Seismic Performance and Fragility of Substation Equipment Using Hybrid Simulation

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Outline

1. Background and Brief History

2. Overview and Objectives

3. Shaking Table Tests

4. Hybrid Simulations

5. Other Tests, Computational Modeling, and On-Going Research
Background: Hybrid Model

- **Physical models** of structural resistance
- **Computer models** of structural damping and inertia

\[ m \cdot a + c \cdot v + k \cdot d = -m \cdot a_g \]
\[ m \cdot a + c \cdot v + R = -m \cdot a_g \]
\[ m \cdot a + m \cdot a_g + c \cdot v = -R \]

- **m**: mass
- **k**: spring constant
- **c**: damping coefficient
Background: Hybrid Model

Need to assemble:

a) Restoring forces (Geometric stiffness may be considered, $\overline{R} = R - K_g d$)
b) Damping forces from physical dampers
c) Inertia forces from the mass of the physical specimens

Desired $d(t)$ + Error in current position $\rightarrow$ Feedback dynamics $\rightarrow$ Force value $\rightarrow$ Dynamics of the system $\rightarrow$ Current position $d(t)$
Background: Hybrid Model

- By definition, a hybrid model is sub-structured
- Multiple sub-structures can be used
  - Many analytical sub-structures (Soft models)
  - Many physical sub-structures (Hard model)
Background: Hybrid Model

- Testing infrastructure must enable:
  1. Simulation of individual sub-structures
  2. Integration of equations of motion
Advantage and Disadvantages

- **Advantages:**
  1. Physical model resistance of sub-structures whose computer models are not good enough.
  2. Model the inertia forces (and damping, and second-order effects) in the computer.

- **Disadvantages:**
  1. Substructures are connected and interact at their boundaries.
  2. Specimens have inertia and damping, too.
Pioneering HS Research at UC-Berkeley

- Initial theoretical foundation – Mahin (1973)
- Random & systematic error propagation studies – Williams & Mahin (1979-81)
- Refinement and implementation of stable explicit formulations – Shing & Mahin (1980-84)
- Experimental/numerical partitioned simulations with mixed implicit/explicit operators – Dermitzakis & Mahin (1983-85)
- Multi-directional testing – Thewalt & Mahin (1984-87)
- Implicit formulations based on numerical & analog correctors – Thewalt & Mahin (1984-87)
- “Effective force” dynamic testing – Thewalt & Mahin (1984-87)
- Error bound estimation – Thewalt, Stojadinovic, & Mosqueda (1992-04)
- Theory & implementation of network-based local & distributed simulation – Thewalt, Stojadinovic, Campbell, & Mosqueda (1987-04)
- Event-driven digital control – Stojadinovic & Mosqueda (01-04)
- Force/displacement control switching & feed forward error compensation – Mosalam & Elkhoraibi (2003-05)
- Real time hybrid simulation – Mosalam et al. (2008-present)
- Next generation hybrid simulation: theory, evaluation, & development – Mosalam & Govindjee (2011-presnet)
Pioneering HS Research Worldwide

• Development of the HS method
• Investigation of the effect of experimental errors
• Development of suitable integration methods
• Geographically distributed HS
• Real-time HS
Example: Base-Isolated Structural Model

Example: Base-Isolated Structural Model

Example: Base-Isolated Structural Model

Proxy Server: a computer system acts as an intermediary for requests from clients seeking resources from other servers.


Objectives

1. Acquire better knowledge of the performance and potential failure modes of disconnect switch post insulators.

2. Develop recommendations for new approach in qualification tests of substation equipment for IEEE 693 Standards.

3. Develop recommendations for the performance criteria to improve seismic design, e.g. selection of support structural system of disconnect switches and similar equipment.
Equipment Type

Major elements of an electrical substation (distribution substation shown)

Disconnect switches are key components of power transmission and distribution systems.

1. Primary power lines
2. Ground wire
3. Overhead lines
4. Transformer
5. Disconnect switch
6. Circuit breaker
7. Current transformer
8. Lightning arrester
9. Main transformer
10. Control building
11. Security fence
12. Secondary power lines

* Courtesy of Wikipedia
Why Disconnect Switches?

1. **Disconnect switches**: Key components of power transmission & distribution systems to control flow of electricity between substation equipment & to isolate them for maintenance.

2. Seismic qualification tests in **typical field installation** according to IEEE 693 requirements.
Failure of Porcelain Insulators After Earthquakes

vertical disconnect switch (500-kV) [Photo credit: E. Fujisaki, PG&E]
Failure of Porcelain Insulators After Earthquakes

Ertai Shan Substation (220kV) Destruction (PGA ~ 0.5g), Yingxiu Town, Wenchuan Earthquake, China, May 12, 2008 [Photo credit: Q. Xie, Tongji University]
Shaking Table Tests

Several tested configurations
Shaking Table Tests

500-kV switch testing

Support structure identification tests (stiffness & frequency) with two typical installation:

a) Leveling bolts, no grout
b) Leveling bolts with space packed with grout
Shaking Table Tests

Sub-structuring tests w/o support structure in different configurations
Shaking Table Tests

Test w/ support structure

Test w/o support structure

A: Trans. in Y dir.

B: Rot. @ X dir.

Workshop on Fragility of Electrical Equipment and Components, Richmond Field Station, June 20–21, 2012
**Shaking Table Tests**

Strains at Jaw Insulator Bottom East Side - Open/Open Conf.

- **Y-direction Input (Signal A only)**

Strains at Jaw Insulator Bottom w/o support structure

Strains at Jaw Insulator Bottom w/ support structure

**WEST SG#4**

**EAST SG#2**
Shaking Table Tests

Strain at Jaw Insulator Bottom East Side - Open/Open Conf.

Y-direction + Rotation Input
(Signals A + B)
Major Elements

- Jaw Post
- Braced frame support structure
Hybrid Simulations

For benefits of HS: Support structures $\rightarrow$ computational substructures

& insulator posts $\rightarrow$ physical substructures
Hybrid Simulations

A method of analysis where a structure is split into physical and numerical substructures
Hybrid Simulations

RTHS: Real Time Hybrid simulation

Further discussion on RTHS by S. Günay tomorrow!
Hybrid Simulations

Comparison RTHS vs. Shaking Table tests

RTHS test
(UC Berkeley, 2011)

Full switch shaking table test
(PEER, 2008)

VS.
Hybrid Simulations

Comparison RTHS vs. Shaking Table tests

Accelerations at top
Strains at bottom

Strains measured at insulator bottom

Acceleration measured at insulator top
Hybrid Simulations

Comparison RTHS vs. Shaking Table tests

Total and Relative Displacements at top

Relative Displacements

Total Displacements
Static Experiments

Fragility testing of complete assembly of 230-kV porcelain insulators
## Static Experiments

<table>
<thead>
<tr>
<th>Specimen</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus [Ksi]</td>
<td>15227.08</td>
<td>13831.37</td>
<td>16257.52</td>
<td>15105.33</td>
</tr>
<tr>
<td>Poisson’s ratio: $\nu = -\frac{\varepsilon_x}{\varepsilon_y}$</td>
<td>-</td>
<td>0.204</td>
<td>-</td>
<td>0.204</td>
</tr>
<tr>
<td>Limit tensile stress [Ksi]</td>
<td>10.052</td>
<td>5.888</td>
<td>7.121</td>
<td>7.687</td>
</tr>
<tr>
<td>Limit compressive stress [Ksi]</td>
<td>20.544</td>
<td>27.475</td>
<td>35.334</td>
<td>27.784</td>
</tr>
</tbody>
</table>
Static Experiments
FE Modeling

Geometry

Laser scan

Further discussion on Laser Scanning by S. Takhirov tomorrow!
FE Modeling

Caps Geometry and Meshing
FE Modeling

DIANA detailed model (Model M6)

Failure model 1

Failure mode 2

Detailed bottom cap

Grout part

Cast iron part
DIANA approximate model (Model M5)

1st mode (19.6 Hz)

2nd mode (90.6 Hz)

3rd mode (276.1 Hz)
FE Modeling

Dynamic Push-over static

[Images of FE models with labels Dynamic and Push-over static]
FE Modeling

Comparisons

- Pull Test
- $E_p$ Upper Bound
- $E_p$ Mean
- $E_p$ Lower Bound

Force [kips] vs. Displacement [inch]
FE Modeling

Deterministic Sensitivity Analyses (Tornado Diagram)

<table>
<thead>
<tr>
<th>Random variable</th>
<th>Structural analysis</th>
<th>Swing</th>
<th>Tornado diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>$X_2, \ldots, X_n$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X_2$</td>
<td>$X_1, X_2, \ldots, X_n$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X_3$</td>
<td>$X_1, X_2, X_3, \ldots, X_n$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\vdots$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X_{n-1}$</td>
<td>$X_1, \ldots, X_{n-2}, X_n$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X_n$</td>
<td>$X_1, \ldots, X_{n-1}$</td>
<td></td>
<td>EDP corresponding to medians of all random variables</td>
</tr>
</tbody>
</table>

Sorting
FE Modeling

Deterministic Sensitivity Analyses (Tornado Diagram)

Further discussion on material and other tests & FE modeling by M. Aly tomorrow!
Other Tests

Hollow Core Polymer Insulators

Sheds are FLEXIBLE

Further discussion on material and other tests & FE modeling by M. Aly tomorrow!
On-Going Research

Current Generation of Hybrid Simulation

- Analytical substructure with few degrees of freedom
- Experimental substructure: each experimental node is connected to a single analytical node

Next Generation of Hybrid Simulation

- Large analytical substructure with many degrees of freedom: need for the evaluation of integration methods that can overcome the excitation of higher modes due to experimental errors
- Each experimental node is connected to more than a single analytical node: need for proper interface
- Need for the evaluation and development of integration methods with limited number of iterations
On-Going Research

Large scale computational model with multiple physical substructures tested in real time (Lab. demo. tomorrow!)

Accounting for physical setup constraints in the large computational models
Thank You!
Questions?