Session:

Dynamic behavior of concrete dams: data processing from the JCOLD database records on concrete dams
SUMMARY

1. INTRODUCTION

2. PRESENTATION OF THE JCOLD ACCELERATION DATA OF DAMS

3. DATA PROCESSING FOR CONCRETE DAMS FROM EARTHQUAKES RECORDS
   METHODS OF ANALYSIS FOR MODAL IDENTIFICATION
   APPLICATION ON TAGOKURA AND KUROBE DAMS

4. SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAMS
   ANALYSIS OF ASAHI ARCH DAM RECORDS
   ANALYSIS OF KASHO GRAVITY DAM RECORDS

5. ANOTHER SIMPLIFIED FORMULA FOR GRAVITY DAM
INTRODUCTION

- JCOLD provided acceleration records on dams and foundation, including a lot of concrete dams (more than 150)

- As conventional monitoring of concrete dams provides essential informations about static behavior, acceleration records, correctly processed, might also prove to be very useful to better understand behavior under earthquakes

- From accelerations records, data processing is essential and results are strongly dependent of the method used: an evaluation of several methods is then proposed

- Correctly analysed, these datas will be used to assess our calculation method
PRESENTATION OF THE JCOLD DATABASE

- « Acceleration records on dams and foundation n°3» in 2014 by the Japan Commission On Large Dams
  - Earthquake records on rock foundation – 1978
  - Acceleration records on dams and foundation n°2 – 2002

- Including records from:
  - 1995 Southern Hyogo prefecture earthquake (M7.3)
  - 2000 Western Tottori Prefecture Earthquake (M7.3)
  - 2004 Mid Niigata Prefecture Earthquake (M6.8)
  - 2008 Iwate-Miyagi Nairiku Earthquake (M7.2)
  - 2011 off the Pacific coast of Tohoku Earthquake (M9.0)
## PRESENTATION OF THE JCOLD DATABASE

Data processing from the JCOLD database records on concrete dams

Source : T. SASAKI

<table>
<thead>
<tr>
<th>Dam Type</th>
<th>Symbol</th>
<th>Number of Dams&lt;sup&gt;1)&lt;/sup&gt;</th>
<th>Number of Records</th>
<th>Number of Component of Records</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Gravity</td>
<td>G</td>
<td>135</td>
<td>223</td>
<td>1681</td>
</tr>
<tr>
<td>Concrete Arch</td>
<td>A</td>
<td>22</td>
<td>59</td>
<td>573</td>
</tr>
<tr>
<td>Rockfill</td>
<td>R</td>
<td>59</td>
<td>163</td>
<td>1888</td>
</tr>
<tr>
<td>Earthfill</td>
<td>E</td>
<td>18</td>
<td>99</td>
<td>899</td>
</tr>
<tr>
<td>Combined</td>
<td>GF</td>
<td>11</td>
<td>18</td>
<td>207</td>
</tr>
<tr>
<td>Concrete Facing</td>
<td>FC</td>
<td>3</td>
<td>15</td>
<td>89</td>
</tr>
<tr>
<td>Asphalt Facing</td>
<td>FA</td>
<td>3</td>
<td>15</td>
<td>249</td>
</tr>
<tr>
<td>Hollow Gravity</td>
<td>HG</td>
<td>5</td>
<td>5</td>
<td>33</td>
</tr>
<tr>
<td>Buttress</td>
<td>B</td>
<td>1</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>257</strong></td>
<td><strong>602</strong></td>
<td><strong>5649</strong></td>
</tr>
</tbody>
</table>

<sup>1)</sup> Number of dams which collected earthquake records
PRESENTATION OF THE JCOLD DATABASE

Data processing from the JCOLD database records on concrete dams

T : Crest,  M : Dam Body,  F : Dam Foundation (Dam Bottom),  G : Ground

Source : T. SASAKI
**PRESENTATION OF THE JCOLD DATABASE**

- Example from the database
  - Name and type of dam
  - Height of the dam
  - Location of seismograph, axis and positive directions
  - Waterlevel during the earthquakes
  - Information about the earthquake (M, depth, epicentral distance, name..)
  - Digital accelerograms file

- Allow massive data processing with Python software

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Data processing from the JCOLD database records on concrete dams | 7
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5. A(NOTHER) SIMPLIFIED FORMULA FOR GRAVITY DAM
DATA PROCESSING FOR CONCRETE DAMS FROM EARTHQUAKES RECORDS

Quick reminder of some basic operations

- **Input:**
  - Acceleration vs time

- **Output**
  - Peak acceleration
  - Fourier spectrum = FFT[acc(t)]
  - Response spectrum (peak response of single DOF oscillator of varying natural frequency)
  - Velocity, Displacement, Energy…

Data processing from the JCOLD database records on concrete dams
DATA PROCESSING FOR CONCRETE DAMS FROM EARTHQUAKES RECORDS

- Quick reminder of some hidden operations
  - Filtering..
  - Smoothening..
  - Windowing..

- To make the results more clear..
MODAL IDENTIFICATION FOR CONCRETE DAMS FROM EARTHQUAKES RECORDS

- Evaluate the 1st natural frequencies of the dam
  - Useful to conduct FE back analyses (calibration of FE model)
  - To compare with natural frequencies guessed from other methods (ambient vibration tests, simplified formula..)
  - Useful for further data processing (damping evaluation..)

- Methods available are initially design for conventional structures and long records (20-30 min)

Data processing from the JCOLD database records on concrete dams
DATA PROCESSING : MODAL IDENTIFICATION

- Application on Tagokura gravity dam and Kurobe arch dam with several earthquakes records
DATA PROCESSING : MODAL IDENTIFICATION

Application on Tagokura gravity dam and Kurobe arch dam with several earthquakes records

<table>
<thead>
<tr>
<th>Dam</th>
<th>Earthquake Date</th>
<th>Epicentral Distance</th>
<th>Magnitude</th>
<th>Water level (m)</th>
<th>PGA (g)</th>
<th>Max crest acceleration (g)</th>
<th>Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tagokura dam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>10/23/2004</td>
<td>37km</td>
<td>6.8</td>
<td>507.1</td>
<td>0.10</td>
<td>0.46</td>
<td>431 s</td>
</tr>
<tr>
<td>2</td>
<td>10/23/2004</td>
<td>34km</td>
<td>5.3</td>
<td>507.2</td>
<td>0.07</td>
<td>0.71</td>
<td>99 s</td>
</tr>
<tr>
<td>3</td>
<td>10/27/2004</td>
<td>33km</td>
<td>6.1</td>
<td>507.2</td>
<td>0.12</td>
<td>0.61</td>
<td>168 s</td>
</tr>
<tr>
<td>4</td>
<td>10/23/2004</td>
<td>23km</td>
<td>6.5</td>
<td>507.2</td>
<td>0.08</td>
<td>0.51</td>
<td>401 s</td>
</tr>
<tr>
<td>5</td>
<td>12/22/2007</td>
<td>9km</td>
<td>4.4</td>
<td>495.5</td>
<td>0.03</td>
<td>0.32</td>
<td>85 s</td>
</tr>
<tr>
<td>Kurobe dam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>03/25/2007</td>
<td>114km (off Noto peninsula)</td>
<td>6.9</td>
<td>1381.7</td>
<td>0.02</td>
<td>0.17</td>
<td>75.21 s</td>
</tr>
<tr>
<td>2</td>
<td>10/05/2011</td>
<td>3km (Hida mountain region)</td>
<td>5.2</td>
<td>1430.4</td>
<td>0.13</td>
<td>0.97</td>
<td>119 s</td>
</tr>
<tr>
<td>3</td>
<td>10/06/2011</td>
<td>1km (Hida mountain region)</td>
<td>4.7</td>
<td>1431.4</td>
<td>0.11</td>
<td>0.46</td>
<td>232 s</td>
</tr>
<tr>
<td>4</td>
<td>10/05/2011</td>
<td>4km (Hida mountain region)</td>
<td>5.4</td>
<td>1430.4</td>
<td>0.07</td>
<td>0.38</td>
<td>77 s</td>
</tr>
<tr>
<td>5</td>
<td>03/11/2011</td>
<td>3km (Hida mountain region)</td>
<td>4.1</td>
<td>1394.4</td>
<td>0.06</td>
<td>0.26</td>
<td>50 s</td>
</tr>
<tr>
<td>6</td>
<td>03/11/2011</td>
<td>2km (Hida mountain region)</td>
<td>2.9</td>
<td>1394.1</td>
<td>0.02</td>
<td>0.10</td>
<td>44 s</td>
</tr>
</tbody>
</table>
DATA PROCESSING : MODAL IDENTIFICATION

- Rely on frequency-domain analyses with peak-picking
- Translation from temporal to frequency domain with Discrete Fourier transform (DFT) or spectrum response output (SRO)

<table>
<thead>
<tr>
<th>Method</th>
<th>Mathematical Expression</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Domain Decomposition (FDD)</td>
<td>$FDD(f) = \sum_{k=1}^{n}</td>
<td>s_{sensor_k}(f)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- slight variations from earthquakes to earthquakes</td>
</tr>
<tr>
<td>Cross-Spectrum (CS)</td>
<td>$CS_a(f) =</td>
<td>Crest1(f) \ast Crest1(f)</td>
</tr>
<tr>
<td></td>
<td>$CS_b(f) =</td>
<td>Crest1(f) \ast Crest2(f)</td>
</tr>
<tr>
<td></td>
<td>$CS_c(f) =</td>
<td>Crest1(f) \ast Crest3(f)</td>
</tr>
<tr>
<td>Transfer Function (TF)</td>
<td>$TF(f) = \frac{</td>
<td>Crest(f)</td>
</tr>
<tr>
<td>Mean Transfer Function (TFm)</td>
<td>$TFm(f) = \frac{1}{N} \sum_{\tau=0}^{N-1} TF_{[\tau,\tau+\tau]}(f)$</td>
<td>- normalized ordinate, good reproducibility over the earthquakes</td>
</tr>
</tbody>
</table>

Data processing from the JCOLD database records on concrete dams
DATA PROCESSING : MODAL IDENTIFICATION
FREQUENCY DOMAIN DECOMPOSITION (FDD)

\[ FDD(f) = \sum_{k=1}^{n} |\text{sensor}_k(f)|^2 \]

- Estimation of the dam’s kinetic energy
- For Kurobe, FDD method shows peak around 2.3 and 3.3 Hz
- More difficult to reach any conclusion in Tagokura’s case.
DATA PROCESSING : MODAL IDENTIFICATION CROSS SPECTRUM

\[
CS_a(f) = |Crest_1(f) \times Crest_1(f)| \\
CS_b(f) = |Crest_1(f) \times Crest_2(f)| \\
CS_c(f) = |Crest_1(f) \times Crest_3(f)|
\]

- Dependent of the input frequency content
- For Kurobe, CS method shows peak around 2.2 and 3.2 Hz
- More difficult to reach any conclusion in Tagokura’s case : first peak around 3.8 Hz for earthquake n°1 and 3 but nothing for earthquake n°2.
DATA PROCESSING : MODAL IDENTIFICATION
TRANSFER FUNCTION

\[ TF(f) = |Crest(f)/Base(f)| \]

- Characteristics of each dam
- No big variations between earthquakes
- Results from different earthquake can be compared since the TF is normalized
**DATA PROCESSING : MODAL IDENTIFICATION**

**MEAN TRANSFER FUNCTION**

\[ TF_m(f) = \frac{1}{N} \sum_{i=0}^{N-1} TF_{[i\tau,t_0+i\tau]}(f) \]

- **Averaging TFs calculated on ‘sliding windows’:**
  - TF[0] computed over [0s:15s]
  - TF[1] computed over [1s:16s]
  - …

- **If the standard deviation does not vary too much**
DATA PROCESSING : MODAL IDENTIFICATION
MEAN TRANSFER FUNCTION

\[ TFm(f) = \frac{1}{N} \sum_{i=0}^{N-1} TF_{[i\tau, t_0+i\tau]}(f) \]

- Averaging TFs calculated on 'sliding windows':
  - TF[0] computed over [0s:15s]
  - TF[1] computed over [1s:16s]
  - ...

- If the standard deviation does not vary too much
- For Kurobe (high water leve) : 2.3 and 3.3 Hz
- For Tagokura : 3.3 and 3.9 Hz
- Use of smoothing function 0.06 Hz
DATA PROCESSING : MODAL IDENTIFICATION
COMPARISON WITH SHAKE AND AMBIENT NOISE TESTS

<table>
<thead>
<tr>
<th>Date</th>
<th>Water level (m)</th>
<th>Method</th>
<th>1st symmetrical</th>
<th>1st asymmetrical</th>
<th>2nd symmetrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>July, 15th 1965</td>
<td>1430 m</td>
<td>Shaker test</td>
<td>2.0 Hz</td>
<td>2.4 Hz</td>
<td>3.6 Hz</td>
</tr>
<tr>
<td>July, 1st 1969</td>
<td>1448 m</td>
<td>Shaker test</td>
<td>1.8 Hz</td>
<td>2.1 Hz</td>
<td>3.2 Hz</td>
</tr>
<tr>
<td>October, 28th 1996</td>
<td>1417 m</td>
<td>Ambient noise</td>
<td>2.3-2.5 Hz</td>
<td></td>
<td>3.7 Hz</td>
</tr>
<tr>
<td>October, 5th 2011</td>
<td>1430 m</td>
<td>Earthquake’s record analysis</td>
<td>2.3 Hz</td>
<td>3.3 Hz</td>
<td>(mode shape unevaluated)</td>
</tr>
</tbody>
</table>

- For comparable water level, eigenfrequencies evaluated by earthquake’s record analysis are close from 1996 test
- Differences with 1965 and 1969 test might come from thermal effects
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SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

- Analysis of ASAHI arch dam records (H=81.5m)
  - 17 jan 1995 (M7.3)
    PGA 0.017 g – water level: 434.5
  - 5 sept 2004 (M7.1)
    PGA 0.041 g – water level: 447.3
  - 5 sept 2004 (M7.4)
    PGA 0.044 g – water level: 447.3

- Mean Transfer function
  - 1st natural freq varies:
    4.9 Hz for low water level + winter
    5.5 Hz for higher water level + summer

Data processing from the JCOLD database records on concrete dams
SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

- Analysis of ASAHI arch dam records (H=81.5m)
  - 17 jan 1995 (M7.3)
  - PGA 0.017 g – water level : 434.5

From crest record:
- bandpass filter [3-7Hz] (around nat. freq)
- FFT(acc[0-15s]), FFT(acc[1-16s])….
- Evaluation of 1st natural frequency
- Evaluation of damping by halfpower bandwidth method
SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

- Analysis of ASAHI arch dam records (H=81.5m)
  - 17 Jan 1995 (M7.3)
  - PGA 0.017 g – water level: 434.5
  - PCA/PGA = 4.1
  - From crest record:
    - Damping around 7% for eq1
SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

- Analysis of ASAHI arch dam records (H=81.5m)
  - 5 sept 2004 (M7.1)
  - PGA 0.041g – water level: 447.3
  - PCA/PGA=3.9
  - From crest record:
    - damping around 7% for eq1
    - damping 10--> 5% for eq2

Data processing from the JCOLD database records on concrete dams
SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

- Analysis of ASAHI arch dam records (H=81.5m)
  - 5 sept 2004 (M7.4)
  - PGA 0.044g – water level : 447.3
  - PCA/PGA=3.3
  - From crest record:
    - damping around 7% for eq1
    - damping 10--> 5% for eq2
    - damping 7--> 10% for eq3
SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

Analysis of ASAHI arch dam records (H=81.5m)

- 8% damping
  - PGA=0.017g
  - PGV=0.011m/s
  - PGD=1.08mm
  - PCA/PGA=3.3

- 6% damping
  - PGA=0.041g
  - PGV=0.012m/s
  - PGD=0.65mm
  - PCA/PGA=4.15

- 10% damping
  - PGA=0.044g
  - PGV=0.015
  - PGD=1.02mm
  - PCA/PGA=3.9
SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

- Analysis of Kasho dam records (H=46.4m)
  - 6 oct 2000 (M7.3)
  - PGA 0.54 g recorded at the bottom of the dam

- Mean Transfert function

Data processing from the JCOLD database records on concrete dams | 28
SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

- Analysis of Kasho dam records (H=46.4m)

Evaluation of the damping with halfpower bandwith method:
- values vary with data processing (smoothening, hanning window)

Data processing from the JCOLD database records on concrete dams
SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

- Analysis of Kasho dam records (H=46.4m)
- Evolution of the damping and 1st frequency

Data processing from the JCOLD database records on concrete dams | 30
SPECIFIC DYNAMIC BEHAVIOR OF CONCRETE DAM

In this case: during the high intensity content of the earthquake:

- increase of the damping from 5→11%

- slight decrease of the first frequency (might be due to the opening of the vertical joint opening = reduction of the 3D effect)

- Analysis of Kasho dam records (H=46.4m)
  - Evolution of the damping and 1st frequency

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ANALYSES OF GRAVITY DAM RECORDS

- From the records of 115 gravity dams (135) with F1 (bottom) and T1 (crest) records available
- 8 dams with more than 4 records available
  - (among them: 10 for Tagokura dam, 9 for Kasho dam, 8 for Tase dam)
- Height of dam from 20.3 → 155m with a good representation of each size

Data processing from the JCOLD database records on concrete dams
ANALYSES OF GRAVITY DAM RECORDS

- Peak acceleration at crest vs peak ground accélération
  (With 1-15 Hz filter)
ANALYSES OF GRAVITY DAM RECORDS

- Peak acceleration at crest vs peak ground acceleration

Data processing from the JCOLD database records on concrete dams
ANALYSES OF GRAVITY DAM RECORDS

- Peak acceleration at crest vs peak ground acceleration

Data processing from the JCOLD database records on concrete dams
ANALYSES OF GRAVITY DAM RECORDS

- Peak acceleration at crest vs peak ground acceleration

For 80% of the dams:
- $20 < H < 30\text{m}$: $\frac{PCA}{PGA} < 2$
- $30 < H < 60\text{m}$: $\frac{PCA}{PGA} < 5$
- $60 < H < 130\text{m}$: $\frac{PCA}{PGA} < 6.3$
- $130 < H < 160\text{m}$: $\frac{PCA}{PGA} < 9.6$

Roughly: $PCA = PGA \times 0.07 \times H$
ANALYSES OF GRAVITY DAM RECORDS

- Peak acceleration at crest vs peak ground accélération

For 80% of the dams:
- $20 < H < 30m : \frac{PCA}{PGA} < 2$
- $30 < H < 60m : \frac{PCA}{PGA} < 5$
- $60 < H < 130m : \frac{PCA}{PGA} < 6.3$
- $130 < H < 160m : \frac{PCA}{PGA} < 9.6$

Roughly: $PCA = PGA \times 0.07 \times H$
ANALYSES OF GRAVITY DAM RECORDS

- Peak acceleration at crest vs peak ground acceleration

Interesting to look for results well over the average:

- due to the position of the accelerometer (Kasho dam?)

- due to the dam’s characteristics?

- due to the earthquake input? (Tase dam?)

Data processing from the JCOLD database records on concrete dams | 39
CONCLUSION

- Data processing of the JCOLD database should be very useful to:
  - Better understand dam’s behavior under earthquake
  - Try to quantify characteristics (damping, 1st natural frequency)
  - Calibrate and evaluate FE and simplified analyses
- Still a lot of analyses to do to understand response’s variation for a dam with several earthquakes
- To be continued
Merci de votre attention