Total Project Planning – Case Study 3: *BNCS* Building

**Building Nonstructural Components & Systems Project**

Tara C. Hutchinson, Professor
UC San Diego
December 15, 2015
Outline

- **Motivation**
  - Terminology, Justification

- **Project Overview**
  - Vision, Scope, Resources (human & $$), Timeline

- **Specifics**
  - Design, Construction, Instrumentation, Test Planning & Sequencing, Execution Guidance

- **A Few Important Findings**
  - (there are many)

- **Project Accolades**
What is an NCS?

- **Nonstructural Components & Systems** = **NCS** = common short name adopted in a number of building design codes. Visual elements around us in finished structures...

- **Supported** by primary structural system – not **contributing** to primary structural system load bearing needs

- **Lightweight & low stiffness**, compared with supporting structure
  - Low damping (lack protection from sharp resonant motions)

- **Designed for functionality** – often not considering earthquake loads

- Often termed “secondary” systems

- Broad classification: 1) MEP (mechanical/electrical/plumbing), 2) Architectural & 3) Contents
Consequences of NCS damage

- Major problem during rescue operations
- Loss of functionality, facility downtime
- Excessive economic losses
- Threat to life

- Hospitals & other critical facilities: post-earthquake operability of NCSs are essential (life saving equipment)
- Numerous NCSs play a critical role in minimizing post-earthquake fire impacts – fire protection NCSs
Project Motivation: 2011 Tohoku Earthquake, Japan

Sendai Mediatheque (library, constructed 2000)

Before the earthquake

After the earthquake

Plaster board ceiling

Sprinkler head

Courtesy of Shojiro Motoyui
Vision, Scope, Resources, Timeline

PROJECT OVERVIEW
Project Vision

- To make breakthrough advances in the understanding of total building systems performance (structural and nonstructural systems) under moderate and extreme seismic conditions through full-scale testing.

- Obtain data, which are sorely needed to characterize the earthquake performance of structural and nonstructural building systems, including nonstructural systems with protective measures.

- Use this data to validate nonlinear simulation tools, which in turn can be used for higher-performance code design and performance-based seismic design of nonstructural and building systems.

- Infuse findings into seismic design guidelines and codes
  - Validate current code assumptions
  - Advance current code guidelines
Project Overview

- Three-phased full-scale test program conducted on a 5-story building-NCS system ("total building system")

**Summary of Major NCSs:**

- **Egress systems:**
  - Operable Elevator
  - Stairs

- **Facades:**
  - Concrete cladding
  - Balloon framing

- **Hospital equipment**
  - Roof mounted equipment

- **HVAC equipment**
  - Sprinkler and riser systems
  - Ceilings
  - Interior partition walls
Testing Scope & Project Resources

➢ Three Test Phases
  1. Base isolated building-nonstructural system
  2. Fixed base building-nonstructural system
  3. Controlled live fire tests

➢ ~5M US$, multi-organizational 4 year project (2010-2014)
  • NSF-NEES core research project - $1.2M
  • Englekirk Advisory Board - $1.5M (est)
  • Charles Pankow Foundation - $250k
  • California Seismic Safety Commission (hospitals) - $360k
  • Industry consortium - remainder $ resources, materials, equipment, technical expertise, etc.
Large, Multi-disciplinary Team

- **Core Project Team (>20 faculty, students, engineers)**
  - UCSD, SDSU, Worcester Polytechnic & Howard University

- **Advisory Boards**
  - Industry steering committee (ISC) (>40 companies)
    - Manufacturers, Sponsors, Technical Advisors
  - Engineering & regulatory advisory committee (ERAC) (10)
    - Technical oversight (code-perspective)
  - Academic/international liaison group (AILG) (10)
    - Technical oversight (academic perspective)
  - Englekirk Advisory Board (EAB)
    - Building (skeleton) design & funding

- **Federal & state partners, foundations**
  - NSF-NEESR, California Seismic Safety Commission, California Hospital Authority, Charles Pankow Foundation, FEMA

*More than 300 individuals interacting within this project!*
# Core Team

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
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<tbody>
<tr>
<td>Tara Hutchinson (PI)</td>
<td>UC San Diego</td>
</tr>
<tr>
<td>José Restrepo (Co-PI)</td>
<td>UC San Diego</td>
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<tr>
<td>Joel Conte</td>
<td>UC San Diego</td>
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<tr>
<td>Ken Walsh</td>
<td>UC San Diego</td>
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<tr>
<td>Claudia Marin</td>
<td>Howard University</td>
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<tr>
<td>Robert Bachman</td>
<td>RE Bachman Structural Engineers</td>
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<tr>
<td>Brian Meacham</td>
<td>Worcester Polytechnic Institute</td>
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<tr>
<td>Matt Hoehler</td>
<td>HILTI North America</td>
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<tr>
<td>Robert Englekirk</td>
<td>UC San Diego / Englekirk &amp; Sabol Consulting S.E., inc.</td>
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<tr>
<td>Mahmoud Faghihi</td>
<td>Englekerk &amp; Sabol Consulting Structural Engineers, inc.</td>
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<tr>
<td>Consuelo Aranda</td>
<td>San Diego State University</td>
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<td>Elias Espino</td>
<td>San Diego State University</td>
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<td>Rodrigo Astroza</td>
<td>UC San Diego</td>
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<tr>
<td>Michelle Chen</td>
<td>UC San Diego</td>
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<td>Hamed Ebrahimian</td>
<td>UC San Diego</td>
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<td>Steven Mintz</td>
<td>UC San Diego</td>
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<td>Elide Pantoli</td>
<td>UC San Diego</td>
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<td>Xiang Wang</td>
<td>UC San Diego</td>
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Partners

Funded by the National Science Foundation under Grant no.: CMMI-0936505

- Academic: University of California, San Diego (UCSD), Worcester Polytechnic Institute (WPI), San Diego State University (SDSU), and Howard University (HU)

- Broad stakeholder participation (industry and government)
e.g. Hilti Team (32 individuals >10%!)
Project Chronology

Pre-proposal workshop

NEESR Funding & Kick-off meeting

Construction (~9m)

Seismic Testing Phases (~1m)

Live Fire Testing (~0.5m)

Elan: Aug 8, 2007

Temus: March 31, 2011

2007 | 2008 | 2009 | 2010 | 2011 | 2013+

"I knew this would be easy. We built it last year."
Shake Table Specimen Design Questions

- **What type of structural skeleton is needed?**
  - Structural skeleton role: provide a vehicle for delivering demands to NCSs (accelerations & deformations)
  - Many iterative discussions, options…
    - Flexible steel frame-braced structure
    - Stiff steel braced structure
    - Podium-style (lower concrete wall & upper flexible frame)
    - Reinforced concrete frame-braced
  - Decisive aspects: cost (design team), balance between benefits of flexible frame (expect large lower floor drifts) & nominally large accelerations (upper floors); shake table platen size

- **What types of nonstructural components are essential?**
  - Secure the key “bad actors” (or those lacking data!) early on prior to NEESR proposal submission e.g. (egress, façade, passive & active fire systems)
  - “If we build it they will come”
Structural System

- **Design (criteria – community decision):**
  - Downtown LA (site class D; 7 MCE motions, 3 service motions; 2-2.5% design interstory drift ratio, peak ~0.7-0.8g floor acceleration)
- Poured-in-place concrete
- 2 bay x 1 bay; pair of SMRF (shaking direction)
  - 4.2m story heights; 5 floors; 21.3m + 1.5m foundation + 4m tower = 26.8m (tallest on UCSD table)
- Elevator shaft and stairway openings at floor diaphragms
- 10.4m x 6.1m c/c footprint
- ~1 sec longitudinal (fixed base)
- ~2.5 sec longitudinal (base isolated)

- **Bare structure:** ~4900kN
- **Building+NCSs:** ~6300kN
- (Foundation = 1870kN)
Architectural (NCS) Design

1: Utility

2: Lab + residential

3: Servers + Burn Floor

4: ICU

5: Surgery suite

South Face
NW View

APC panels

North side

West side

37' 4"

22' 8"

14'

Direction of motion

E

W

Architectural Precast
Concrete Cladding

Balloon-framed
metal stud+EIFS

Exterior Facades
Construction Management

- During construction, such a complex project needed careful planning. For this effort, SDSU led a comprehensive construction management effort
  - Coordinating all superstructure construction phasing
  - Coordinating all nonstructural installation phasing
  - Documenting on-site deliveries
  - Dealing with construction delays (reorganizing subs)
  - We held multiple planning meetings (2009, 2010, 2011) with all industry partners & researchers
Construction (Superstructure)

**FOUNDATION:**
June 27th, 2011

**SECOND FLOOR SLAB:**
July 15th, 2011

**THIRD FLOOR SLAB:**
August 3rd, 2011

**FOURTH FLOOR SLAB:**
August 19th, 2011

**FIFTH FLOOR SLAB:**
September 6th, 2011

**ROOF SLAB:**
September 21st, 2011

**FOUNDATION:**
June 27th, 2011
Construction (Nonstructural)

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<th>March</th>
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- **Foundation**
- **Elevator/Stairwell Walls**
- **Stairs (I)**
- **Stairs (II)**
- **Superstructure**
- **Installation of Balloon Framing**
- **White Noise Test**

NHERI @ UCSD Workshop, 14-15 December, 2015
### Construction (Nonstructural)

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- Internal Partition walls (ONGOING)
- Electrical system (ONGOING)
- Fire sprinklers (ONGOING)
- HVAC
- Gas Pipes
- Elevator
- Waterproofing paint on balloon framing
- Precast concrete cladding
- Cooling Tower
- AHU
- Isolators arrived on site
Construction (Nonstructural)

Feb & Mar 2012: Final architectural installation & instrumentation

- Internal Partition walls (ONGOING)
- Electric system (ONGOING)
- Fire sprinklers (ONGOING)
- HVAC Elevator (ONGOING)
- Styrofoam exterior balloon framing
- Roof pipes MI grid

- Medical Equipment Ceiling

JANUARY 2012

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Research Activities (pre-test)

During construction, research team needed to multi-task

- Conduct pre-test simulations (guide motion selection, instrumentation layout)
- Watch, document, & take part in (as feasible) construction
- Create instrumentation drawings
- Watch, document, & take part in (as feasible) construction

✓ We created a weekly construction log documenting all key construction activities digitally & disseminating them during a weekly team meeting
Instrumentation, Test Planning & Sequencing

SPECIFICS
Instrumentation

**ANALOG SENSORS**

Three DAQs provided by NEES@UCSD and NEES@UCLA (UCLA1 and UCLA2)

**VIDEO CAMERAS**

Provided by industry partners and by NEES@UCSD

**GPS**

Provided by the Scripps Institute of Oceanography

**STILL CAMERAS**

High resolution digital images were taken during construction and testing by the research team and industry partners

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**Analog:**

420 channels: NEES@UCSD + 90 channels: NEES@UCLA = 510 channels

**Structure (~1/3) + NCSs (~2/3)**

We produced an entire 200pg report summarizing the instrumentation (cameras & analog sensor details)
Every sensor was:
- Physically attached to the structure
- Provided a unique name
- Cable-based connected to the DAQ
- Connected to a NODE
- Visually & digitally documented (during testing as well!)

Medical Freezer: Level 5
The importance of high quality video cannot be understated

### Table 1. Cameras used during seismic test phase.

<table>
<thead>
<tr>
<th>Camera Type</th>
<th>Typical Image of Camera</th>
<th>Number of Cameras</th>
<th>Uncut Data Collected (GB)</th>
<th>Sample Snapshot of Camera View</th>
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<tbody>
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<td>56</td>
<td>~140</td>
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<td>Coax</td>
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<td>7</td>
<td>~200</td>
<td><img src="image" alt="Sample Snapshot" /></td>
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</table>

*Note: Not all cameras were used for each earthquake motion.
Panoramic Imagery

Third Floor (before fire testing)

Third Floor (after fire testing)
Phase 1: **Base isolated building-nonstructural system**

1. High damping rubber, cylindrical bearings placed @ each corner of building (4 total)
2. Building elevated from shake table

4 days of seismic motion testing (April 16-27, 2012)
Building Lift

- We lifted our ~700 ton building twice (to install & remove isolators)
  - Building was cast with a 12” pedestal, isolator was 3-1/16” taller, therefore we lifted it 4”

- Safety was of upmost importance; UCSD Site staff were outstanding in supporting and executing this effort

- Process:
  - Propose a sequence of lift in close consultation site staff
  - Collect materials
    - Purchase/rent/pickup jacks (we used 8x enerpac pancake jacks, 200 & 240ton@10ksi; we rented 4 of these, site had 4)
    - Test jacks
  - Un-PT and unbolt vertical rods, unbolt pedestals
  - Install jacks
  - Install linear potentiometers & redundant needle valves
  - Maneuver plates
  - Install isolators (or pedestal for the second lift)
Building Lift (artistic rendering, Gunthardt)
Phase 2: **Fixed-base building-nonstructural system**

1. Building resting on shake table
2. Post-tensioned at its perimeter

4 days of seismic motion testing (May 7-15, 2012)
White Noise Motions

We performed WN before and after seismic tests to assess the state of the structure (SI).
Tracking the Table Performance

![Graph showing velocity and displacement over time](image)
Table Performance: Guidance for Subsequent Motions

In the cases of significant table-specimen interaction & specific need to NOT overshoot a demand target (such as final MCE motion)

Astroza & Conte, et al
Motion selection, sequencing & scaling strategy

- Overlap between portion of BI & FB motions
- < 0.5% Peak Interstory drift ratio (IDR) BI Phase
  - Service level hazards (~43yr event)
  - Preserve structure for FB phase
- Motions with varied characteristics
  - Motion from CA/West coast US
  - Long duration of shaking
- Achieve design performance objectives in building (FB)
  - 2-2.5% Peak IDR
  - 0.8g or so PFA
  - ~Design earthquake event
- Achieve well above design demands
Seismic Motions: Achieved
Phase 3: Controlled live fire, pressurization & smoke tests

3 days of live fire testing (May 23-25, 2012)
Test Execution, some informal guidance

SPECIFICs
Plan well in advance “between-motion activities”

- **Safety inspection – site staff – NO ENTRANCE into test specimen**
- **Tier 1 video & data analysis**
  - Rapid review of individual data channels
  - Safety & subsystem integrity checks
- **Tier 2 video & data analysis**
  - Specific components, subsystems
- **Tier 3 video & data analysis**
  - More detailed analysis (as time allowed)
- **Physical inspection – research team**
  - 2-3 research (core team) members were teamed with ALL invited industry partners (no industry partners were allowed to freely roam the building)
Functionality checks
Compartment pressurization tests (WPI)
Replenish water cooling tower
Replace push-pull rods at PCC connections
Replace damaged ceiling tiles
Replace sensors, reposition cameras
Reposition equipment, replace component of a subsystem as needed
QuakeHold – free BI; strapped FB
…
Media Exposure

- Large-scale tests are a terrific opportunity to provide visibility to our efforts as a research community
  - Video documenting the entire process (construction, testing, demolition)

- Look for help/suggestions/media teams to provide support and help document all aspects

- We held three key “media days”
  - UCSD-JSOE advertised (sent out media advisories & coordinated all incoming media groups)
  - All major national news channels were allowed on-site, several international media channels; interviewed project PIs & industry sponsors
  - Within one of these hosted an NSF-Live Science Webcast with Dr. Joy Pauschke (answering questions live between tests)
Media Exposure = Society Awareness

Video: Shake Table Simulates 8.8-Magnitude Earthquake

At the University of California, San Diego, a group of researchers is subjecting a five-story mock hospital to the force of an 8.8-magnitude earthquake to see how well our best building and preparedness practices stand up to the rage of a huge quake.

A shake table is a large mechanical platform that can move and shake in various directions. Engineers use shake tables to test the seismic resistance of structures, such as buildings, bridges, and other infrastructure.

Engineers' earthquake simulation ready to roll

Intricate structure at UC San Diego facility will undergo intense tests

Video: Shake Table Simulates 8.8-Magnitude Earthquake

Engineers' earthquake simulation ready to roll

Intricate structure at UC San Diego facility will undergo intense tests

Video: Shake Table Simulates 8.8-Magnitude Earthquake

Engineers' earthquake simulation ready to roll

Intricate structure at UC San Diego facility will undergo intense tests
A FEW IMPORTANT FINDINGS

(there are many)
Phase 1: Base isolated building-NCS system

Peak Floor Acceleration (g)

< 0.3g

Peak Inter-Story Drift Ratio (%)

< 0.4%
Phase 2: Fixed base building-NCS system

max ~ 1.0g
Peak Responses

~DE (FB5-Den67)

- Plastic deformation in APC connections
- Balloon framing clip detachment
- Toppled equipment

Failure of Stair Flight-Landing Connections

Upper flight
Angle
Embed

Peak Floor Acceleration (g)

Peak Inter-Story Drift Ratio (%)
Egress: Stairs

$PIDR_{design} = 2.5\%$

Damage Level:
- Yellow = Minor
- Orange = Moderate
- Red = Severe

Peaks Interstory Drift Ratio (%)
Upper Flight–Slab Connection Plate Fracture

![Image of structural staircase and connection plate]

- Damage occurred
- Peak occurred

**Graph:**
- **IDRmax (%)**: 2.10
- **IDR@damage (%)**: 1.88

**FB-5: DEN67**

- Time (s)
- IDR (%)

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*UC San Diego*
Drift-Compatible Façade Connections

1) Intended performance of flexing connections
2) Unexpected yielding of sliding connections at low drift amplitudes
Colliding Corner – Ductile Fuse (new idea)

New corner system design to allow for smaller corner joints:

- **Elastic Drifts** → Gap closure
- **Inelastic drifts** → Impact but overload prevented by ductile fuse
Ductile, Colliding Corners

Direction of motion

IP PANEL

OP PANEL

Roof slab

Black = Initial position of panels
Red = Position of panels during joint closing

Force in threadrod

Force (kips) vs Displacement (inch)

Ductile fuse design force

Connection Displacement (relative)
Live Fire Tests

- Series of 6 fires, heat release rate (HRR) varying from about 0.5 MW to about 1.5+ MW
- Goals: (a) obtain temperature data for simulations, (b) assess smoke spread, (c) assess potential for flame spread, and (d) assess potential for structural impact
- Burn time limited to about 15 minutes
- Heptane fuel - burned in pans (1 to 3, depending on desired fire size)
EL Fire Test 1/2: Representative Effects

- Elevator controls melted
- Spalling of concrete slab
- Intumescing of fire stop
- Failure of wall system (after EL 2 test)

With the damage to the gypsum wall system due to seismic motions, the fire was able to bring the system to failure much more quickly than any fire rating would suggest.
Egress: Elevator

Door Jamb After FB5-DEN67 (functional)

Door Jamb After FB6-DEN100 (non-functional)

Damage to hoistway enclosure

Door buckling

Hoistway door damaged
Elevator Improvements

Schindler Corp
Phase 2: Fixed base building-NCS System

UC San Diego

Videos: bnsc.ucsd.edu
(there are many)

PROJECT ACCOLADES
Project Accolades: Human Resources

- UCSD: Astroza, Ebrahimian, Wang (PhD 2015) & Pantoli, Chen (PhD 2016)
- WPI: Park (2014 PhD); Kim (MS 2013)
- SDSU: Espino & Aranda (MS 2012, 2014)
- Univ of Bologna: Selva & Bezzi (MS 2012, 2014)
- NEES-REU (8 UGs from SJSU, VPI, UCSD)
- NEES-RET: 6 SD teachers outfitted with mini-shake tables
- 3 Payload projects: WPI (fire), SIO (GPS) & Cal Poly SLO (mini-shakers)
Project Accolades: Technical Contributions

- Award in Excellence for Research Projects (Western States Seismic Policy Council, 2014)
- Numerous technical papers (conference, journal)
  - 2-part Earthquake Spectra (overarching, 2015)
  - “Data Paper” Earthquake Spectra
- Large volume of data (image, analog) publically available -> NEESHub
- ASCE 7-16 Code Changes
  - Precast cladding connections
  - Stair (drift limits, importance factor)
  - Elevator detailing
Project Accolades: Public Impact

- Professional video publication (UCSD-TV)

- Educational video module series (4-part structural; 2-part nonstructural; geared towards undergraduate learning)

- Documented extensive media exposure
Demolition – Don’t forget it!

- $135k ++ lots of help from industry ($98k in just structural concrete; removal of ceiling, stairs, elevator by others)
The real stars of the show....
<table>
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<th>Base</th>
<th>Station-scale (Earthquake)</th>
<th>Name</th>
<th>Type</th>
<th>Notes</th>
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<tbody>
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<td>Base</td>
<td>Canoga Park-100% (1994 Northridge earthquake)</td>
<td>BI-1: CNP100</td>
<td>SM</td>
<td>Serviceability level</td>
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<td>LA City Terrace-100% (1994 Northridge earthquake)</td>
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<tr>
<td>Isolated (BI)</td>
<td>San Pedro-100% (2010 Maule-Chile earthquake)</td>
<td>BI-4: SP100</td>
<td>AM</td>
<td>Long duration</td>
</tr>
<tr>
<td></td>
<td>ICA-50% (2007 Pisco-Peru earthquake)</td>
<td>BI-5: ICA50</td>
<td>AM</td>
<td>Long duration, multiple runs</td>
</tr>
<tr>
<td></td>
<td>ICA-100% (2007 Pisco-Peru earthquake)</td>
<td>BI-6: ICA100</td>
<td>AM</td>
<td>Long duration, multiple runs</td>
</tr>
<tr>
<td></td>
<td>ICA-140% (2007 Pisco-Peru earthquake)</td>
<td>BI-7: ICA140</td>
<td>AM</td>
<td>Long duration, multiple runs</td>
</tr>
</tbody>
</table>

![Graph 1](Image 1)

![Graph 2](Image 2)
<table>
<thead>
<tr>
<th>Base</th>
<th>Station-scale (Earthquake)</th>
<th>Name</th>
<th>Type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Canoga Park-100% (1994 Northridge earthquake)</td>
<td>FB-1:CNP100</td>
<td>SM</td>
<td>Low amplitude - expect service</td>
</tr>
<tr>
<td></td>
<td>LA City Terrace-100% (1994 Northridge earthquake)</td>
<td>FB-2:LAC100</td>
<td>SM</td>
<td>Low amplitude - expect service</td>
</tr>
<tr>
<td>Fixed</td>
<td>ICA-50% (2007 Pisco-Peru earthquake)</td>
<td>FB-3:ICA50</td>
<td>AM</td>
<td>Long duration, multiple runs</td>
</tr>
<tr>
<td>(FB)</td>
<td>ICA-100% (2007 Pisco-Peru earthquake)</td>
<td>FB-4:ICA100</td>
<td>AM</td>
<td>Long duration, multiple runs</td>
</tr>
<tr>
<td></td>
<td>Pump Station #9-67% (2002 Denali eq.)</td>
<td>FB-5:DEN67</td>
<td>SM</td>
<td>~Target design demand</td>
</tr>
<tr>
<td></td>
<td>Pump Station #9-100% (2002 Denali eq.)</td>
<td>FB-6:DEN100</td>
<td>SM</td>
<td>~&gt;50% larger than Design demands</td>
</tr>
</tbody>
</table>

![Graphs](image-url)

**Graphs:**
- **Left:** Graph of $S_d$ (m) vs. Period (sec) for different stations:
  - FB1:CNP100 (Yellow)
  - FB2:LAC100 (Orange)
  - FB3:ICA50 (Red)
  - FB4:ICA100 (Pink)
  - FB5:DEN67 (Purple)
  - FB6:DEN100 (Blue)

- **Right:** Graph of $PS_a$ (g) vs. Period (sec) for different stations:
  - FB1:CNP100 (Yellow)
  - FB2:LAC100 (Orange)
  - FB3:ICA50 (Red)
  - FB4:ICA100 (Pink)
  - FB5:DEN67 (Purple)
  - FB6:DEN100 (Blue)