SLOPE STABILIZATION AT CANON DEL PATO
HYDROELECTRIC PROJECT, PERU
– PART 1: BACKGROUND AND SITE STUDIES

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30/11/98 Bocatoma - Vista de la excavación después del deslizamiento.
Phase I

• September 1998 to March 2000
  – Construction of the Complementary Intake Structure
    • A-Anchor Installation
    • Drainage Holes
    • Initial Instrumentation Installed – Piezometers, Inclinometers, and Extensometers
Trabajos en Túnel Principal y Túnel de Purga. Observamos Grua Gigante
Canon del Pato
Complementary Intake Structure
Extensometer MPBX-01
Movement Between Anchors

Movement (mm)

Days

0 to 5 Meters
5 to 15 Meters
15 to 40 Meters

Rate of Movement
= 0.99 mm/month

Day 0
15 Jul 99

Day 510
6 Dec 00

Day 600
06 Mar 01

Day 259
30 Mar 00
Construction Completed

Construction Completed
Phase II

- **April 2000 to January 2001**
  - Design and Installation of Cable Anchors (C-Anchors) and Additional Instrumentation
C-Anchors
46 Anchors @ 135 Tonnes (60% GUTS)
Total Working Load = 6210 Tonnes
Canon del Pato
Complementary Intake Structure
Extensometer MPBX-04
Movement Between Anchors

1.08 mm/month

Explanation
- Fill
- Alluvium
- Colluvium
- VOID
- FAULT
- Breccia
- Hornfels-Wea/Frac
- Hornfels
- Mica Schist
- Int Hornfels/Schist
- Sheared Hornfels/Schist
- Pegmatite
- Mica Quartzite-Wea/Frac
- Mica Quartzite
- Quartzite
- Sheared Mica Schist
- Fine Granite
- Granite

Rate of Movement
= 1.08 mm/month

Days
0 100 200 300 400 500 600
0 5 10 15 20 25 30
-5 -10

Movement (mm)

0 to 9 meters
9 to 26 meters
26 to 34.5 meters - Main Failure Zone
34.5 to 43 meters
43 to 50 meters

Anchor 1
Anchor 2
Anchor 3
Anchor 4
Anchor 5

Rate of Movement
= 1.08 mm/month

Day 0
18Nov00
Day 18
26Jan01
Day 300
18Sep01
Day 571
12Jun02
Day 743
1Jan01
C-Anchors Completed

1.08 mm/month
Phase III

- August 2001 to February 2002
  - Geological/Geotechnical Investigation
Phase III

• Crack Mapping – Concrete & Shotcrete
• Review of All Previous Geological and Geotechnical Work
• Air Photo Interpretation
• Boreholes with Inclinometers (7)
• Seismic Refraction Lines (1460 meters)
• Geologic Mapping
• Lift-Off Tests on A- and C-Anchors
GEOLOGIC MAP OF THE VICINITY OF THE CANON DEL PATO HYDROELECTRIC PLANT, PERU

EXPLANATION

ALLUVIUM

ALLUVIUM

SUNAY FORMATION: Volcanic, conglomeratic rocks, primarily scoria in composition.

COROLLINA BLANCA BATHOLITH: Granodiorite/lamprophyre

CABALLERITO FORMATION: Metamorphic, gneissic, schist, amphibolite, and pelites. Includes metabasalt and metabasaltic intrusions.

CABALITO FORMATION: Orthoquartzite with interbedded siltstone and limestone.

SANTA FORMATION: Fossiliferous limestones with minor interbeds of interbedded sandstone and shale.

CHINQUU FORMATION: Orthoquartzite, conglomeratic, and breccia, interbedded with carbonate rocks of contemporaneous age of 80-70 million years.

CHIMPA FORMATION: Breccia-claystone shale with interbedded carbonates and interstratified sandstone and siltstone.

CHUMPA FORMATION: Shale with interbedded fine-grained sandstone. Metamorphosed near the Corollina Batholith and exposed at the surface.

Other symbols:
- Cordillera Blanca Fault - Normal
- OTHER FAULTS
- CONTACT
- CONTOUR 200 meter interval
- ROAD
- WATER
- TRANSMISSION LINE

Geology from INGEMET Bulletin No. 50, 1975

Figure 3
Failure zone from 24.65 to 28.00 meters consisting of weathered hornfels and sheared mica schist in borehole S02.

Photo 33: Failure zone from 21.23 to 22.10 meters consisting of weathered hornfels and sheared mica schist in borehole P207.

Sheared hornfels/mica schist, highly weathered and damp, along the failure surface in the south wall of the intake excavation. Note extensive cracking of the shotcrete.

Breccia in sliding zone above the Complementary Intake Structure, borehole S13. Rock fragments in the breccia include hornfels, sheared mica schist, and sheared hornfels. The contact with the sound bedrock (hornfels) at ~24.42 meters in depth dips approximately 25°.

Failure zone from 24.65 to 28.00 meters consisting of weathered hornfels and sheared mica schist in borehole S02.
Future Location of Canon del Pato Dam & Original Intake
Chicama Formation
(shale/slate with interlayered sandstone;
Metamorphosed to hornfels & quartzite)

Cordillera Blanca Batholith
(granodiorite/tonalite)

Mode 5 – Zone of Likely Deep-Seated Movement

Mode 4 – Bedding Plane & Foliation Joint Sliding

Mode 3 – Translational Sliding

Mode 2 – Rock Falls

Mode 1 – Can occur where Colluvium is present

Direction of Movement
Location of New Intake

-~730,000 m³
-~1,600,000 m³

~200 Meters

Rio Cedros

Rio Santa

Canon del Pato
Dam & Old Intake

~1,600,000 m³
0
Yellow – COLLUVIUM (Vp: 400 to 850 m/sec)
Green – OVERBURDEN (Vp: 900 to 2050 m/sec)
Purple – SOUND ROCK 1 (Vp: 2700 to 4200 m/sec)
Blue – SOUND ROCK 2 (Vp: 4400 to 5000 m/sec)

NOTE: Vp = P-Wave (Compressional) Velocity

Canon del Pato
Intake Slope
Geologic Section 3

Canon del Pato
Intake Slope
Seismic Section 8
Figure 5: Geologic Section 1. Note that the Overburden is thin to not present in P201 and P204 and the Failure Zone is not present in either of these two borings. This is evidence that the area of potential sliding is not north of these borings at this location (see Drawing Geo-1 for this interpretation).
Figure 9: Geologic Section 5 – Note clear correlation of Overburden/Failure Zone from borehole S12 to P206. The failure zone is not present in S11. The computer program used to generate these cross-sections thins the failure zone from P206 to S11. The interpretation shown on the geologic map (Drawing Geo-1) and related cross-sections (Geo-8 and Geo-9) shows the failure zone truncated between P206 and S11 by a high angle fracture, probably related to the NE-striking joint set.
Photo 17: Slope above the dam and intake structure, looking southwest. Shows the contact (and contrast) between map units Hfc (hornfels with 0 to 2 meters colluvial cover) with Cu (2 to 5 meters of colluvium overlying hornfels) and Cy (Colluvium/Hornfels - area of movement). Note the larger rock blocks associated with unit Cy. Mode 5.
Photo 10: Area of major translational sliding (Mode 3) on the right (east) bank of the Rio Santa.
Hd - Hornfels that have been displaced in the slide area. Qrb - Recent rock fall material (Mode 2). B - Bedding Plane (~N85E; 48SE) that defines the northern limit of a rock block that slid on FJ - Foliation Joint (~N18W; 43SW). JS1 - Joint Set 1 (~N48W; 73NE). JS2 - Joint Set 2 (~N49E; 82NW).
The near vertical west bank of the Rio Santa upstream of the intake structures showing the relationship between original bedding (B - Average = N85E; 48SE) cut by the sheared mica schist/hornfels layer (Sh - Striking NW and dipping SW).

Contact (C) between the Cordillera Blanca Batholith (granodiorite/tonalite - gd) and Hornfels with interlayered quartzite of the Chicama Formation (hf). Dashed lines are foliation surfaces related to the intrusion of the batholith.

Complementary Intake Structure showing the location of the failure plane/zone (cracked shotcrete) and the distribution of geological map units Cy, Cu, Hfc, and Hd/Hpd. Unit Cy is moving.
Bedding - Canon del Pato - N = 96 - Slide Area Only

Joints - Canon del Pato - N = 149

Foliation - Canon del Pato - N = 90

1) N48W; 73NE
2) N49E; 82NW

N18W; 43SW
N85E; 48SE
N50W; 30SW

FAILURE PLANE
Zona actual de movimiento de escase.

Zona de posible movimiento en la base.

~730,000 m³

~1,600,000 m³

Nueva estructura de Bocatoma

Límite de la zona con movimiento en la base

FIGURA 4
Phase IVb

March 2002 to May 2002
Design, Cost Estimate, Technical Documents, and Specifications

June 2002 to July 2002
Bid Process
Complementary Intake Structure showing the location of the failure plane/zone (cracked shotcrete) and the distribution of geological map units Cy, Cu, Hfc, and Hd/Hpd. Unit Cy is moving.
*The slope can be modeled using a 2-dimensional analysis.
*The failure plane daylights into the slope face.
*The analysis is performed on a unit width of the slope.
*All forces are assumed to act through the centroid of the wedge. Moments are not considered.
*Assumed failure mode is translational sliding.
*Release surfaces are present parallel to the cross-section of the analysis and provide negligible resistance to sliding at the lateral boundaries.
**SAFETY FACTOR OF SLOPE WITH NO SUPPORT**

\[ SF = 0.88 \]

**CALCULATE NUMBER OF ANCHORS REQUIRED FOR SF = 1.20**

1. Set SF = 1.20, calculate load per meter of slope required, set anchor inclination to 15° down from horizontal.

Resulting Active Anchor Force Required = 59.5 T

File No: CDPSectionA-2_rtf-2_CDPSectionA-2a.jpg

2. Estimate width of slope to be stabilized:

   Horizontal area = 2.189 m²
   Area on failure plane = \( 2.189 \text{ m}^2 \times \cos(15°) = 2.423 \text{ m}^2 \)
   Width of slope = Area of failure plane/Length of failure plane
   Width of slope = \[ \frac{2.423 \text{ m}^2}{9.68 \text{ m}} = 30.4 \text{ m} \]

3. Total Anchor Load Required:

   \[ 59.5 \text{ T} \times 30.4 \text{ m} = 1808 \text{ T} \]

4. Estimate number of anchors:

   Use 12 strands - 0.5" anchors, 100% GUTS = 225 Tones;
   60% GUTS = 135 Tones, for normal loading use 60% GUTS.

   \[ \frac{1808 \text{ Tones}}{135 \text{ Tones/Anchor}} = 13.4 \text{ Anchors} \]

   Anchors to be installed in an area (horizontal) of 1152 m².

**Drawing:**

- **Diagram:** Shows the slope, anchor forces, and other relevant data.

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Sensitivity Analysis

A sensitivity analysis was performed on the following inputs:
Slope Angle, Slope Height, Unit Weight, Failure Plane Angle, Plane
Weakening, Distance of Tension Crack from Crest, Upper Face Angle,
and Friction Angle. The plot of the analysis (File No. CDP-secma-A-8.jpg)
is in the attached computer file printout.
The analysis is most sensitive to the failure plane Angle and
Friction Angle and least sensitive to the Plane Weakening Angle
and the lower slope Angle.

Estimate Safety Factor at Seismic Loading = 0.76

Use same inputs as before, assume anchor load is at 100% GUTS
(225 Tonne).

\[
\frac{595 \text{ T}}{135.5 \text{ T}} = \frac{X}{225 \text{ T}}
\]

\[
X = 992 \text{ T/m} \Rightarrow \text{Input into calculation.}
\]

SF = 0.76 @ Seismic Loading = 0.27g

File Nos: CDPsecma-A-5, rtf.jpg

Estimate Seismic Loading at SF = 1.00 with Anchor Load
at 100% GUTS (225 T):

Set SF = 1.00; Anchor load = 992 T/m.

Seismic Loading for SF = 1.00 is 0.15g

File Nos: CDPsecma-A-4, rtf.jpg

Calculate conservation of Design due to differences in volume of
Sliding Rock Mass Assumed for Design and Calculated from
Cross-Sections.

Assumptions: All input values on CDP-009 are correct. Volume directly related to
SF.

1. Calculate volume of sliding block using design values.
   - Area of Section A = 1853.9 m²; Width of Slope = 30.41 (CDP-009)
   - Volume A = 18539 m³ x 30.41 m = 56,378.3 m³

2. Calculate volume of sliding block using Sections A, B, and C.
   - Area of Block B = 837.5 m²; for 3.5 m; Section A for 13.9 m
   - Area of Block C = 1157.2 m²; for 11.0 m
   - Volume of Block B = 837.5 m² x 3.5 m = 4606.7 m³
   - Volume of Block C = 1157.2 m² x 11.0 m = 12751.2 m³
   - Volume of Block A = 1853.9 m² x 13.9 m = 25769.7 m³
   - Total = 43127.4 m³

3. Calculate Retain of Design Volume to Calculated Volume

56378.3 m³

43127.4 m³

4. Multiply Design SF by 1.30 to get Equivalent Smaller
   Volume SF with existing Support.

\[
1.2 \times 1.3 = 1.56 = SF_{eq}
\]

Files: CDPsecma-A-6a.jpg

5. Use SF = 1.56 to calculate equivalent anchor load for
   Section A.

Anchor Load = 1028 T/m for SF = 1.56

6. Calculate SF for Seismic loading of 0.27g using
   100% GUTS for Anchor Load 1157.2 T

\[
1028 \text{ T/m} = \frac{X}{215.7 \text{ T}} \Rightarrow X = 1730 \text{ T}
\]

SF = 1.07

Files: CDPsecma-A-6a.jpg

Files Attached.
Phase IVc

September 2002 to August 2003

Installation of D-Anchors
Installation of Rock Bolts
New Catch Wall
Lift-Off Tests on A- and C-Anchors
Installation of New Instruments
9 Cables of 15.24 mm (5/8”) diameter, 7 wires. Guaranteed Ultimate Tensile Strength (GUTS) of Anchor = 239 Tonnes. Working Load = 143.5 Tonnes (60% GUTS); Total Installed Working Load = 19,229 Tonnes.
## Re-Calculation of Safety Factor

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<td>Equivalent Safety Factor (SF_E)</td>
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<td>Equivalent Safety Factor (SF_E) for Earthquake Loading of 0.27g</td>
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PERFORMANCE TEST

a) whether the anchor has sufficient load carrying capability
b) that the apparent tendon free length has been established
c) the magnitude of the residual movement
d) that the rate of creep stabilizes within the specified limits.

### PROYECTO: MITIGACIÓN DEL MOVIMIENTO DEL TALUD - FASE IV. C. H. CAÑÓN DEL PATO

#### EQUIPO DE TENSADO

- **ANCLAJE Nº:** D-02
- **LONG. TOTAL (m):** 47.50
- **BOMBA HIDRAULICA:** MH-300/450
- **Nº DE CABLES:** 9.0
- **LONG. EXTERNA (m):** 0.36
- **MANOMETRO:** LEO 1 - KELLER - 3770
- **FECHA INSTALACION: 1/7/2003**
- **LONG. LIBRE (m):** 38.14
- **ALTURA GATA (m):** 1.13
- **Cable cortado (m):** 1.52
- **FECHA INYECCION: 1/7/2003**
- **LONG. ANCLADA (m):** 9.00
- **CARGA DE TRABAJO (Ton):** 143.50
- **TIPO DE ENSAYO:** PERFORMANCE
- **CARGA DE ENSAYO(Ton):** 191.40
- **FECHA DE ENSAYO:** 24-Apr-03

#### INTERVALO PRESION CARGA DESPLAZAMIENTOS (mm) HORA TIEMPO MANOMETRO 

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**Creep (mm):** 0.22

### OBSERVACIONES:

- **Lift off inicial:** Fecha-hora: 24 Abr 03 - 12:00  
  Presión (Bar)= 268  
  Carga (ton)= 149.33
- **Lift off:** Fecha-hora: 07 Jul 03 - 13:25  
  Presión (Bar)= 267.7  
  Carga (ton)= 149.16

**Análisis gráfico de los datos del ensayo**

- **Línea A:** 80% Free Length
- **Línea B:** Free Length + 50% Bond Length
- **Residual Movement**
- **Elastic Movement**

**PLOTEO DE LOS DATOS DEL ENSAYO**

![Graph of test data](image-url)
PROYECTO: MITIGACIÓN DEL MOVIMIENTO DEL TALUD - FASE IV, C. H. CAÑÓN DEL PATO
EQUIPO DE TENSAO:
D-91

ANCLAJE Nº: 141

BOMBA HIDRAULICA:
MH-300/450

Nº DE CABLES: 9.0
LONG. EXTERNA (m): 0.26

MANOMETRO:
LEO 1 - KELLER - 3770

FECHA INSTALACION: 4/1/2003
LONG. LIBRE (m): 39.24

ALTURA GATA (m): 1.12
Cable cortado (m): 1.38

FECHA INYECCION: 4/1/2003
LONG. ANCLADA (m): 9.00

CARGA DE TRABAJO (Ton): 143.50
TIPO DE ENSAYO:
COMPROBACIÓN (PROOF TEST)

CARGA DE ENSAYO (Ton):
191.40
FECHA DE ENSAYO:
16-Jun-03

LONG. VALORIZABLE (m): 47.23

INTERVALO PRESION
CARGA DESPLAZAMIENTOS (mm)
HORA TIEMPO MANOMETRO
Δ TOTAL LECTURA Δ TOTAL

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PROOF TEST
a) whether the anchor has sufficient load carrying capability
b) that the apparent tendon free length has been established
c) that the rate of creep stabilizes within the specified limits.
SUMMARY

• Installed 143 Multiple Strand Anchors with capacity of 239 Tonnes (100% GUTS) and a working load of 143.5 Tonnes (60% GUTS) each.
  – Total Length of Installed Anchors = 5591.79 meters; Average Length = 41.73 meters.
• Consolidation grouting with cement grout and mortar. Total bags of cement 12,455 (2.24 bags/m) and 24,306 (4.37 bags/m) bags, respectively. Maximum bags in one hole – 1376 bags in a 53 meter hole.
• Installation of 13 Hydraulic Load Cells. 10 with maximum capacity of 227 Tonnes; 3 with maximum capacity of 136 Tonnes.
• Installation of 2 extensometers and 3 inclinometers.