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Guide Brief 4 – Determining Anticipated Performance

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Guide Brief 4 – Determining Anticipated Performance

Applicable Section(s) of Guide: Volume 1, Section 4.1.4, Determine Anticipated Performance, p. 46

**Guide Briefs supplement the Community Resilience Planning Guide
for Buildings and Infrastructure Systems (NIST SP1190)**

Purpose and Scope

This Guide Brief supports Step 3, Determine Goals and Objectives. It provides guidance for determining the anticipated performance of building clusters and infrastructure systems when subjected to hazard events. This information is needed to complete the performance goals tables, establish existing system performance, and determine resilience gaps.

It is intended for use by facility managers, operators, or consultants who have an engineering background but may not be familiar with how to estimate the anticipated performance of facilities after a disruptive event. The methodology described herein applies to building clusters and all supporting infrastructure systems. Guide Brief 4A, *Example for Determining Anticipated Performance*, presents an example of how to assess a small water and wastewater system when subjected to a subduction earthquake.

1. Introduction

Determining the anticipated performance of the built environment, which includes post-event damage levels and the corresponding time to recover functionality, is a critical step for identifying gaps and needs for community resilience planning. It includes assessments of the performance of existing infrastructure systems and building clusters. The time and costs to recover functionality of the infrastructure system is based on its critical system components.

In the Riverbend example (Guide Chapter 9), the anticipated performance for the water systems response to an extreme flood event is shown as an “X” in the blue boxes of Table 9-28 (repeated here as Table 1). The desired performance goals represent the community’s plans for recovery that would minimize long-term impacts on the community, and are indicated as 30 %, 60 %, and 90 % of system functionality, recognizing the need for phased recovery at the community scale. The anticipated performance represents the time at which the major water infrastructure sub-systems are expected to recover to 90 % of the pre-event capacity given their current condition, configuration, and recovery plans.

Table 1: Riverbend, USA water infrastructure performance goals for extreme flood (Guide Table 9-28)

Disturbance[1]	
Hazard Type	Flood
Hazard Level	Extreme
Affected Area	Regional
Disruption Level	Severe

Restoration Levels[2,3]	
30 %	Function Restored
60 %	Function Restored
90 %	Function Restored
X	Anticipated Performance

Water Infrastructure	Support Needed[4]	Design Hazard Performance								
		Phase 1 Short-Term			Phase 2 Intermediate			Phase 3 Long-Term		
		Days			Weeks			Months		
		0	1	1-3	1-4	4-8	8-12	4	4-24	24+
Source										
Raw or source water and terminal reservoirs	R, S, MS	30 %		60 %	90 %			X		
Raw water conveyance (pump stations and piping to WTP)	R, S, MS				60 %	90 %			X	
Potable water at supply (WTP, wells, impoundment)	R, S, MS			30 %	60 %	90 %			X	
Water for fire suppression at key supply points (to promote redundancy)	R, S, MS			90 %	X					
Transmission (including Booster Stations)										
Backbone transmission facilities (pipelines, pump stations, and tanks)	R, S, MS	30 %				60 %		90 %	X	
Control Systems										
SCADA or other control systems	R, S, MS				30 %	60 %	90 %	X		
Distribution										
Critical Facilities										
Wholesale Users (other communities, rural water districts)	R, S, MS					60 %		90 %	X	
Hospitals, EOC, Police Station, Fire Stations	R, S, MS				60 %	90 %		X		
Emergency Housing										
Emergency Shelters	R, S, MS				60 %	90 %		X		
Housing/Neighborhoods										
Drink water available at community distribution centers	R, S, MS			30 %	60 %	90 %		X		
Water for fire suppression at fire hydrants	R, S, MS				60 %	90 %			X	
Community Recovery Infrastructure										
All other clusters	R, S, MS						60 %	90 %		X

Footnotes:

1 Specify hazard type being considered
Specify hazard level – Routine, Design, Extreme
Specify the anticipated size of the area affected – Local, Community, Regional
Specify anticipated severity of disruption – Minor, Moderate, Severe

2 30 % | 60 % | 90 % Desired restoration times for percentage of elements within the cluster

3 X Anticipated performance for 90 % restoration of cluster for existing buildings and infrastructure systems
Cluster recovery times will be shown on the Summary Matrix

4 Indicate levels of support anticipated by plan
R = Regional; S= State; MS=Multi-State; C = Civil (Corporate/Local)

The methodology to estimate the anticipated performance of an infrastructure system, such as a power, water, or transportation system, when subjected to a natural hazard event, includes:

- ***Section 2 – Determine Anticipated Performance of Infrastructure System Components.*** Assess system performance by considering the anticipated performance of the individual components. Anticipated performance of each critical component can be determined through fragility curves. Fragility curves are damage relationships expressed in terms of the hazard intensity or magnitude and the corresponding probability of failure for the component. Sources of component fragility curves are provided.
- ***Section 3 – Determine Anticipated Performance of Infrastructure System.*** Infrastructure system performance is estimated using the anticipated performance of the system components. System performance may also be affected by external site characteristics and factors (e.g., soil characteristics and expected ground motions in the case of earthquakes) that should be considered in combination with the performance of individual components. Other external factors, such as the performance of surrounding utilities or co-located facilities (e.g., pipes co-located on bridges), may also impact system performance.
- ***Section 4 – Determine the Anticipated Performance of Building*** Clusters**.** A building cluster is a set of buildings that supports a common function, such as housing, health care, or retail sales. Fragility curves are also used to estimate the performance of building types within a building cluster. The anticipated performance of building clusters is determined in much the same way as infrastructure systems —the anticipated performance of individual building types is aggregated to determine the performance of the cluster.
- ***Section 5 – Use of Hazus.*** This Guide Brief concludes with a brief discussion of Hazus, a national damage and loss estimation tool distributed by FEMA. Hazus provides a wide variety of fragility curves for the anticipated performance of many building types and infrastructure system components for earthquake, flood, and hurricane hazards.

An example of the approaches described is provided in Guide Brief 4A for the analysis of a water infrastructure system and an earthquake hazard.

2. Determine Anticipated Performance of Infrastructure System Components

This section provides guidance for determining the anticipated performance of infrastructure system components for selected hazards. It is assumed that each community will identify multiple hazards that could potentially impact it, with three hazard levels for each hazard, as described in Guide Section 4.1.3, *Define Community Hazards and Levels*.

Divide the infrastructure system into its various components, as described in Guide Section 3.2, *Characterize the Built Environment*. Communities may assess several infrastructure systems, including transportation, energy, communication, and water and wastewater systems. A water system, for example, might include a dam and a reservoir, transmission pipelines, a water treatment plant, pump stations, storage tanks, and distribution pipelines. Systems may contain many of the same component (e.g., multiple storage tanks or segments of distribution pipelines). Components with dependencies on other infrastructure systems should be identified, as the dependency can drive the optimal sequencing of response and recovery activities. Similarly, components that other infrastructure systems depend on should also be identified.

Identify the critical components required to keep the system functional. Components required to meet post-event demands need to be identified. Post-event demands differ from peak demands during normal operations, due to reduced demand or different demands during recovery (although there likely will be overlap between these two conditions). For example, water systems facilities may not need to meet peak summer demand flows. Instead, meeting average, or winter, demands may suffice. With that in mind, a water utility may have a performance goal of delivering average winter demand within a defined timeframe, which is half of the peak daily demand. Components that play a secondary role may not be critical to recovery of system function.

A component's performance is defined in terms of its anticipated level of functionality following the hazard event, its associated capacity, and the time and cost to recover the component functionality given the type and level of damage. Component recovery time is used as an input to determine the overall system recovery time. Any recovery costs that are avoided or reduced through pre-event planning or mitigation can be treated as benefits in a benefit-cost analysis.

Estimate component performance with fragility curves. A fragility curve estimates the anticipated performance of a system component for a hazard level as the probability that some well-defined level of damage will occur, often expressed as a *probability of failure*. For example, a building may be evaluated for several types of damage based on the hazard type, such as loss of the roof or exterior cladding for wind events, foundation damage for flood events, or structural damage for earthquake events. Levels of damage can range from *minor* (i.e., a level of damage that can be quickly repaired with off-the-shelf tools and replacement parts) to *complete* (i.e., a level of damage that cannot be repaired, requiring the component to be completely replaced with a new component)[1]. However, site specific evaluations should be carried out for components that may present a risk to the community when they are damaged.

Fragility curves provide a relationship between the hazard magnitude and the probability of damage for a component. These are sometimes also referred to as *fragility relationships* or *fragilities*. Figure 1 shows an example fragility relationship for the probability of failure for two types of storage tanks and three earthquake ground shaking intensity levels. The failure mode could be overturning, buckling near the foundation, or other modes of failure that impact the functionality of the water tank (refer to Guide Volume I, Table 4-5 for an example description of seismic hazard levels). Tank #1 is designated as having high vulnerability for this seismic environment as it was not designed to withstand the design event. Tank #1 has a small probability that the tank would fail during a routine event, about a 50 % chance it would fail for a design event, and a 100 % chance it would fail for an extreme event. Tank #2 is designated as a low vulnerability tank as it was designed for the design level event. The Tank #2 probabilities of failures are: near zero for the routine event, about 5 % for the design event, and 20 % for the extreme event. Note the increasing probability of failure as the hazard intensity increases from routine to

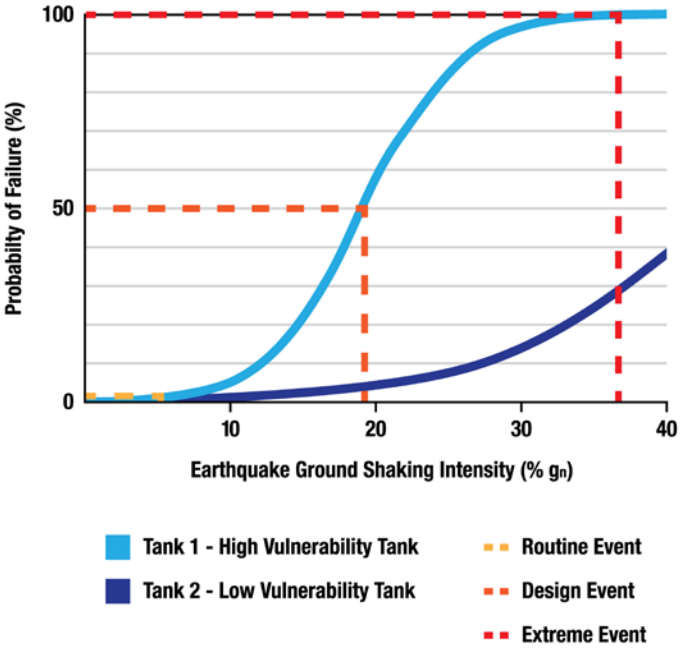

Figure 1. Example fragility relationships for two water storage tanks, with probability of failure versus earthquake ground shaking intensity (peak ground acceleration expressed as percent of gravity)

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[1] Refer to Hazus Damage States, discussed in Section 6 of this Guide Brief (typical for all damage descriptors in this paragraph).

design to extreme levels. The shape of the fragility may differ depending on the nature of the component. If the component performance is clearly linked to a single element with a well-understood failure mechanism, the fragility curve will be steep, or close to vertical, as shown by Tank #1. If the component performance is based on several elements, so that there is less likelihood that the failure mode will occur, the fragility curve tends to be flatter, as shown by Tank #2.

If there are several possible failure modes for a component, separate fragility curves may be developed for each failure mode to determine their relative influence on the component performance. For instance, bridge overpass structures may have failure of the supporting columns or failure of the bridge deck. Or, electrical equipment located on the first floor of a building may be more vulnerable to a flood hazard than the integrity of building foundation; either type of damage would impact the intended function of the building. In some cases, the component failure probability can be adequately approximated as the probability of the most likely failure mode. In other cases, it may be necessary to combine multiple failure modes. If the failure modes are independent and their probabilities are small, a simple approximation is to add the failure probabilities together.

When a system has many of the same type of components, the probability of failure can be thought of as the expected number of components failing out of 100 when subjected to a specified hazard intensity. For the example in Figure 1, about 2 of 100 storage tanks would be expected to fail in a routine event; about 45 of 100 would fail in a design event; and nearly all would fail in an extreme event.

Map spatial hazard intensity for system components. A Geographic Information System (GIS) can illustrate spatial variation in hazards, such as flood or seismic hazards, for critical components in distributed infrastructure systems A GIS map for each of the three hazard levels—routine, design, and extreme—can help visualize how system damage levels and extent varies for the three hazard levels.

Sources of published fragilities. Fragility curves can be developed using various methods, or a combination of methods, as shown in Table 2. An overview of fragility curve development and use is provided by Porter (2016).[2]

Many fragility curves have already been developed, based on such methods, and are available in through the following sources. Hazus provides one of the broadest sets of publicly available fragilities (see Section 5). The U.S. Army Corps of Engineers developed fragility relationships to characterize system reliability for water resource structures (http://www.usace.army.mil/Media/News-Archive/Story-Article-View/Article/477787/partnering-equals-teamwork/).

Researchers and academic institutions also develop fragility curves for buildings and infrastructure systems. Seismic fragilities have been developed by earthquake research centers in Buffalo, NY (NCEER/MCEER) (http://www.buffalo.edu/mceer.html); Champaign, IL (MAE Center) (http://mae.cee.illinois.edu/); Memphis, TN (CERI) (http://www.memphis.edu/ceri/); and Berkley, CA (PEER) (http://peer.berkeley.edu/). The Center for Risk-Based Community Resilience Planning (http://resilience.colostate.edu/) is developing a community scale model of the built environment and associated social and economic functions, which includes a database of fragility curves. The Center fragility database will be available in 2017.

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[2] Porter, K., 2016. *A Beginner's Guide to Fragility, Vulnerability, and Risk.* University of Colorado Boulder, 92 pp., http://spot.colorado.edu/~porterka/Porter-beginners-guide.pdf

Table 2: Examples of Fragility Curve Development Methods

Method	Description/Example
Expert Opinion	***Type of facility.*** An engineer familiar with performance of various categories of structures estimates the performance based on their experience and judgment. For example, steel moment frame structures perform well in earthquakes, whereas unreinforced masonry walls are much more prone to collapse.
	Date of Construction. Building codes are regularly updated, reducing hazard vulnerability. An engineer familiar with code changes will understand the consequences of code changes on building and infrastructure system performance.
	Vulnerable subcomponents. The facility may have particularly vulnerable elements that are critical for maintaining functionality. For example, some types of breakers used in high voltage substations are vulnerable to earthquake ground motions, while other components may perform better for the same hazard intensity.
Empirical Damage Data	***Damage data*** collected from multiple hazard events can be used in a regression analysis to develop a fragility curve. The damage data must include a detailed description of the component, the hazard intensity, and the performance of the particular component being evaluated. The pipe fragility curves developed by the American Lifelines Alliance used this technique.[3]
Analysis	***Structural analysis*** is used to determine the performance of potentially vulnerable elements for a range of hazard intensities. The analysis should consider the uncertainties in both the loads on the structure and the ability of the structure to resist those loads.
Testing	***Load tests*** demonstrate the performance (strain, displacement, etc.) as the hazard intensity is increased. Similarly, shake tables are used to qualify equipment using input ground motions from selected earthquakes. Repeated tests are generally required to capture the variability or uncertainty in the response. Additional consideration should be given to how well the test conditions represent the actual conditions to which the component will be exposed.

3. Determine Anticipated Performance of Infrastructure System

The estimated probability of failure and associated damage state and level of functionality for system components for a hazard event informs the anticipated post-event performance of the overall infrastructure system. Overall system performance depends on the performance of the system components, the connectivity of the components within the system, and dependencies on other supporting systems. The anticipated system performance can be compared against the desired performance goals, as illustrated in Table 1, to identify performance gaps.

To determine the post-event functionality of a system component based on its fragility curve, consider the anticipated type of damage or failure mode and how that might affect its performance, and whether there are levels of performance, or simply a binary condition of ‘functional’ or ‘not functional.’ Many system components might be assumed non-functional for planning purposes if the probability of failure exceeds 50 percent. For example, pump stations usually either work or do not work following an earthquake. A treatment plant may be considered partially functional if it can provide some level of primary treatment.

Three general approaches are available for assessing post-event system performance: 1) similar event method, 2) workshop assessment method, and 3) system modeling method. The assessment of post-event system performance is then used to estimate the recovery cost and time for achieving the desired performance goals of the community and its buildings and infrastructure systems.

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[3] American Lifelines Alliance, Seismic Fragility Formulations, Part 1 Guidelines, April 2001, http://www.americanlifelinesalliance.com/pdf/Part_1_Guideline.pdf; American Lifelines Alliance, Seismic Fragility Formulations, Part 2 Appendices, April 2001, http://www.americanlifelinesalliance.com/pdf/Part_2_Appendices.pdf

3.1. Similar Event Method

The anticipated infrastructure system performance may be estimated based on the performance of a similar system for a similar hazard event. However, there are many variables to consider and such a process is not likely to result in quality results. For optimal results, consider an event where the topography or terrain and hazard event, the type and age of the infrastructure system, and the available resources to restore the system are similar. Adjustments should be made for any differences.

3.2. Workshop Assessment Method

The workshop assessment method brings together a team with knowledge about various aspects of the infrastructure system, such as engineering and operations staff that make operating decisions every day. As part of the evaluation, the team determines whether the post-event system can be operated without infrastructure system components that are identified as damaged or failed based on the performance assessment in Section 2.

The workshop process includes sequentially stepping through the decisions, materials, staffing, and functions required to recover the system and make it operable in phases that are consistent with the desired performance goals for the community, as indicated in Table 1. Some recovery steps will focus on a single component, but others may be able to consider system redundancies or alternate methods of obtaining labor and materials that may provide flexibility or alternatives. For example, for a power system that includes transmission lines, transmission substations, distribution substations, and distribution lines, redundant components can improve a plan for phased recovery (e.g., 30 % or 60 % operational) of electric power.

System redundancy is highly dependent on the type of system and where the redundancy occurs within the system. Many power systems, for example, purchase bulk power from multiple providers, none of whom may be impacted by the hazard event. However, failure of a local substation may result in loss of service to the area if there is no redundancy in transmission or distribution lines. Many water utilities are self-contained, and may have only a single supply of water. If that supply is lost, the entire system may become non-functional.

3.3. System Modeling Method

To assess infrastructure system performance, analytical models need to include system connectivity and the post-event functionality level of system components and expected operational demands. Many infrastructure systems use models to evaluate their performance under normal operating conditions. Most of these models are deterministic and cannot account for uncertainties or component failures and their impact on the system. However, the model operator may be able to test the impact of one or two component outages on the system at a time.

EPANET, developed by the Environmental Protection Agency (https://www.epa.gov/water-research/epanet), is one example of a commonly applied water network software application. EPANET is used in the water industry to assess the functionality of damaged water systems. Users can remove damaged system components (as determined separately by a fragility analysis) to determine the operational impact. If the system damage is extensive, the modeler can conduct sensitivity studies by removing some but not all damaged system components to determine which components have the greatest impact. This approach is sometimes followed for assessing earthquake damage of water systems when failures of distribution pipelines are expected. Pipeline failures are grouped by pressure zone. The modeler then adds or removes the demand from the various pressure zones to evaluate overall impact on system functionality. Other system models allow probabilistic modeling when, for example, probabilities of delivery are required, but implementation of such a model is time-consuming and may provide limited value.

The disadvantage of deterministic models is that they cannot incorporate fragilities and other uncertainties into the system analysis to better predict anticipated performance. Probabilistic risk assessment models are routinely used in the nuclear power industry where the consequences of failure can be extreme. These models typically use Monte Carlo simulation to calculate the probability of damage and the potential range of impacts on system functionality. Such models have been developed for several wholesale water delivery systems on the west coast to estimate probabilities of delivering water to local communities following various earthquake scenarios. These models are typically proprietary. These types of models are effective, but are expensive to develop and have limited application beyond the specific use for which they were intended.

3.4. System Recovery Costs and Time

Recovery Costs. First-order recovery costs are sometimes estimated as a percentage of component replacement cost. With fragility estimates, a starting point for a first-order recovery cost estimate could be based on the percent probability of failure. For example, if a component has a replacement cost of $1 million, and has a 30 % probability of failure (or when applied to estimate repair costs, an expected average cost) , it might be initially estimated to cost $300 000 for recovery. Note that the 30 % is an expected average cost, and that the uncertainty in the estimate can be large. Some facilities with a 30 % probability of failure may cost $500 000 (e.g., complete tank replacement – site/piping/control facility undamaged) to repair and others $100 000 (e.g., repair of elephant’s foot buckling).

While such estimates are useful for early first-order recovery costs, a substantiated recovery cost can be obtained by detailed estimates of costs to purchase, ship, and install the component, as well as removing and disposing of the damaged components. Such estimates can then be updated over time.

Recovery Time. Recovery time estimates should consider post-hazard event environment for conducting operations, supporting staff, and receiving equipment and supplies. For instance, memorandums of understanding or contracts for post-event support can greatly accelerate the recovery process. Planning for reduced or altered support staff and the desired rate of recovery will highlight areas of concern. Identifying available transportation methods for incoming supplies and materials can provide options and flexibility during the recovery process, and inform the range of recovery times that might be expected.

An estimate of infrastructure system recovery time, the time between the event and the time when it once again becomes 90 % functional (i.e., operating at normal capacity), is needed to complete the performance goals tables (see Table 1 as an example). The focus is on recovery of system function, which can include temporary measures until permanent repairs are completed.

For components that are critical to recovery of system functionality, system engineers and operations personnel can estimate recovery time each component. If multiple critical components are out of service, the evaluation team would consider whether recovery of the components can be accomplished in parallel or sequentially.

Considerations. Emergency equipment should be considered when evaluating recovery. For critical societal functions, infrastructure service can be temporarily met with emergency equipment, such as generators and portable toilets. As another example, tank trucks can deliver water to local distribution points. Communities may be able to achieve minimal system functionality (i.e., 30 % functionality) with emergency equipment.

Recovery of systems with numerous occurrences of the same type of damage or failure need to be considered. As an example, consider downed power lines. To estimate system or partial system restoration time, assume the time it takes to repair one downed line, multiply that time by the total number of downed lines, and divide that total by the available number of crews. The time and costs to repair one downed power line following a hazard event may be longer than during normal operations. Some assumptions are required to determine the availability of crews. For instance, local crews may be delayed by family commitments. Or mutual aid crews may take days or more if transportation routes or fuel systems are damaged.

Equipment required for repairs may be the limiting factor in recovery rather than the availability of repair crews. For example, large excavators may be required to repair large water transmission mains. Following a hazard event, large excavators could be in high demand. Recovery priorities would be set by the state or county; the excavators may first be directed to clear debris from streets, next to restore water service, and finally wastewater service.

Availability of repair materials may also become an issue. For example, earthquakes often damage many distribution pipelines. Repairs require repair clamps, and utilities usually only stock a limited supply. Also consider the sources and time needed to acquire additional materials. Similarly, damaged equipment and materials with long lead times could hamper recovery. Large diameter pipe may have to be manufactured to repair water transmission main failures. For power utilities, damaged high voltage transformers may take months to replace.

In some cases, the hazard event may also damage other infrastructure systems that slow recovery work (e.g., transportation systems limiting access). Damaged underground power lines may be located above damaged sewers and sewers may need to be restored first because they are deeper.

A timeline for the expected sequence of such activities following the hazard event will help clarify and document the plans and support communication with other stakeholders and community members.

4. Determine the Anticipated Performance of Building Clusters

Determining the performance of building clusters has both similarities and differences relative to determining the performance of infrastructure systems. A building cluster is a set of buildings that supports a common function, such as housing, health care, or retail sales. The buildings in a cluster need not be located in a single geographic area.

The performance of one building may or may not depend on the performance of another building in the cluster. The dependency could be in terms of a specific function served by the building within the overall building cluster. For example, one building in the financial services cluster may provide data storage – if it is not functional (with no redundancy or backup), other buildings dependent on the data storage may not be functional. In some cases, such as houses of worship, each building in a cluster may be functionally independent. In such cases, a community may have significant redundancy.

4.1. Individual Building Fragilities

Building cluster components (e.g., each building) may be designed to different codes over time and may have different building materials and construction types. The anticipated performance of each building, or set of structurally similar buildings, may be evaluated using fragility curves.

Building performance depends on its most probable failure modes for a given hazard type and magnitude. For example, the most probable failure mode might be structural collapse for extreme earthquake ground motions or equipment damage for design level floods. If a building has emergency equipment to mitigate the impacts of a known vulnerability, another failure mode may become significant for that building.

Approaches available to assess building component fragilities include expert opinion, empirical damage information, and analysis (see Table 2). Like infrastructure system components, expert opinion can rely on the type of structure, date of construction, the code to which it was designed and vulnerable elements within the building.

The Applied Technology Council (ATC) has developed a methodology for assessing the performance of buildings subject to earthquakes for FEMA P-58-1, *Seismic Performance Assessment of Buildings*. The ATC methodology addresses both structural and non-structural system performance. The American Society of Civil Engineers (ASCE) developed guidance for evaluating existing buildings in ASCE 41-13, Seismic Evaluation and Retrofit of Existing Buildings with Tier, 1, 2, or 3 analyses. While these documents go into great detail, a preliminary Tier 1 evaluation may be adequate for analysis of a building cluster component.

4.2. Building Cluster Performance

Once the anticipated performance of building cluster components (individual buildings) is determined, all of the components are grouped together to determine the anticipated performance of the building cluster. For a building cluster with a large number of similar buildings, a representative sample could be used to establish the cluster fragility. The goals are to determine the expected degradation in functionality and the expected time required to return to 90 % functionality (see Table 1). To achieve 90 % functionality, it might be assumed that all components would have to be functional. However, in some instances, there may be temporary measures that allow 90 % operation while one or more components remain non-functional. For example, an operational facility that normally works one shift could be pushed to operate two shifts while the other facility is being restored.

5. Use of Hazus

Starting in the 1990s the National Institute of Building Sciences (NIBS) led a project named Hazus (a contraction of Hazards-US), funded by the Federal Emergency Management Agency (FEMA), to develop a comprehensive method to estimate damage and losses for earthquake, flood, and hurricane. The Hazus technical manuals for earthquake, flood, and hurricane hazards include fragility curves for buildings and many infrastructure systems and components.

The earthquake hazards modeled in Hazus are ground motion, liquefaction, landslide, and fault rupture. For flood, both riverine and coastal flooding are addressed. There is also an option to compute combined hurricane wind and storm surge damage using the coastal surge option in the hurricane and flood models. The building fragility curves in the hurricane model include the combined effects wind pressure, windborne debris, and rain infiltration, and there are separate curves for tree fall damage to residential structures. Infrastructure fragilities have not been addressed yet in the hurricane model.

Hazus includes methods to quantify hazards, quantify the anticipated performance of buildings and infrastructure systems (referred to as lifelines in Hazus) to those hazards, and in some cases, to quantify the effects of a hazard event on the overall community.

The Hazus technical manuals provide detailed information on the fragilities they use and are available from FEMA at http://www.fema.gov/media-library/assets/documents/24609. The Hazus software is available from FEMA at https://msc.fema.gov/portal/resources/hazus. To run the full loss assessment software package, Hazus must be installed as an extension to a commercially available geographic information system called ArcGIS. The Hazus earthquake fragility curves were developed by expert opinion for:

- Buildings and facilities, including capacity and fragility curves for ground shaking, ground failure, and peak ground displacement. A special section addressed essential and high potential loss facilities. Fragilities are included for 15 categories of building types, including low, moderate and high building heights, and constructed with low, moderate or high-code design. Building types included wood, five steel categories, five concrete categories, and reinforced and unreinforced masonry.
- Transportation systems, including highway systems, railways, light rail, bus, ports and harbors, ferries, and airports.
- Lifeline utility systems, including potable water supply, wastewater, oil systems, natural gas, electric power, and communications.
- Induced damage for inundation, fire following earthquake, hazardous material release, debris, casualties, direct social and economic losses, indirect economic losses, and annualized losses.

Figure 2 shows an example set of a Hazus earthquake fragilities for concrete tanks.

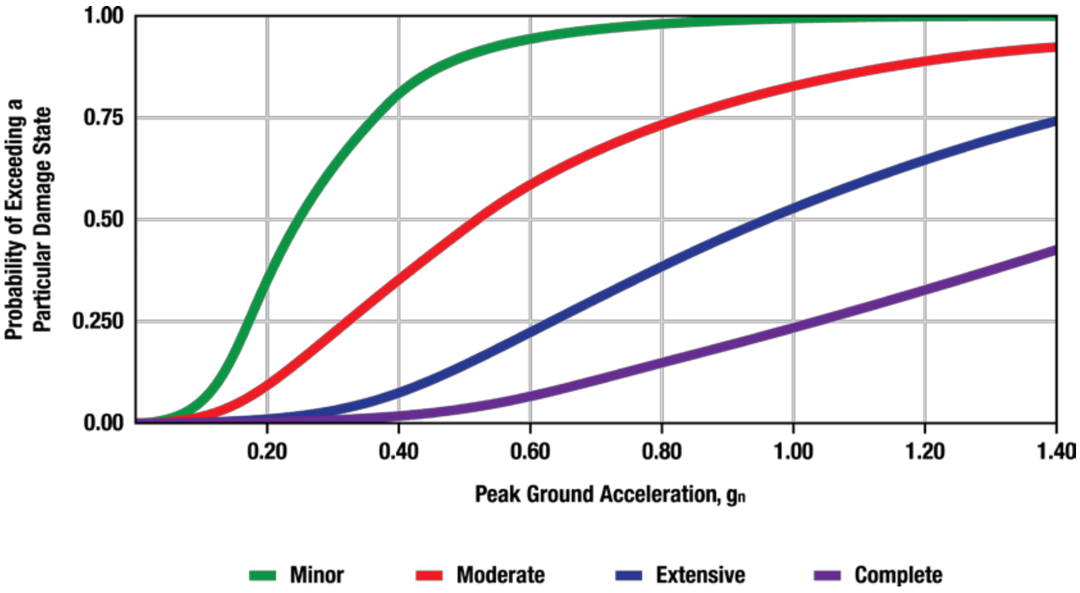

Figure 2. Earthquake ground motion fragility curves for anchored on-ground concrete tank (after Hazus Earthquake Technical Manual Chapter 8, Direct Damage to Lifelines – Utility Systems)

The general damage descriptive terms are:

- ***Slight* –** Minor repairable damage. The component remains fully functional.
- ***Moderate* –** Repairable damage. The component can be repaired while remaining operable but potentially at reduced capacity or function.
- ***Extensive* –** Inoperable but repairable.
- ***Complete* –** Component cannot be reasonably repaired or the repair cost would exceed the cost to replace with a new facility.

System components with slight or moderate levels of damage are still considered functional. These damage descriptive terms can also be interpreted in terms of percent of replacement cost or some parameter relating it to recovery time.

Using the fragility curves in Figure 2 for on-ground concrete tanks, the functionality of such a tank following an earthquake can be estimated. For a 0.40 g_n peak ground acceleration (where g_n is acceleration due to gravity), it can be seen in Figure 2 that there is an 80 % chance the tank will have at least minor damage, a 35 % chance it will have at least moderate damage, a 10 % chance for at least extensive damage, and a 2 % chance for complete damage. Based on these fragilities, the tank will most likely experience minor to moderate damage. With moderate damage, the tank is repairable and can be repaired while remaining operable, but potentially at a reduced capacity. Therefore, there is a 90 % likelihood that the tank will remain operable at a peak ground acceleration intensity level of 0.40 g_n.

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