plastic deformation of 3 mm to 6 mm in 15 years
- Pier movement due to ground movement adjacent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

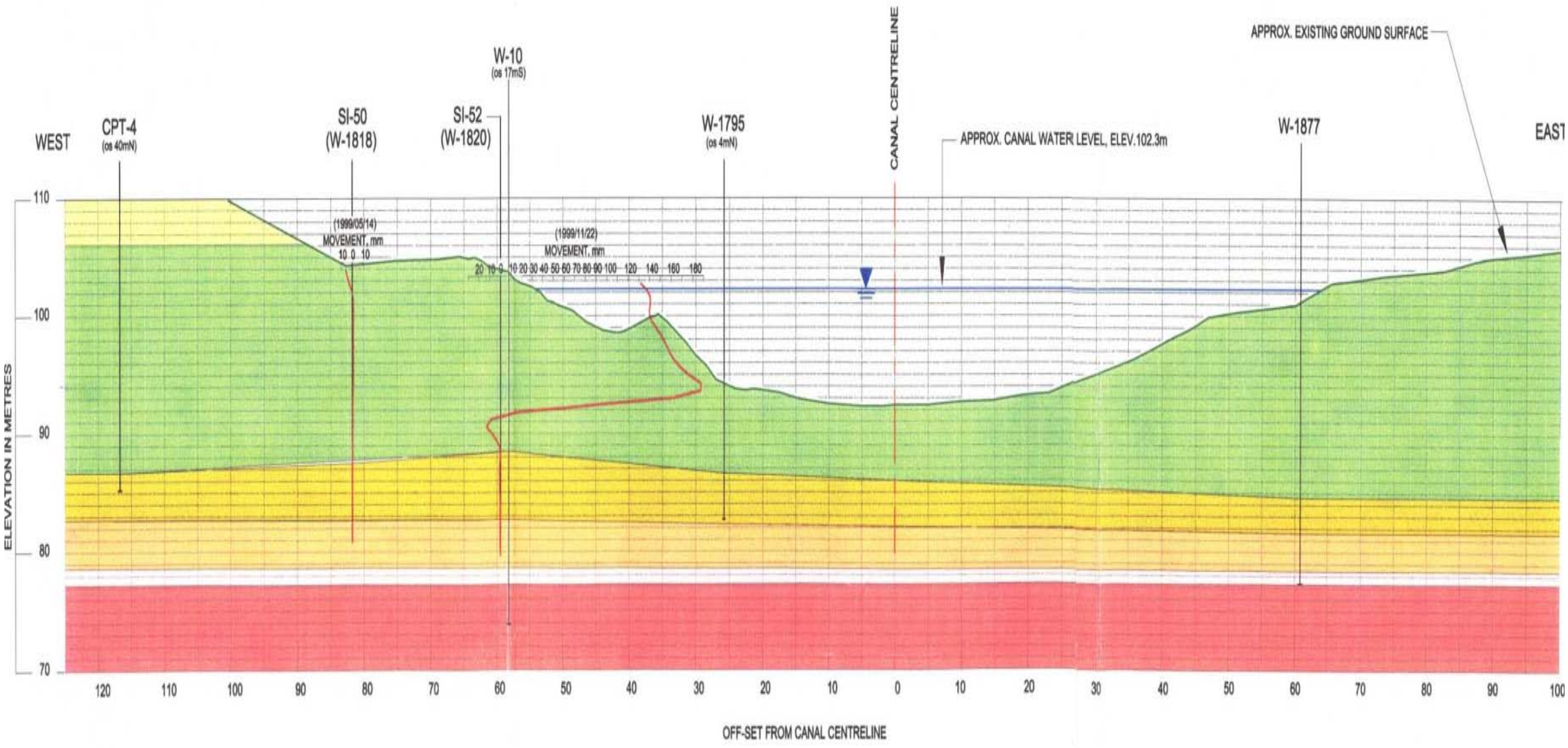


A
B
C
CPT-6
CPT-5
G87-2
SI-68(W2000)
W-1780
W-2001
W-278
W-1877
W-1050
W-1904
W-1098
SI-169(W2348)
PARKING
9+000
9+040
9+100
9+200
9+300
8+950
℄ WSC
SI-64(W1944)
W-1795
W-1782
W-359
W-1690
W-1778
W-10
W-1687
SI-53(W1868)
W-2119
SI-52(W1820)
S1-50(W1818)
W-2022
W-1779
SI-183
CPT-1A
CPT-3
W-2019
G87-1
CPT-2
CPT-4
C
A
B



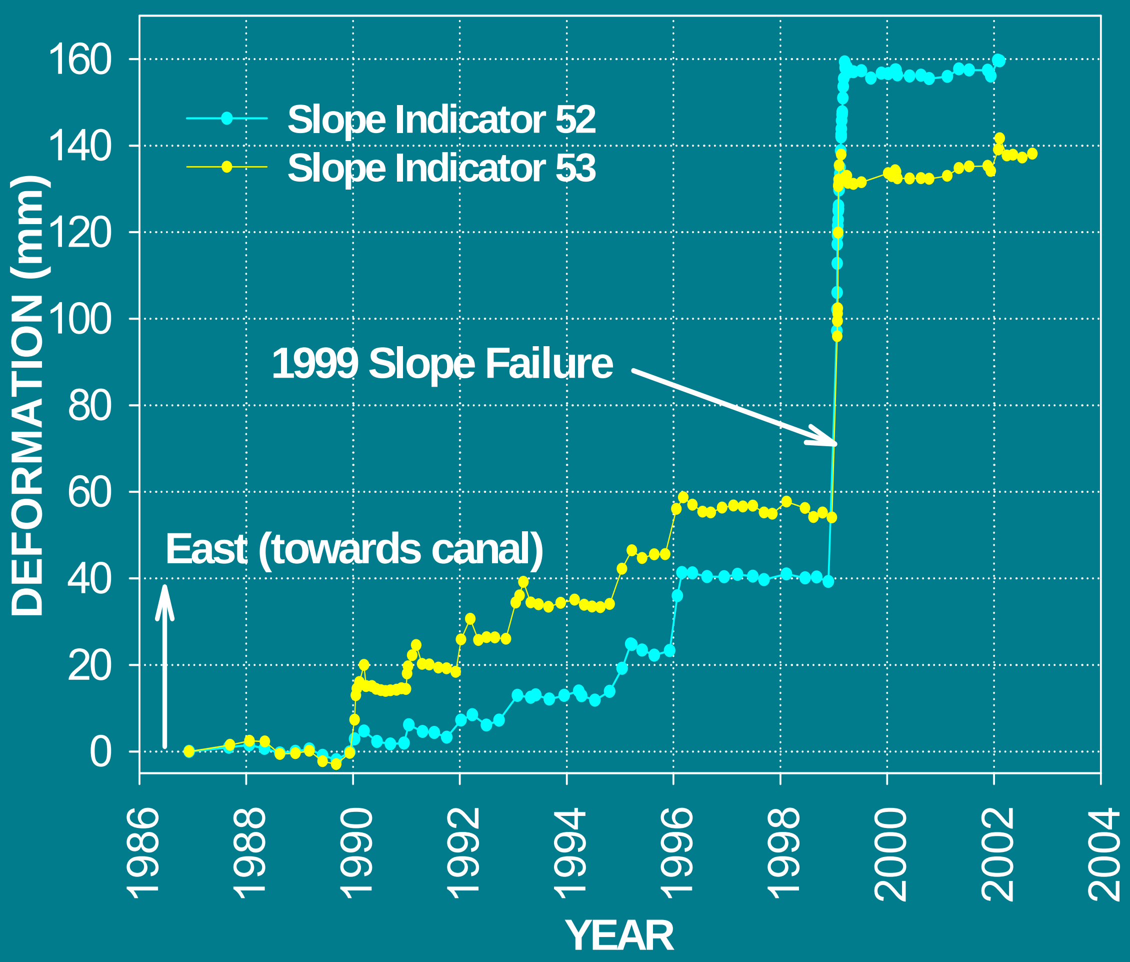
SECTION B-B (Bridge 4)


5. FOR LOCATION OF SECTION REFER TO FIGURE 2.
CANAL CENTRELINE
WEST
EAS
W-2019
SI-183
SI-53
(W-1868)
SI-68
(W-2000)
APPROX. CANAL WATER LEVEL, ELEV.102.3m
APPROX. EXISTING GROUND SURFACE
(1999/09/10)
MOVEMENT, mm
(1999/07/08)
MOVEMENT, mm
(1999/01/23)
MOVEMENT, mm
ELEVATION IN METRES
110
100
90
80
70
OFF-SET FROM CANAL CENTRELINE
SECTION A-A

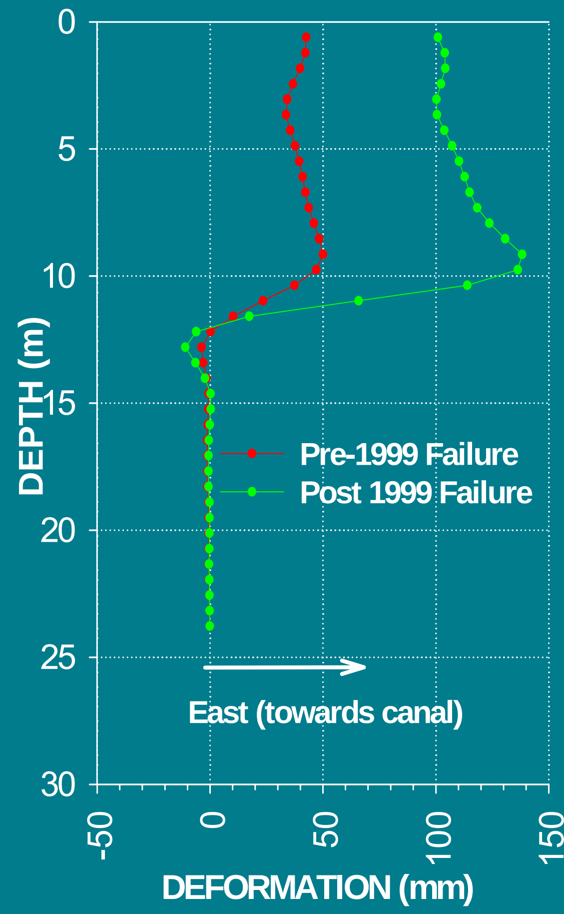

W-10
(os 17mS)
SI-52
(W-1820)
SI-50
(W-1818)
CPT-4
(os 40mN)
WEST
W-1795
(os 4mN)
CANAL CENTRELINE
APPROX. CANAL WATER LEVEL, ELEV.102.3m
W-1877
APPROX. EXISTING GROUND SURFACE
EAST
(1999/05/14)
MOVEMENT, mm
10 0 10
(1999/11/22)
MOVEMENT, mm
20 10 0 10 20 30 40 50 60 70 80 90 100 120 140 160 180
ELEVATION IN METRES
110
100
90
80
70
120 110 100 90 80 70 60 50 40 30 20 10 0 10 20 30 40 50 60 70 80 90 100
OFF-SET FROM CANAL CENTRELINE

SECTION C-C

West Bank Movements

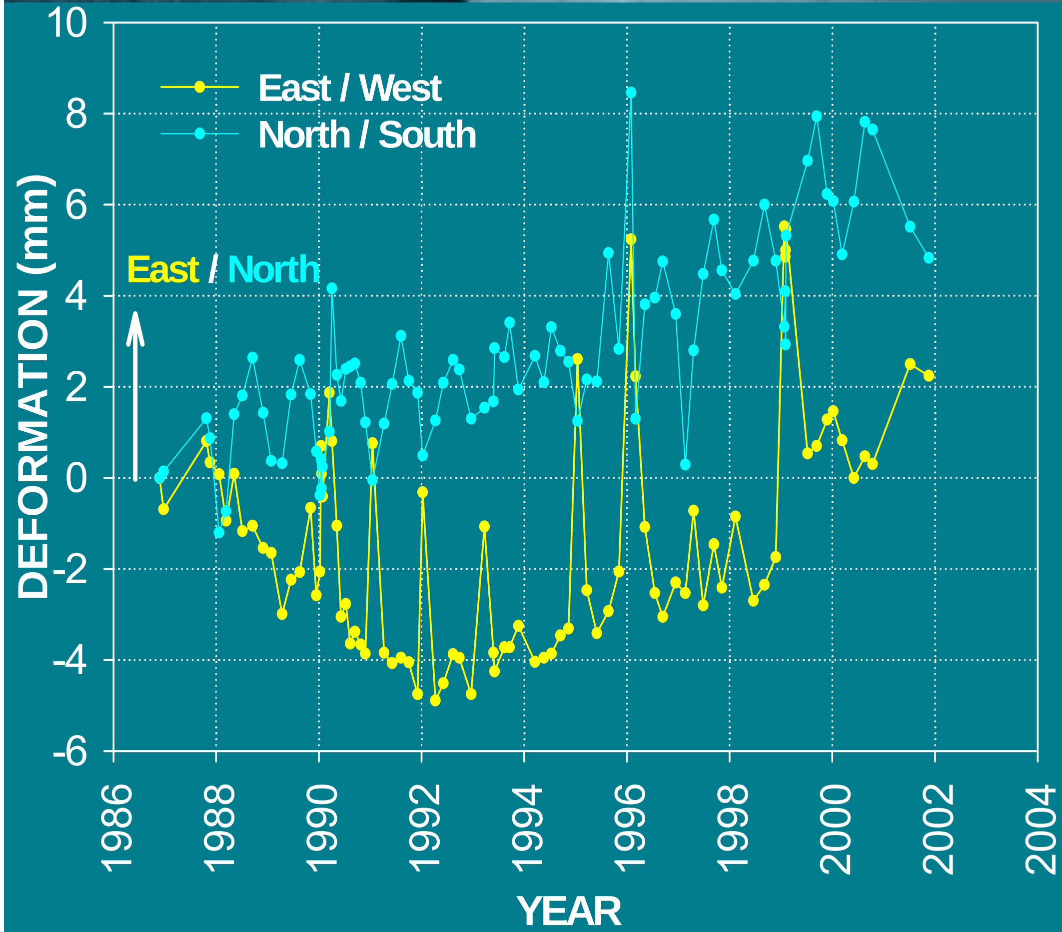


History of Slope Indicators 52 and 53
6 m depth

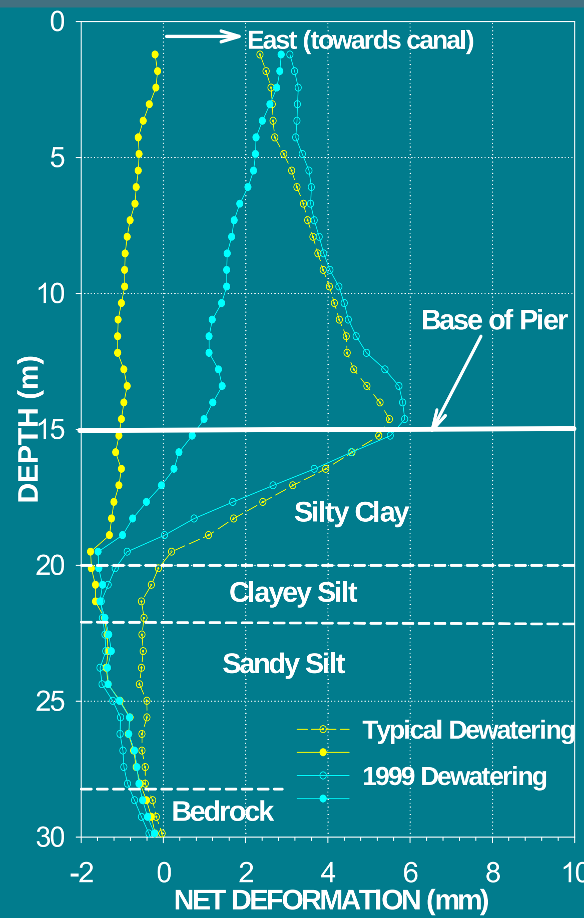


Profile of Slope Indicator 52
Pre and Post 1999 Slope Failure

West Pier Movements



History of Slope Indicator 64
6 m depth

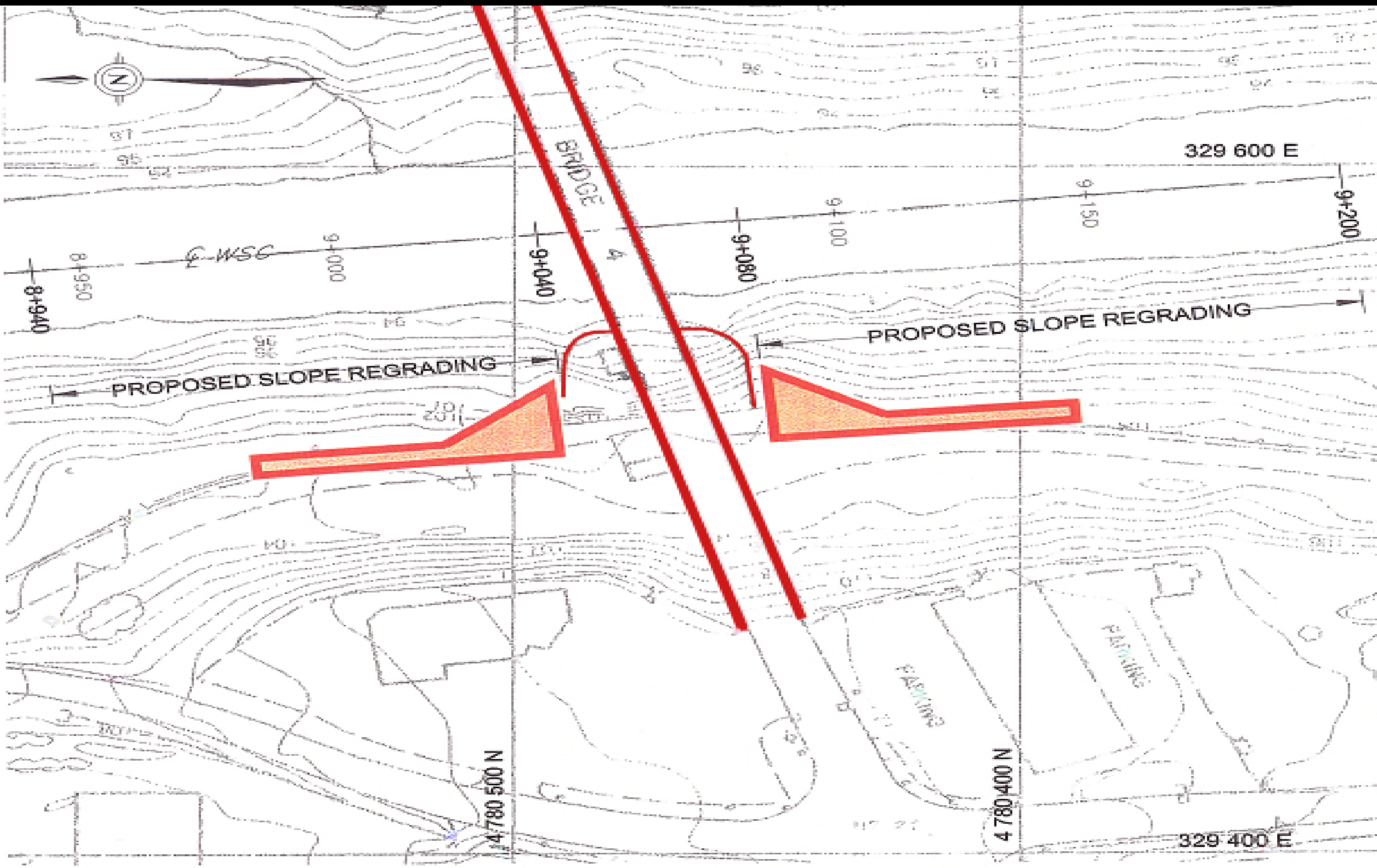


Response of Slope Indicator 64
after 1999 Bank Failure

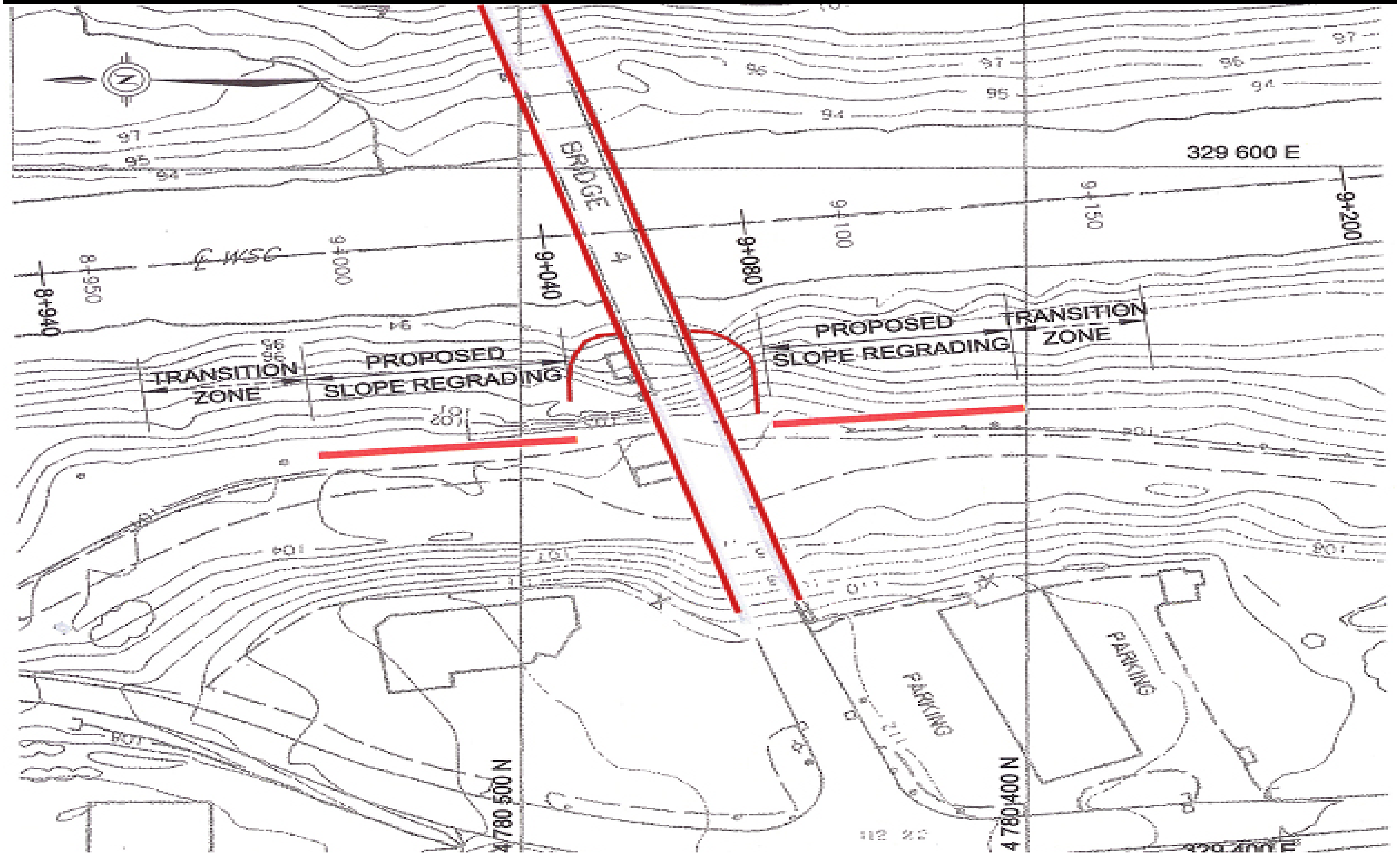
Possible Remedial Measures

- 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



Plan of Anchored Caisson Wall

South **North**

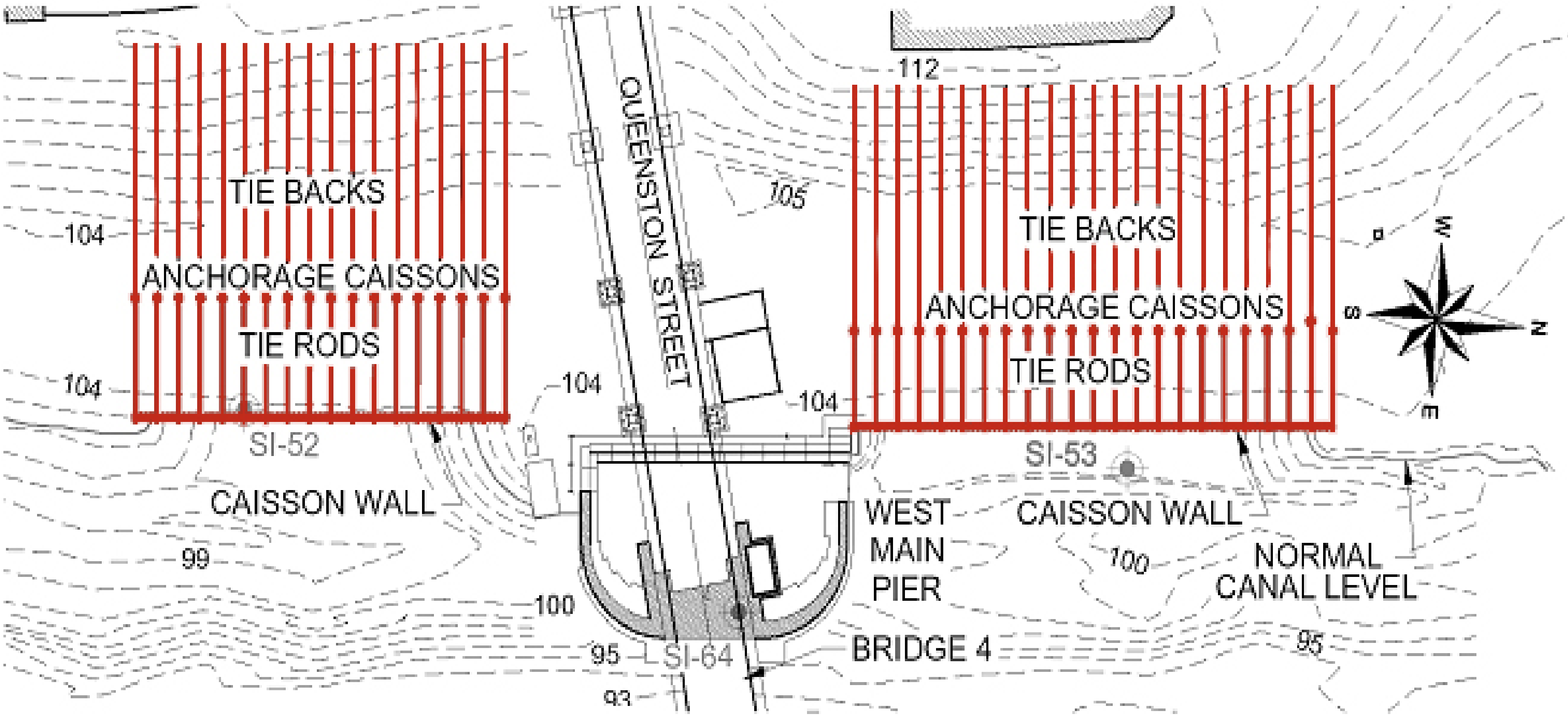
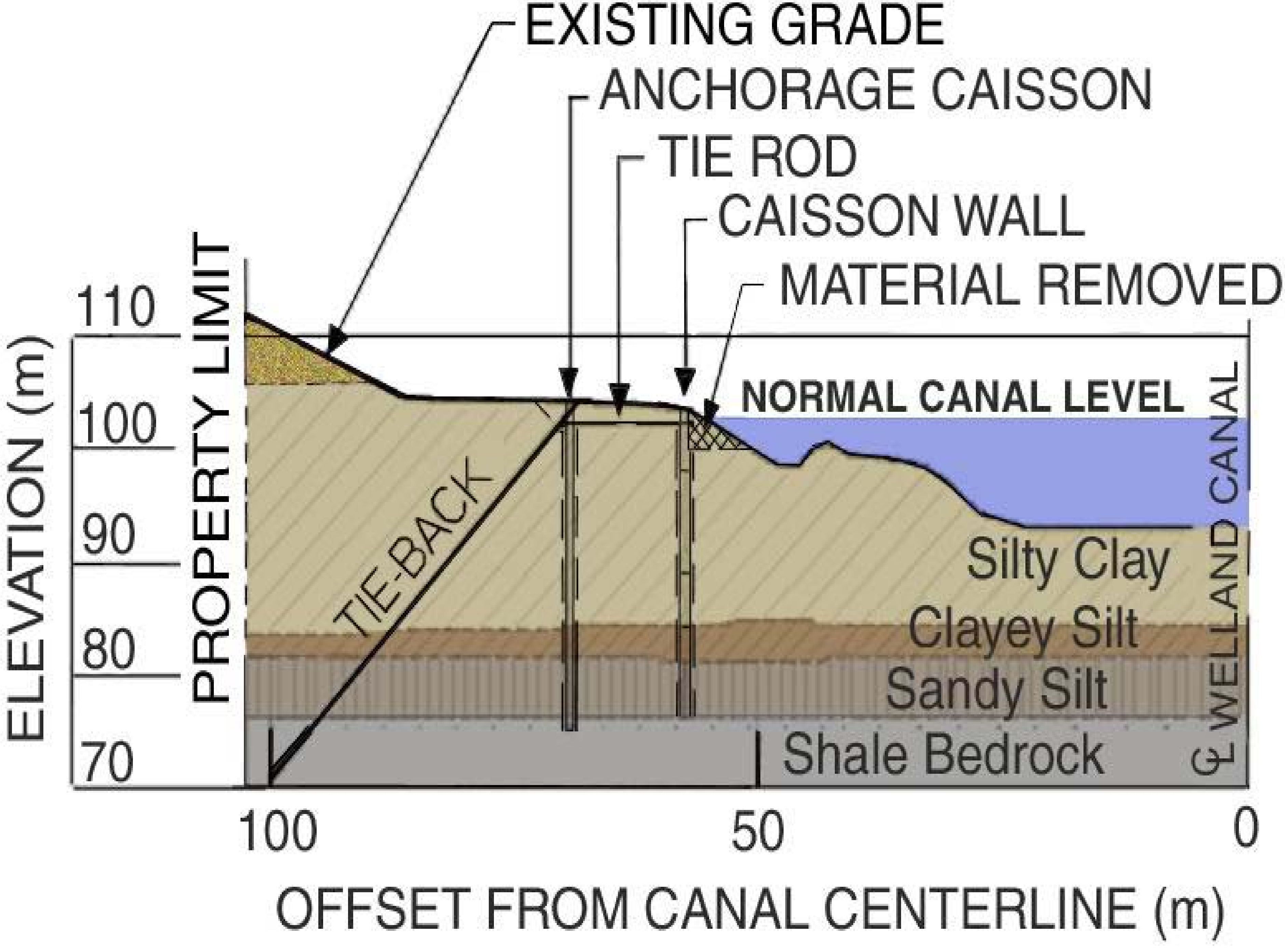


Figure 8 – Plan view of Caisson Wall System.



EXISTING GRADE
ANCHORAGE CAISSON
TIE ROD
CAISSON WALL
MATERIAL REMOVED
NORMAL CANAL LEVEL
PROPERTY LIMIT
TIE-BACK
ELEVATION (m)
110
100
90
80
70
Silty Clay
Clayey Silt
Sandy Silt
Shale Bedrock
℄ WELLAND CANAL
100
50
0
OFFSET FROM CANAL CENTERLINE (m)

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

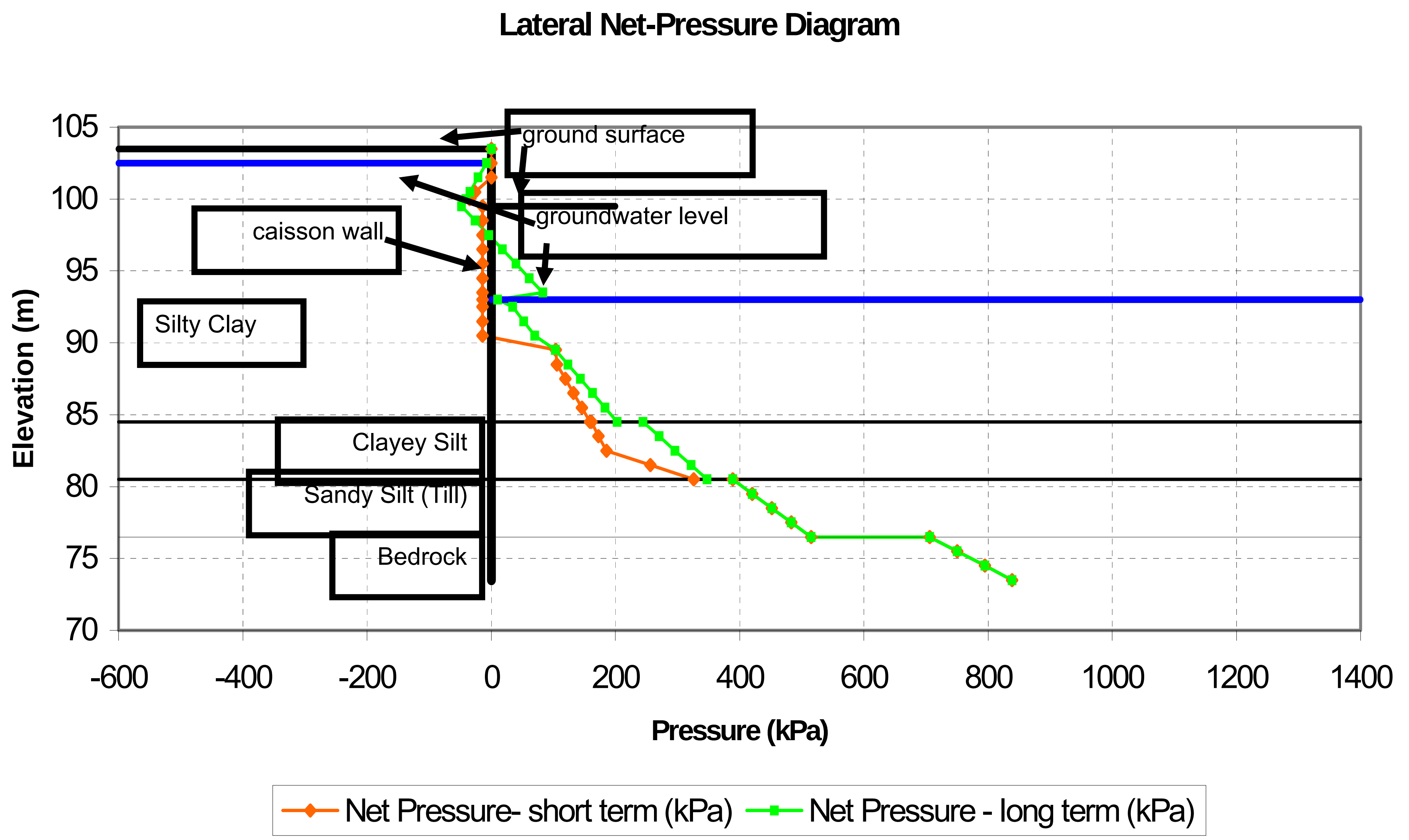
Caisson Wall (cont)

- 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)



Anchors

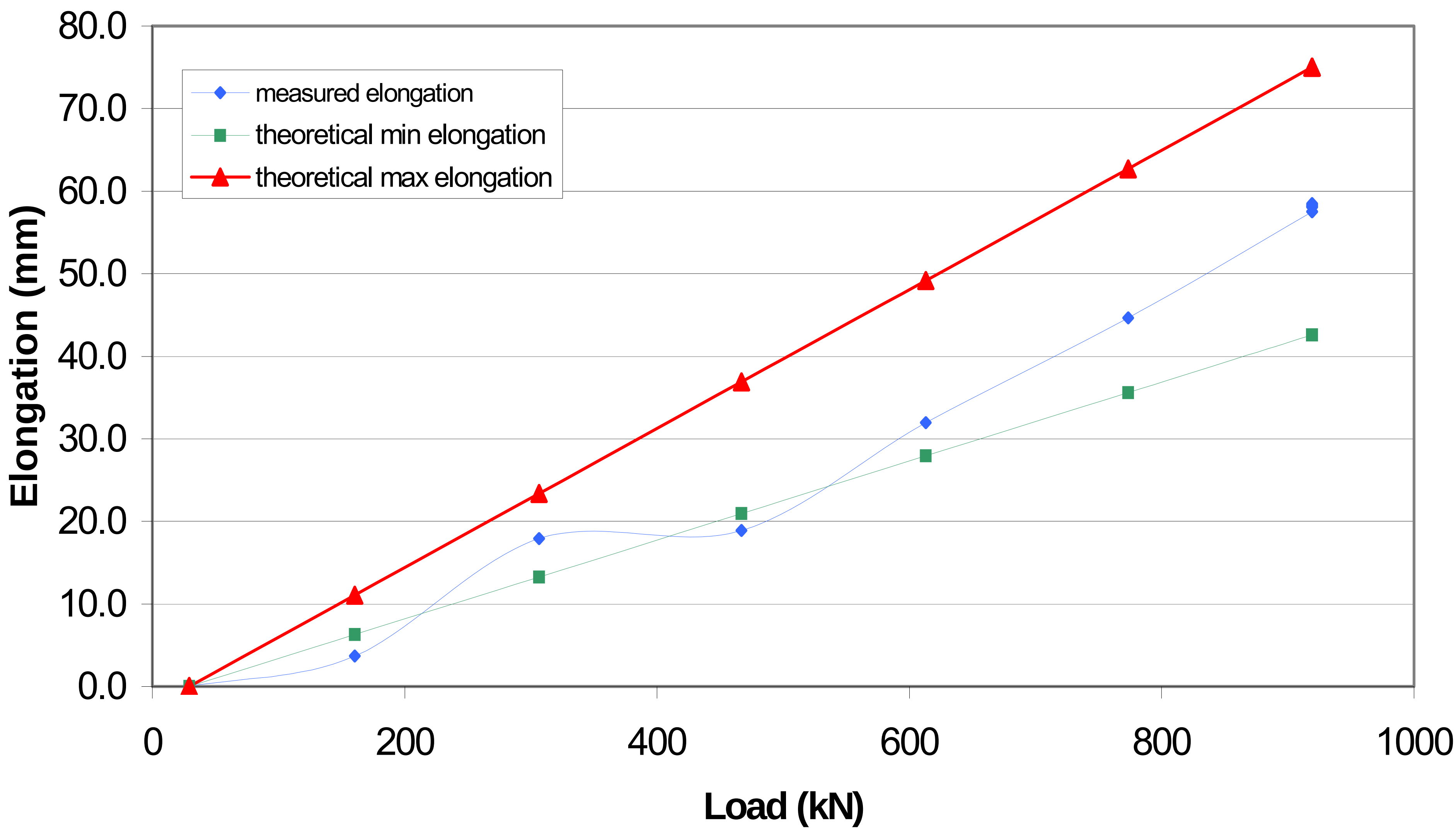
- Anchored into shale bedrock
- Approximately 40 m free length (FREEL)
- 6 m bond length in shale bedrock (BONDL)
- Allowable bond stress:
  - 350 kPa in shale bedrock
- Anchor load of:
  - 600 kN – proof tests
  - 900 kN for performance tests

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)



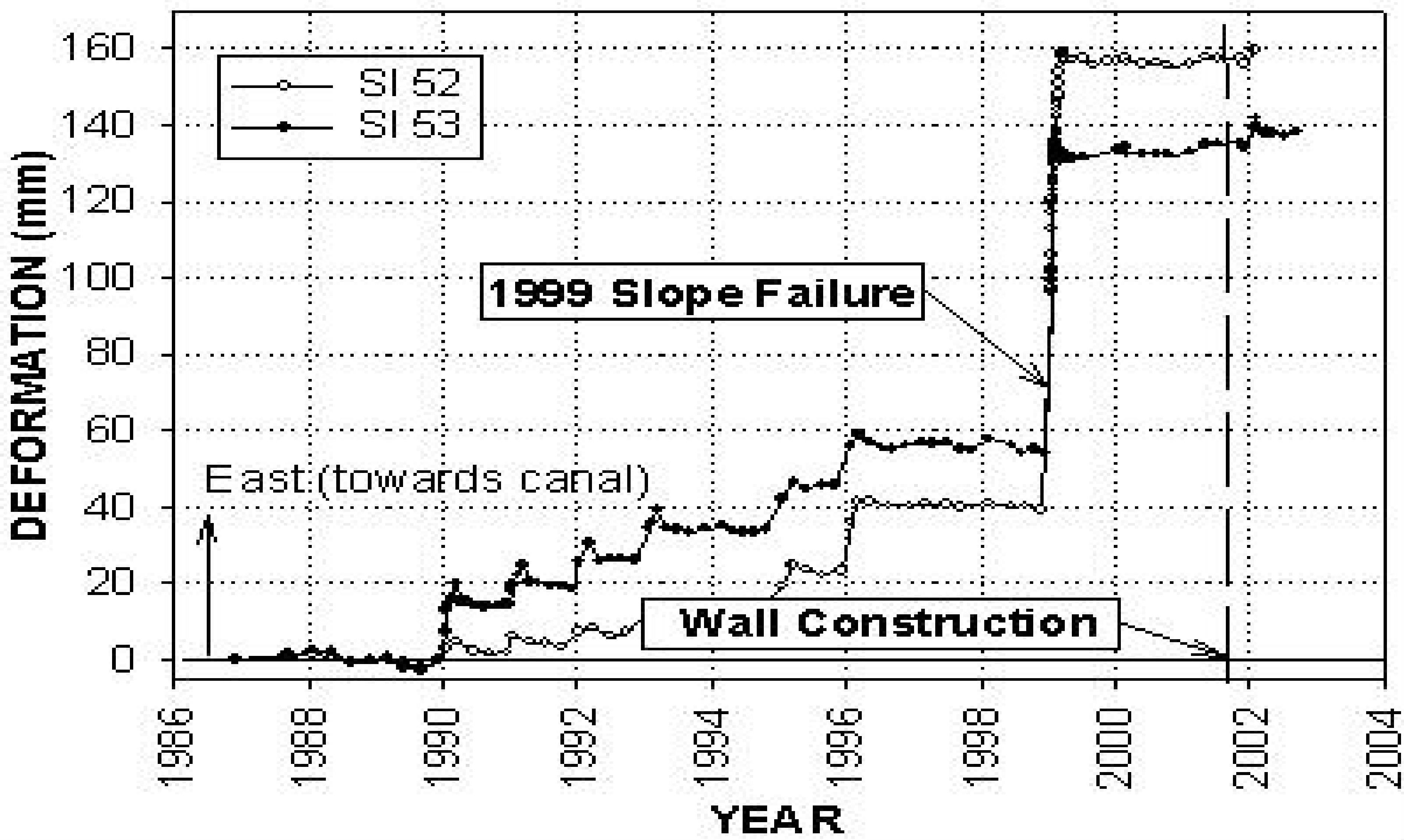
Tieback Pile and Caisson Wall Performance

- 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

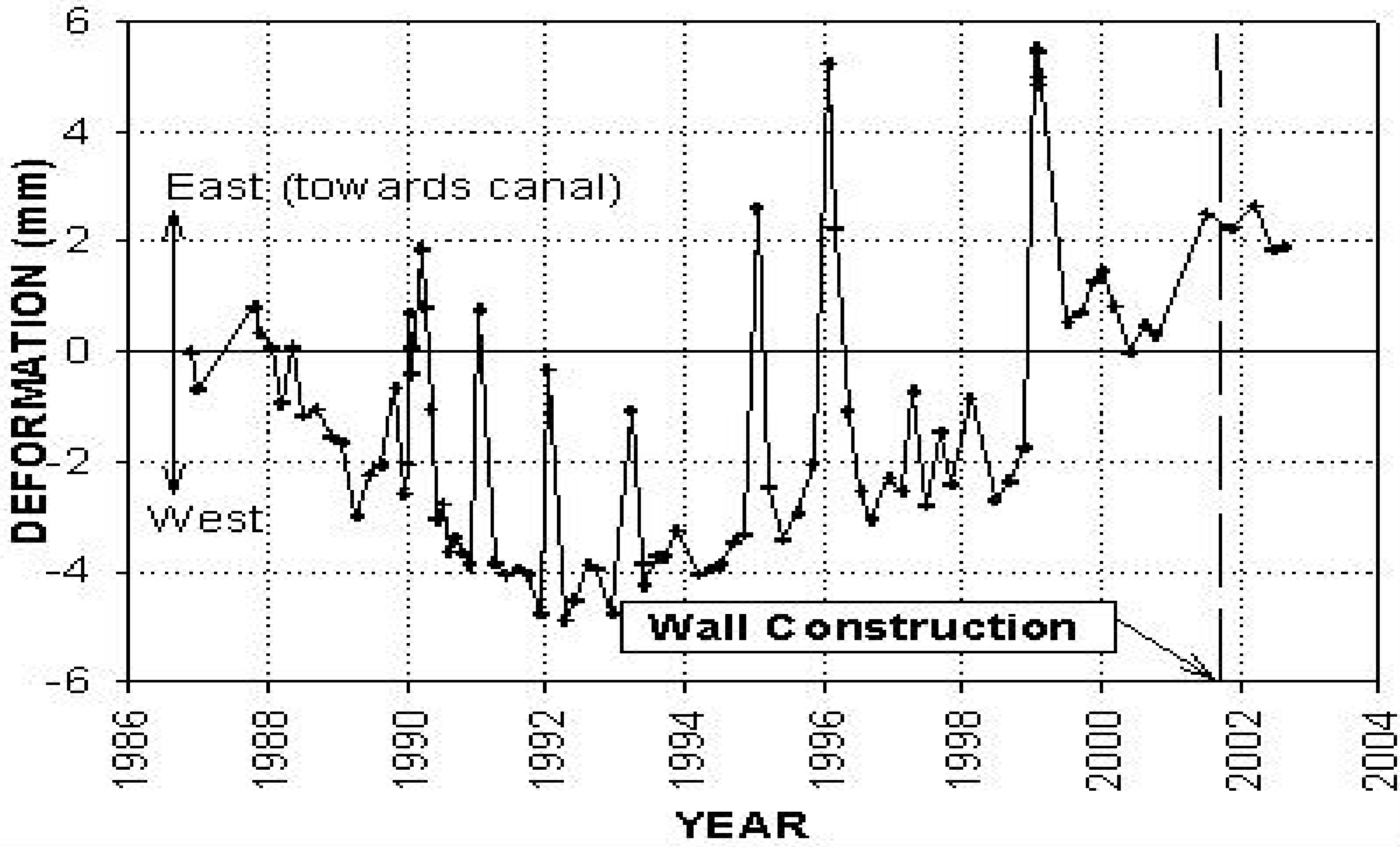
Tieback Pile and Caisson Wall Performance (cont)

- 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)

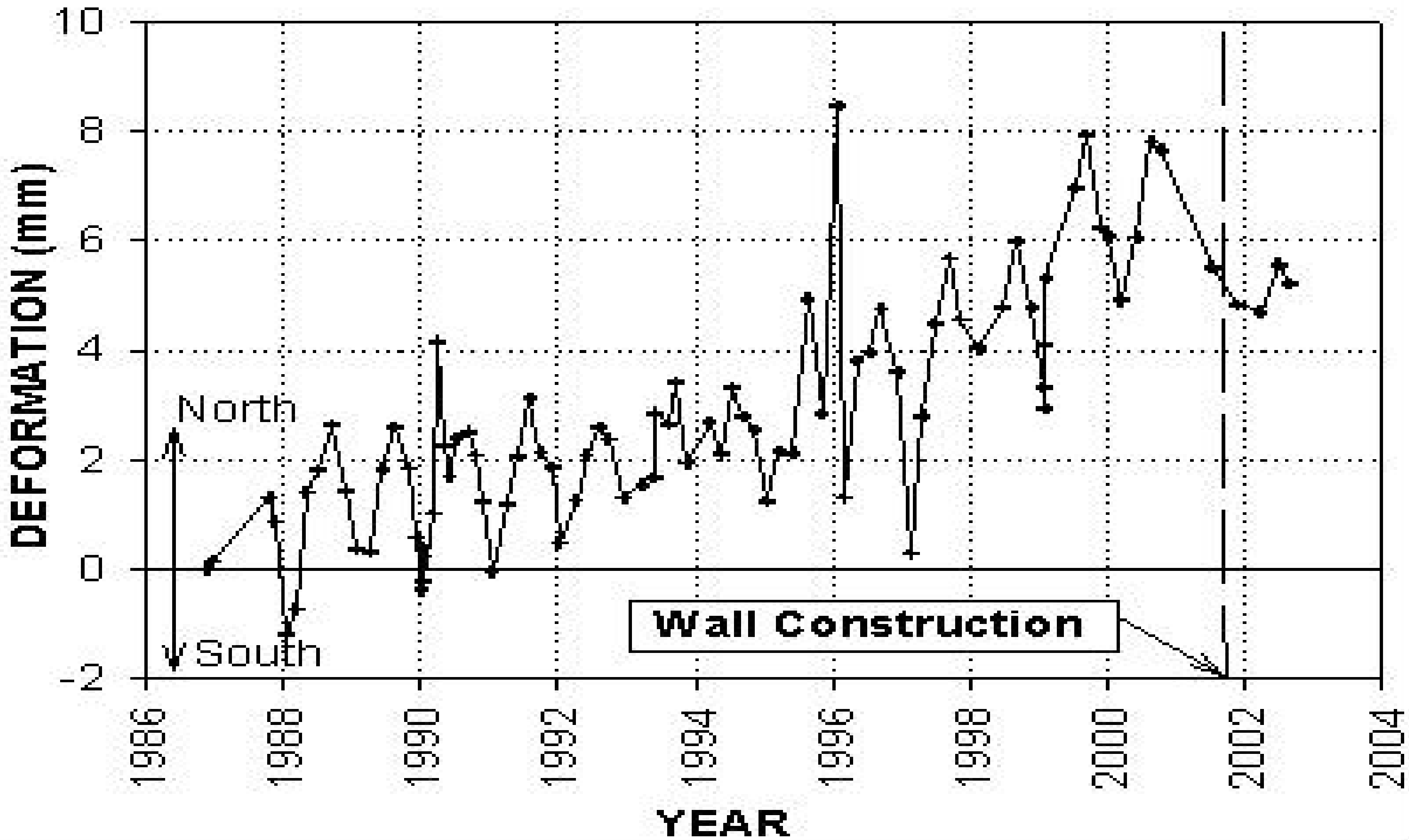
History of SI-52 and SI-53 at 6 m Depth



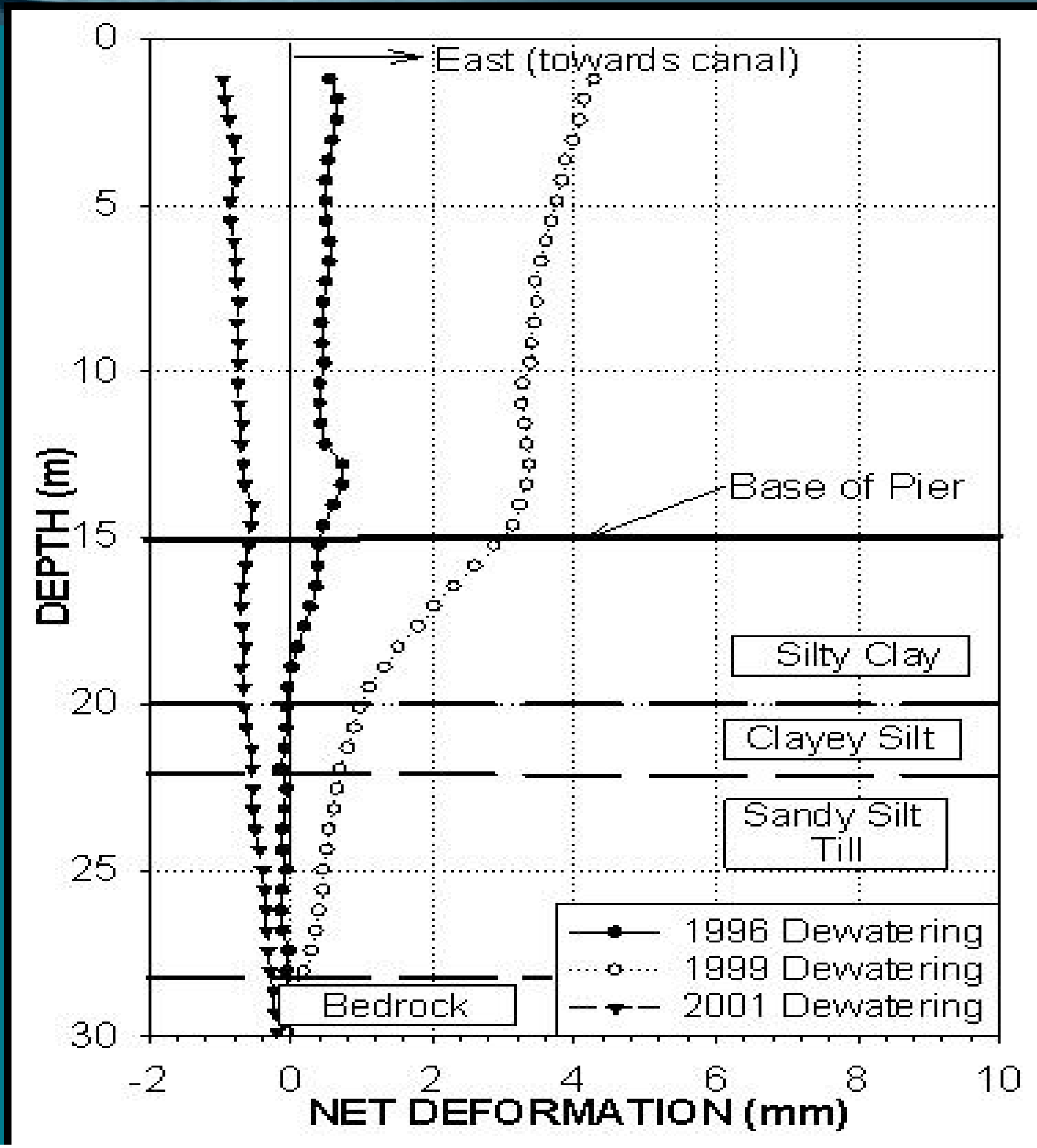
History of SI-64 at 6 m Depth (East-West Direction)



History of SI-64 at 6 m Depth (North - South Direction)



SI-64 Profile for Complete Canal Dewatering Cycles



Construction Highlights

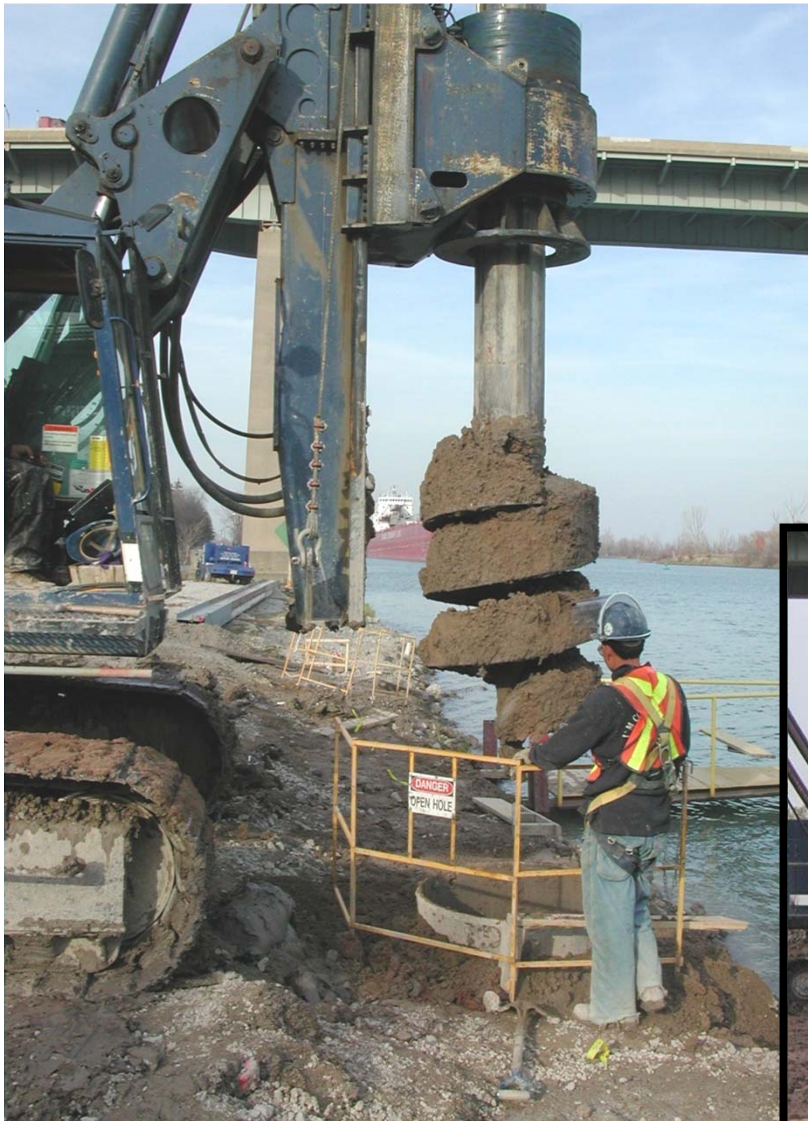
- Constructed between November 2001 and February 2002
    - Total cost of CAN $2.4 Million
    - Canal dewatered December 2001 for maintenance
    - Wall portion completed prior to dewatering to minimize risk of bank / pier movement

Anchorage Caissons south of Bridge

Wall 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

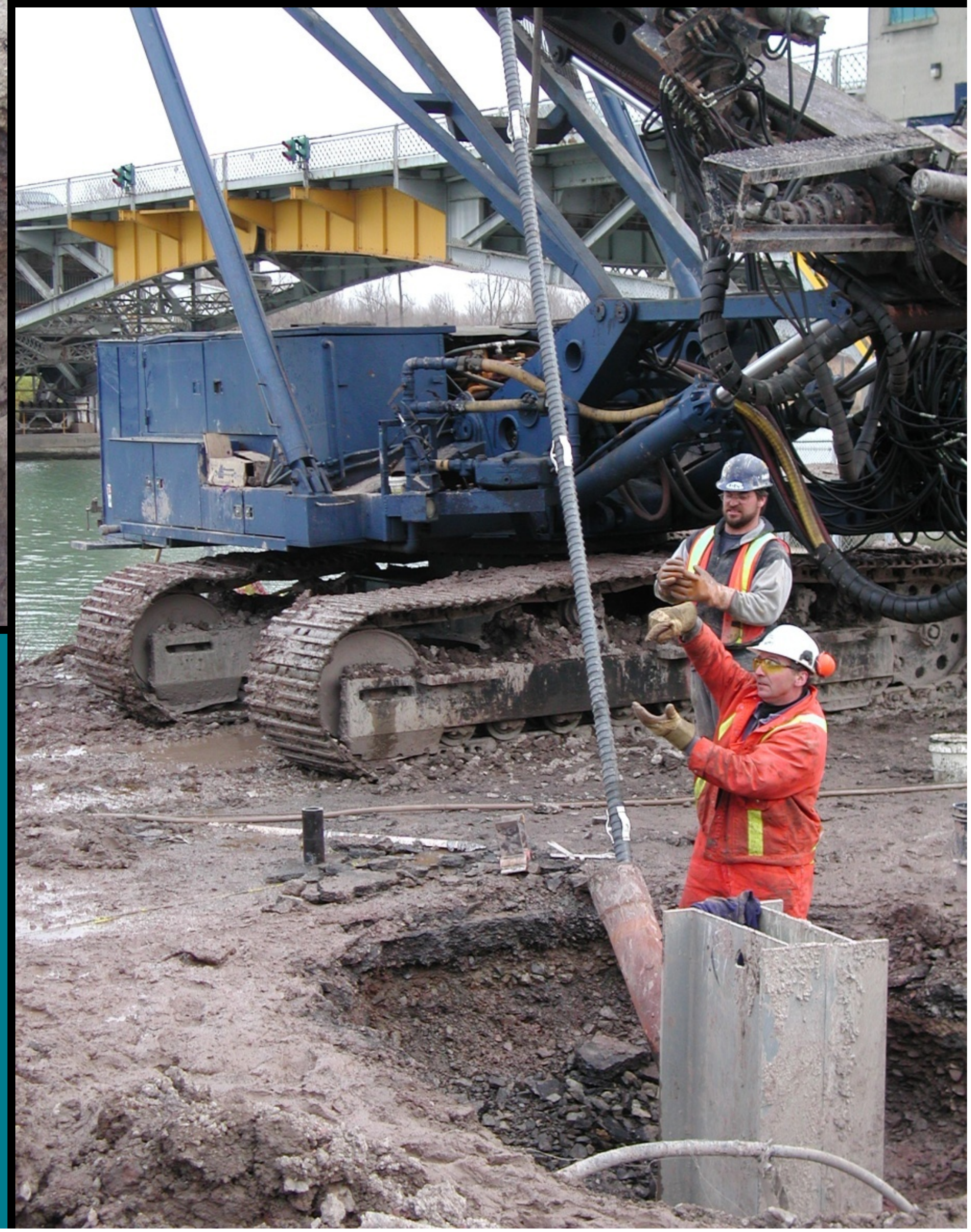
- Lower slope in front of wall regraded after wall in place to improve stability

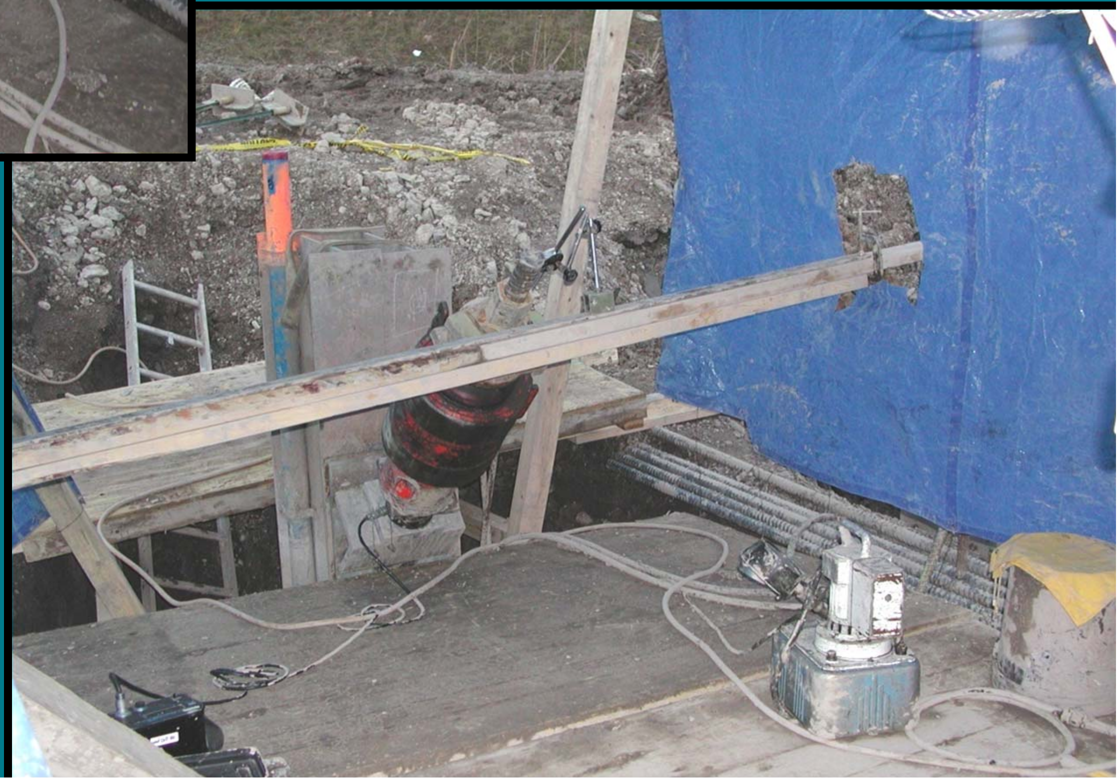

DANGER
OPEN HOLE


Frato's DINING
LOUNGE


Link-Belt


MAXIMUM
5
km/h




SLOPE

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

THANK YOU