Aging, Cracking and Shaking of Concrete Dams

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Acknowledgements:
Tokyo Electric Power Service Company (TEPSCO)
Dams are BIG!

2,335 m, 185 m

9,000 m, m

2,335 m, 185 m
Major Issues

- **Cracking**: Massive un-reinforced concrete.
- **Aging**: Alkali-Aggregate Reactions
- **Shaking**: Earthquakes
Some Relevant Publications


Joints & Cracks
Testing Joints; Monotonic

Dry Static; Different Sizes

Mixed-Mode

Dry and Wet Dynamic
Testing Joint Cyclic

cyclic shear displacement
constant confinement

threaded bars
aluminium plates
confining actuators

confining bars
concrete
steel plates
teflon sheet
Interface Crack Model (ICM)

At the heart of our numerical model, is an interface/joint element.

**Hyperbolic Failure Envelope**

![Hyperbolic Failure Envelope Diagram]

Failure Function

\[ F = \left( \tau_1^2 + \tau_2^2 \right) - 2c \tan(\phi_f) (\sigma_t - \sigma) - \tan(\phi_f)^2 (\sigma^2 - \sigma_t^2) = 0 \]

Cohesion and Tensile Strength

\[ c = c \left( u^{\text{eff}} \right) \quad \sigma_t = \sigma_t \left( u^{\text{eff}} \right) \]

Displacement decomposition:

\[ u = u^e + u^i \quad u^i = u^{p^i} + u^{f^i} \]

Softening parameter:

\[ u^{\text{eff}} = \left\| u^i \right\| = \left( u_x^2 + u_y^2 + u_z^2 \right)^{1/2} \]
The asymptotes of the hyperbola rotate of angle \( \alpha \).

\[
\varphi = \begin{cases} 
  \left( \frac{\mu_\beta}{\mu_{\beta+\alpha}} \right)^2 & p_t^2 - (c_\beta - p_n \mu_\beta)^2 + (c_\beta - \chi_\beta \mu_\beta)^2 \\
  \left( \frac{\mu_\beta}{\mu_{\beta-\alpha}} \right)^2 & p_t^2 - (c_\beta - p_n \mu_\beta)^2 + (c_\beta - \chi_\beta \mu_\beta)^2 
\end{cases} \quad \forall p_t \geq 0 \quad \forall p_t < 0
\]

Asperity degradation depends on confinement \( p_n \) and shear work \( L_t^i \)

\[
w_n^i = f(p_n, L_t^i) \cdot y(w_t^i) \quad \dot{L}_t^i = p_t \cdot \dot{w}_t^i
\]
Validation 1: Interface

Note: 1. No crack overlap; 2. Crack advances; 3. Cohesive tensile stresses
Application 1

Diagonal and horizontal cracks

- $t_1 = 0.485$ m
- $t_2 = 0.545$ m
- $t_3 = 0.692$ m
- $t_4 = 0.848$ m
- $t_5 = 1.000$ m
- $t_6 = 1.091$ m
Laboratory Tests to model reinforced joints
3D Nonlinear Numerical Simulation
Crack Modeling

- 10 buttress-buttress cracks
- Interface cracks
- 14 beams
- 28 beams-buttress cracks
Application 2
Alkali-Aggregate Reaction causes an expansion of concrete which may lead to structural cracks.

Courtesy R. Charlwood

Slice the dam to relieve stresses due to expansion.
What we know

- Reaction is
  - Sensitive to RH
  - Thermodynamically driven (Temperature).

- Laboratory tests at LCPC have shown that
  - Expansion follows a typical sigmoidal curve
  - Expansion is inhibited in presence of confinement (~8 MPa).
  - There is a redistribution of expansion.
  - Cracks reduce expansion
  - Degradation of tensile strength and Young’s modulus
Model

\[ \dot{\varepsilon}_{vol}^{AAR}(t) = \Gamma_t \left( f'_t \left| \mathcal{W}_c, \sigma_I \right| \text{COD}_{max} \right) \Gamma_c \left( \overline{\sigma}, f'_c \right) f(h) \dot{\xi}(t, \theta) \varepsilon^\infty \bigg|_{\theta=\theta_0} \]

\[ \dot{\xi}(t, \theta) = \frac{1 - e^{-t / \tau_c(\theta)}}{1 + e^{t - \tau_L(\theta, I_\sigma, f'_c) / \tau_c(\theta)}} \]

\[
\begin{cases}
\tau_c(\theta) = \tau_c(\theta_0) \exp \left[ U_c \left( \frac{1}{\theta} - \frac{1}{\theta_0} \right) \right]; \\
\tau_L(\theta, I_\sigma, f'_c) = f(I_\sigma, f'_c) \tau_L(\theta_0) \exp \left[ U_L \left( \frac{1}{\theta} - \frac{1}{\theta_0} \right) \right];
\end{cases}
\]

\[ f(I_\sigma, f'_c) = \begin{cases} 
1 & \text{if } I_\sigma \leq 0 \\
1 + \alpha \frac{I_\sigma}{3f'_c} & \text{if } I_\sigma > 0
\end{cases} \quad \text{if } I_\sigma = \sigma_I + \sigma_{II} + \sigma_{III} \]

\[ \varepsilon^\infty, \tau_c, \tau_L \] These parameters must be determined (possibly through an inverse analysis or laboratory Tests)

\[ \begin{cases} 
U_c = 5,400 \pm 500K \quad \text{Activation energy for the char. time} \\
U_L = 9,400 \pm 500K \quad \text{Activation energy for the lat. time}
\end{cases} \]

\[ f(h) = \begin{cases} 
H^m & \text{in general} \\
1 & \text{for dams}
\end{cases} \]
AAR gel absorption

\[ \dot{\varepsilon}_{vol}^{AAR} (t) = \Gamma_r \left( f_f' \left| f_c, \sigma_I \right| COD_{\text{max}} \right) c \left( \sigma_c' \right) v \dot{\xi}(t, \theta) \varepsilon^\infty \bigg|_{\theta=\theta_0} \]

Tension causes cracks which absorb the gel and inhibit expansion.

\[ \Gamma_t = \begin{cases} 1 & \text{if } \sigma_I \leq \gamma_t f'_t \\ \Gamma_r + (1 - \Gamma_r) \frac{\gamma_t f'_t}{\sigma_I} & \text{if } \gamma_t f'_t < \sigma_I \\ \Gamma_r + (1 - \Gamma_r) \frac{\gamma_t w_c}{COD_{\text{max}}} & \text{if } COD_{\text{max}} \leq \gamma_t w_c \\ \Gamma_r + (1 - \Gamma_r) \frac{\gamma_t w_c}{COD_{\text{max}}} & \text{if } \gamma_t w_c < COD_{\text{max}} \end{cases} \]

- Linear elastic
- Smeared crack

**Linear Analysis**

\[ \gamma_t f'_t = f'_t \]

**Non-Linear Analysis**

\[ \gamma_t w_c = w_c \]

\[ COD_{\text{max}} \]
There is a reduction in expansion under biaxial or triaxial state of stress

\[
\dot{\varepsilon}_{vol}^{AAR}(t) = \Gamma_c \left( \begin{array}{c} f t' \\ f_w h \sigma_I \\ COD_{max} \end{array} \right) \left( \sigma \begin{array}{c} c' \\ c' \end{array} \right) \xi(t, \theta) \varepsilon^\infty \bigg|_{\theta=\theta_0}
\]

\[
\Gamma_c = \begin{cases} 
1 & \text{if } \bar{\sigma} \leq 0 \text{ Tension} \\
1 - \frac{e^{\beta \bar{\sigma}}}{1 + (e^{\beta} - 1)\bar{\sigma}} & \text{if } \bar{\sigma} > 0 \text{ Compression}
\end{cases}
\]

\[
\bar{\sigma} = \frac{\sigma_I + \sigma_{II} + \sigma_{III}}{3f_c'}
\]

Principal Stresses

\[\beta = -2, -1, 0, 1, 2\]
Redistribution of volumetric strain

\[ \varepsilon_i^{AAR}(t) = W_i \varepsilon_{Vol}^{AAR}(t) \]

**Assumptions**

**Uniaxial/Biaxial load:** the AAR-expansion in direction \( i \) is reduced (or eliminated if \( \sigma < \sigma_u \)) in presence of compression.

**Triaxial load:** the AAR-expansion is reduced in the direction of the highest compression; Note: we can have expansion if \( f'c < \sigma < \sigma_u \)

The AAR volumetric expansion is **redistributed** into the three principal directions on the basis of the multiaxial state of (principal) stresses.

Reduction of AAR volumetric strain accounted for by \( \Gamma_c \)
Weights

Must consider different scenarios; based on $f'_t$, $\sigma_u$ and $f'_c$

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Degradation of Young’s modulus and tensile strength

\[ E = E_0 \left[ 1 - (1 - \beta_E) \xi(t, \theta) \right] \]

\[ f_t = f_{t,0} \left[ 1 - (1 - \beta_f) \xi(t, \theta) \right] \]

\[ \xi(t, \theta) = \frac{1 - e^{\frac{t}{\tau_C(\theta)}}}{1 + e^{\frac{t}{\tau_C(\theta)}}} \]

\( \beta_E \) residual fraction of Young’s modulus

\( \beta_f \) residual fraction of tensile strength

\( \beta_E = \beta_f = 70\% \)
Arch-gravity dam.
Data Preparation for Stress Analysis

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<th>Increments</th>
<th>Initialization</th>
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### Body force

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### Temperature

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Matlab Based System Identification for Key parameters

Program

Merlin

GUI
Cracks inside the dam

Principal stresses: maximum

The presence of high tensile stresses inside the dam can explain the origin of the cracks which appeared along the upper gallery. Other cracks can exist inside the dam and may not be yet identified.

Crack along the upper gallery

Crack inside core borehole in the upper gallery
Application 2

AAR Localized

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<td>Mpa</td>
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**Analyses**

- Maximum principal strain: 4.67E-03
- **Observation**
  - Upper side: 4.40E-03
  - Lower side: 9.00E-04
  - Facing North: 1.18E-03
  - Facing South: 1.33E-04

**Graphical Representation**

- Color scale for stress (MPa)
- Diagram showing stress distribution on different sides of the structure.
Cracking

Aging

Shaking
Deconvolution

Thermal

Initial Stresses

LOADS

INTERACTIONS

MODELS

TESTS

APPLICATIONS

TOOLS
Modes of heat transfer in a dam analysis

Conductivity
\[ q_i = k_i \frac{\partial T}{\partial x_i} \]

Convection
\[ q_{conv} = h \left( T_{surface} - T_{fluid,\infty} \right) \]

Radiation
\[ q_r = eC_s \left( T_{surf}^4 - T_{fluid,\infty}^4 \right) \]
Deconvolution

- Observe (or determine a synthetic) earthquake on surface O
- Must apply the seismic record at I
- Must model (elastic) foundation

Q: Which record should be applied at base of foundation such that the computed one at O will match the desired earthquake?

A: Need to Deconvolute the signal
(t) Time Domain; (ω) Frequency Domain (via FFT)

\[ X(\omega) = \int_{-\infty}^{\infty} x(t) e^{-i2\pi\omega t} dt; \quad x(t) = \int_{-\infty}^{\infty} X(\omega) e^{i2\pi\omega t} d\omega \]

\[ x(t) \xrightarrow{\text{FFT}} X(\omega) \]

Transfer Function (Fourier Spectral Ratio) (1D)

1. FFT input, \( I(t) \) and output \( O(t) \) signal to go from time to frequency domain; \( I(\omega) \) and \( O(\omega) \);

2. Determine the TF by dividing amplitudes of each frequency of the Output by the corresponding one of the input: \( TF_{I-O} = \frac{O(\omega)}{I(\omega)} \)
1D Deconvolution

1. \[ i'(t) \xrightarrow{FFT} I'(\omega); \quad a(t) \xrightarrow{FFT} A(\omega) \]

2. \[ TF = \frac{A(\omega)}{I'(\omega)} \]

3. \[ I(\omega) = TF^{-1} A'(\omega) = \frac{I'(\omega)}{A(\omega)} A'(\omega) \]

4. \[ I(\omega) \xrightarrow{FFT^{-1}} i(t) \]
Initial Stress Analysis; Staged Construction Simulation; Static-Dynamic Analysis

Weight in one block

Excessive Deformation and Stresses (tensile)

Staged Construction of individual monoliths (2D)

Grouting (3D)

More realistic initial stresses

Static Analysis followed by a Dynamic Analysis (change in material properties & Boundary Conditions)
In a nonlinear analysis, uplift is automatically adjusted in accordance with crack opening/failure.
Uplift must be adjusted as crack propagates in a nonlinear analysis; in Dynamic analysis as $d(COD)/dt \uparrow$, $p \downarrow$ and $d(COD)/dt \downarrow$, $p \uparrow$.

Model must be calibrated with Boulder and Montreal Tests.
Dynamic Uplift Validation

We note that:

1. Uplift is non-zero for an open (or previously opened) crack

2. Water/crack front advances with time.
• Base of the dam excited by a seismic wave.

• Wave will travel through the model, and eventually hit the boundary.

• As with all waves, it will be reflected by the free surface.

• In actuality, it keeps propagating in the foundation.

• Reflected wave may either amplify or decrease seismic excitation, in either case, it must be eliminated.

• Reflection can be eliminated either by a) “infinitely” large mesh (expensive), b) “infinite” (boundary) element; or through Radiation Damping which will absorb the incident waves (P and S).
Radiation Damping

M ≠ 0; g ≠ 0

M=0; g=0

It is erroneous not to account for the mass in the rock

Current Practice
 Assumes rigid support, no effect of free field

Current Practice 2; Lysmer

\[ t_n = \rho V_p u; \quad t_{s1} = \rho V_s v; \]

\[ V_s = \sqrt{\frac{\mu}{\rho}}; \quad V_P = \frac{1}{s} V_s; \]

\[ s^2 = \frac{1 - 2\nu}{2(1 - \nu)} \]
Account for free field analysis results, and analyse foundation-structure next

\[
M^\Omega \ddot{u}^\Omega + C^\Omega \dot{u}^\Omega + K^\Omega u^\Omega + C_{lft}^{dp} (\ddot{u}^\Gamma_{lft} - \ddot{u}^\Gamma_{lft}) + C_{rgt}^{dp} (\ddot{u}^\Gamma_{rgt} - \ddot{u}^\Gamma_{rgt}) + C_{bot}^{dp} \dot{u}^\Omega_{bot} = 0
\]

\[
t_{bot}^{\Omega} = \left( C_{lft}^R \ddot{u}^\Gamma_{lft} + K_{lft} u^\Gamma_{lft} \right) - \left( C_{rgt}^R \ddot{u}^\Gamma_{rgt} + K_{rgt} u^\Gamma_{rgt} \right)
\]

\[
\Rightarrow \left[ M^\Omega \ddot{u}^\Omega + C^\Omega \dot{u}^\Omega + K^\Omega u^\Omega \right] + \left[ C_{lft}^{dp} \dot{u}^\Omega_{lft} + C_{lft}^{dp} \dot{u}^\Omega_{rgt} + C_{bot}^{dp} \dot{u}^\Omega_{bot} \right] = \left[ \right]
\]

\[
t_{bot}^{\Omega} + \left[ F_{lft}^C + F_{lft}^K + F_{lft}^R \right] + \left[ F_{rgt}^C + F_{rgt}^K + F_{rgt}^R \right]
\]

Derived from Principle of Virtual Work
Meshing
Validation; Harmonic excitation at Base

Free Boundaries

Lysmer

Miura-Saouma
3D Validation

Lysmer

Miura-Saouma
Effect of Boundary Conditions

<table>
<thead>
<tr>
<th>Criteria</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation Damping</td>
<td>No</td>
<td>Lysmer</td>
<td>Miura</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocking</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Gravity Load Transfer</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- Perform static analysis with supports
- Determine reactions
- Restart a dynamic analysis with initial stress, zeroed displacements, remove supports and replace them by forces (i.e. no BC)
Detailed parametric study of Folsom Dam subjected to harmonic excitation (different frequencies), and 1971 San Fernando Earthquake, 0.30 peak ground acceleration
Observations

1. If no radiation damping is present, “very large” foundations should be used.
2. For “soft” rock, the mass of the foundation should be modeled as we can have substantial amplification of the input signal.
3. When the mass is modeled, we have a larger inertia and thus slightly reduced dam accelerations. However this effect is mitigated by deconvolution of the input signal which should be performed.
4. Massless foundation will generate larger response than when the foundation mass is accounted for.
5. One should not apply vertical support in a seismic analysis of a massive concrete structures with its foundation as rocking will induce additional accelerations (and stresses).
6. When radiation damping is present we greatly reduce the dependency on the size of the foundation.
7. Even when radiation damping is present, the height of the foundation should be carefully selected to correspond to a multiplier (one should be enough) of the shear wave length.
8. Interface (or joint) elements between the dam and the foundation may not substantially reduce the accelerations but will reduce the stresses.
9. A model based on Saouma-Miura with interface element is equivalent to a “simpler” model (with no interfaces, no radiation damping) with a Rayleigh damping of about 15%.
Beaver (Dam Definition)

Pre-Processor: KUMO

Analysis: MERLIN

Post-Processor: SPIDER

Analysis Sequence

LOADS

INTERACTIONS

MODELS

TESTS

APPLICATIONS

TOOLS
MERLIN

http://civil.colorado.edu/~saouma/Merlin
**CENTRIFUGE**

Maxi Payload: 7 t  
Platform Size: 2.2 x 2.2 m  
Model Height: 2.5 m  
Max. Accel.: 120 g  
Max. Payload: 700 g-t

**Shaking Table**

4 Electro-Hydraulic Actuators  
(1,176 kN Total)  
Max. Payload: 3 t  
Platform: 2.2 x 1.07 m  
Max. Accel.: 500 m/s²  
Max. Freq.: 200 Hz
Centrifuge Test of Dam

Place Specimen on Shaking table
Place shaking table on centrifuge

<table>
<thead>
<tr>
<th>Prototype</th>
<th>100 m</th>
<th>10 sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>1 m</td>
<td>0.1 sec.</td>
</tr>
</tbody>
</table>
載荷・加振条件

細心力場 (g)

105
30
0

経過時間 (min)

6段階で加速度を増加させる

◆ 最大加速度450m/s²

ならし運転

振動実験

空虚時

最大加速度：6段階

満水時

加振波形：4段階

加振1段階当たりの波形イメージ

加速度

時間 (s)

167Hz漸増正弦波

0.06 sec
Transfer Functions to Detect Cracks
加速度応答の比較

基盤に対する天端の伝達関数の比較

弾性領域での応答

（同定値）

- 弾性係数: 9,370MPa
- 引張強度: 1.01MPa
- 減衰定数: 7％

Finite Element Simulation captured the experimental response; “Validation” of FEM Code
For How Long Can we Ignore the Problem?

John Hendrix
END
Thank you for your Attention
Bilinear Evolution Laws

Constitutive Equation: \( \sigma = \alpha E \left( u - u^p \right) \)

Integrity Parameter: \( \alpha = 1 - \frac{|\sigma| + \sigma}{2|\sigma|} \)
\( \begin{cases} 1 \text{ if } \sigma > 0; \\ 0 \text{ otherwise} \end{cases} \)

Damage Parameter: \( D = \frac{A_F}{A_0} = 1 - \frac{K_{ns}}{K_{n0}} \)

\( K_{ns} = \frac{\sigma}{u - u^p} \)

Energy dissipated in shear test under high confinement

Stiffness Degradation
Dilatancy & Damping

\[ \sigma_n = \eta \frac{d\text{COD}}{dt} \]

Maybe difficult to calibrate.
Useful to dissipate energy
User input data

\[
\begin{align*}
\varepsilon^\infty_{\theta=\theta_0} & \quad \text{Maximum volumetric strain at temperature } \theta_0 \\
\tau_C(\theta_0) & \quad \text{Characteristic time at temperature } \theta_0 \\
\tau_L(\theta_0, \overline{\sigma}/f'_{cn}) & \\
\end{align*}
\]

\[
\begin{align*}
\Gamma_r & \quad \text{Residual value in tension for } \Gamma_t \\
\alpha & \quad \text{Retardation factor due to compressive stresses} \\
\beta & \quad \text{Coefficient that determines the shape of } \Gamma_c \\
\gamma_t & \quad \text{Fraction of } \sigma_t \text{ or } w_c \text{ prior to reduction of AAR expansion} \\
\sigma_U & \quad \text{Upper compressive stress before zero AAR expansion in uniaxial load} \\
f'_{c} & \quad \text{Compressive strength} \\
f'_{t} & \quad \text{Tensile strength} \\
G_f & \quad \text{Fracture energy} \\
\beta_E & \quad \text{Reduction coefficient for Elastic modulus} \\
\beta_f & \quad \text{Reduction coefficient for tensile strength} \\
U_C & \quad \text{Activation energy associated with } \tau_C(\theta_0), \text{ default value 5,400 K} \\
U_L & \quad \text{Activation energy associated with } \tau_L(\theta_0), \text{ default value 9,400 K} \\
T_0 & \quad \text{Laboratory temperature for determination of } \varepsilon^\infty_{\theta=\theta_0}, \tau_C(\theta_0) \text{ and } \tau_L(\theta_0) \\
\end{align*}
\]

Reference dam temperature
Representative year cycle
Generate mesh for thermal analysis (without cracks or foundation).

Carry out a transient thermal analysis for 4 years (2 week increments).

Select last year as “typical thermal load”
Air temperature and pool elevation

For 1 year

Cyclic load generation

Air temperature is necessary to determine the temperature on the upstream and downstream surfaces exposed to the air.

Water level is necessary to determine the upstream surface below water level during a year.
Yearly temperature variation (should add 7°C)
Mesh for 3D stress analysis

Only the dam body with joint between each cantilever
7,552 nodes
5,196 elements (tetrahedral, pyramidal and hexahedral linear elements)
- A Matlab driver for Merlin analysis has been written
- It reads experimental/field measurements, and then seeks to determine the primary parameters through a least square nonlinear optimization function
- Driver (AARSI), will internally read Merlin output file to extract numerical predictions, and edit Merlin input file to write new set of input parameters
- Graphical user interface.
Areas of Research

1. Can we extract cores from a dam, perform laboratory tests, and characterize the remaining expansion curve (kinetics) of the concrete (i.e. what is the maximum AAR expansion, and when would it stop)?

2. Improve our understanding of AAR expansion when concrete is subjected to uniaxial, biaxial or triaxial confinement.
• The red curve is with respect to global coordinates and is what we are seeking
• We can obtain the blue curve with respect to the laboratory coordinate system
• We want to get the entire curve with respect to the global coordinate system
• Thus we have 5 unknowns for each test: $\tau_{\text{lat}}$, $\tau_{\text{char}}$, $\varepsilon_{\text{field}}$, $t_0$, $\varepsilon_0$ Will need to perform at least 3 tests at 3 different temperatures to also determine UL and UC (activation Energies)
Check validity of AAR redistribution when concrete is subjected to uniaxial, biaxial or triaxial confinement under controlled temperature and 100% humidity
Display Panel

Web Based Monitoring