Dynamic properties of earth-core Italian dams from in-situ and laboratory tests

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Seismic assessment of existing dams in Italy

 ✓ More than 500 dams (∼ 170 embk dams) are located in the Italian territory, majority of which constructed between 1950-1970;

 ✓ most dams are placed in zones with a degree of seismic hazard that was generally underestimated at the time of their construction as compared with the new national seismic hazard map;

 ✓ seismic design was based on the "classical" pseudo-static approach;

 ✓ a new standard for dam design and evaluation was issued in 2014 (pseudo-static approach no ore allowed; dynamic deformation analysis requested)

 Safety of large dams needs to be reassessed
Dynamic analyses for seismic assessment

Dynamic analyses requires proper characterization of material dam behavior.

Fundamental input parameters for core material:

- $V_s (G_0)$ profile
- modulus reduction $(G/G_0 - \gamma)$ and damping $(D - \gamma)$ curves
**Dynamic properties of core materials**

**Very limited data:**

\( V_s (G_0) \) profile through geophysical methods:

- **invasive** (DH, CH, SCPT, suspension logging); these methods are generally prohibited (concerns of potential leakage);

- **non-invasive** surface seismic methods (e.g., MASW)

  applicability of these techniques is restricted by unfavourable testing conditions

**Nonlinear stiffness and damping curves**

- laboratory testing on undisturbed samples seldom available
**Vs ($G_0$) profile in the core of the dams**

**Empirical correlations used for core material**

**Mostly used**

$$G_0 = f(e, \sigma'_m, OCR, soil \ type)$$

**Japan & Korea**

Sawada & Takahashi (1975)

**Based on Korean data**

Park & Kishida (2018)

Vs measurements (DH tests) in the core of 21 ECR dams
Natural, fine-grained, saturated soils

Effect of plasticity index PI

Vucetic & Dobry (1991)
*G/G_0*-γ and D-γ curves

Natural, fine-grained, saturated soils

Four-parameter model: most influential parameters on *G/G_0*-γ and D-γ curves are plasticity index and confining pressure

Darendeli (2001)
$G/G_0-\gamma$ curves

Lab-compacted soils

Partially saturated and saturated, Metramo silty clayey sand using a suction-controlled RC/TS apparatus

Vinale et al. (2001)
**G/G_0-γ curves**

*Lab-compacted soils*

- sandy-silty clay using RC/TS and CTX apparatus
- soil compacted at \(w_{\text{opt}}\), \(w_{\text{opt}}-1\%\) and \(w_{\text{opt}}+2\%\)
- high range of confining stress (15-900 kPa)

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Xenaki & Athanasopoulos (2008)
$G/G_0 - \gamma$ and $D - \gamma$ curves

Field-compacted, undisturbed core samples

✓ Undisturbed samples from 13 Korean dams
✓ RC tests on 17 undisturbed and 14 reconstituted
✓ Plasticity index PI=4–50; confining stress $\sigma'_m < 400$ kPa

Park & Kishida (2018)
## Italian earth-core rockfill dams

### List of dams examined

<table>
<thead>
<tr>
<th>#</th>
<th>Dam</th>
<th>Construction period</th>
<th>$H_{\text{max}}$ (m)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Angitola (VV)</td>
<td>1960-1966</td>
<td>22.8</td>
<td>unpublished</td>
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<td></td>
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<td>22.6</td>
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<td>3</td>
<td>Camastra (PZ)</td>
<td>1963-1964</td>
<td>54</td>
<td>Pagano et al. (2008)</td>
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<tr>
<td>4</td>
<td>Farneto (CS)</td>
<td>1970-1980</td>
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<td>5</td>
<td>Montedoglio (AR)</td>
<td>1977-1986</td>
<td>64.3</td>
<td>Lanzo et al. (2015)</td>
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<tr>
<td>6</td>
<td>Penne (PE)</td>
<td>1966-1969</td>
<td>35.7</td>
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<tr>
<td>7</td>
<td>Poggio Cancelli (AQ)</td>
<td>1950-1951</td>
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<tr>
<td></td>
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<td>1964-1971</td>
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<td>8</td>
<td>Polverina (MC)</td>
<td>1963-1967</td>
<td>27.5</td>
<td>unpublished</td>
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</table>
### Italian earth-core rockfill dams

#### Field and laboratory tests

<table>
<thead>
<tr>
<th>#</th>
<th>Dam</th>
<th>In situ dynamic</th>
<th>Laboratory cyclic/dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Angitola (VV)</td>
<td>DH, SCPT</td>
<td>DSDSS</td>
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<tr>
<td>2</td>
<td>Bilancino (FI)</td>
<td>DH</td>
<td>RC/TS</td>
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<tr>
<td>3</td>
<td>Camastra (PZ)</td>
<td>SDMT</td>
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<tr>
<td>4</td>
<td>Farneto (CS)</td>
<td>CH</td>
<td>RC/TS</td>
</tr>
<tr>
<td>5</td>
<td>Montedoglio (AR)</td>
<td>CH</td>
<td>DSDSS</td>
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<tr>
<td>6</td>
<td>Penne (PE)</td>
<td>-</td>
<td>DSDSS</td>
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<td>Poggio Cancelli (AQ)</td>
<td>CH</td>
<td>RC/TS</td>
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<tr>
<td>8</td>
<td>Polverina (MC)</td>
<td>CH</td>
<td>DSDSS, RC/TS</td>
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<td>9</td>
<td>San Pietro (AV)</td>
<td>CH</td>
<td>RC/TS</td>
</tr>
<tr>
<td>10</td>
<td>San Pietro in Villa (AR)</td>
<td>CH</td>
<td>DSDSS</td>
</tr>
</tbody>
</table>

**In situ tests:** DH=Down-Hole, CH=Cross-Hole, SCPT=Seismic cone, SDMT=Seismic dilatometer.

**Cyclic/Dynamic tests:** DSDSS (Double Specimen Direct Simple Shear); RC=Resonant Column; TS=Torsional Shear.
The DSDSS device
Double Specimen Direct Simple Shear (DSDSS)

Doroudian and Vucetic (1995)
Italian earth-core rockfill dams

Vs profiles in the core materials

- Angitola DH
- Bilancino CH
- Camastra SDMT
- Farneto del Principe CH
- Montedoglio CH
- Poggio Cancelli CH
- Polverina CH
- San Pietro CH
- San Pietro in Villa CH
Italian earth-core rockfill (ECR) dams

Italian data vs. empirical correlations

Sawada e Takahashi (1975)

Park e Kishida (2018)
Core materials of Italian zoned dams

Grain size distributions

Sandy-clayey silt

PI=12-30
Core materials of Italian zoned dams

Results of cyclic DSDSS tests

✓ Nonlinear stiffness and damping properties from DSDSS test results on undisturbed core samples (PI=23)

Angitola dam

Angitola (PI=23)
- $\sigma'_v=250$ kPa
- $\sigma'_v=500$ kPa
Core materials of Italian zoned dams

Results of cyclic DSDSS tests

✓ Nonlinear stiffness and damping properties from DSDSS test results on undisturbed core samples (PI=15-29)
Core materials of Italian zoned dams

Resonant Column (RC) and Torsional Shear (TS) tests

✓ Nonlinear stiffness and damping properties for Farneto (PI=22-32) and San Pietro (PI=22) dams

(data of Farneto dam are courtesy of Prof. Dente, Univ. of Calabria)
Core materials of Italian zoned dams

Cyclic and dynamic test results

✓ Nonlinear stiffness and damping properties of core material of Italian dams

![Graphs showing nonlinear stiffness and damping properties of core materials](image_url)
Core materials of Italian zoned dams

Nonlinear stiffness and damping properties

✓ Lab-compacted vs field-compacted core materials

Data with PI=15-30
Core materials of Italian zoned dams

Results of cyclic and dynamic tests

Comparison with Vucetic & Dobry curves
Core materials of Italian zoned dams

Results of cyclic and dynamic tests

Comparison with Darendeli curves

Darendeli (2001)
\(\sigma'_0=100-300\) kPa

- \(I_p=15\)
- \(I_p=30\)

\(\gamma_c\) (%) vs. \(G/G_0\) and \(D\) (%) vs. \(\gamma_c\) (%) graphs comparing different sites with Darendeali curves.
Final remarks

The use of dynamic analyses of embankments dams is increasing significantly in engineering practice, therefore a proper characterization of dynamic properties of dam body is needed. Data on dynamic properties of core materials is extremely limited.

Based on the results on the core of Italian dams:

✓ Vs measured data does not satisfactory agree with empirical correlations

✓ $G/G_0-\gamma$ and $D-\gamma$ curves from lab tests on undisturbed samples do not follow trends typical of natural saturated fine-grained soils.

- for medium plasticity soils (PI=15-30), there is no significant effect of plasticity index and confining stress
- lab-compacted modulus reduction curves show higher nonlinearity than undisturbed core materials
- the use of predictive models (Vucetic & Dobry and Darendeli) is questionable.

Site-specific laboratory tests are recommended to model the nonlinear deformation behavior of core materials.
Thank you!!