The Panama Canal
The World's Greatest Engineering Feat.
Geo-risk management at the Panama Canal

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University of Maryland

With appreciation to Dr. Luis Alfaro
Vice President, Engineering
Autoridad del Canal de Panamá

Outline
• Why a risk management program
• Recent experiences
• Risk components
• Geotechnical risks
• The new 3d locks
Logistical network through Panama

- Transits per year: ~15,000, 300Mt
- Revenue: USD 2.4b (profit: USD 1b)
- Indirect impact on Panamanian economy: 30%
- Indirect impact on the global economy: ?

5% of world trade transits the Isthmus
Col. David DuBose Gaillard (1859-1913)

In charge of excavations through the continental divide (Culebra Cut)
La Purisima 7-9 Dec 2010

Risk
Average precipitation
2000 mm to 4500 mm/year
La Purisima storm 7-9 Dec 2010
Gatun Lake. Storm of 7-9 December 2010

Maximum hourly flow (5-6 a.m.)
Dec. 8th, 2010. Q = 335,067 cfs

Maximum historic elevation of Gatun Lake: 88.57 ft. 14 gates open in Gatun Spillway, plus the lock culverts in Pedro Miguel and Gatun.

14 gates at Gatun open since 1 a.m. on Dec. 8th.
Gatún Dam (December 2010 – La Purisima)
Madden Dam (December 2010 – La Purisima)
Alejuela Lake (Madden Dam)
Panama City 1621

More risk
EXCERPTS FROM THE HISTORICAL AND GEOGRAPHICAL REPORT OF THE
PROVINCE OF PANAMA ABOUT THE MAY 2, 1621 EARTHQUAKE

Juan Requejo Salcedo translated by Alice E. Westman

"The majority of the houses are of wood, but there are many
of stone and brick including most of the convents. Those of
wood are very strong as was clearly shown during an earthquake
and its subsequent tremblors which lasted for more than three
and a half months from 2 May until 21 August, on the Eve of
Saint Bartholomew, in the year 1621, and during which twelve,
ten, and six of less quakes were felt daily".

"...if it dealt so severely with this place where the
buildings were strongly made of wood and stone, it would leave
nothing but rubble from the adobe houses of Lima or Trujillo.
It did great damage to the buildings made of stone, mortar and
brick, cracking the walls and tearing others, although the
oldest houses of wood, termitesaten and supported by props,
came through unseathed. It happened as follows:

On Sunday, 2 May, on the feast of Saint Atanasio and Eve of
the Invention of the Cross in the year 1621, between nine and
ten in the morning the first quake was felt while I was in the
sacristy fully vested to go out to say mass. Those of us who
were there all felt it keenly, but it did no damage. However,
we did not know what was yet to come, for the first quake was
short and passed quickly.

At 4:30 or 4:45 in the afternoon, the second
2 May, 1621 Earthquake

M 5.6 – 7.0 Richter (estimated)

Epicentro probable
7 September, 1882 Earthquake

M 7.9 Richter (estimated)
Paleoseismic investigations
Río Gatun Fault
Limón Fault
Azota Fault
Miraflores Fault
Pedro Miguel Fault

active faults
Paleoseismic investigations

Pedro Miguel Fault
Pedro Miguel Fault
International Conferences on Applications of Statistics and Probability in Civil Engineering

- ICASP 1 Hong Kong, 1971
- ICASP 2 Aachen, 1975
- ICASP 3 Sydney, 1979
- ICASP 4 Florence, 1971
- ICASP 5 Vancouver, 1987
- ICASP 6 Mexico City, 1991
- ICASP 7 Paris, 1995
- ICASP 8 Sydney, Australia, 1999
- ICASP 9 San Francisco, 2003
- ICASP 10 Tokyo, 2007
- ICASP 11 Zurich, 2011

International Conferences on Structural Safety & Reliability

- ICOSSAR'69: WDC (A.M Freudenthal)
- ICOSSAR 77: Munich, Germany (H. Kupfer)
- ICOSSAR'81: Trondheim, Norway (T. Moan)
- ICOSSAR'85: Kobe, Japan (I. Konishi)
- ICOSSAR'89: San Francisco, CA, USA (A.H-S. Ang)
- ICOSSAR'93: Innsbruck, Austria (G.I. Schueller)
- ICOSSAR'97: Kyoto, Japan (N. Shiraishi)
- ICOSSAR'01: Newport Beach, CA, USA (M. Shinozuka)
- ICOSSAR'05: Rome, Italy (Giuliano Augusti)
- ICOSSAR'09: Osaka, Japan (Hitoshi Furuta)
- ICOSSAR'13: NYC, USA (Columbia)
History of the Management of Physical Risks in the Canal

- USACE design criteria (1904-1914)
- Flood Control Program (since construction)
- Protection of the Canal (since 1909)
- Landslide Control Program (modern program since 1968)
- Erosion Control Program (aggravated by larger ships and tugs)
- Dam Safety Program (since 1979)
- Corrosion Control (since construction)
- Structural codes for buildings (CZ Code was implemented 1907)
- Seismic Risk criteria (since 1991)

1 - Slopes in Gaillard Cut (no LCP)
2 - Slopes in Gaillard Cut (with LCP)
3 - Large Igneous Hills in Gaillard Cut
TONEN Tank Farm (1978)
<table>
<thead>
<tr>
<th>#</th>
<th>Category</th>
<th>Structure</th>
<th>Event</th>
<th>Description</th>
<th>Component</th>
<th>Description</th>
<th>Failure Mode</th>
<th>Failure Cause</th>
<th>Likelihood of occurrence</th>
<th>Severity of consequences</th>
<th>Remark</th>
<th>Risk Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Spillways</td>
<td>Gatun spill</td>
<td>Floods</td>
<td>PMF</td>
<td>Gates</td>
<td>Steel structure, and all castings in concrete</td>
<td>Gate out of commission</td>
<td>Overload, mechanical, under maintenance or repair, impact by barge or large object</td>
<td>2</td>
<td>4</td>
<td>Se asumio la falla en una soa compuerta y la misma esta cerrada</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Concrete piers</td>
<td>Concrete damage</td>
<td>Previous damage from EQ</td>
<td></td>
<td>Concrete piers</td>
<td>Concrete damage</td>
<td>Cavitation</td>
<td>High water velocity</td>
<td>2</td>
<td>4</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Concrete section</td>
<td>Concrete damage</td>
<td>Previous damage from EQ</td>
<td></td>
<td>Concrete section</td>
<td>Concrete damage</td>
<td>Cavitation</td>
<td>High water velocity and low water pressure</td>
<td>2</td>
<td>4</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Discharge channel</td>
<td>Loss of baffle blocks</td>
<td>Overload</td>
<td></td>
<td>Discharge channel</td>
<td>Loss of baffle blocks</td>
<td>Overload</td>
<td></td>
<td>3</td>
<td>4</td>
<td>Criticality- Los contrafuertes evitarian la propagacion de la erosion aguas arriba y la perdida de la represa</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Gate machinery</td>
<td>Mechanical, electrical, and</td>
<td>Overload</td>
<td></td>
<td>Gate machinery</td>
<td>Gate motor's circuit breaker tripped and/or motor failure</td>
<td>Gate out of commission</td>
<td>Gate motor's circuit breaker tripped and/or motor failure</td>
<td>3</td>
<td>4</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>control systems (control house and gallery)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Motor damage</td>
<td></td>
<td>3</td>
<td>4</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Concrete piers</td>
<td>Structural failure</td>
<td>Concrete overstressed</td>
<td></td>
<td>Concrete piers</td>
<td>Structural failure</td>
<td>Gate jamming</td>
<td>Foot bridge collapse on top of gate</td>
<td>2</td>
<td>3</td>
<td>C queda abierta</td>
<td>2</td>
</tr>
</tbody>
</table>
Rational Investment Decisions (using F-N charts)

Annual Exceedance Probability

Consequences ($)

- marginally acceptable
- acceptable
## Risk mitigation

<table>
<thead>
<tr>
<th>Type</th>
<th>Catastrophic Natural Risks</th>
<th>Chronic Natural Risks</th>
<th>Anthropogenic Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drivers</strong></td>
<td>• Meteorological</td>
<td>• Time</td>
<td>• Human activities</td>
</tr>
<tr>
<td></td>
<td>• Seismic</td>
<td>• Degradation use</td>
<td></td>
</tr>
<tr>
<td><strong>Events</strong></td>
<td>• Floods</td>
<td>• Erosion</td>
<td>• Terrorism</td>
</tr>
<tr>
<td></td>
<td>• Earthquakes</td>
<td>• Sedimentation</td>
<td>• Sabotage</td>
</tr>
<tr>
<td></td>
<td>• Landslides</td>
<td>• Corrosion</td>
<td>• Accidents</td>
</tr>
<tr>
<td></td>
<td>• Droughts</td>
<td>• Aging</td>
<td></td>
</tr>
<tr>
<td><strong>Mitigation Strategy</strong></td>
<td>Improve Capacity of Structures through Engineering Analysis</td>
<td>Implement Maintenance Programs through systematic inspections</td>
<td>Implement appropriate operations and protection policies</td>
</tr>
</tbody>
</table>
Risk Analysis Procedure

AEP = annual exceedance probability
PI = Performance Indicator
pf = probability of failure
September 13, 1913
East Cucaracha Slide
Inauguration of the Canal Steamship Ancón

August 15, 1914
East & West Culebra slides

October 1915
When surveys of Culebra Cut were first made by US engineers, it was thought a cut back at the top to 670 feet would be adequate for the hillside to remain stable in the area near Gold Hill. As it turned out, the top width had to be increased three times and the angle of repose, when the hillside remains stable, has never been achieved.

Culebra (or Gaillard) Cut

- French excavation – 19 million cubic yards
- American excavation – 96 million cubic yards
- Additional excavation of canal bottom
Beginning of the landslide control program
East Culebra slides 1974
Modern Landslide Control Program

Threshold Values
> 30mm / month
> 100mm / year
<table>
<thead>
<tr>
<th>Category</th>
<th>Volume (Mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>French effort</td>
<td>23</td>
</tr>
<tr>
<td>U.S. construction</td>
<td>201</td>
</tr>
<tr>
<td>Landslides (post-construction)</td>
<td>70</td>
</tr>
<tr>
<td>Improvement projects</td>
<td>394</td>
</tr>
<tr>
<td>Canal Expansion</td>
<td>545</td>
</tr>
<tr>
<td>Landslides (post-construction)</td>
<td>123</td>
</tr>
<tr>
<td>Improvement projects</td>
<td></td>
</tr>
</tbody>
</table>

**Historical Excavation Volumes (Mm³)**
The new 3d locks
2.10M m³ of structural concrete
New Pacific Locks

2.34M m³ of structural concrete
Thank you.
Thank you.