The Expansion of the Panama Canal

*The Impact of Developments in Rock Mechanics*

presentation to the
American Rock Mechanics Association

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Vicepresident of Engineering
Panama Canal Authority

June 25, 2012
Creation of the Canal

Atlantic

Chagres

Obispo

Rio Grande

Pacific
The Canal Expansion Program
History of Panama Canal Traffic
FY 1915 – FY 2010

PCUMS Tonnage in millions

Transits per year

Fiscal Year

PCUMS 299.1

Transits 14,342
Long Term Demand Forecast

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

PCUMS in Millions
- 100
- 150
- 200
- 250
- 300
- 350
- 400
- 450
- 500
- 550
- 600

Canal Capacity (Tonnage)
- Historical
- Revised Forecast (January 2009)

Additional capacity after expansion

Existing Canal maximum capacity (Tonnage)
**Program Components**

- **Deepening and widening Atlantic entrance**: 17.65 M m³
- **Gatun Lake widening and deepening and widening of Gaillard Cut navigation channels**: (26.5 M m³)
- **Existing Locks**
- **Access Channel**
- **Existing Locks**
- **New Locks**
- **Atlantic Pospanamax Locks**
- **Pacific Pospanamax Locks**
- **Increase of the maximum operating level of Gatun Lake**: 26.7 m → 27.1 m
- **Pacific Access Channel**: 50.1 M m³
- **Program Components**
  - **New Locks**
  - **Access Channel**
  - **Existing Locks**
  - **Existing Locks**
  - **New Locks**
  - **Atlantic Pospanamax Locks**
  - **Pacific Pospanamax Locks**
  - **Increase of the maximum operating level of Gatun Lake**: 26.7 m → 27.1 m
  - **Pacific Access Channel**: 50.1 M m³
Program Components

- Atlantic entrance deepening and widening
- Pacific entrance deepening and widening
- Atlantic Site pospanamax Locks
- Pacific Site pospanamax Locks
- Increase of the maximum operating level of Gatun Lake (26.7 m → 27.1 m)
- Gatun Lake widening and deepening and widening of Gaillard Cut navigation channels (26.5 M³)
- Pacific Access Channel (49 M³)
- 17.65 M³
- 9.06 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%
### Main Contractors

<table>
<thead>
<tr>
<th>Project</th>
<th>Design</th>
<th>Construction</th>
</tr>
</thead>
<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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<tr>
<td>Jan De Nul – Belgium</td>
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<td>CUSA – Panama</td>
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<tr>
<td>Montgomery Watson Harza - US</td>
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<tr>
<td>Pacific Access Channel – Phase 4</td>
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<tr>
<td>ICA - Mexico</td>
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<td>🇲🇽</td>
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<tr>
<td>FCC - Spain</td>
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<tr>
<td>MECO – Costa Rica</td>
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<tr>
<td>Atlantic Entrance</td>
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<tr>
<td>Jan De Nul - Belgium</td>
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<tr>
<td>Pacific Entrance</td>
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<tr>
<td>Dredging International - Belgium</td>
<td>🇧🇪</td>
<td>🇧🇪</td>
</tr>
</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
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
New Locks Project

Completed 24%
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

New Pacific Access Channel

Miraflores Faults

Pedro Miguel Fault

Aguadulce Faults

Tb: Basalt
Tpa: Pedro Miguel Agglomerate
Tca: Cucaracha Soft Rocks
TL: La Boca Soft Rocks
Layout of Excavation Projects

Pacific access channel

Borinquen Dam 1E

Cellular Cofferdam
Pacific Access Channel

Estimated date of completion: 31-Oct-13

40.6 M m³ excavated / 50.1 M m³

Actual: 81%

PAC-1: Completed 25-Jan-2010
PAC-2: Completed 25-Feb-2010
PAC-3: Completed 15-May-2011
PAC-4
Pacific Access Channel – Phase 4
26 M m³ 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 m³ excavated / 26 M m³
Pacific Access Channel – Phase 4
The Borinquen Dams
The Borinquen Dams

- Dam 1W: +26m
- Dam 2W: +26m
- Dam 1E: +16m
- Dam 2E: -3m to +3m
PostPanamax navigation channel & Miraflores Lake

- Pacific access channel
- Rockfill
- Clay core
- Miraflores Lake

10 m
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
Gatun Lake and Gaillard Cut Dredging Areas

Completed by Dredging International

18.2 M m³ completed / 26.5 M m³

Work underway by ACP

Completed by ACP

Gatun Lake

Peña Blanca

Bohio

Bulba Vista

Barro Colorado

Tabernilla

San Pablo

Juan Grande

Mamey

Gamboa

Chagres

Actual: 69%
### Total Excavation and Dredging - May 2012

<table>
<thead>
<tr>
<th>Category</th>
<th>Volume (M m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locks</td>
<td>47.5</td>
</tr>
<tr>
<td>Pacific Access</td>
<td>50.1</td>
</tr>
<tr>
<td>Dredged</td>
<td>53.2</td>
</tr>
<tr>
<td>Estimated</td>
<td>150.8</td>
</tr>
</tbody>
</table>

#### Program Details

- **Program Total**: 150.8
- **Completed**: 112.7
- **Percentage Completed**: 75%
Excavation Volumes (Mm$^3$)

- French effort: 23
- U.S. construction: 201
- Landslides (post-construction): 271
- Improvement projects: 394
- Canal Expansion: 545

Landslides include post-construction volumes.
Expansion Program Progress

**Pacific Access Channel**
37.62 M³ excavated / 49 M³
End of last Contract: 31-Oct-2013

**Pacific Entrance Deepening and Widening**
7.68 M³ dredged / 8.7 M³
End of Contract: 31-Aug-2012

**Gatun Lake and Gaillard Cut Deepening and Widening**
16.8 M³ dredged / 28 M³
End: 11-Apr-2014

**Locks Design and Construction**
23.2 M³ excavated / 40 M³

**Atlantic Entrance Deepening and Widening**
17.3 M³ dredged / 17.6 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
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)
“... 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

Monument with prism

Incipient slide

EDM on Master Station
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
Borehole SARMP-1_SARDINILLA SECTOR

Depth (m) vs Piezometric Elevation (m) chart showing various layers such as Fill, Agglomerate, Tuff, Andesite, and Tuff agglomeratic. Dates like 20-Oct-03, 5-Oct-04, 18-Nov-05, etc., indicate specific measurements or events at different times.
Shear strength characterization for weak rocks

Hoek-Brown envelope

\[ \tau = (\cot \phi' - \cos \phi') \frac{m \sigma_c}{8} \]

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

\[ h = 1 + 16(m\sigma' + s \sigma_c)/(3m^2 \sigma_c) \]
Strength Envelopes for weak tuffs
Cucaracha, Culebra, La Boca and Gatuncillo Formations

UCC = 3,500 kPa (500 psi)

- Hoek-Brown
  - \( m = 0.2 \)
  - \( s = 0.001 \)

- Barton
  - \( \phi_R = 7.5^\circ \)
  - \( JRC = 10 \)
  - \( JRC = 5 \)
ACP’s Geotechnical Laboratory
![Modulus Ratio for the Cucaracha Formation in Gaillard Cut](image)

<table>
<thead>
<tr>
<th>Modulus Ratio for the Cucaracha Formation in Gaillard Cut</th>
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<tbody>
<tr>
<td>Uniaxial Compressive Strength, $\sigma_{ult}$ MPa</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>VERY LOW STRENGTH</td>
</tr>
<tr>
<td>100:1</td>
</tr>
<tr>
<td>500:1</td>
</tr>
</tbody>
</table>

![Cucaracha](image)
Modulus Ratio for Soft Rocks in Gaillard Cut

<table>
<thead>
<tr>
<th></th>
<th>E</th>
<th>D</th>
<th>C</th>
<th>B</th>
<th>A</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>VERY LOW STRENGTH</td>
<td>LOW STRENGTH</td>
<td>MEDIUM STRENGTH</td>
<td>HIGH STRENGTH</td>
<td>VERY HIGH STRENGTH</td>
</tr>
<tr>
<td>Mpa</td>
<td>100:1</td>
<td>50:1</td>
<td>300:1</td>
<td>1,000:1</td>
<td>500:1</td>
</tr>
<tr>
<td></td>
<td>200:1</td>
<td>50:1</td>
<td>300:1</td>
<td>1,000:1</td>
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<td>500:1</td>
<td>50:1</td>
<td>300:1</td>
<td>1,000:1</td>
<td>500:1</td>
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<td></td>
<td>1,000:1</td>
<td>50:1</td>
<td>300:1</td>
<td>1,000:1</td>
<td>500:1</td>
</tr>
</tbody>
</table>

Young's Modulus, E MPa

Uniaxial Compressive Strength, $\sigma_{ult}$ MPa
Strength Characterization

Geological Strength Index (GSI)

From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that the table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourable orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rocks that are prone to deterioration as a result of changes in moisture content will be reduced as water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for conditions. Water pressure is dealt with by effective stress analysis.

<table>
<thead>
<tr>
<th>Surface Conditions</th>
<th>Structure</th>
<th>Decreasing Surface Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact or Massive</td>
<td>Intact</td>
<td>N/A</td>
</tr>
<tr>
<td>Blocky</td>
<td>Well interlocked undisturbed rock mass consisting of cubical blocks formed by 3 intersecting discontinuity sets</td>
<td></td>
</tr>
<tr>
<td>Very Blocky</td>
<td>Interlocked, partially disturbed mass with multi-faceted angular blocks formed by 4 or more joint sets</td>
<td></td>
</tr>
<tr>
<td>Blocky/Disturbed/Seamy</td>
<td>Fissured with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity</td>
<td></td>
</tr>
<tr>
<td>Disintegrated</td>
<td>Poorly interlocked, heavily broken rock mass with mixture of angular and rounded rock pieces</td>
<td></td>
</tr>
<tr>
<td>Laminated/Sheared</td>
<td>Lack of blockiness due to close spacing of weak schistosity or shear planes</td>
<td></td>
</tr>
</tbody>
</table>

Shear Strength Envelopes

- Hard Rocks
- Soft Rocks
- Soft Soils

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

<table>
<thead>
<tr>
<th>NORMAL STRESS, MPa</th>
<th>SHEAR STRESS, MPa</th>
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</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>0.25</td>
<td>0.25</td>
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<tr>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>0.75</td>
<td>0.75</td>
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<tr>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Thank you!!