SEVEN OAKS DAM
Outlet Tunnel Invert Damage
Seven Oaks Dam

- Flood Control Purpose
- Operate in Tandem with d/s Prado Dam
- Non-Federal Sponsors:
  - Orange County Flood Control District
  - San Bernardino County Flood Control District
  - Riverside County Flood Control and Water Conservation District
Seven Oaks Dam
Seven Oaks Dam
Pertinent Data

- River: Santa Ana River
- County and State: San Bernardino County, California
- Purpose: Flood Control
- Drainage Area: 177 mi²
- Type: Rolled, zoned, earth and rockfill
- Crest elevation (excluding overbuild): 2,610 feet, NGVD
- Foundation elevation at dam axis: 2,060 feet, NGVD
- Maximum height above foundation at dam axis: 550 feet
- Freeboard: 5.3 feet
- Crest length: 2,760 feet
- Crest width: 40 feet
- Crest overbuild: varies from 0 to 3 feet
- Downstream: 1.8H to IV
- Upstream: 2.2H to IV
- Total embankment volume: 38,372,510 cubic yards
Seven Oaks Dam
Pertinent Data

- Debris pool (year 1) 2,200 feet, NGVD
- Debris pool (year 100) 2,300 feet, NGVD
- Reservoir design flood pool 2,580 feet, NGVD
- Probable maximum flood pool 2,604.7 feet, NGVD

Gross capacity
- Reservoir design flood pool (spillway crest) 147,970 acre-feet
- Probable maximum flood pool 169,177 acre-feet
- Top of dam 174,609 acre-feet

Storage allocation (below spillway crest)
- Flood control 115,970 acre-feet
- Sedimentation (100 year storage) 32,000 acre-feet
Seven Oaks Dam
Pertinent Data

Reservoir design flood (general storm)
- Total volume (4 day) 115,000 acre-feet
- Peak inflow 85,000 ft³/sec
- Peak outflow 7,000 ft³/sec

Probable maximum flood (general storm)
- Total volume 326,000 acre-feet
- Peak inflow 185,000 ft³/sec
- Peak outflow 180,000 ft³/sec
Chronology

- 1980 Phase I General Design Memorandum
- 1988 Phase II GDM
- 1989 Construction of Pilot Tunnel
- 1991 Partial Intake Structure
- 1992 Diversion Tunnel
- 1999 Dam and Outlet Works
- 2005 High Flow Testing and Tunnel Damage
SEVEN OAKS DAM
OUTLET WORKS PROFILE

OUTLET WORKS
- 1,500-FOOT LONG TUNNEL
- 200-FOOT HIGH INTAKE STRUCTURE
- 300-FOOT HIGH AIR SHAFT
- GATE CHAMBER
- EXIT CHANNEL
- PLUNGE POOL

EMBANKMENT CROSS SECTION

DAM
- 550-FOOT HIGH
- 3,000-FOOT LONG
- 40-FOOT WIDE AT CREST
- 2,000 FEET FROM U/S TOE TO D/S DOT

<table>
<thead>
<tr>
<th>ZONE</th>
<th>PURPOSE</th>
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<tbody>
<tr>
<td>CORE</td>
<td>WATER BARRIER</td>
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<tr>
<td>TRANSITION</td>
<td>DRAINAGE, STABILITY, AND ECONOMICAL USE OF EXCAVATED MATERIALS</td>
</tr>
<tr>
<td>ROCKFILL</td>
<td>STABILITY AND ECONOMICAL USE OF EXCAVATED MATERIALS</td>
</tr>
<tr>
<td>SHELL</td>
<td>DRAINAGE, EROSION CONTROL, AND STABILITY</td>
</tr>
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</table>
Embankment and Intake Structure
Intake Structure
Embankment and Plunge Pool
Hydraulic Design Requirements

- High velocity flow cavitation concern
- 1:25 physical model testing at WES/ERDC
- Flow aeration
- Embed pressure transducers in tunnel for flow testing
- High flow testing to verify design
## WATER YEAR PRECIPITATION SUMMARY

Summary by River Basin (% of Historic Average)
For the period Oct 1, 2004 to Jun 30, 2005

<table>
<thead>
<tr>
<th>Area</th>
<th>Oct-Jun</th>
<th>Season</th>
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<tbody>
<tr>
<td>Santa Barbara Area</td>
<td>221</td>
<td>217</td>
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<tr>
<td>Ventura – Los Angeles Area</td>
<td>236</td>
<td>231</td>
</tr>
<tr>
<td>Santa Ana River</td>
<td>226</td>
<td>217</td>
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<tr>
<td>San Diego Area</td>
<td>190</td>
<td>183</td>
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Ref: California Cooperative Snow Surveys
(http://cdec.water.ca.gov/cgi-progs/iodir/PRECIPSUM.2005)
High Pool El. 2392 (March 2005)
High Pool El. 2392 (March 2005)
# Hydraulic Testing

## Table 1: Testing Schedule and Maximum Discharge Rates

<table>
<thead>
<tr>
<th>Testing Schedule</th>
<th>Feb 17 - Mar 9</th>
<th>Testing Pool (ft)</th>
<th>Range of Gate Openings</th>
<th>Maximum Test Flow Rate (cfs)</th>
<th>Maximum Operational Flow Rate* (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21-Feb MDL Test</td>
<td>2373</td>
<td>10%-100%</td>
<td>135</td>
<td>120</td>
<td></td>
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<tr>
<td>22-Feb MDLE Test</td>
<td>2373</td>
<td>100%</td>
<td>115</td>
<td>100</td>
<td></td>
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<tr>
<td>25-Feb Low Flow Test</td>
<td>2383</td>
<td>0.25' - 3'</td>
<td>560</td>
<td>700</td>
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<tr>
<td>8-Mar Right RO Gate Test low Openings</td>
<td>2391</td>
<td>0.5' - 3'</td>
<td>1540</td>
<td>4900</td>
<td></td>
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<tr>
<td>9-Mar Right RO Gate Test-High Openings</td>
<td>2392</td>
<td>3.5' - 8' - 5'</td>
<td>2990 2520</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40-Mar Combined RO Gate Test**</td>
<td>2200</td>
<td>0.5' - 6.8'</td>
<td>6800</td>
<td>8000</td>
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</tbody>
</table>


Maximum pool for RO gates is 2580 ft, Maximum pool for MDL and MDLE = 2300 feet. Max. opening for two gate operation = 6.8 feet; max. opening for single gate operation = 8 feet.

** Stricken items were cancelled due to slab failure.
Minimum Discharge Line Flow Test
Cone Valves Flow Jet
High Flow Test (9Mar05)
High Flow Test (9Mar05)
High Flow Test (9Mar05)
What Happen?

- Was it caused by cavitation?
- Debris impact?
- Groundwater uplift?
- Negative air pressure?
- Differential concrete shrinkage?
- Design deficiency?
- Construction defect?
- Earthquake?
“Just the Facts, Ma’am”

Courtesy of Sgt. Joe Friday
“Dragnet” Detective Drama Series
1952-59, 1967-70
SEVEN OAKS DAM

- TOP OF DAM EL. 2610
- EL. 2302
- EL. 2100
- INTAKE TOWER
- 18’ DIA. PRESSURE TUNNEL
- AIR INTAKE
- OUTLET TUNNEL
- GATE CHAMBER W/ 2 RO GATES & 1 LOW FLOW GATE
- OUTLET CHANNEL
- CONE VALVES
- PLUNGE POOL
- Cone valves
SEVEN OAKS DAM

- Reservoir Height - 291 ft.
- Tower Height - 200 ft.
- U/S Tunnel - 18’ dia., 1000’ long
- D/S Tunnel - 18’ X 18.5’, 600’ long
- Gate Chamber - 50’ dia.
- Air Shaft - 11’ dia., 320’ vertical, max. v=140 fps
- 2 RO Gates - 5’ wide X 8.5’ high
- 1 Low Flow Gate – 2’ wide X 3.5’ high
- Max. Q=8,000 cfs, max. v=115 fps @ RO gates
Downstream Tunnel Plan
Downstream Tunnel
Section 1 and Section 2
Figure 3 Plan View of Instrumentation (Flush Mounted Pressure Transducers)
Design Assumptions

- Resist external rock and groundwater
- Invert designed as full-depth beam
- High strength silica fume topping for erosion resistance of high velocity flow
- Silica fume bond to base concrete and act monolithically
- No epoxy bonding agent
- No reinforcement across transverse joints
SEVEN OAKS DAM
Investigation and Repair

- Phase 1 - Concrete Cores for Visual, Petrography, and Strength Tests
- Phase 2 – Additional Concrete Cores for Visual, Detail Petrography, and Tensile Tests
- Phase 3 – Demolition of Critical Slabs
- Phase 4 - Repair of Critical Slabs
- Phase 5 – Repair of Additional Slabs
Concrete Coring Investigation
(Apr & May 05)
67% Cores Debonded
Fig. 3a – Cracking, delamination, and erosion of Slab 1 surface
Slab 2 Concrete Cores

Fig. 6 – Top surfaces (SFC-CC interface) of Slab 2 cores
Slabs 1 to 17 Typical Concrete Cores

Fig. 9 – Typical failure surfaces on cores from Slabs 7-17
Concrete Cores Investigation

• Phase 1 - Concrete Core Testing
  > Completed – 27 Apr 05
  > 67 % cores debonded
  > Compressive strength tests pending
  > Cursory petrography suggests tensile failure from incomplete bond development due to improper surface preparation or cold joint formation;
  > Veneer of carbonate deposit
Concrete Cores Investigation

• Phase 2 – Additional Concrete Core Testing
  > Completed – 4 May 05
  > 63 % cores debonded
  > Prelim detailed petrography confirms SC/CC interface exhibits layer of solidified carbonate-based residue;
  > Inadequate surface roughness for mechanical bonding; weak concrete at interface due higher W/C;
  > Final report pending
Analysis

- Reservoir at el.2392
- Gate opening at 5.0 ft
- Flow rate 2,520 cfs
- Velocity 130 ft/s
- Stagnation pressure 120 psi, but jet impingement pressure estimated 5 to 10 psi
- Pressure highest at invert joint with wall
- Only 0.7 psi to uplift silica fume layer
Plan View of Damaged Slab Area

- Damaged area in Slab 2
- Jet centerline impact location
- Bottom of jet impact location
- Outer edge of jet

Stations:
- Sta. 21+32
- Sta. 22+27
- Sta. 22+52
- Sta. 22+82

Sections:
- Station A

Additional Markings:
- RO 1
- RO 2
- LF
Free-Body Diagram of Damaged Slab Cross-section

SECTION A-A

24'

Negative Pressures from Air Demand

Dynamic Pressures from Jet

Right Wall

Uplift Pressure

R-rebars

W-concrete

Uplift Pressure

R-rebars

conduit

Figure 24 Tunnel Floor Free Body Diagram
Flow Jet Trajectory

Figure 23 Schematic of Jet Trajectory at Gate Opening 5 feet, Prior to Failure Event
• Water Pressure from high velocity flow jet penetrates construction joints.
Pressure migrates through seams between poorly bonded to debonded silica fume concrete overlay and substrate concrete and increases.
Tunnel Invert Damage - Cause

- Water pressure under overlay combined with reduced air pressure breaks bond between overlay and substrate concrete, and lifts up overlay.
Impact from jet breaks up overlay slab, pulverizes slab into smaller pieces, and completely erodes away edge of overlay.
SEVEN OAKS DAM
Tunnel Invert Repair Plan

• Remove Damaged and Suspect Slabs
• Anchor New Overlay to Base Concrete
• Assure Proper Joint Preparation & Bond Enhancement
• Use Non-Shrink High Strength Concrete
Slab Repair Plan
Slab Repair Plan
SEVEN OAKS DAM

Repair Schedule

• Phase 3 – Demolition Critical Slabs 1 to 6
  Construction Complete – 5 Aug 2005

• Phase 4 – Repair Critical Slabs 1 to 6
  Construction Complete – 30 Sep 2005

• Phase 5 – Demolition and Repair Additional Slabs as Required
  Construction Complete – 30 Sep 2006
“Dum Dee Dum Dum Dum Dee Dum Dum Dum Dum”

Music Theme
“Dragnet” Detective Drama Series
1952-59, 1967-70
1920 - 1982
Creator and Main Character of “Dragnet” TV Series

Picture Courtesy of:
http://www.amazon.com/exec/obidos/ASIN/092976529X/thefiftieswebsit/