A Proposed Performance Based Seismic Design Process for Lifeline Systems

C. A. Davis, Ph.D., P.E., G.E.

Water System Chief Resilience Officer and Resilience Program Manager, Los Angeles Department of Water and Power

January 17, 2019
Contents

Some Lifeline System Aspects of 1994 Northridge Earthquake
Target Performance Objectives
Performance Based Design Methodology Applied to a Water Lifeline System
  • Applicable to other lifeline systems
Relationship with PEER PBEE Methodology
Summary
Lifelines Performance during 1994 Northridge Earthquake

- Balboa Blvd
- Tailrace
- Pardee Substation
- Granada High Tank
- Pacoima Dam
- Lower San Fernando Drain Line No. 1
Performance Categories & the 1994 Northridge Earthquake

<table>
<thead>
<tr>
<th>Performance Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Services</td>
<td>Limit service outages and restore lost services rapidly</td>
</tr>
<tr>
<td>Life Safety</td>
<td>Preventing injuries and casualties from direct or indirect damages to water system facilities; includes safety matters related to response and restoration activities</td>
</tr>
<tr>
<td>Property Protection</td>
<td>Preventing property damage as a result of damage to water system components; also includes preventing water system damage.</td>
</tr>
</tbody>
</table>

Lifeline Systems were fairly resilient in limiting the loss of services and restoring them in a timely manner.

Few lives were lost, and not likely related to lifeline system performance.

There was some serious damage to private property caused by lifeline system damages.

Damage to system components was costly.
Lessons and Challenge

Can improve lifeline system performance

Performance could be worse for larger events, or similar events in other locations

The challenge is getting all the:

1. components within a system to perform consistently to meet a defined target objective, and

2. lifeline systems to perform consistently, relative to the needs of the other lifeline systems and the communities they serve

For all potential earthquake events.

To start we need a common platform to work from, initiating with a definition.
Infrastructure Resilience

**Definition** (modified from Davis and Giovinazzi, 2015)

“A resilient infrastructure network is designed and constructed to accommodate hazard-related impacts with ability to continue providing services or limit service outage times tolerable for community recovery efforts.”

Performance Based Design
As Proposed for the Los Angeles Water System
A useful tool to help lifeline systems achieve infrastructure resilience in support of the communities they serve. By itself, PBSD does not create a resilient system, but it is an important instrument for achieving needed characteristics of resilient lifeline systems.

To understand Lifeline System Resilience Characteristics:


Undertaken as part of the ASCE Infrastructure Resilience Division
Performance Based Seismic Design

The remaining presentation is based on a recently adopted procedure developed for the LADWP Water System;

This can be generalized for other lifelines.

Based on:

**LADWP (2019).** “Performance Based Seismic Design for the LADWP Water System.


What is Performance Based Seismic Design and How is it Applied to Lifeline Systems?

PBSDD is a process that explicitly evaluates how a facility or system is likely to perform, given the potential hazard it is likely to experience, considering uncertainties inherent in the quantification of potential hazard and in assessment of the actual response (modified from FEMA, 2006).

The System is to be designed to match targeted objectives

Components are designed to prepare system to meet the targeted objectives

Objectives are scaled relative to the probability and size of earthquake events
  ◦ The larger/less probable events will have more expected service losses and longer time to restore

System performance accounts for geospatial characteristics of the infrastructure and hazard systems, and their interactions
Performance Based Design Flow Diagram

1. Select Target Performance Objectives
2. Analyze System
3. Develop Preliminary Design
4. Assess Performance Capability
5. Does Performance Meet Objectives?
   - No: Revise System/Design and/or the Performance Objectives
   - Yes: Finalize system/design & performance objectives
This PBEE procedure is for single lifeline system. Each lifeline system performance is dependent upon other lifeline systems. Need for overarching set of goals so all lifeline systems can achieve a performance needed by the community.
### Draft Target System-Level Performance Criteria

<table>
<thead>
<tr>
<th>Level</th>
<th>Hazard Return Period Criteria</th>
<th>Target System Performance</th>
<th>( M_w ) Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100 years</td>
<td>Limited damage to water system, no casualties, few to no water service losses. All customer services operational within about 3 days.</td>
<td>Less than 3.8 to 5.6</td>
</tr>
<tr>
<td>2</td>
<td>500 years&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Life safety and property protection. All customer services operational within about 20 days, except water quantity; rationing may extend up to 30 days.</td>
<td>4.6 to 8.0&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>3</td>
<td>2,500 years&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Life safety and property protection. All customer services operational within about 30 days, except water quantity; rationing may extend up to 60 days.</td>
<td>5.4 to 8.2&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>4</td>
<td>&gt;2,500 years up to about 10,000 years</td>
<td>Life safety and property protection. All customer services operational within about 45 days, except water quantity; rationing may extend up to 12 months.</td>
<td>6.2 to 8.3&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>1</sup>Highly active faults like the San Andreas have major to great earthquakes within Level 2 and 3 return periods. Performance criteria may need to be prudently relieved to a higher level; see procedure to assess potential modifications.
Earthquake Sources

Over 40 faults
30 impact City
More than 20 rupture ground surface in LA
Identify the rupture magnitude probability for each Level 1 to 4 (UCERF 3).
Why Include Level 4 Events?

They are plausible

When they occur, but were not considered, communities often find infrastructure performance to be unacceptable

May apply to entire event

May apply to specific hazard occurrence within the event

Encourage everyone to think resiliently and cost-effectively improve serviceability after such events

New and innovative solutions can be brought forward

Higher criteria does not always equate to greater expense and longer projects

Based on PBEE procedures, it does not require all designs to meet Level 4 criteria, but needs a check on the decision making to use or not to use

Select Target Performance Objectives

Analyze System

Develop Preliminary Design

For specific project or component

For system assessment

Assess Performance Capability

Does Performance Meet Objectives?

Revise System/Design and/or the Performance Objectives

Yes

No

Finalize system/design & performance objectives
## System Level Performance

### Water System Service Categories

<table>
<thead>
<tr>
<th>Service Categories</th>
<th>Description</th>
<th>Does water come out of tap?</th>
<th>Is it safe to Drink?</th>
<th>Can you get the amount you need?</th>
<th>Does Fire Dept. get what they need?</th>
<th>Is the water system in working order?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water Delivery</strong></td>
<td>Able to distribute water to customers, but the water delivered may not meet water quality standards (requires water purification notice), pre-disaster volumes (requires water rationing), fire flow requirements (impacting fire fighting capabilities), or pre-disaster functionality (inhibiting system operations).</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Quality</strong></td>
<td>Water to customers meets health standards (water purification notices removed). This includes minimum pressure requirements.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Quantity</strong></td>
<td>Water flow to customers meets pre-event volumes (water rationing removed).</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fire Protection</strong></td>
<td>Able to provide pressure and flow of suitable magnitude and duration to fight fires.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Functionality</strong></td>
<td>The system functions are performed at pre-event reliability, including pressure (operational constraints resulting from the disaster have been removed/resolved).</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1994 NORTH RIDGE EARTHQUAKE, L.A., EXAMPLE WATER RESTORATIONS
OPERABILITY VS FUNCTIONALITY

**Operability** is achieved once water delivery, quality, quantity, and fire protection services are restored

- System is able to completely service customers at pre-disaster levels
- However, system may not be fully functional
- *e.g.*, LA Water restored operability in 12 days after repairing 8 of about 80 transmission line leaks/breaks.
- **Measure of resilience in support of the community**

**Functionality** services describe the ability of a system to reliably perform.

- A highly functional system can provide water delivery, quality, quantity, and fire protection services prior to completing all water infrastructure repairs
- Damage imposes constraints that do not allow the system to function with its pre-earthquake performance and reliability
- *e.g.*, LA Water restored functionality in 9 years after repairing all necessary damaged facilities (some remaining damage deemed acceptable).
- **Measure of system resilience**
Water Accessibility Services

Accessibility Services: the provision of water to customers through alternate sources or locations when the network is unable to provide normal services

Example A: Providing prepackaged water while portable water cannot be provided through the network

Example B: Aiding the Fire Department with alternate sources when water cannot be delivered through the network with sufficient volume and pressure
Community Resilience

Service restoration to critical customers, defined as:

- Critical A Customers: public health and safety
  - Examples: Hospitals, Evacuation Centers Fire Department, etc.
- Critical B Customers: critical community resilience services
  - Examples: schools not used as evacuation centers, lifeline utilities not providing public health services, etc.
<table>
<thead>
<tr>
<th>Service Category</th>
<th>Service Description</th>
<th>Target restoration time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Delivery</strong>&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Limit losses to approximately 20% of customers</td>
<td>0 days</td>
</tr>
<tr>
<td></td>
<td>Restore to 90% of customers</td>
<td>5 days</td>
</tr>
<tr>
<td></td>
<td>Restore to all customers</td>
<td>10 days</td>
</tr>
<tr>
<td><strong>Quality</strong>&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Restore to 50% of customers</td>
<td>3 days</td>
</tr>
<tr>
<td></td>
<td>Restore to 90% of customers</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>Restore to all customers</td>
<td>15 days</td>
</tr>
<tr>
<td></td>
<td>Restore to 90% of all Critical A customers&lt;sup&gt;3&lt;/sup&gt;</td>
<td>3 days</td>
</tr>
<tr>
<td></td>
<td>Restore to 90% of all Critical B customers&lt;sup&gt;3&lt;/sup&gt;</td>
<td>7 days</td>
</tr>
<tr>
<td><strong>Quantity</strong></td>
<td>Implement city-wide rationing at average winter day demand (AWD)</td>
<td>0 days</td>
</tr>
<tr>
<td></td>
<td>Limit losses below AWD to approximately 40% of customers&lt;sup&gt;1&lt;/sup&gt;</td>
<td>0 days</td>
</tr>
<tr>
<td></td>
<td>Restore AWD to 90% of customers</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>Restore AWD to all customers</td>
<td>20 days</td>
</tr>
<tr>
<td></td>
<td>Restore to pre-event normal demand</td>
<td>30 days</td>
</tr>
<tr>
<td><strong>Fire Protection</strong></td>
<td>Provide partial&lt;sup&gt;4&lt;/sup&gt; services from pipe network within 5-miles distance of any delivery loss</td>
<td>0 days</td>
</tr>
<tr>
<td></td>
<td>Provide partial&lt;sup&gt;4&lt;/sup&gt; services from pipe network within 2-miles</td>
<td>3 days</td>
</tr>
<tr>
<td></td>
<td>Restore to 90% of hydrants</td>
<td>10 days</td>
</tr>
<tr>
<td></td>
<td>Restore to all hydrants</td>
<td>20 days</td>
</tr>
<tr>
<td><strong>Functionality</strong>&lt;sup&gt;5&lt;/sup&gt;</td>
<td>Limit system losses to approximately 40% (maintain 60% functionality)</td>
<td>0 days</td>
</tr>
<tr>
<td></td>
<td>Restore system to 70%</td>
<td>7 days</td>
</tr>
<tr>
<td></td>
<td>Restore system to 80%</td>
<td>60 days</td>
</tr>
<tr>
<td></td>
<td>Restore system to 90%</td>
<td>180 days</td>
</tr>
<tr>
<td></td>
<td>Restore system to 100%</td>
<td>360 days</td>
</tr>
<tr>
<td></td>
<td>Improve system vulnerabilities identified</td>
<td>5 years</td>
</tr>
<tr>
<td><strong>Emergency Accessibility</strong></td>
<td>Provide 1 gallon per person per day potable water to domestic users within 5 miles from residence&lt;sup&gt;6&lt;/sup&gt;</td>
<td>3 days</td>
</tr>
<tr>
<td></td>
<td>Provide 2.5 gallons per person per day potable water to domestic users within 0.3 miles from residence&lt;sup&gt;7&lt;/sup&gt;</td>
<td>7 days</td>
</tr>
</tbody>
</table>

<sup>1</sup>System is able to contain flow and minimize continued service losses in 1 day or less (i.e., drainage losses are constrained, and the system does not have significant continued drainage). For quantification purposes, delivery services are met when flow reaches about 20% of average winter day (AWD) demand.

<sup>2</sup>Water quality may be effectively lost to all customers out of precaution taken by issuing city-wide public notification for water use (e.g., Boil Water Notification). This has occurred in past earthquakes in LA (e.g., Davis et al., 2012).

<sup>3</sup>Critical customers and facilities are described in Appendix B.

<sup>4</sup>May not meet hydraulic requirements for pressure and volume, but sufficient flow to be used with in-line pumping and hauling.

<sup>5</sup>Functionality can be measured using Davis (2014b) or other similar evaluation methods.

<sup>6</sup>Rough estimate of distance based on expected area of delivery service loss, current water bladder plan, and assumed additional support from other organizations such as FEMA, Red Cross, and other volunteer organizations.

<sup>7</sup>Volume and distance estimates based on recommendations from World Health Organization (2005). Volume includes use for consumption (drinking and food preparation), personal hygiene, and laundry.
Draft Service Goals – Level 2

Normal Service Level

Level 2 Earthquake Event

Restore to pre-event normal demand

Water Service (%) vs Time (days)

- Normal Service Level
- Service Losses from Earthquake
- Water Delivery Service
- Water Quality Service
- Water Quality Service to Critical A Customers
- Water Quality Service to Critical B Customers
- Quantity Service (Average Winter Demand)
- Fire Protection Service

Restore to pre-event normal demand

Restore to pre-event normal demand

Water Service (%)

Time (days)
Draft Delivery Service Restorations

The graph illustrates the restorations of water delivery services following an earthquake event. It shows the percentage of water delivery service over time, categorized into different service levels:

- **Normal Service Level**: The line representing normal service remains constant at 100% throughout the recovery period.
- **Level 1 Water Delivery Service**: Starts at a service level below normal and gradually increases over time, reaching a service level of around 80% by day 30.
- **Level 2 Water Delivery Service**: Begins at a lower service level than Level 1 and takes longer to reach about 70% service level.
- **Level 3 Water Delivery Service**: Starts at a significantly lower service level and takes even longer to reach approximately 60% service level.
- **Level 4 Water Delivery Service**: Begins at the lowest service level and takes the longest time to recover, reaching around 40% service level by day 30.

The graph also includes a vertical line labeled as the "Earthquake Event" at time $t_0$, indicating the initiation of the service restoration process.
Work flow for Modifying Levels 2, 3, and 4 Target Performance Objectives

*Some basic service categories may meet the target performance objectives, while others may not. Only propose modifications to those basic service categories which cannot meet the target performance objectives.

**When evaluating which performance, the system may technically or cost-effectively be able to meet, start with assessing the next level target performance criteria. For example, if the system is unable to meet Level 2 performance objectives (Table 2) for a Level 2 San Andreas Fault Event, then check to see if the Level 3 target performance objectives (Table 3) can be met for the Level 2 event; if not, then check the Level 4 target performance objectives (Table 4). If the system is unable to technically or cost effectively meet the Level 4 objectives, then determine alternate number of basic service category losses restoration times to propose and justify for approval. This procedure may need to be applied for different major to great earthquakes.
## WATER SUBSYSTEMS

Water System is made up of multiple subsystems having their own characteristics

<table>
<thead>
<tr>
<th>Subsystems</th>
<th>Description</th>
<th>Typical Facilities/Components</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Raw Water Supply Systems</strong></td>
<td>Systems providing raw water for local storage or treatment including local catchment, groundwater, rivers, natural and manmade lakes and reservoirs, aqueducts.</td>
<td>Reservoirs, pump stations, wells, pipelines, canals, tunnels, dams, levees, raw water intersystem connections. This may also include pertinent storm water capture facilities.</td>
</tr>
<tr>
<td><strong>Treatment Systems</strong></td>
<td>Systems for treating and disinfecting water to make it potable for safe use by customers.</td>
<td>Treatment plants, ultraviolet treatment processes, filtration systems, settling basins, chlorination stations.</td>
</tr>
<tr>
<td><strong>Transmission Systems</strong></td>
<td>Systems for conveying raw or treated water. Raw water transmission systems convey water from a local supply or storage source to a treatment point. Treated water transmission systems, often referred to as trunk line systems, convey water from a treatment or potable storage point to a distribution area.</td>
<td>Medium to large diameter pipes (&gt;20”), tunnels, reservoirs and tanks, pumping stations, valves and regulating stations. This also includes treated water intersystem connections.</td>
</tr>
<tr>
<td><strong>Distribution Systems</strong></td>
<td>Networks for distributing water to domestic, commercial, business, industrial, and other customers.</td>
<td>All pumping stations, regulating stations, tanks and reservoirs, valves, and piping not defined as part of other subsystems forming a network from connections at the transmission systems to points of service.</td>
</tr>
<tr>
<td><strong>Recycled Water Systems</strong></td>
<td>Systems for producing, disinfecting, conveying, and distributing recycled water to customers.</td>
<td>Treatment plants, pumping stations, regulating stations, tanks, valves, and piping.</td>
</tr>
</tbody>
</table>
Los Angeles Department of Water and Power
Component Level Design

Each component must be designed and constructed in a manner to provide the targeted system performance.

Check component for multiplicity. Ensure Criticality Category is defined by customizing highest seismic importance in accordance with Table 6.

Check multiplicity, redundancy, and branch components for Criticality Category and/or design for isolation capability.

Check component redundancy criteria. If redundancy criteria met, component Criticality Category may be redefined in accordance with Table 9.

Return to Figure 16.

Figure 16
Figure 17
Critically Categories

Each component is to have a designated Criticality Category I, II, III, or IV.

The design of each component for defined hazard return period in table below is expected to aggregate to the desired system-level performance.

<table>
<thead>
<tr>
<th>Criticality Category</th>
<th>Description</th>
<th>Design basis hazard return period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Components that present very low hazard to human life in the event of failure. Not needed for post-earthquake system performance, response, or recovery.</td>
<td>72</td>
</tr>
<tr>
<td>II</td>
<td>Normal and ordinary components not used for water storage, pumping, treatment or disinfection. They provide water for typical residential, commercial, and industrial use within the system and include all components not identified in Criticality Categories I, III, and IV.</td>
<td>475</td>
</tr>
<tr>
<td>III</td>
<td>Components, mainly pipelines, providing water to services that represent a substantial hazard or mass disruption to human life in the event of failure. Failure of these components may result in significant social or economic impacts. Critical B Customers</td>
<td>975*</td>
</tr>
<tr>
<td>IV</td>
<td>Components needed to provide water to essential facilities for post-earthquake response, public health, and safety. This includes components needed for primary post-earthquake firefighting. These components are intended to remain functional during and following an earthquake. Critical A Customers</td>
<td>2,475*</td>
</tr>
</tbody>
</table>

*Note: Also check against Level 4 earthquake scenario hazards,
Redundant Components

- Criticality Category may be reduced based on increased reliability, as long as performance criteria is met
- This redundancy factor shall not be applied to any component which:
  1. Otherwise are required to have a higher Criticality Category based on life safety or other factors,
  2. Are exposed to common cause failures, such as:
     a. A leak or break in one component may lead to damage on other redundant components,
     b. Components are exposed to the same permanent ground deformation hazards (i.e., pipes cross same fault, landslides, liquefaction zones, etc.).
  3. There are foreseeable plans to remove the designated primary redundant component from operation, in which case multiple redundant components shall be designated to be the same highest-level Criticality Category for their intended use.
- Level III still checked against Level 4 earthquake hazard scenarios

<table>
<thead>
<tr>
<th>Criticality Category</th>
<th>$L_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>[P]</td>
</tr>
<tr>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>II</td>
<td>II</td>
</tr>
<tr>
<td>III</td>
<td>III</td>
</tr>
<tr>
<td>IV</td>
<td>IV</td>
</tr>
</tbody>
</table>

$L_R = $ Redundancy Factor
[P] = primary component
[S] = secondary redundant component
[A] = additional component

**LR = Redundancy Factor**

**[P]** = primary component

**[S]** = secondary redundant component

**[A]** = additional component
Component performance objectives are established through definitions of maximum tolerable damage. Each designation of minor, moderate, high, and severe damage have corresponding definitions. Designs for Criticality Category III and IV components are to be checked against Level 4 earthquake scenario hazards.

Level 4 risk assessment: Present recommendations to management including cost differentials and the potential consequences for not mitigating impacts from the Level 4 events.
Technologies needed to Implement PBSD Next-Generation (Resilient) Pipelines

**Ductile Iron Pipes**
- Kubota Earthquake Resistant Ductile Iron Pipe
- US Pipe TR-Extreme
- American Ductile Iron Pipe
- Mcwane Ductile

**Steel Pipes**
- JFE Steel Pipe for Fault Crossings
- Butt Welded Joints
- Welded-Lap bell and spigot joints
- Fiber wrapped joint
- Steel wrapped joint

**Plastic Pipes**
- PVC
- HDPE

**In-Situ Linings**
- EnduroBell
- Steel wrapped joint

**Use to create seismic resilient pipe network**
PEER PBEE Methodology

The PEER Methodology is applicable to the described procedure at the system and component levels.

For building components, the methodology has been well defined.

Fragility models are lacking for many other lifeline system components.

At the system level, service category losses and their restorations need to be tracked.

System can be assessed probabilistically using entire range of possible events:

- Must include probabilities of wide range of permanent ground movements
- Assess system service losses relative to target performance using median values of all possible lost services and restoration times between the best case and the worst-case conditions.
Summary

A Performance Based Seismic Design procedure for lifeline systems has been proposed.

Implementation of the PBSD procedure incorporates many of the characteristics needed for a resilient lifeline system.

Established target objectives for safety, property protection, and basic lifeline system services.

Allows for modification if designs cannot meet performance targets (with management approval).

Provides for efficient design to more extreme events by assessing Level 4 scenario benefits:
- Designing to higher level events does not always cost more.
- Some cases have provided greater resilience at lower cost.

More work is needed to develop methodologies for:
- Assessing geotechnical hazards consistent with PBSD application.
- Incorporating system interdependencies.