# The Expansion of the Panama Canal

*The Impact of Developments in Rock Mechanics*

presentation to the

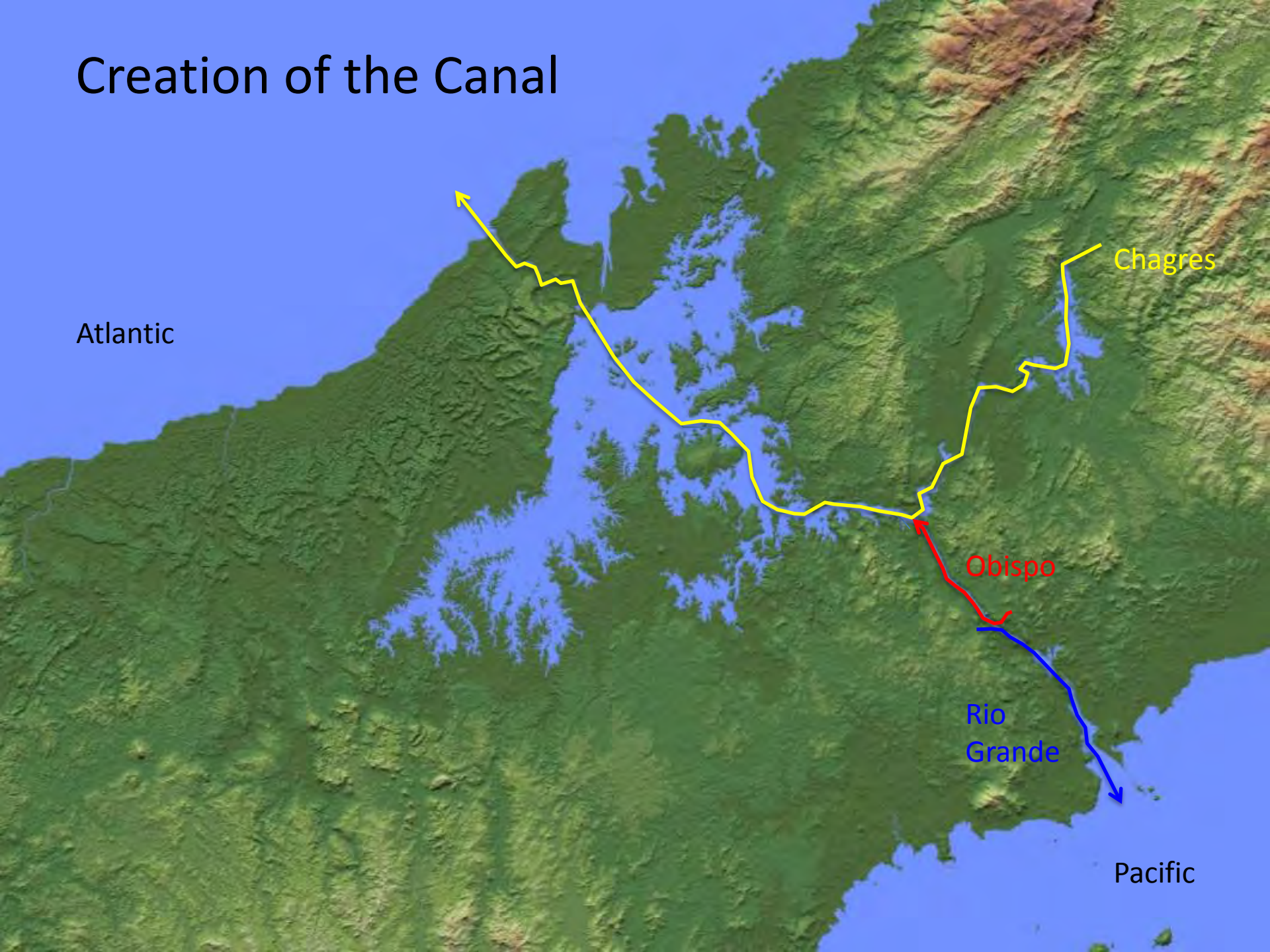
American Rock Mechanics Association

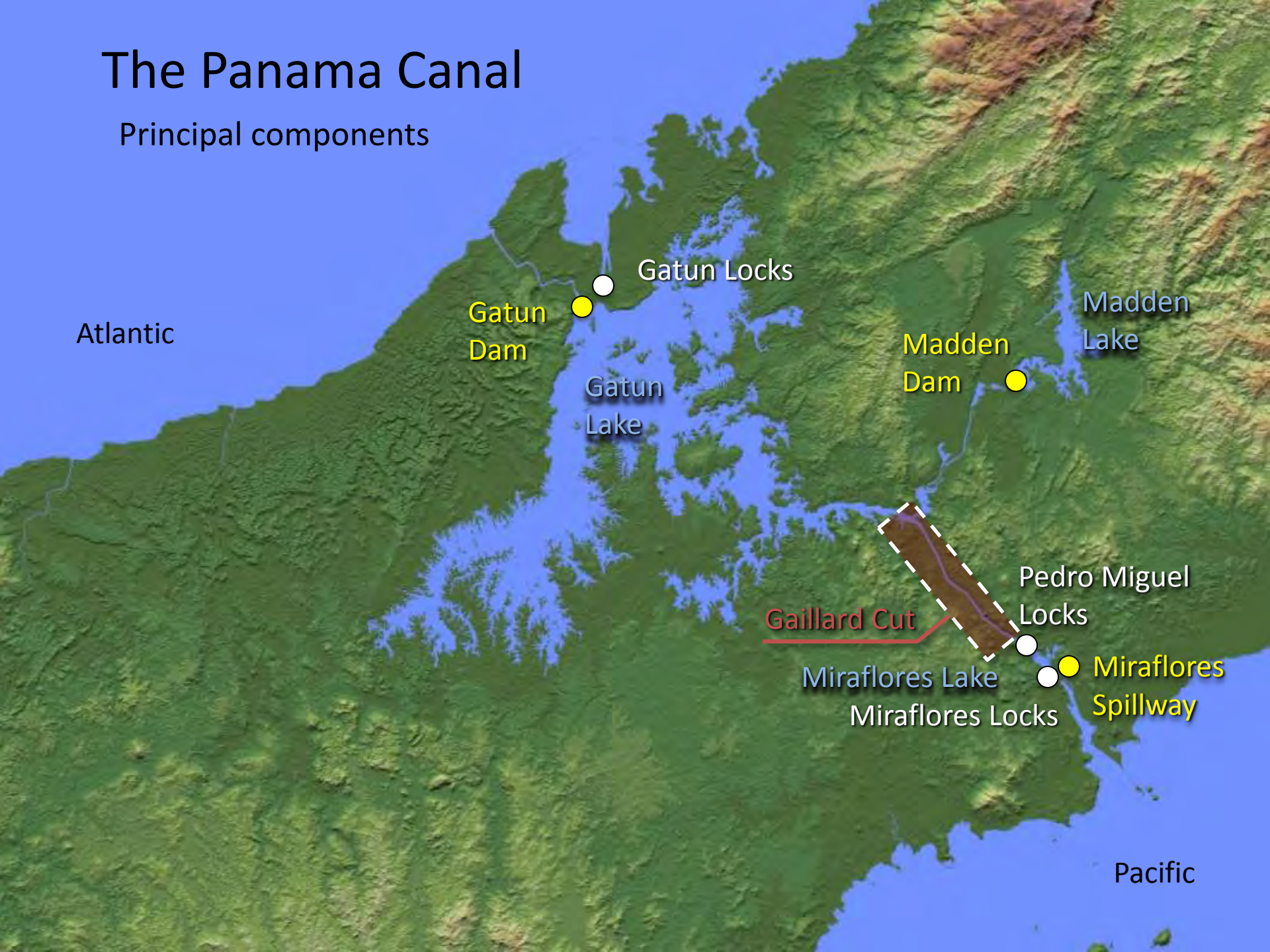

Luis D. Alfaro
Vicepresident of Engineering
Panama Canal Authority

June 25, 2012

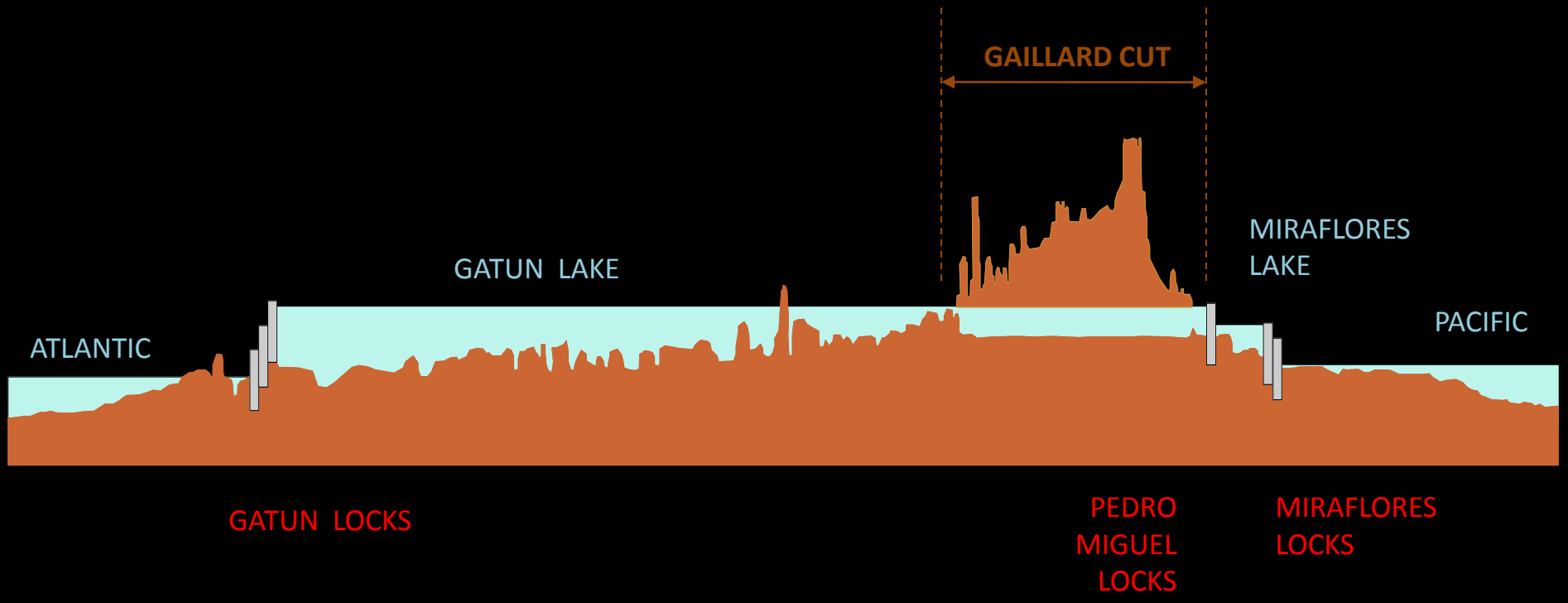
# Panama

# Creation of the Canal




The Panama Canal
Principal components
Atlantic
Gatun Locks
Gatun Dam
Gatun Lake
Madden Dam
Madden Lake
Pedro Miguel Locks
Gaillard Cut
Miraflores Lake
Miraflores Locks
Miraflores Spillway
Pacific

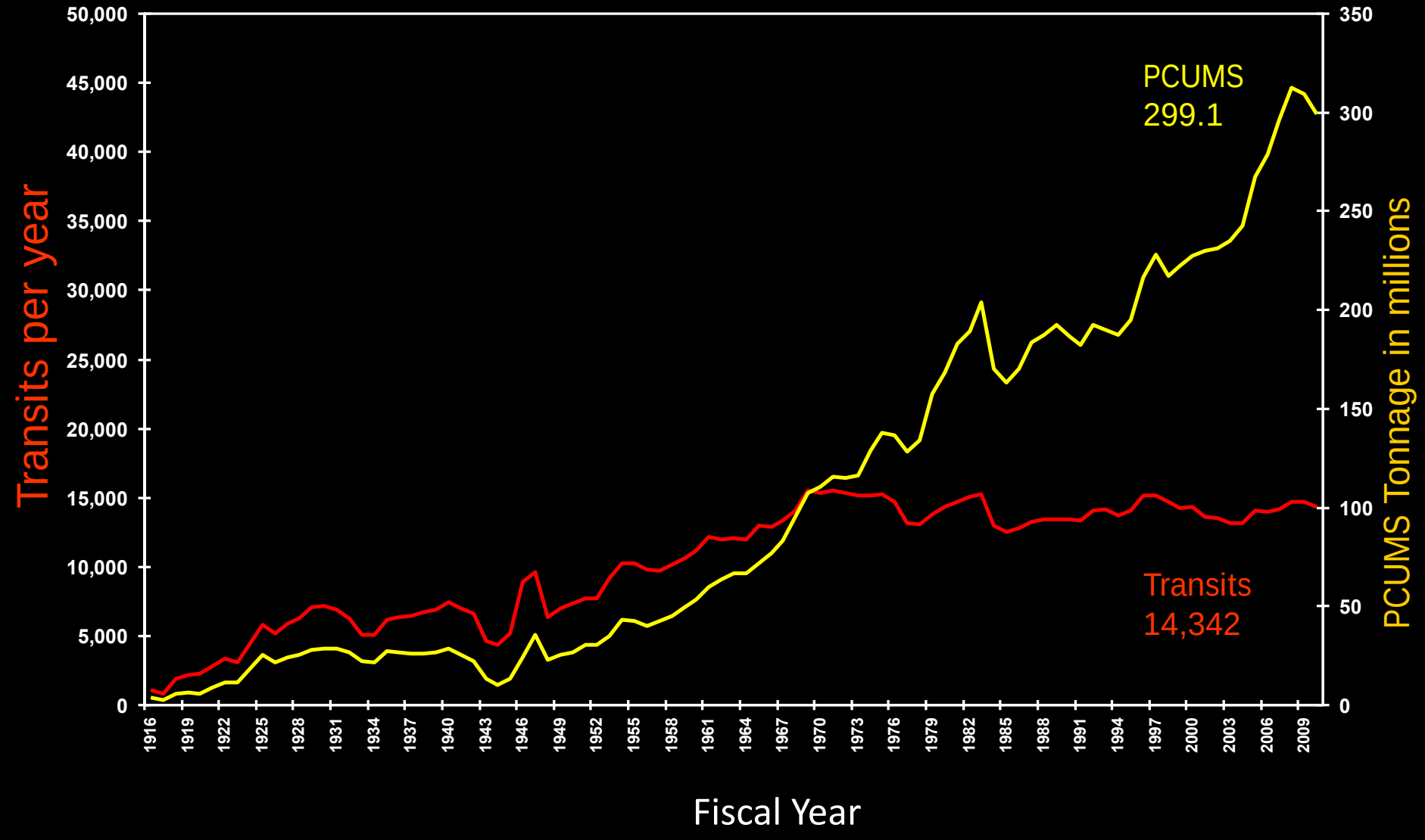
# Longitudinal Profile of the Canal



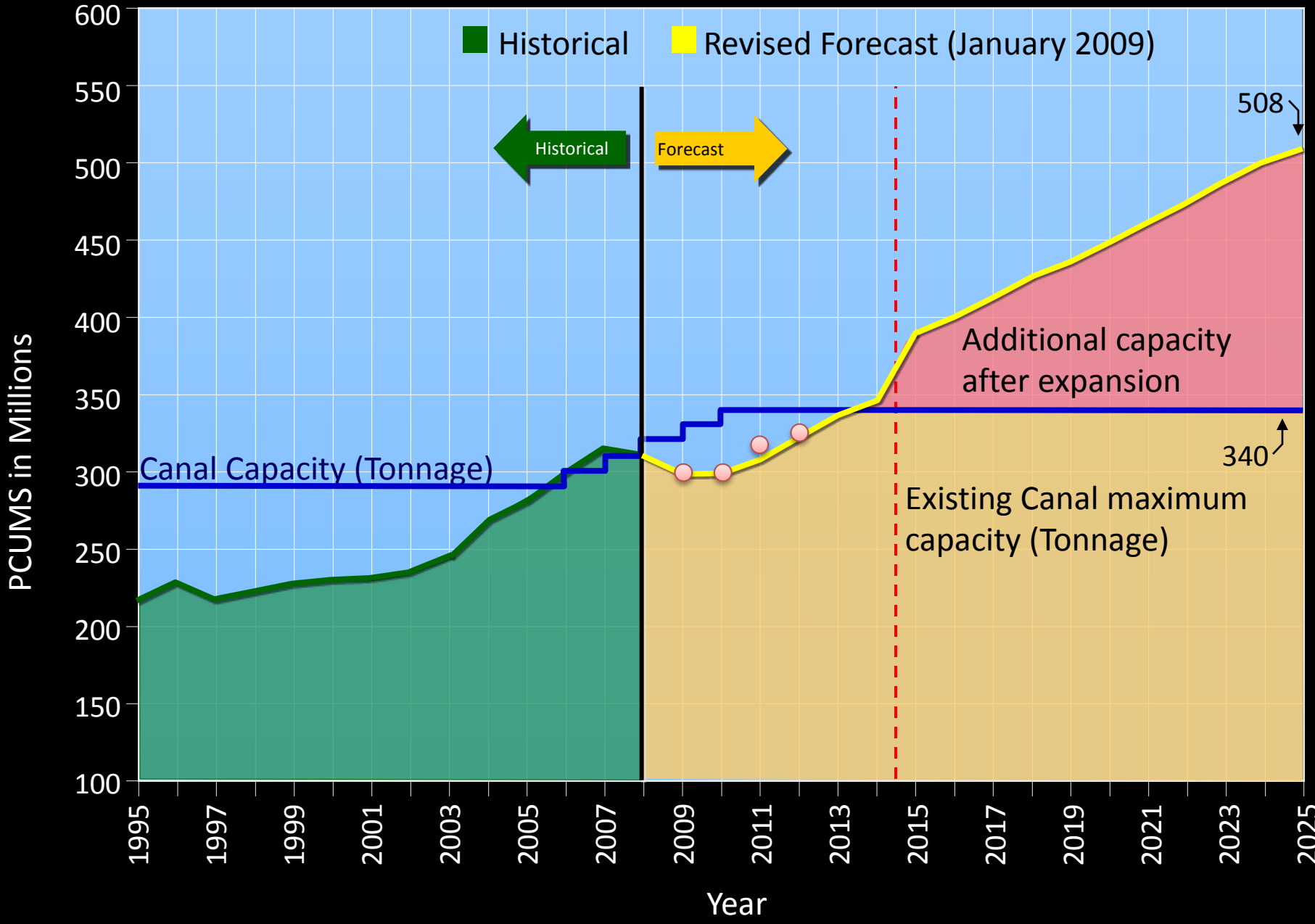
# The Canal Expansion Program

# History of Panama Canal Traffic

FY 1915 – FY 2010

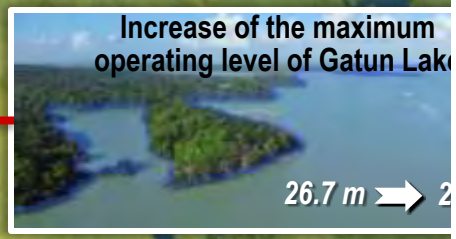


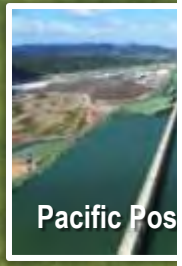
# Demand for shipping



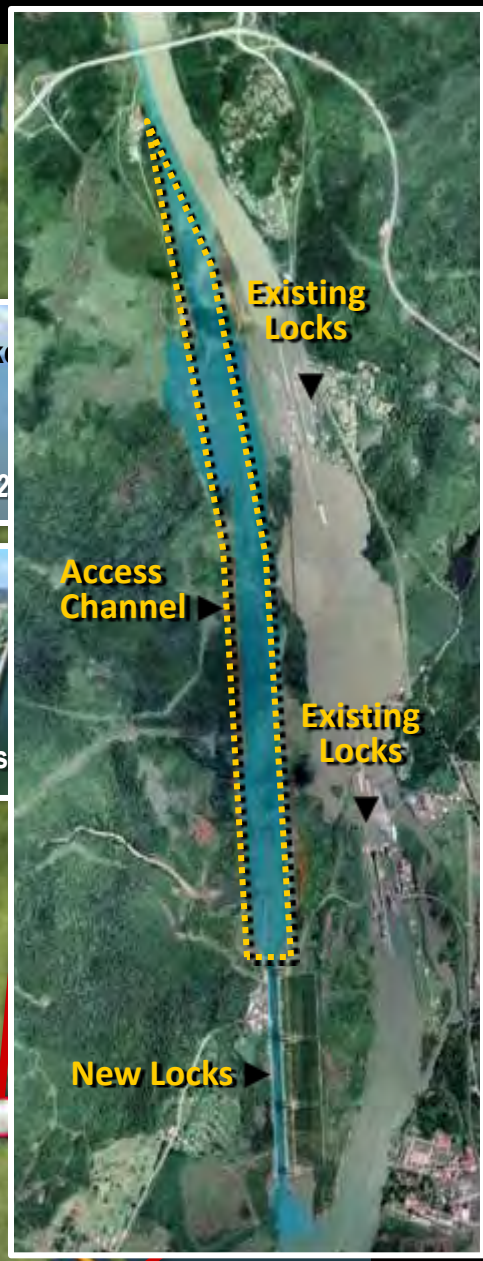
# Program Components



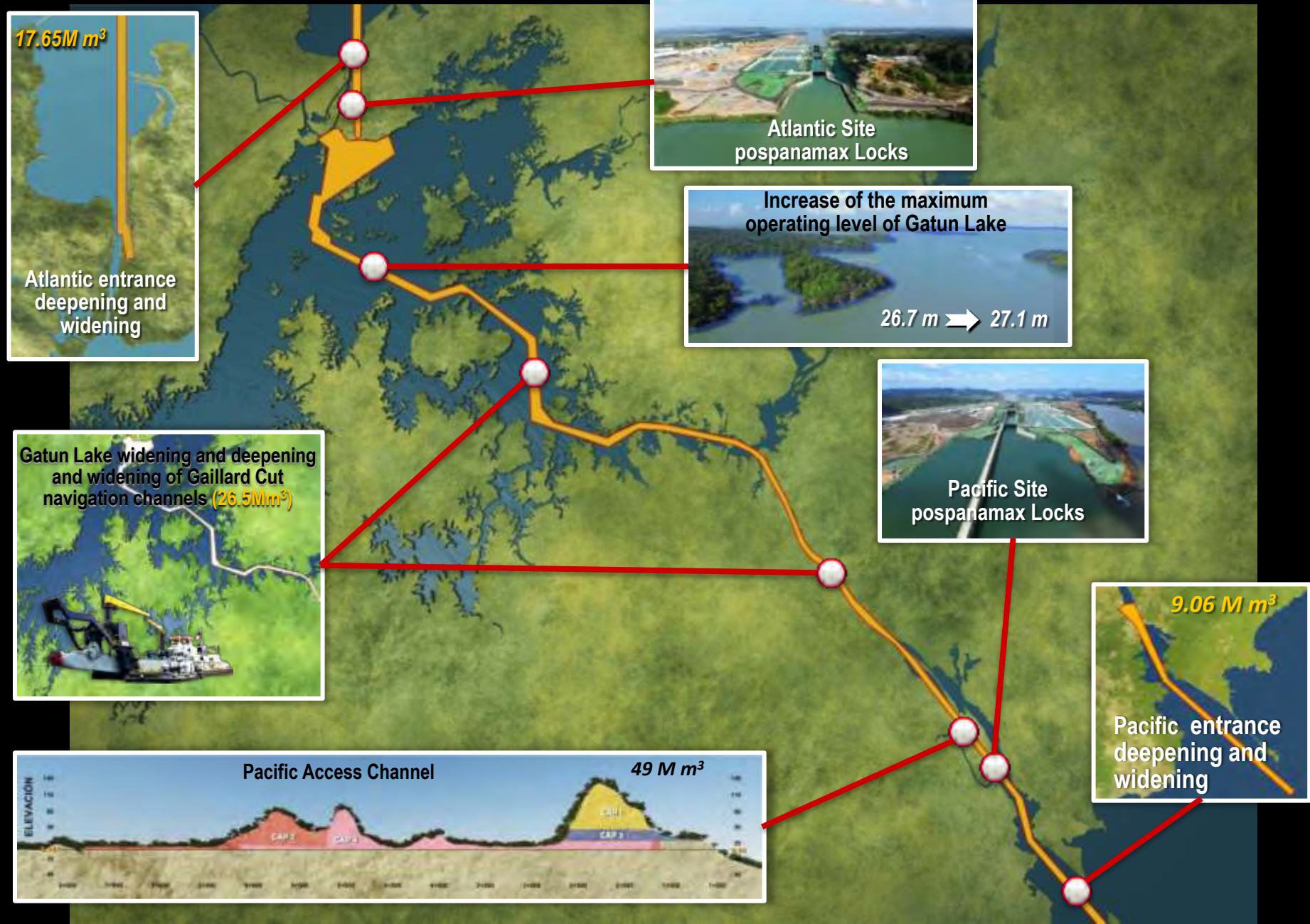




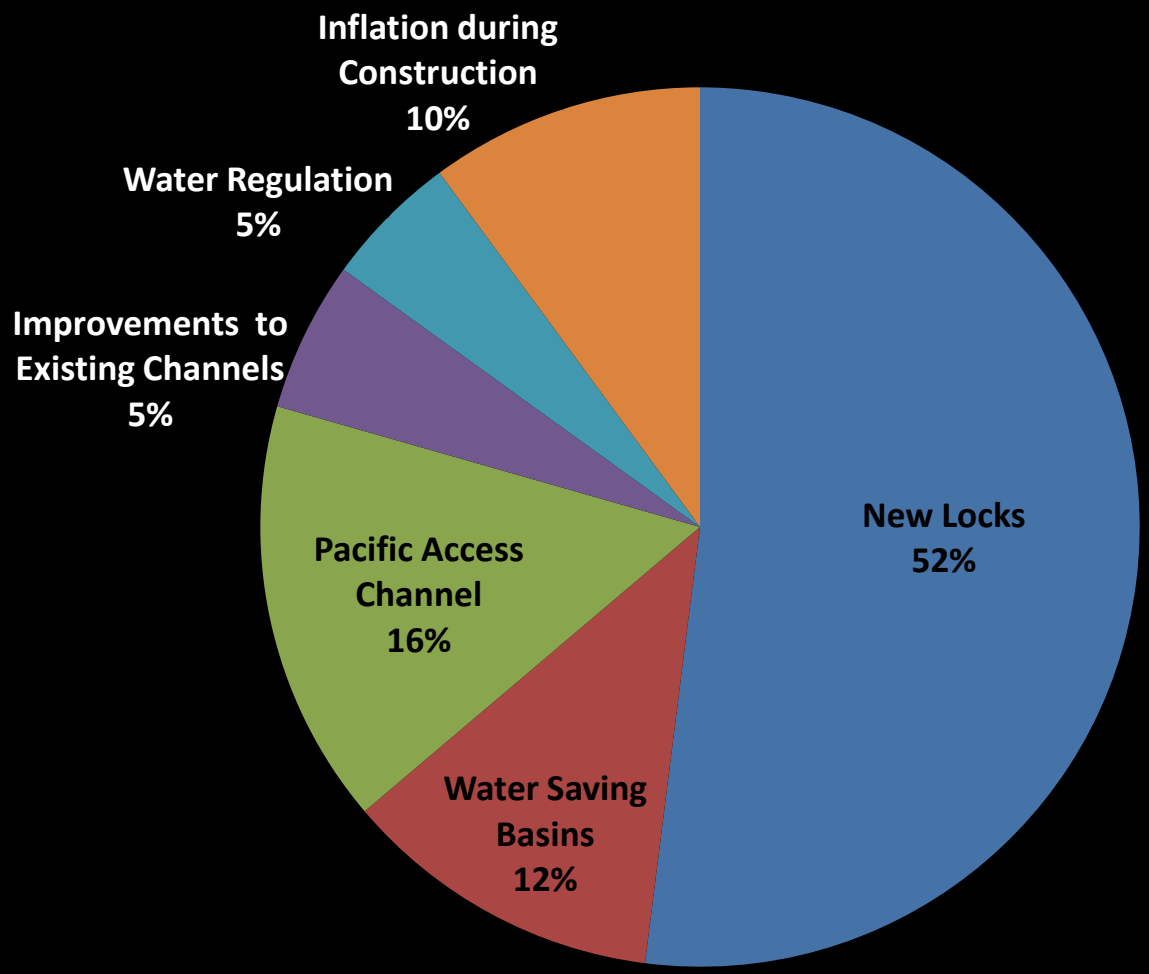



# Program Components



# The Cost of the Canal Expansion Program

## Total: $5.25 Billion



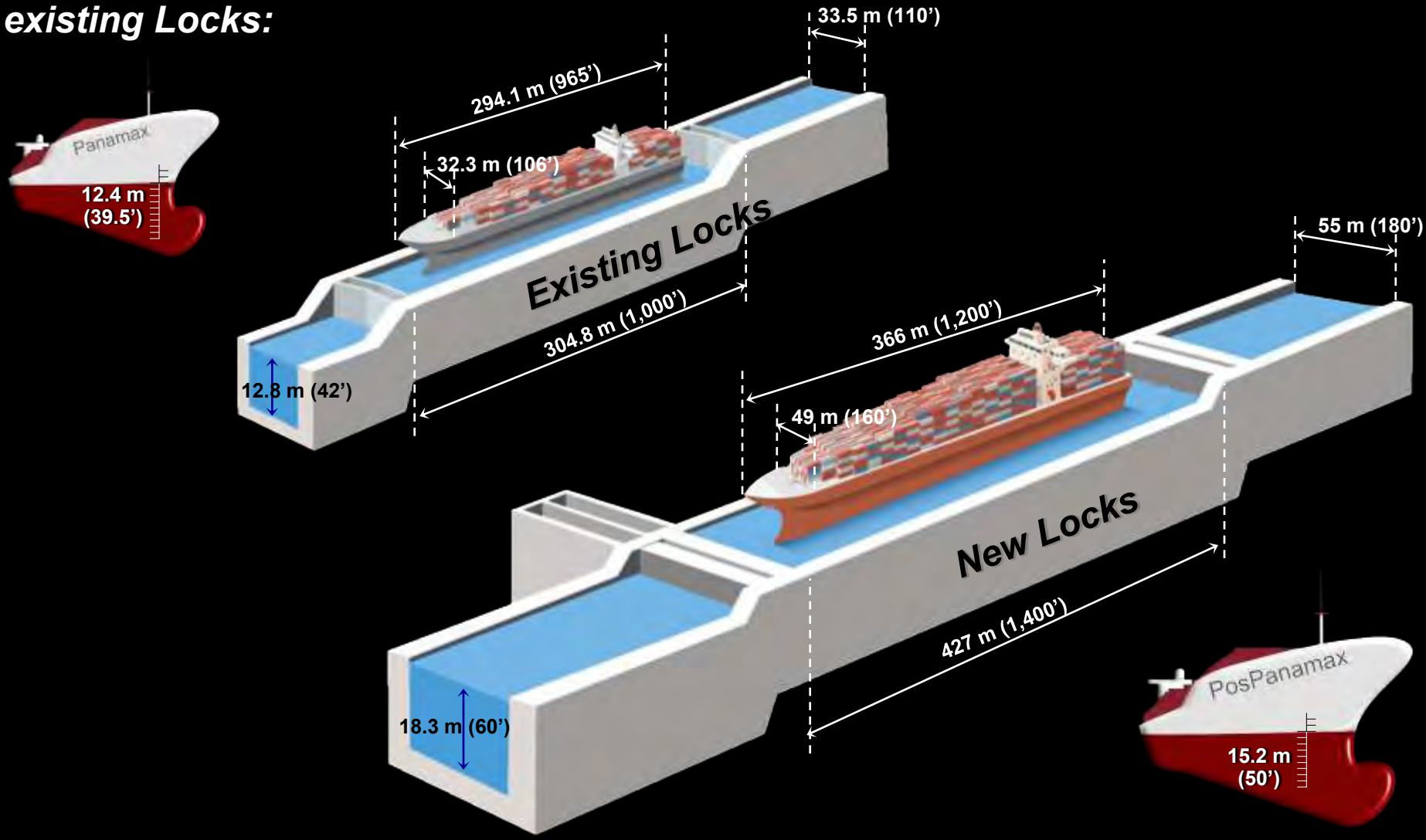
# Main Contractors

| | Design | Construction |
|---|---|---|
| Post-Panamax Locks Project | | |
| Sacyr-Vallehermoso - Spain | |  |
| Impregilo - Italy | |  |
| Jan De Nul – Belgium | |  |
| CUSA – Panama | |  |
| Montgomery Watson Harza - US |  | |
| Pacific Access Channel – Phase 4 | | |
| ICA - Mexico |  |  |
| FCC - Spain | |  |
| MECO – Costa Rica | |  |
| Atlantic Entrance | | |
| Jan De Nul - Belgium |  |  |
| Pacific Entrance | | |
| Dredging International - Belgium |  |  |

# The Post-Panamax Locks

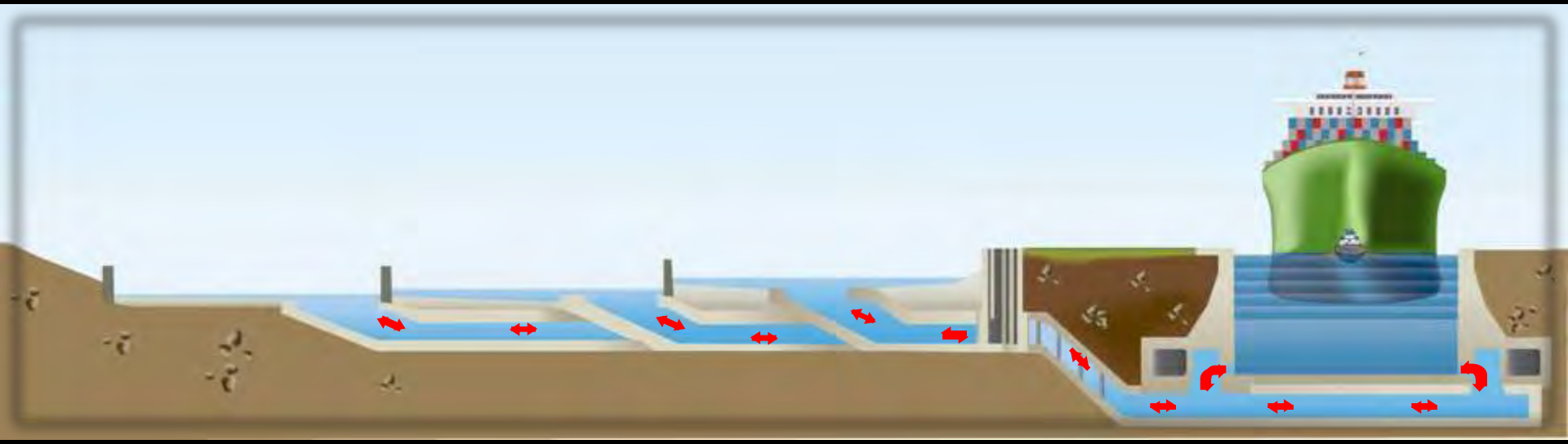
# Dimensions of Locks and Ships

***Maximum size of vessels in existing Locks:*** ***4,400 TEU***




***Maximum size of vessels in new Locks:*** ***13,000 – 14,000 TEU***

# Operation of the Water Saving Basins



With the WSB, the new locks will save 60%
of the water used for a lockage

# New Atlantic Locks

2.10M m3 of structural concrete

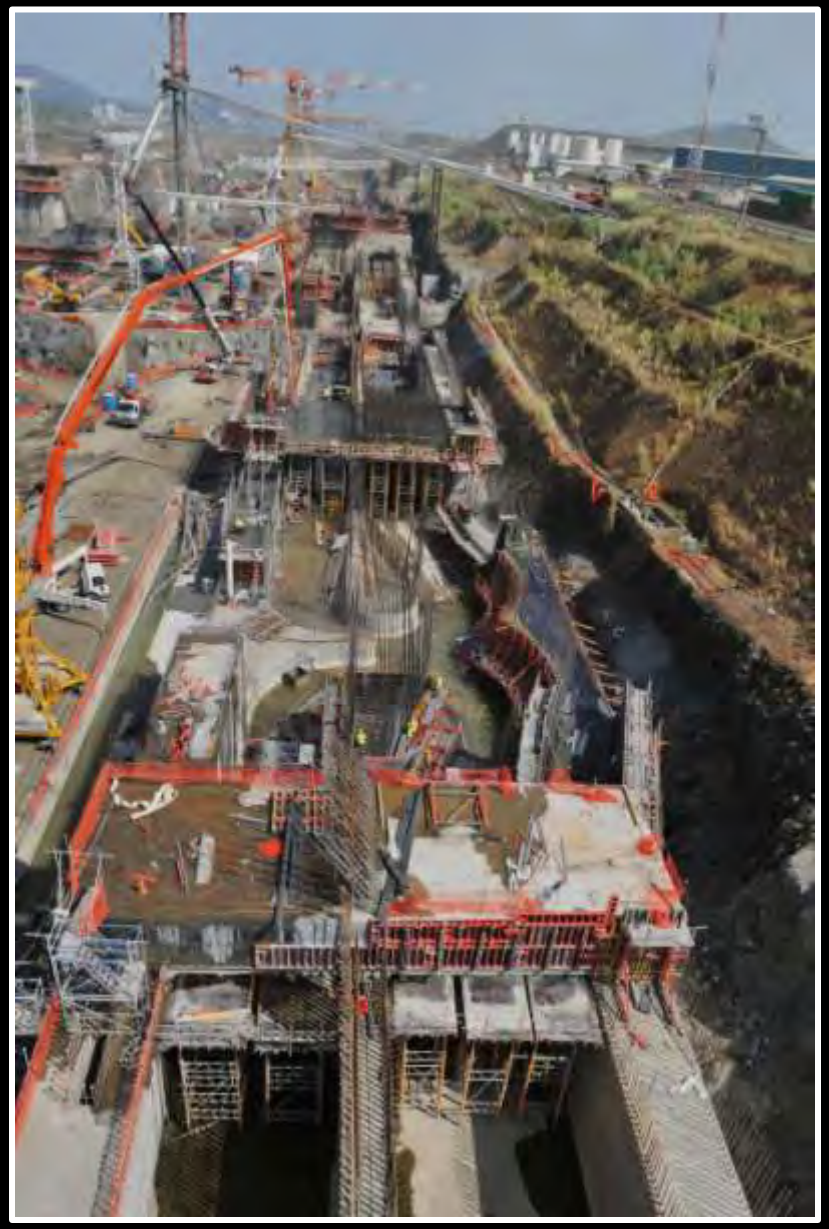
# New Atlantic Locks

# New Pacific Locks

2.34M $m^3$ of structural concrete

# New Pacific Locks

# New Locks Project

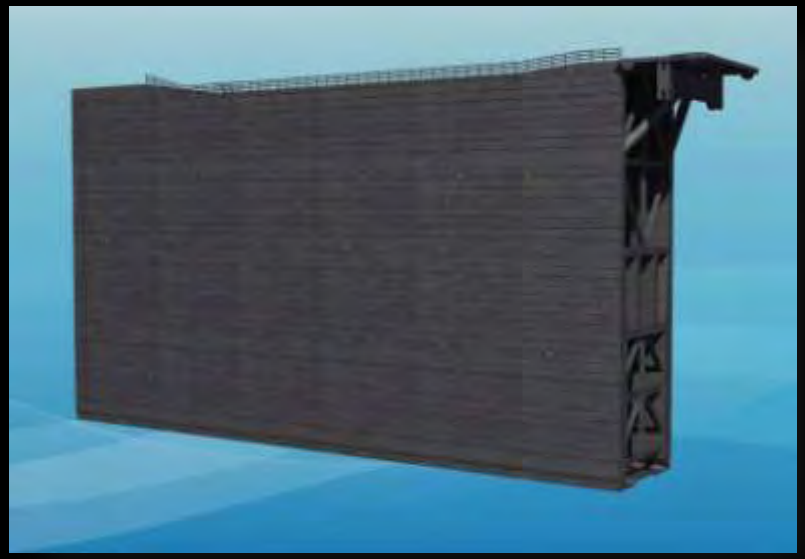


# New Locks Project

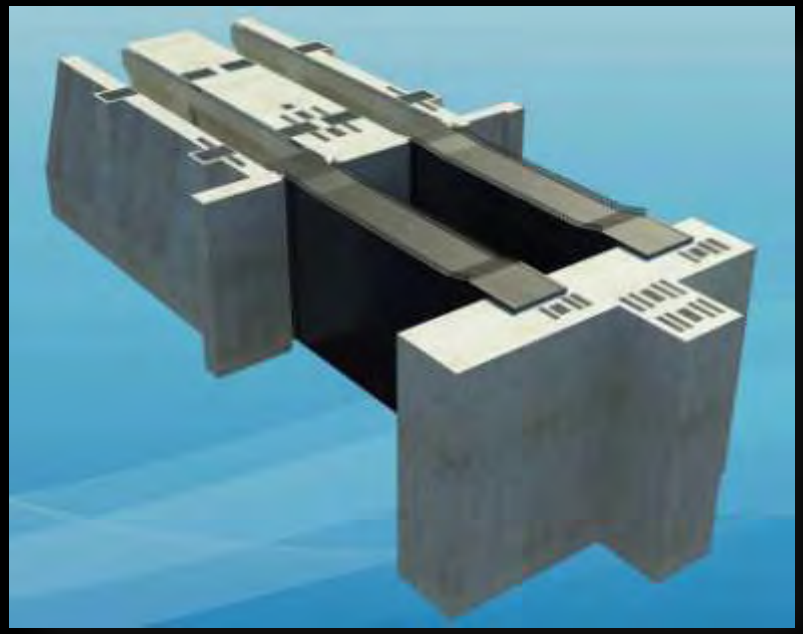
Completed 24%

0% 50% 100%

# Rolling gates



Single Rolling Gate



Lockhead with 2 Rolling Gates

- 8  pairs of rolling gates in 8 lockheads
- Approximately 52,500 tons of steel

# Gate Manufacturing – Cimolai (Pordenone, Italy)

# Gate Manufacturing

# Cimolai Assembly yard

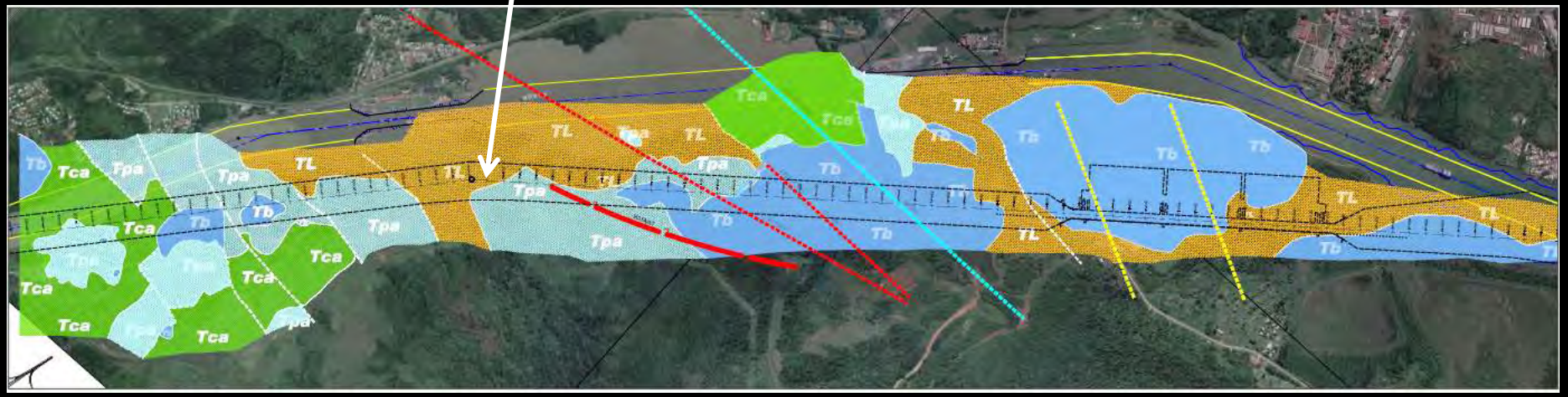
# Pacific Access Channel

(the second Gaillard Cut)

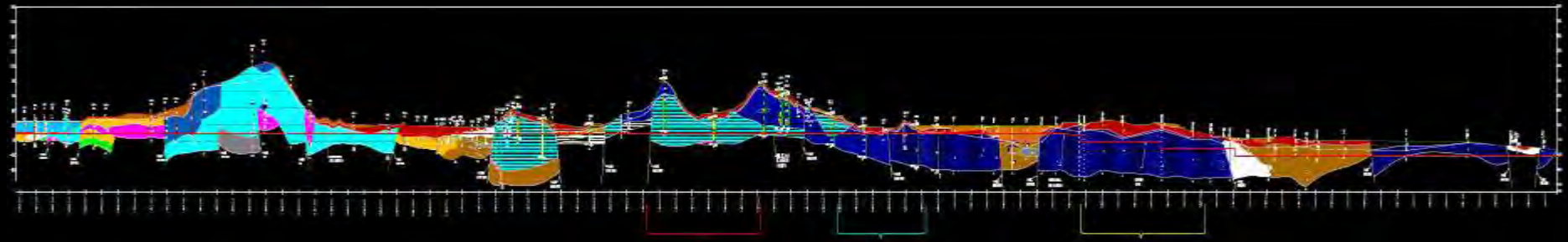
# Structural Geology of the PAC area

Tb: Basalt
Tpa: Pedro Miguel Agglomerate
Tca: Cucaracha Soft Rocks
TL: La Boca Soft Rocks

**New Pacific Access Channel**



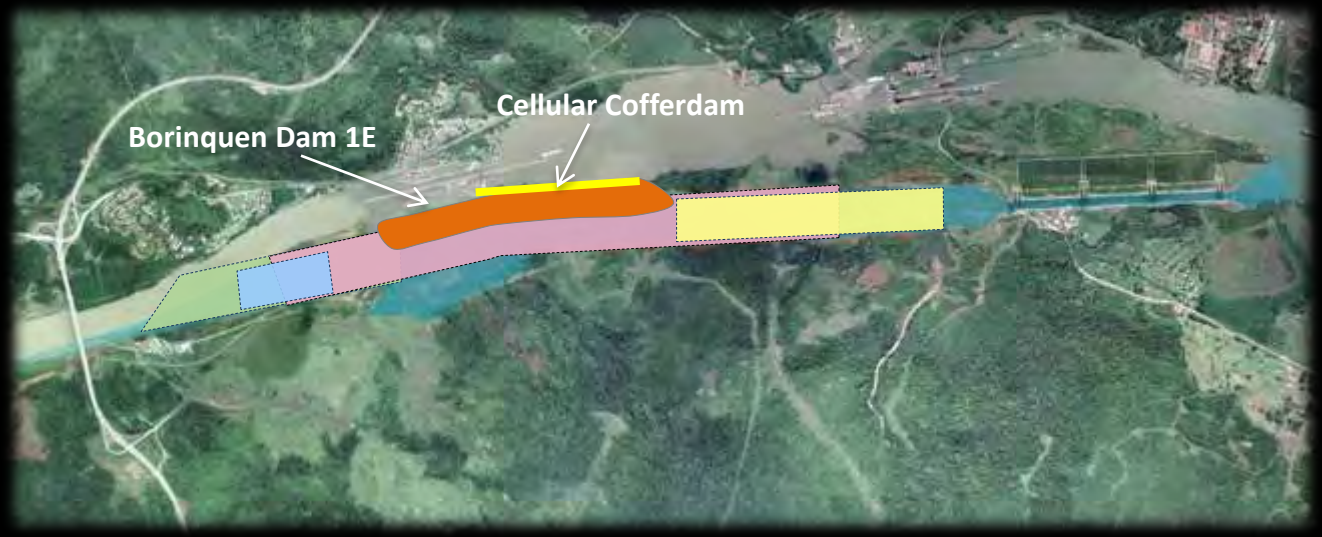

**Miraflores Faults** **Pedro Miguel Fault** **Aguadulce Faults**



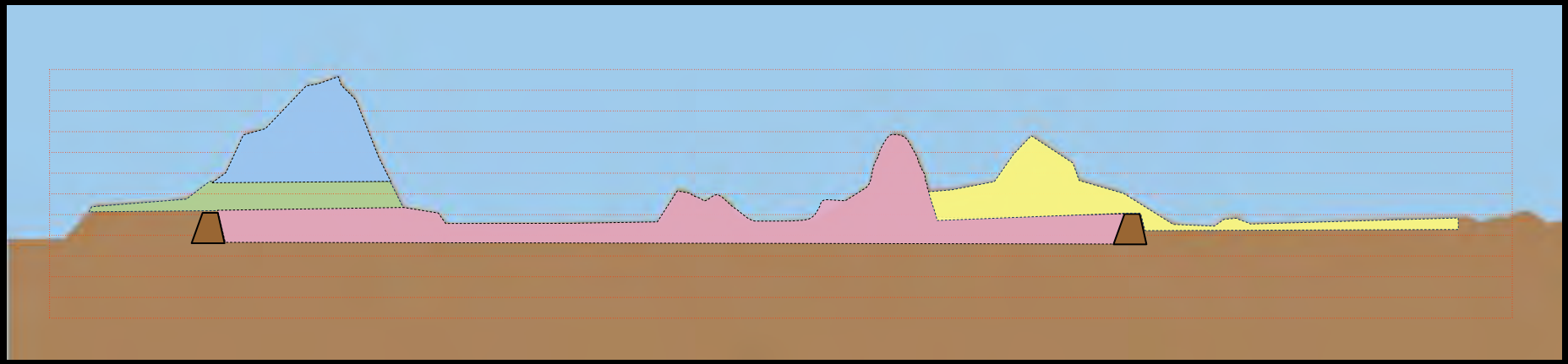
**Miraflores Faults** **Pedro Miguel Fault** **Aguadulce Faults**

# Layout of Excavation Projects

Pacific access channel




PAC-3 PAC-1 PAC-4 PAC-2



# Pacific Access Channel

PAC-1

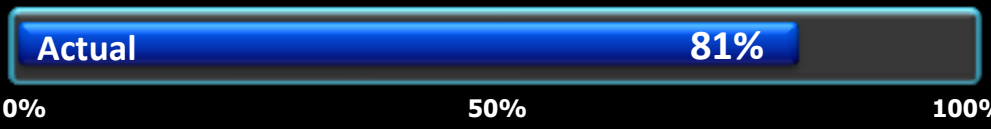

PAC-2


PAC-3


PAC-4

40.6 M $m^3$ excavated / 50.1 M $m^3$

Estimated date of completion: 31-Oct-13

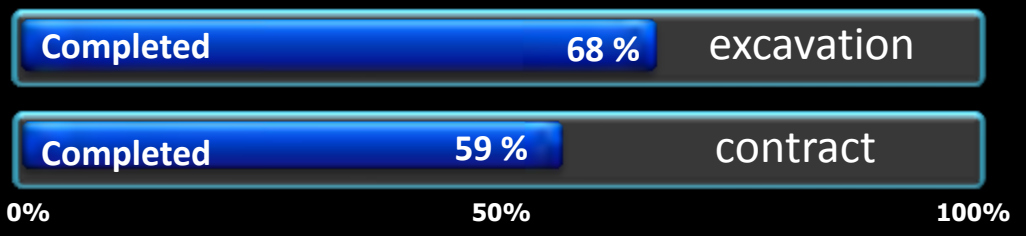


# Pacific Access Channel – Phase 4

## 26 M $m^3$ dry excavation

- Scope of Contract:
  - 26 M m3 excavation
  - Borinquen dam construction
  - Clearing of 80 hectares of UXO.
- Award: January 7, 2010
- Amount: B/. 267,798,795.99
- Company: Consortium ICA-FCC-MECO
- Completion of contract: August 2, 2013

17.7 M $m^3$ excavated / 26 M $m^3$



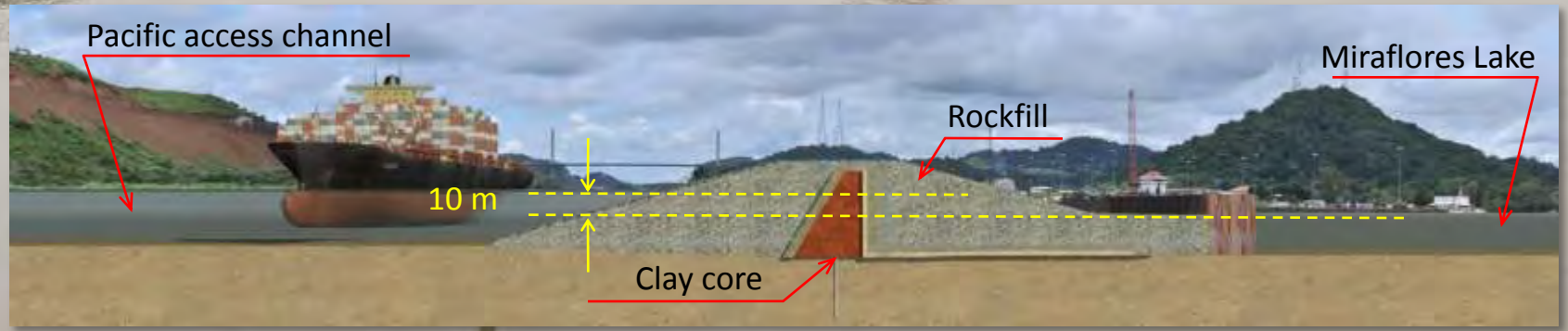
# Pacific Access Channel – Phase 4

# Pacific Access Channel – Phase 4

# The Borinquen Dams

# The Borinquen Dams

# PostPanamax navigation channel & Miraflores Lake



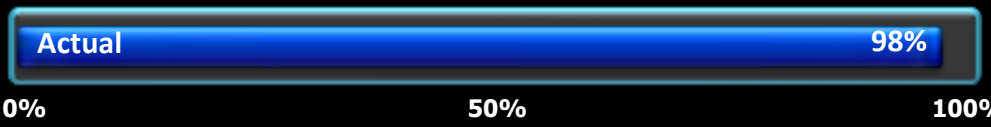
# View of Excavated Slopes, Cofferdam and Rockfill

# View of the cofferdam and construction of Dam 1E

# Widening and Deepening of Existing Navigation Channels

# Widening and Deepening of the Atlantic Entrance

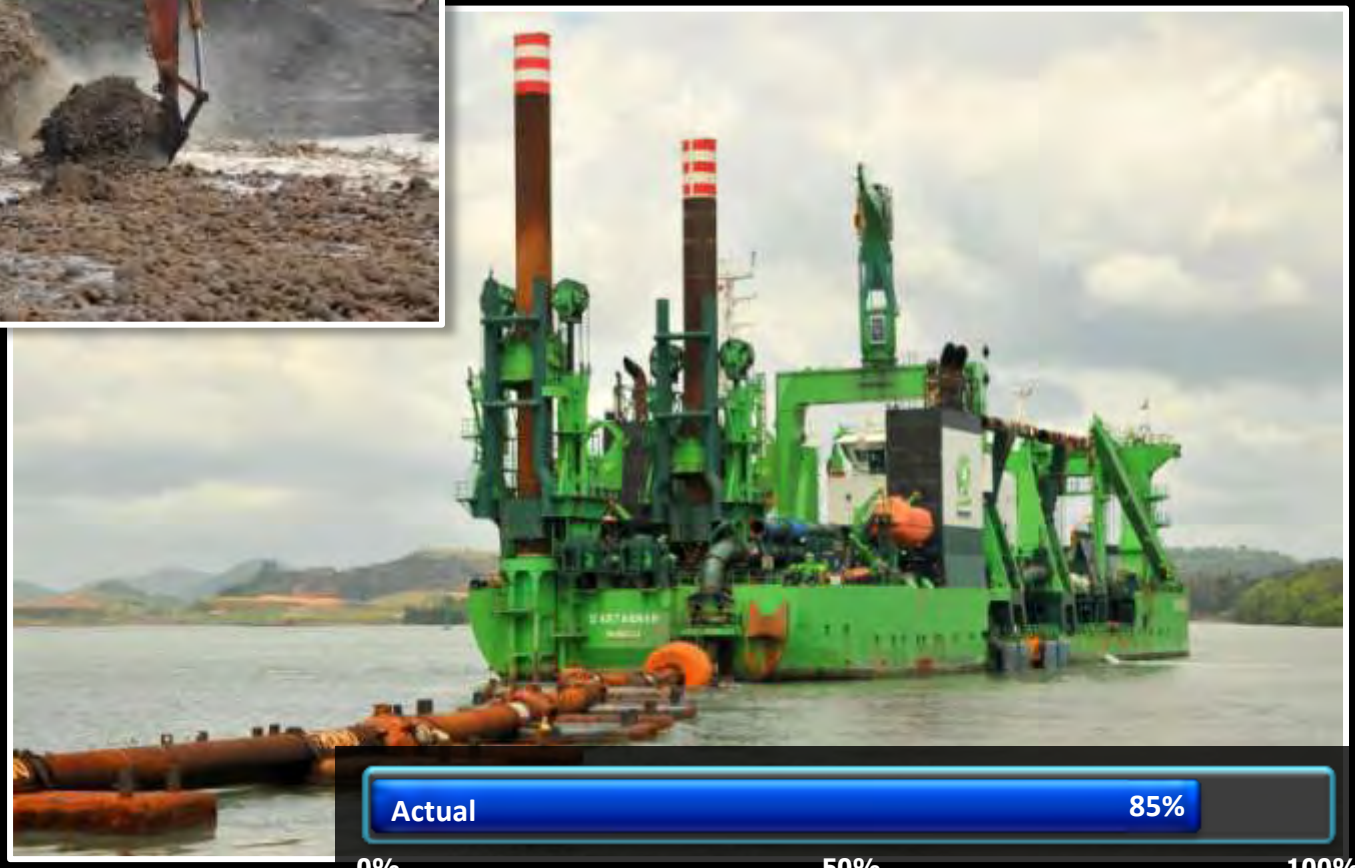
- Total Excavation : 17.65 M $m^3$
- Excavation to date: 17.38 M $m^3$



# Widening and Deepening of the Atlantic Entrance

# Deepening and widening of the Pacific Entrance

- Total Excavation : 9.06 M $m^3$
- Excavation to date: 7.70 M $m^3$



# Gatun Lake and Gaillard Cut Dredging Areas

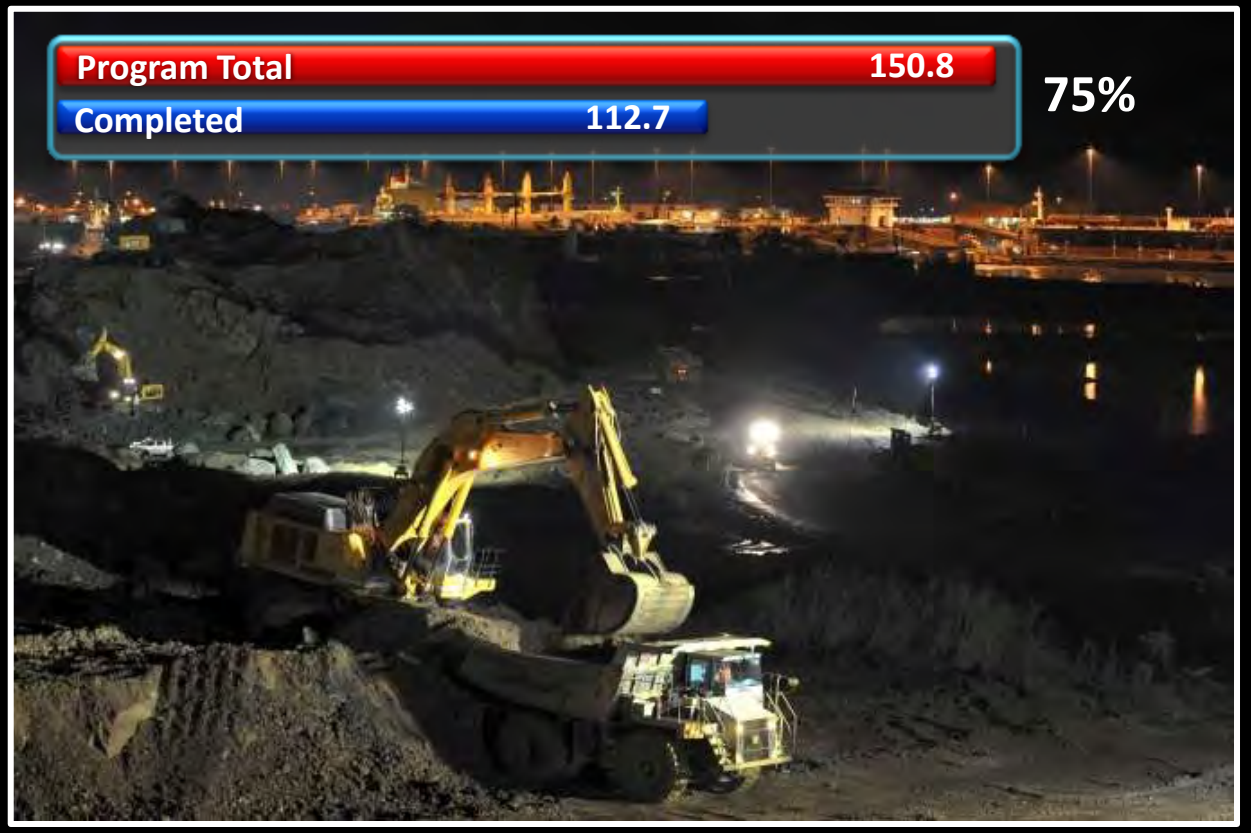

Gatun Lake
Gatún
Completed by Dredging International
Peña Blanca
Bohío
Buena Vista
Barro Colorado
Completed by Dredging International
Tabernilla
Completed by ACP
Work underway by ACP
San Pablo
Juan Grande
Gamboa
Chagres
Mamey
Gamboa

Actual 69 %

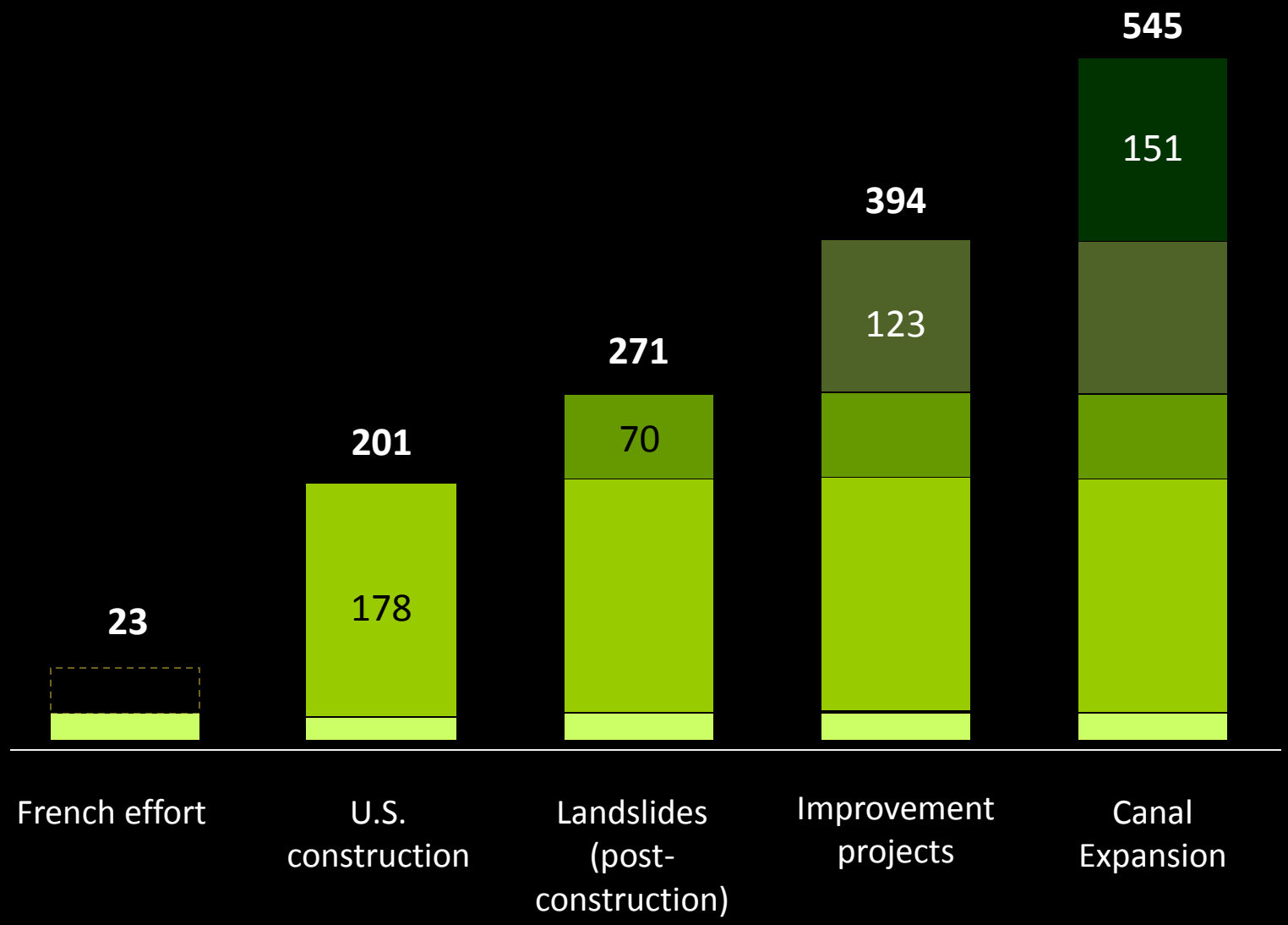
0% 50% 100%

# Total Excavation and Dredging - May 2012

| | |
|---|---|
| **Locks** | 47.5 M $m^3$ |
| **Pacific Access** | 50.1 M $m^3$ |
| **Dredged** | 53.2 M $m^3$ |
| **Estimated** | 150.8 M $m^3$ |



# Excavation Volumes ($Mm^3$)



# Expansion Program Progress

## Pacific Access Channel
37.62 M $m^3$ excavated / 49 M $m^3$
End of last Contract: 31-Oct-2013

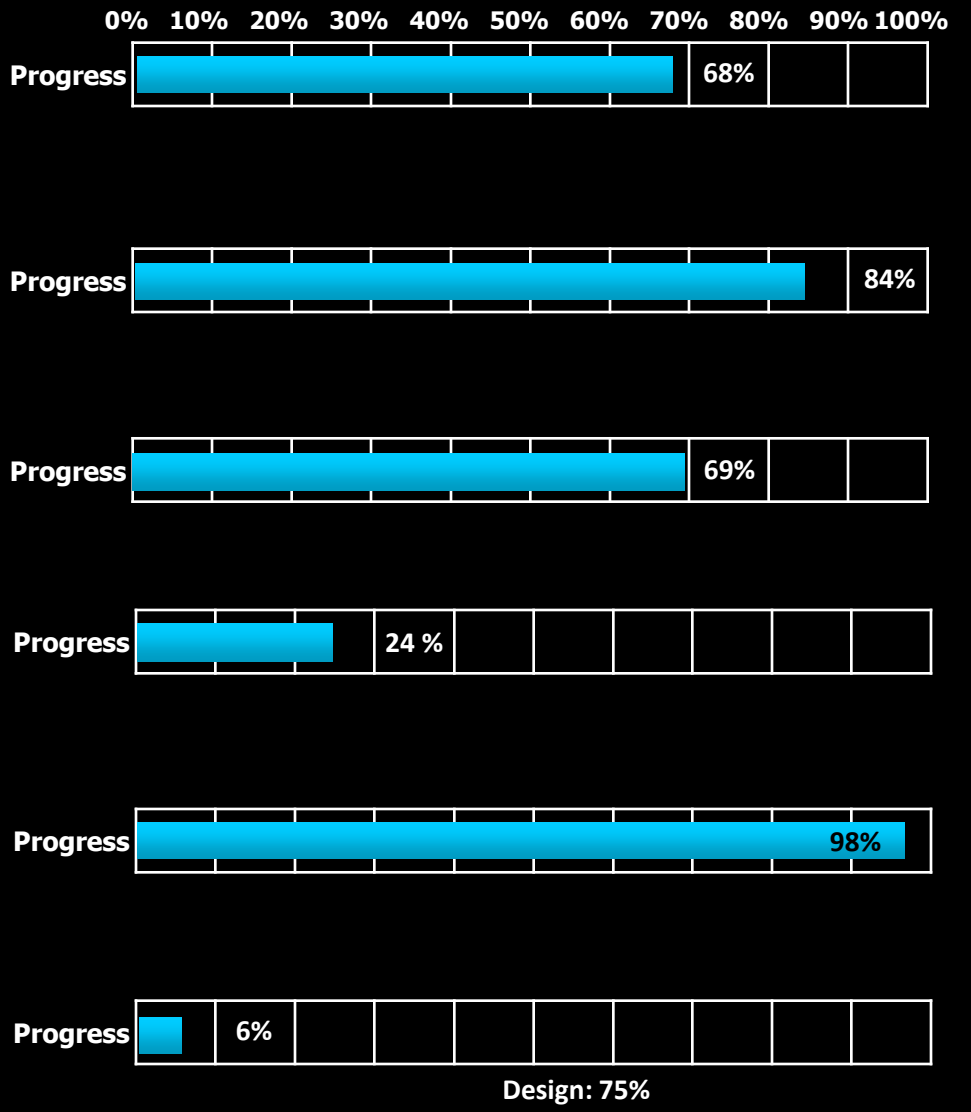
## Pacific Entrance Deepening and Widening
7.68 M $m^3$ dredged / 8.7 M $m^3$
End of Contract: 31-Aug-2012

## Gatun Lake and Gaillard Cut Deepening and Widening
16.8 M $m^3$ dredged / 28 M $m^3$
End: 11-Apr-2014

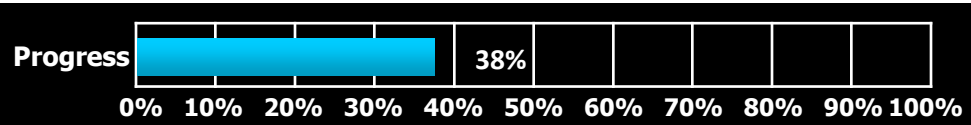
## Locks Design and Construction
23.2 M $m^3$ excavated / 40 M $m^3$
End of Contract: 21-Oct-2014

## Atlantic Entrance Deepening and Widening
17.3 M $m^3$ dredged / 17.6 M $m^3$
End of Contract: 24-Apr-2013

## Raising Gatun Lake's Maximum Operational Level
End: 30-Sep-2013

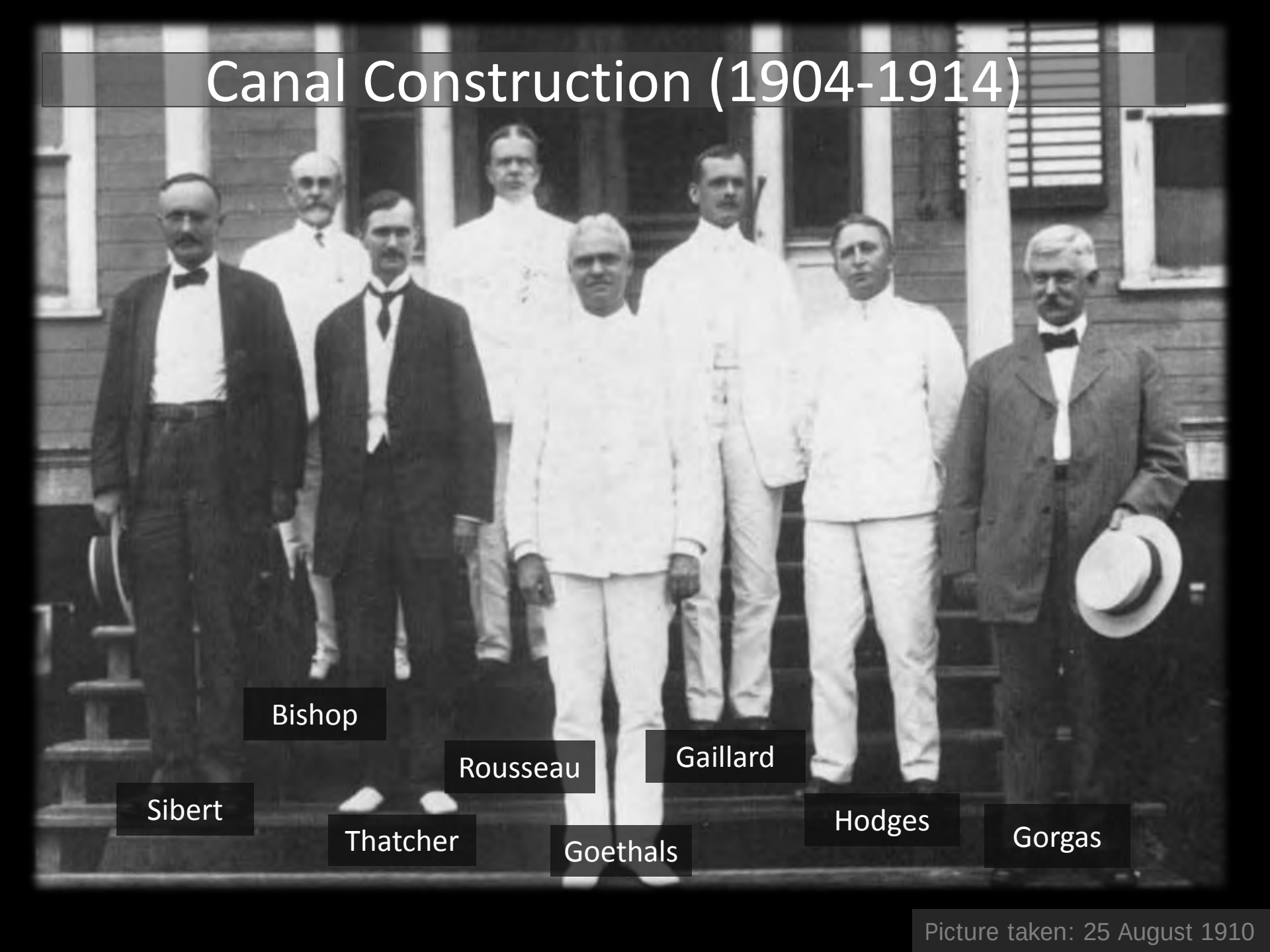



## Expansion Program



# The impact of developments in Rock Mechanics on the Canal

# Canal Construction (1904-1914)




Picture taken: 25 August 1910

1850 1900 1950 2000

**1904 -1913**

Col. David DuBose Gaillard
(1859-1913)

In charge of excavations through the continental divide (Culebra Cut)

Completed the task, considering the extremely limited knowledge and tools at his disposal


September 19, 1912
East Culebra Slide


February 2, 1913
East Cucaracha Slide

February 7, 1913

East Cucaracha Slide

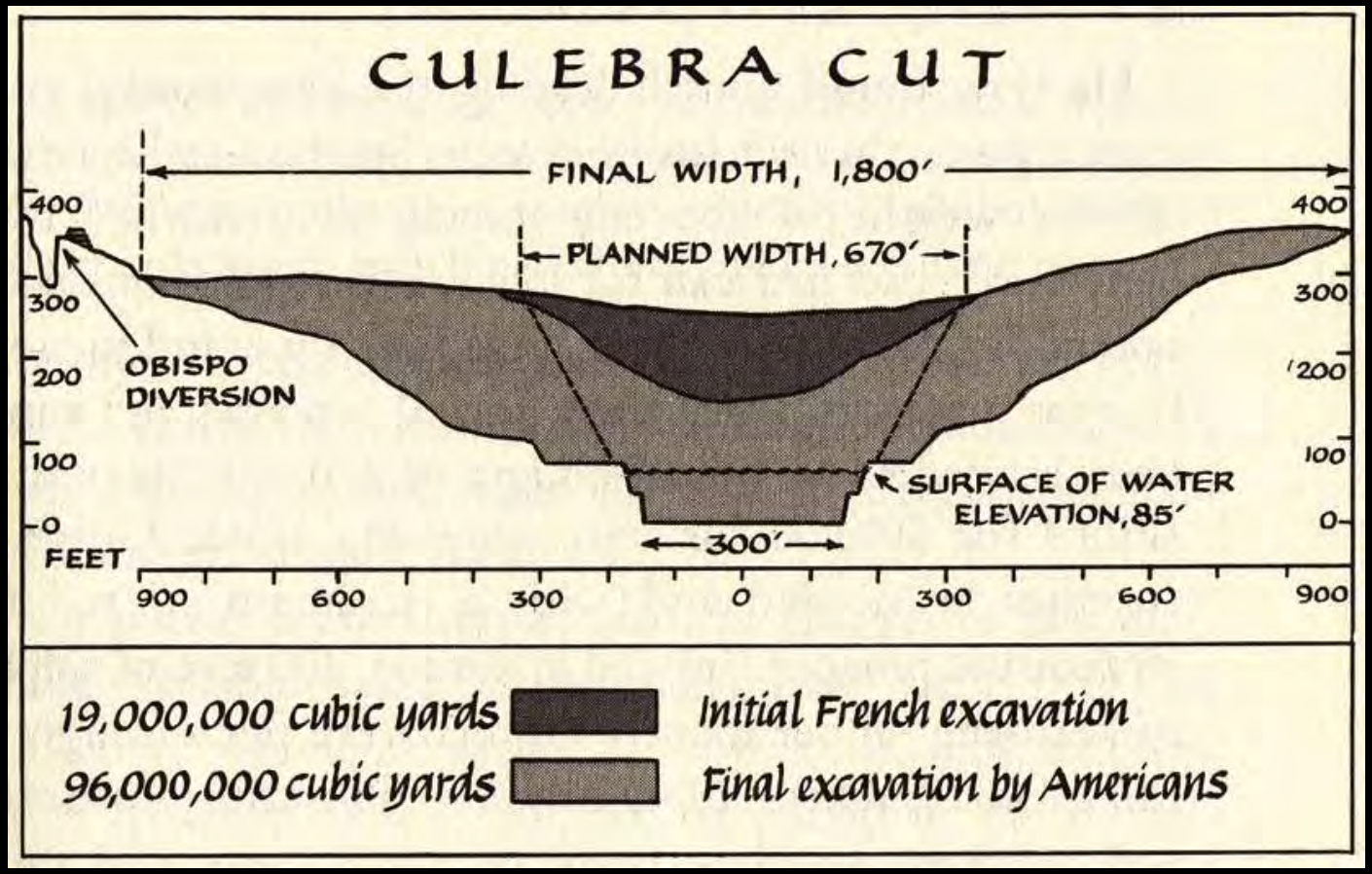
# Inauguration of the Canal

August 15, 1914

East & West Culebra slides (October 1915)

# Original Design of Excavations

Reference: McCullough “The Path Between the Seas” (1977)



1850 1900 1950 2000

1936

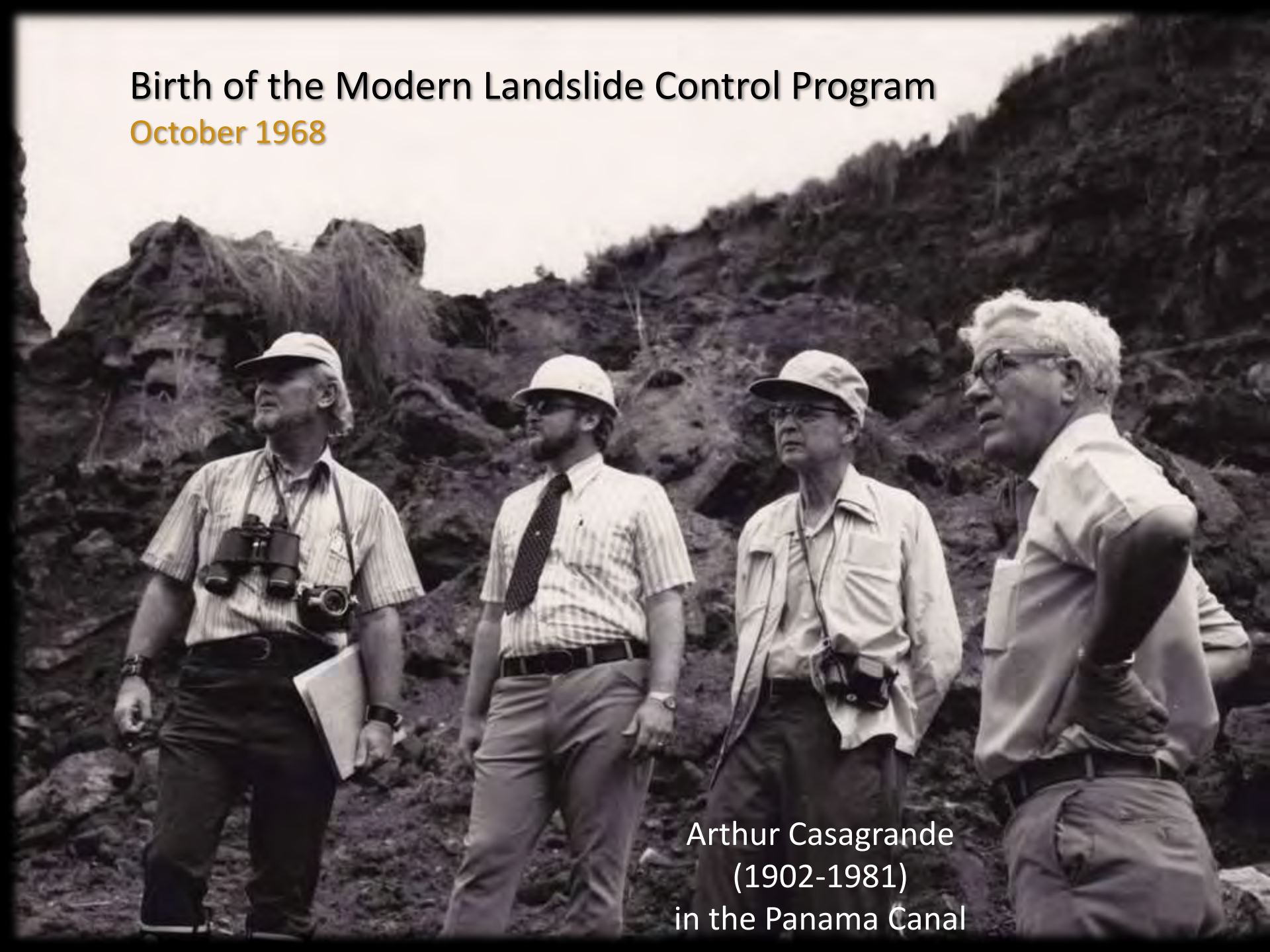
Karl von Terzaghi
(1883-1963)

*"…. the catastrophic descent of the slopes in the deepest cuts on the Panama Canal issued a warning the we were overstepping the limits of our ability to predict the consequences of our actions."*

Presidential Address given at the first International Conference on Soil Mechanics and Foundation Engineering, Cambridge Massachusetts, June 1936

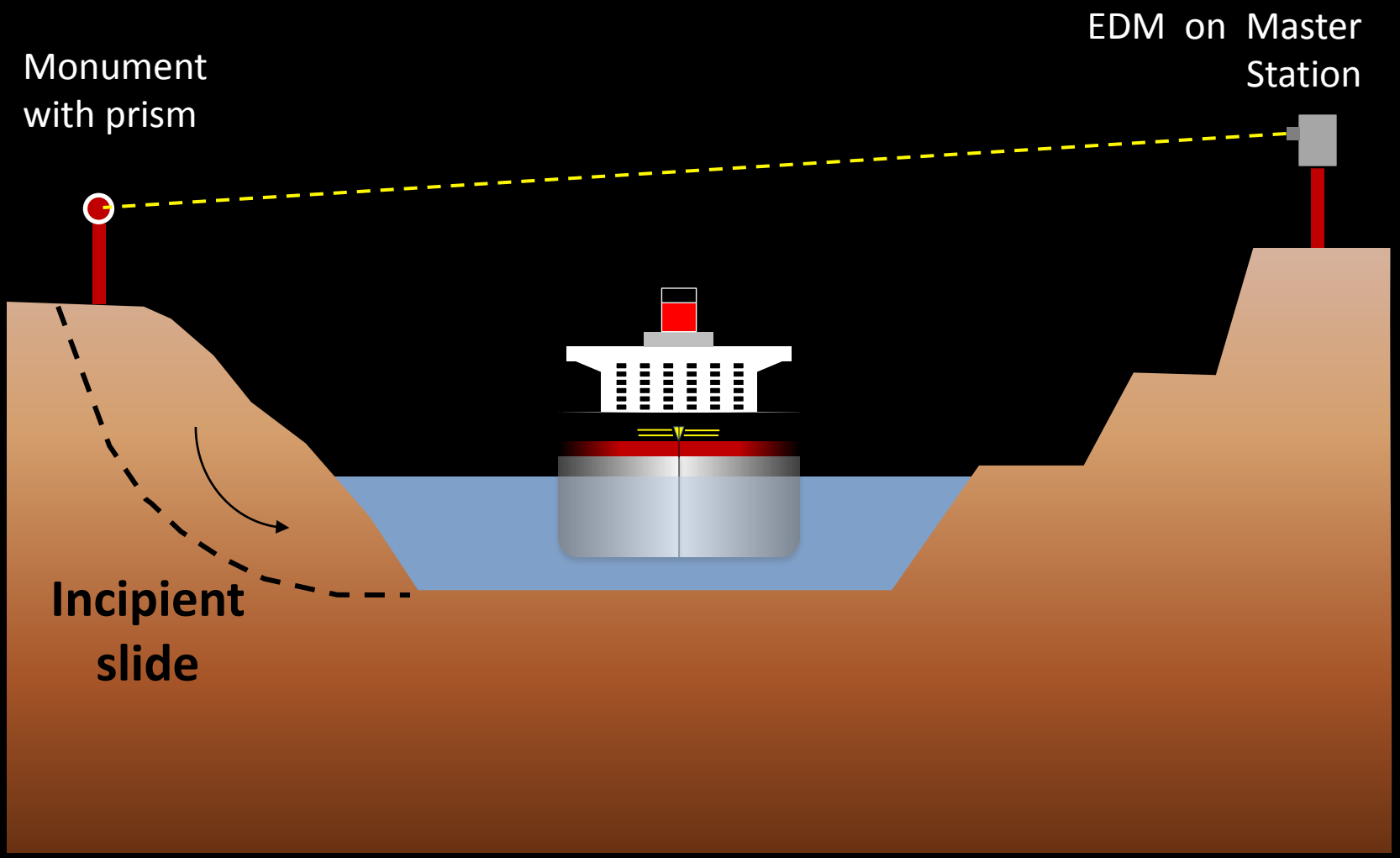
# Birth of the Modern Landslide Control Program

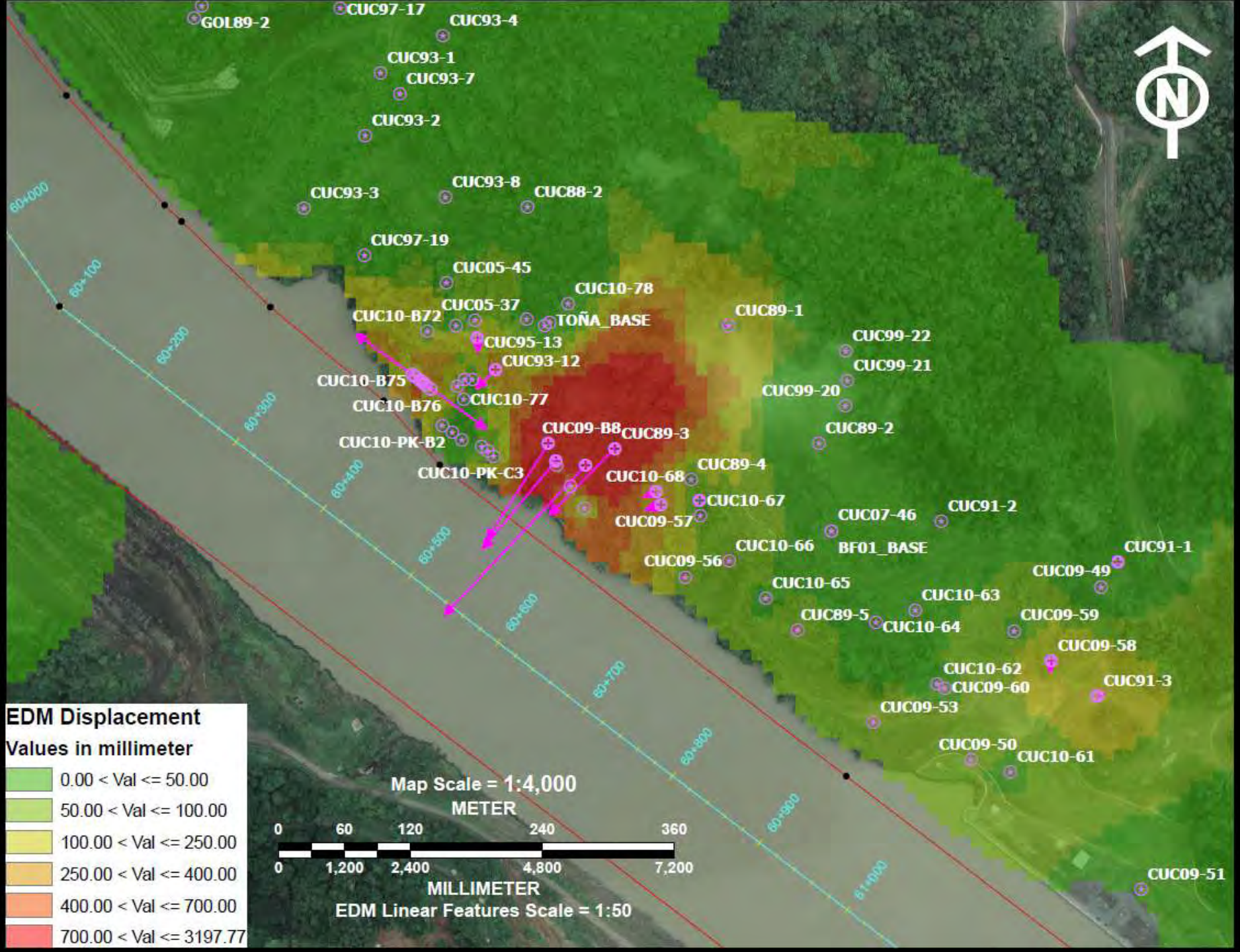
October 1968



Arthur Casagrande
(1902-1981)
in the Panama Canal

# Modern Landslide Control Program




GOL89-2
CUC97-17
CUC93-4
CUC93-1
CUC93-7
CUC93-2
CUC93-3
CUC93-8
CUC88-2
CUC97-19
CUC05-45
CUC10-78
CUC05-37
CUC10-B72
TOÑA_BASE
CUC89-1
CUC95-13
CUC93-12
CUC99-22
CUC99-21
CUC10-B75
CUC99-20
CUC10-77
CUC10-B76
CUC09-B8
CUC89-3
CUC89-2
CUC10-PK-B2
CUC89-4
CUC10-PK-C3
CUC10-68
CUC10-67
CUC09-57
CUC07-46
CUC91-2
CUC10-66
BF01_BASE
CUC91-1
CUC09-56
CUC09-49
CUC10-65
CUC10-63
CUC89-5
CUC10-64
CUC09-59
CUC09-58
CUC10-62
CUC09-60
CUC91-3
CUC09-53
CUC09-50
CUC10-61
CUC09-51
60+000
60+100
60+200
60+300
60+400
60+500
60+600
60+700
60+800
60+900
61+000
N
EDM Displacement
Values in millimeter
0.00 < Val <= 50.00
50.00 < Val <= 100.00
100.00 < Val <= 250.00
250.00 < Val <= 400.00
400.00 < Val <= 700.00
700.00 < Val <= 3197.77
Map Scale = 1:4,000
METER
0 60 120 240 360
0 1,200 2,400 4,800 7,200
MILLIMETER
EDM Linear Features Scale = 1:50

1850 1900 1950 2000

1987-present

## ACP's Geotechnical Advisory Board


Sowers


Duncan


Morgenstern


Schuster

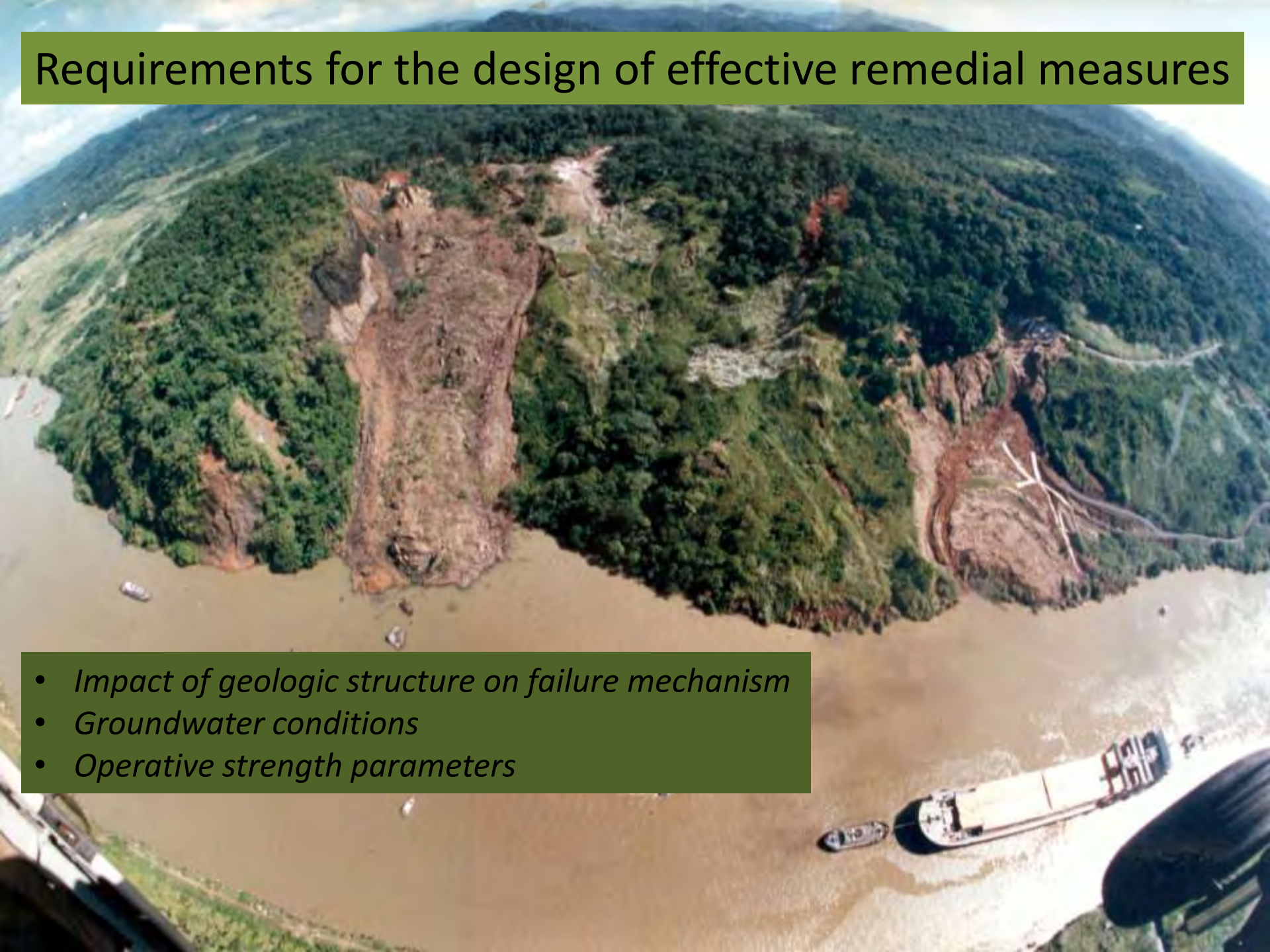

Marcuson


Wesson

Technology Transfer
& Credibility

Canal Personnel

# Requirements for the design of effective remedial measures

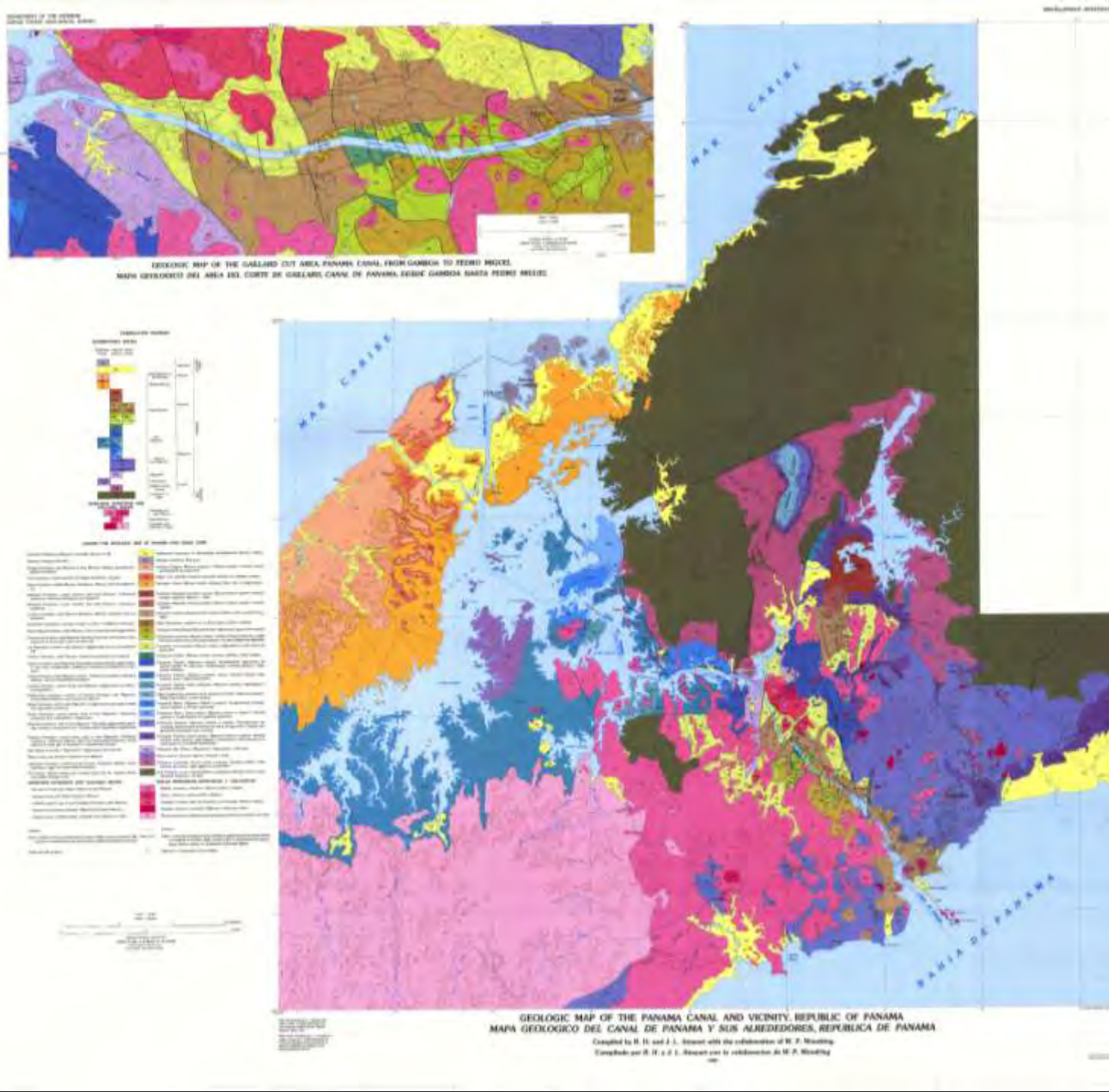


- *Impact of geologic structure on failure mechanism*
- *Groundwater conditions*
- *Operative strength parameters*

# USGS

**Map I-1232**
**(1980)**

R.H. Stewart
J.L. Stewart
W.P. Woodring

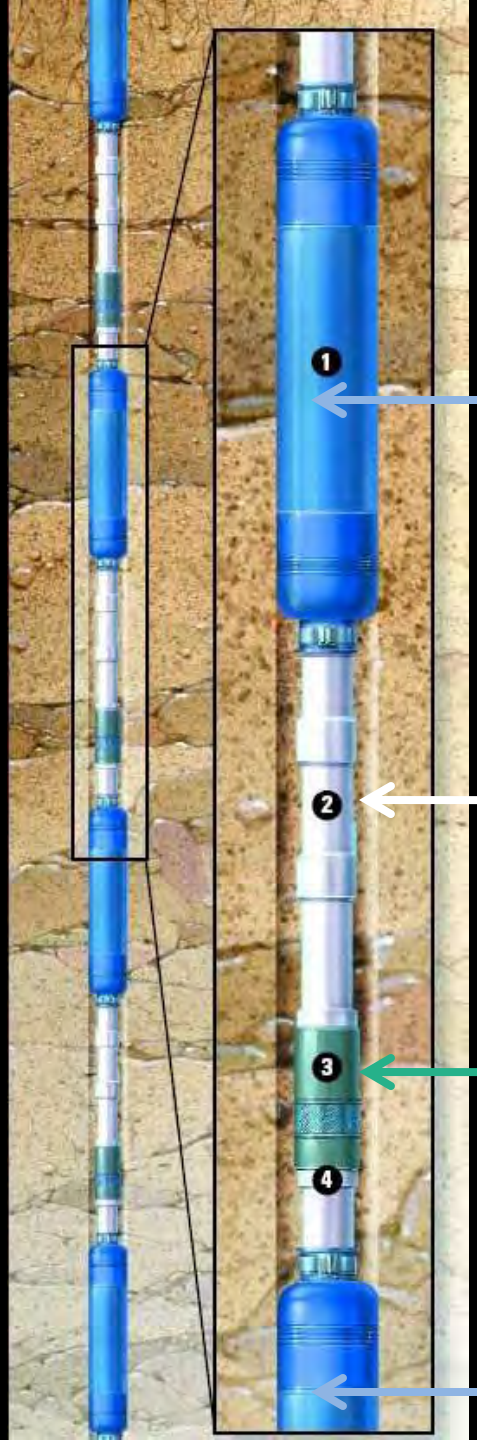


Increased Site Investigation efforts

# Continuous Geological Mapping of the Excavations

# Multi-point Piezometers

Dr. Frank Patton
Westbay Instruments



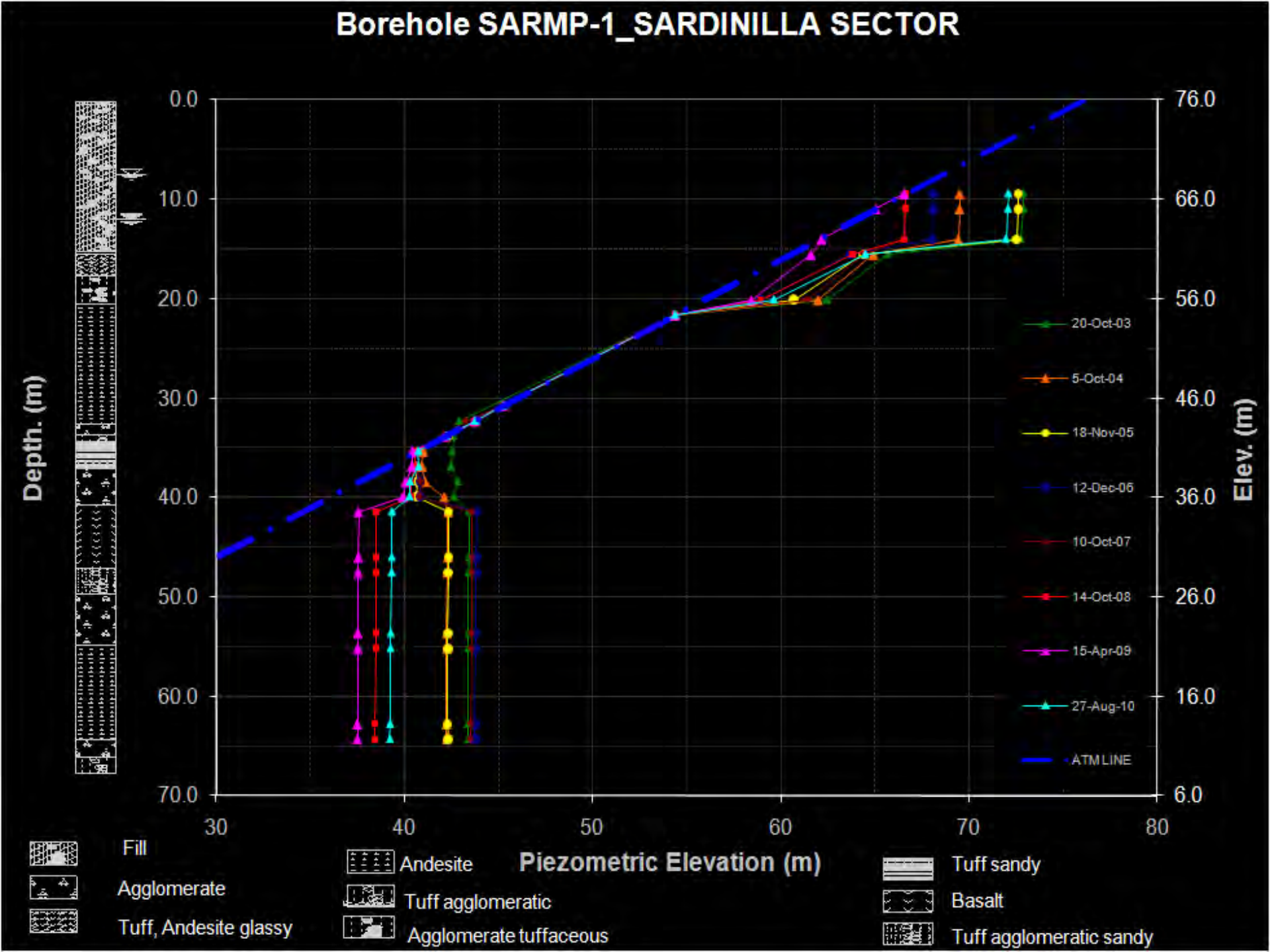

Packer

Measurement Port

Pumping Port (Hydraulic Conductivity)

Packer

# Borehole SARMP-1_SARDINILLA SECTOR



# Dr. Evert Hoek in the Panama Canal

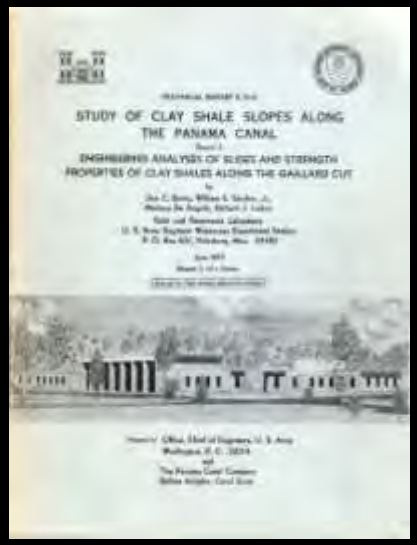
## Shear strength characterization for weak rocks

Hoek-Brown envelope

$$\tau = (\cot \phi_i' - \cos \phi_i') \, m \, \sigma_c / 8$$

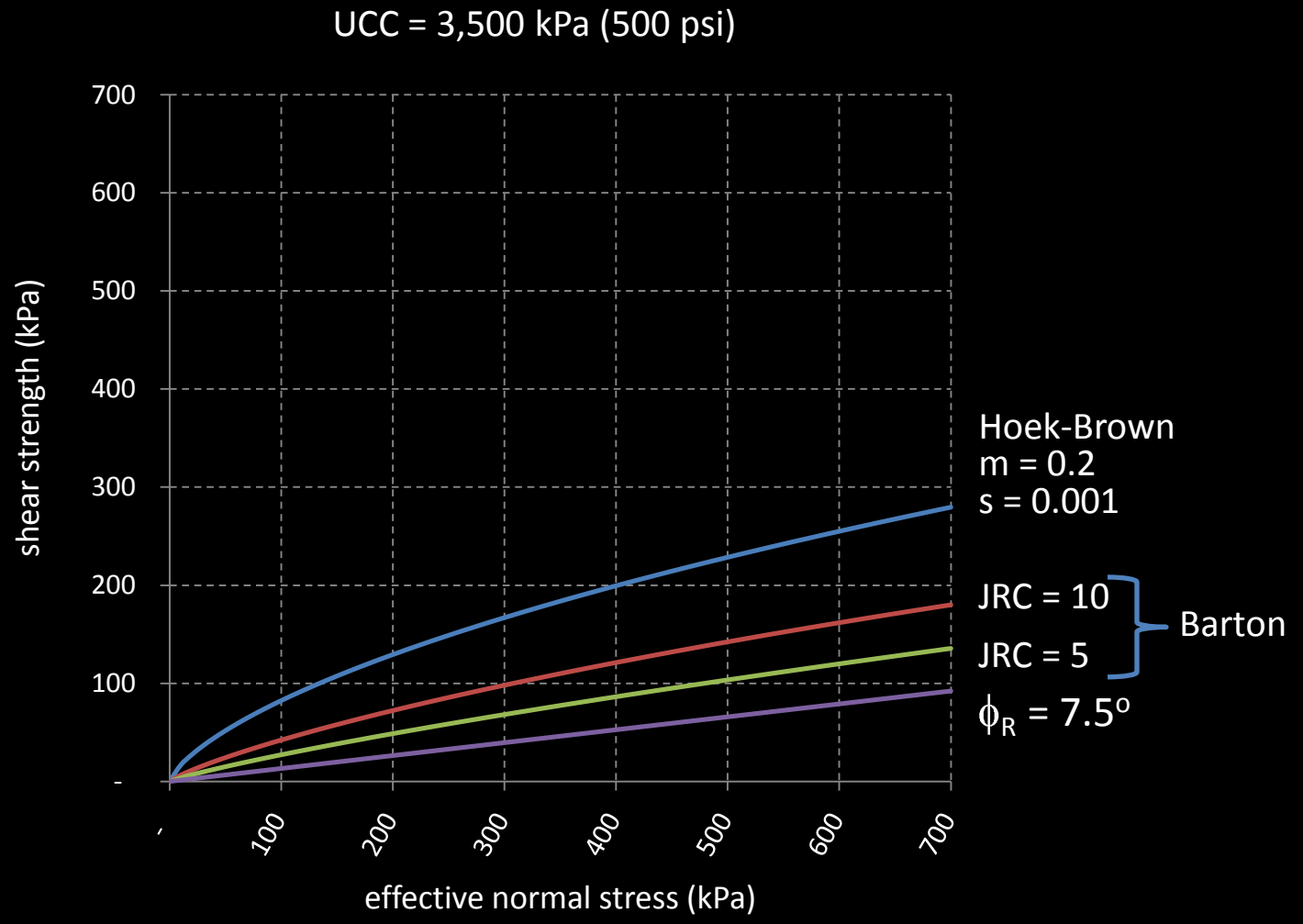
$$\phi_i' = \arctan[4h\cos^2\{30+(1/3)\arcsin h^{-3/2}\} -1]^{-1/2}$$

$$h = 1 + 16(m\sigma' + s \, \sigma_c)/(3m^2 \, \sigma_c)$$




# Strength Envelopes for weak tuffs

## Cucaracha, Culebra, La Boca and Gatuncillo Formations

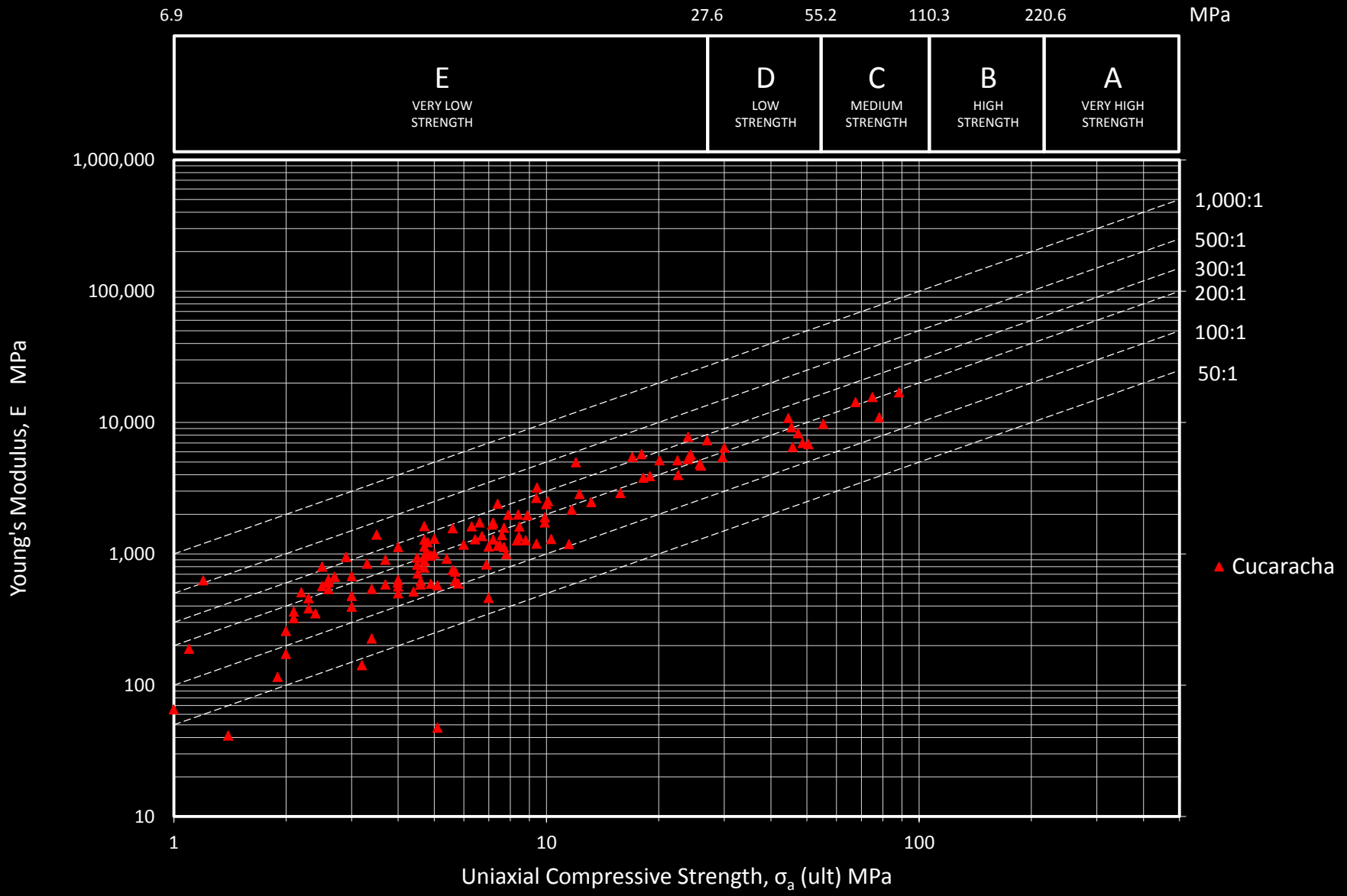


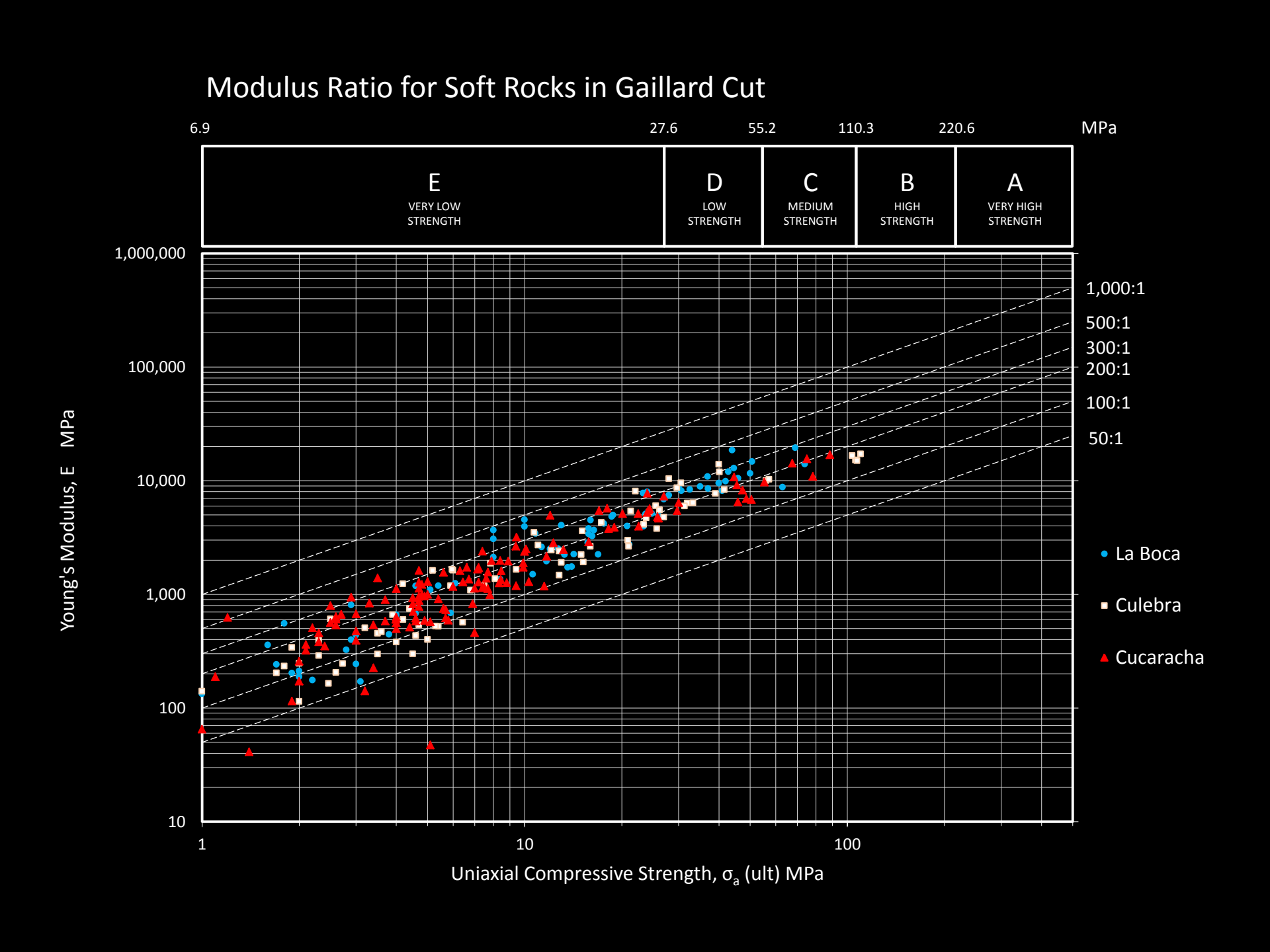
1850 1900 1950 2000

1991

## ACP's Geotechnical Laboratory

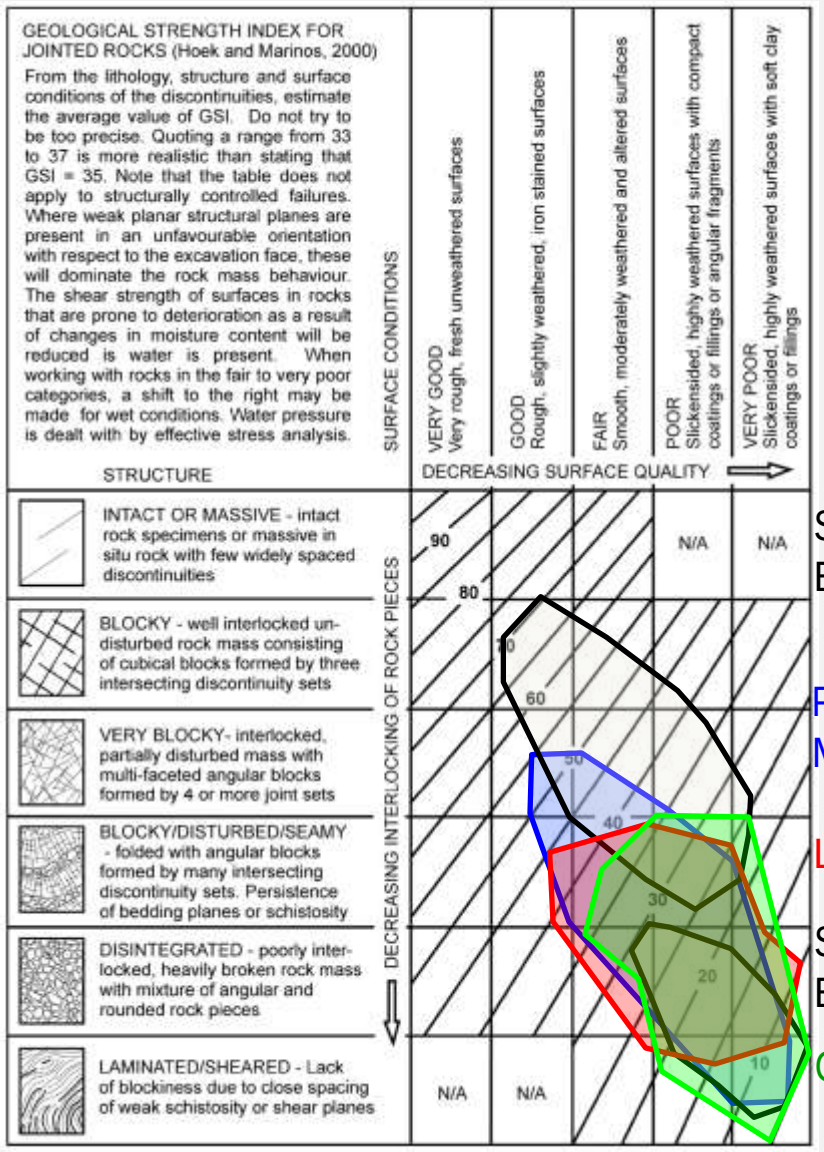
# Modulus Ratio for the Cucaracha Formation in Gaillard Cut



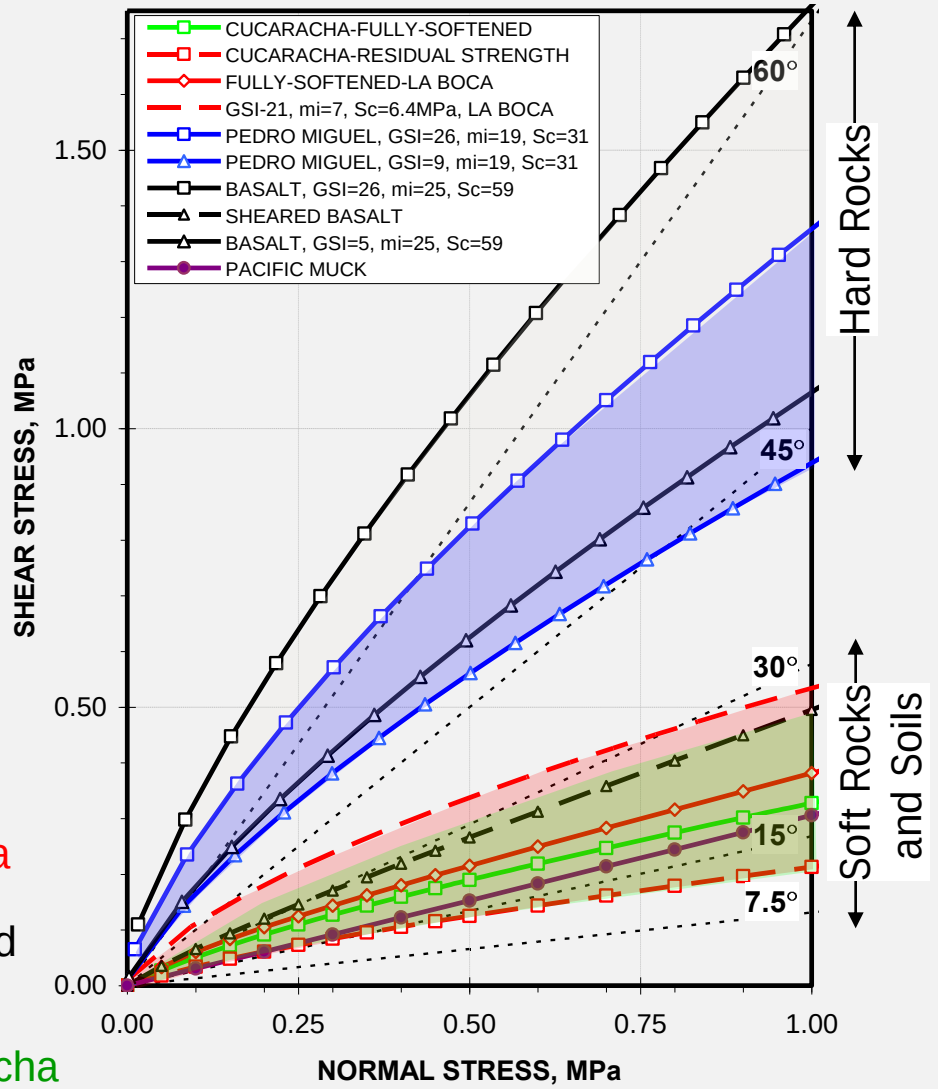

Modulus Ratio for Soft Rocks in Gaillard Cut
6.9
27.6
55.2
110.3
220.6
MPa
E
VERY LOW STRENGTH
D
LOW STRENGTH
C
MEDIUM STRENGTH
B
HIGH STRENGTH
A
VERY HIGH STRENGTH
1,000,000
100,000
10,000
1,000
100
10
Young's Modulus, E MPa
1
10
100
Uniaxial Compressive Strength, σa (ult) MPa
1,000:1
500:1
300:1
200:1
100:1
50:1
La Boca
Culebra
Cucaracha

# Strength Characterization

## Geological Strength Index (GSI)




## Shear Strength Envelopes




2012

*Thank you!!*

CANAL DE PANAMÁ

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