The Expansion of the Panama Canal

*The Impact of Developments in Rock Mechanics*

presentation to the
American Rock Mechanics Association

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Panama Canal Authority

June 25, 2012
Panama
Creation of the Canal

- Chagres
- Obispo
- Rio Grande

Atlantic

Pacific
The Canal Expansion Program
History of Panama Canal Traffic

FY 1915 – FY 2010

Transits per year vs. PCUMS Tonnage in millions

PCUMS 299.1
Transits 14,342
Demand for shipping

- **Historical**
- **Revised Forecast (January 2009)**

**Canal Capacity (Tonnage)**
- **Existing Canal maximum capacity (Tonnage)**
- **Additional capacity after expansion**

**PCUMS in Millions**
- **1995**
- **1997**
- **1999**
- **2001**
- **2003**
- **2005**
- **2007**
- **2009**
- **2011**
- **2013**
- **2015**
- **2017**
- **2019**
- **2021**
- **2023**
- **2025**

**Year**
- **1995**
- **1997**
- **1999**
- **2001**
- **2003**
- **2005**
- **2007**
- **2009**
- **2011**
- **2013**
- **2015**
- **2017**
- **2019**
- **2021**
- **2023**
- **2025**
Program Components

- Deepening and widening Atlantic entrance
- Gatun Lake widening and deepening and widening of Gaillard Cut navigation channels (26.5 M m³)
- Increase of the maximum operating level of Gatun Lake
- 26.7 m → 27.1 m
- Atlantic Pospanamax Locks
- Pacific Pospanamax Locks
- Pacific Access Channel
- Existing Locks
- Access Channel
- Existing Locks
- New Locks

Gatun Lake widening and deepening and widening of Gaillard Cut navigation channels (26.5 M m³)
Program Components

- Atlantic entrance deepening and widening
- Pacific entrance deepening and widening
- Increase of the maximum operating level of Gatun Lake: from 26.7 m to 27.1 m
- Atlantic Site pospanamax Locks
- Pacific Site pospanamax Locks
- Gatun Lake widening and deepening
- Widening and deepening of Gaillard Cut navigation channels (26.5M m³)
- Pacific Access Channel: 49 M m³
- 17.65 M m³
- 9.06 M m³
The Cost of the Canal Expansion Program

Total: $5.25 Billion

- New Locks: 52%
- Pacific Access Channel: 16%
- Water Saving Basins: 12%
- Improvements to Existing Channels: 5%
- Water Regulation: 5%
- Inflation during Construction: 10%
<table>
<thead>
<tr>
<th>Project</th>
<th>Design</th>
<th>Construction</th>
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<tbody>
<tr>
<td>Post-Panamax Locks Project</td>
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<tr>
<td>Sacyr-Vallehermoso - Spain</td>
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<td>Impregilo - Italy</td>
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<td>Jan De Nul – Belgium</td>
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<td>CUSA – Panama</td>
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<td>Montgomery Watson Harza - US</td>
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<tr>
<td>Pacific Access Channel – Phase 4</td>
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<td>ICA - Mexico</td>
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<td>FCC - Spain</td>
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<td>MECO – Costa Rica</td>
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<td>Atlantic Entrance</td>
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<td>Jan De Nul - Belgium</td>
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<td>Pacific Entrance</td>
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<tr>
<td>Dredging International - Belgium</td>
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</tbody>
</table>
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 m³ of structural concrete
New Pacific Locks
New Locks Project
Rolling gates

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

Single Rolling Gate

Lockhead with 2 Rolling Gates
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
Layout of Excavation Projects

Pacific access channel

Borinquen Dam 1E

Cellular Cofferdam

PAC-3  PAC-1  PAC-4  PAC-2
Pacific Access Channel

Estimated date of completion: 31-Oct-13

40.6 M m³ excavated / 50.1 M m³

Actual: 81%
Pacific Access Channel – Phase 4
26 M m$^3$ dry excavation

• Scope of Contract:
  – 26 M m$^3$ 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
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 m³
- Excavation to date: 17.38 M m³
Widening and Deepening of the Atlantic Entrance
Deepening and widening of the Pacific Entrance

- Total Excavation: 9.06 M m³
- Excavation to date: 7.70 M m³
Total Excavation and Dredging - May 2012

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<thead>
<tr>
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<tbody>
<tr>
<td>Locks</td>
<td>47.5 M m³</td>
<td></td>
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<tr>
<td>Pacific Access</td>
<td>50.1 M m³</td>
<td></td>
</tr>
<tr>
<td>Dredged</td>
<td>53.2 M m³</td>
<td></td>
</tr>
<tr>
<td>Estimated</td>
<td>150.8 M m³</td>
<td></td>
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</tbody>
</table>

Program Total: 150.8 M m³
Completed: 112.7

75%
Excavation Volumes (Mm$^3$)

- French effort: 23
- U.S. construction: 178
- Landslides (post-construction): 271
- Improvement projects: 394
- Canal Expansion: 545

23

178

201

70

271

123

394

151

545
Expansion Program Progress

**Pacific Access Channel**
37.62 M m³ excavated / 49 M m³
End of last Contract: 31-Oct-2013

**Pacific Entrance Deepening and Widening**
7.68 M m³ dredged / 8.7 M m³
End of Contract: 31-Aug-2012

**Gatun Lake and Gaillard Cut Deepening and Widening**
16.8 M m³ dredged / 28 M m³
End: 11-Apr-2014

**Locks Design and Construction**
23.2 M m³ excavated / 40 M m³

**Atlantic Entrance Deepening and Widening**
17.3 M m³ dredged / 17.6 M m³
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
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
February 2, 1913
East Cucaracha Slide
East & West Culebra slides (October 1915)
Original Design of Excavations

Reference: McCullough “The Path Between the Seas” (1977)
“…. the catastrophic descent of the slopes in the deepest cuts on the Panama Canal issued a warning that we were overstepping the limits of our ability to predict the consequences of our actions.”

Karl von Terzaghi (1883-1963)

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

Monument with prism

EDM on Master Station

Incipient slide
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
EDM Linear Features Scale = 1:50
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
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)
Borehole SARMP-1_SARDINILLA SECTOR

Piezometric Elevation (m)

Depth (m)

Fill
Agglomerate
Tuff, Andesite glassy
Tuff agglomeratic
Agglomerate tuffaceous
Andesite
Tuff sandy
Basalt
Tuff agglomeratic sandy
ATM LINE

20-Oct-03
5-Oct-04
18-Nov-05
12-Dec-06
10-Oct-07
14-Oct-08
15-Apr-09
27-Aug-10
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

UCC = 3,500 kPa (500 psi)

shear strength (kPa)

effective normal stress (kPa)

Hoek-Brown
m = 0.2
s = 0.001

JRC = 10
JRC = 5
\\phi_R = 7.5^\circ

Barton
Modulus Ratio for the Cucaracha Formation in Gaillard Cut

<table>
<thead>
<tr>
<th>Uniaxial Compressive Strength, $\sigma_a$ (ult) MPa</th>
<th>Modulus Ratio</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>27.6</td>
</tr>
</tbody>
</table>

Strength Categories:
- VERY LOW STRENGTH: E
- LOW STRENGTH: D
- MEDIUM STRENGTH: C
- HIGH STRENGTH: B
- VERY HIGH STRENGTH: A
### Young's Modulus, $E$ (MPa)

<table>
<thead>
<tr>
<th></th>
<th>La Boca</th>
<th>Culebra</th>
<th>Cucaracha</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERY LOW STRENGTH</td>
<td>500:1</td>
<td>100:1</td>
<td>50:1</td>
</tr>
<tr>
<td>LOW STRENGTH</td>
<td>1,000:1</td>
<td>200:1</td>
<td>100:1</td>
</tr>
<tr>
<td>MEDIUM STRENGTH</td>
<td>300:1</td>
<td>200:1</td>
<td>100:1</td>
</tr>
<tr>
<td>HIGH STRENGTH</td>
<td>500:1</td>
<td>300:1</td>
<td>50:1</td>
</tr>
<tr>
<td>VERY HIGH STRENGTH</td>
<td>1,000:1</td>
<td>500:1</td>
<td>100:1</td>
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</tbody>
</table>

### Uniaxial Compressive Strength, $\sigma_{a\text{ (ult)}}$ (MPa)

<table>
<thead>
<tr>
<th></th>
<th>6.9</th>
<th>27.6</th>
<th>55.2</th>
<th>110.3</th>
<th>220.6</th>
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</thead>
<tbody>
<tr>
<td>E</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
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<tr>
<td>C</td>
<td></td>
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<td></td>
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<tr>
<td>B</td>
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</tr>
<tr>
<td>A</td>
<td></td>
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</tbody>
</table>

#### Modulus Ratio for Soft Rocks in Gaillard Cut

- **La Boca**
- **Culebra**
- **Cucaracha**
Strength Characterization

Geological Strength Index (GSI)

- **Sound Basalt**
- **Pedro Miguel**
- **La Boca**
- **Sheared Basalt**
- **Cucaracha**

**Shear Strength Envelopes**
- **Hard Rocks**
- **Soft Rocks**
- **Soils**

**Geological Strength Index (GSI) for Jointed Rocks**

<table>
<thead>
<tr>
<th>GSI</th>
<th>Surface Conditions</th>
<th>Decreasing Surface Quality</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Good</td>
<td>Very Good</td>
<td>Intact or Massive</td>
</tr>
<tr>
<td>0.5</td>
<td>Medium</td>
<td>Good or Fair</td>
<td>Blocky</td>
</tr>
<tr>
<td>1</td>
<td>Poor</td>
<td>Poor or Very Poor</td>
<td>Very Blocky</td>
</tr>
<tr>
<td>1.5</td>
<td>Very Poor</td>
<td>Very Poor</td>
<td>Blocky/Disturbed</td>
</tr>
<tr>
<td>2</td>
<td>Full</td>
<td>Full</td>
<td>Disintegrated</td>
</tr>
<tr>
<td>2.5</td>
<td>Very Full</td>
<td>Very Full</td>
<td>Laminated/Sheared</td>
</tr>
<tr>
<td>3</td>
<td>Full</td>
<td>Full</td>
<td>Laminated/Sheared</td>
</tr>
</tbody>
</table>

**NORMAL STRESS, MPa**

**SHEAR STRESS, MPa**

**CUCARACHA-FULLY-SOFTENED**
- GSI=21, mi=7, Sc=6.4MPa, La Boca

**CUCARACHA-RESIDUAL STRENGTH**
- GSI=26, mi=19, Sc=31

**FULLY-SOFTENED-LA BOCA**
- GSI=21, mi=7, Sc=6.4MPa, La Boca
- GSI=9, mi=19, Sc=31
- BASALT, GSI=26, mi=25, Sc=59
- SHEARED BASALT
- BASALT, GSI=5, mi=25, Sc=59
- PACIFIC MUCK
Thank you!!

June 25, 2012