4.0 COMPONENT VULNERABILITY MODELING

4.1 Introduction

This chapter covers general considerations in estimating the damage of water system components to specific natural hazards referenced in Chapter 3. This chapter covers the shaded box in Figure 1 for "Evaluate Component Performance" (e.g., Level of Function, Repair Cost).

Of special importance in a water system evaluation is how damage is estimated in terms of the component functionality and also its restoration time. How these estimates fit a water system evaluation is elaborated upon in Chapters 5 and 6. Costs of damage are of secondary importance with reference to a water systems evaluation.

The general form of a component vulnerability model may be represented in terms of damage (e.g., functionality, critical downtime, and/or repair cost) as a function of natural hazard intensity (e.g., those intensity measures discussed in Chapter 3). The form of the model may be deterministic or it may be probabilistic. Probabilistic models are often called fragility models. One may use very simple forms of such a vulnerability model—an "S"-shaped curve (See Appendix D). More complex forms are available, and given the robustness of computer methods, non-parametric methods are also useful. However, the greater challenge is how to define credible models for assessing the vulnerability of components—especially in view of the many natural hazards discussed in this document and the comparative dearth of systematic data on which to base these models.

Section 4.2 of this Chapter discusses component vulnerability modeling methods and their challenges. Section 4.3 then provides general considerations for modeling the vulnerabilities of water storage distribution reservoirs. Section 4.4 provides general considerations for modeling the vulnerabilities of mechanical and electrical equipment. Section 4.5 provides general considerations for modeling the vulnerability of underground piping. Section 4.6 provides general considerations for modeling the vulnerability of buildings (housing) insofar as they are critical to water systems operations. Section 4.7 provides a general discussion of how there may be interdependence of damage to structures and components.

Appendix D supplements this Chapter. Included in that Appendix are (a) a discussion of very simple forms for vulnerability modeling and (b) how some facilities—such as major water treatment plants—can be treated as critical sub-systems.

4.2 General Methods for Developing Component Vulnerability Models

4.2.1 Objectives [Outputs Desired]

The objective of methods to develop component vulnerability modes is for each level of site-specific hazard intensity to estimate, for each component (a) direct economic loss and (b) downtime. Direct economic loss (repair cost) is important ultimately for establishing aggregate repair costs given specific natural hazard events. Estimating component downtime is important in ultimately estimating time-lines of system recovery, and time-element losses.

Plots (a) through (d) in Figure 32 exemplify the types of outputs from component vulnerability models. Plots (a) and (b) are deterministic component vulnerability models and (c) and (d) are fragility models (for which many variants exist).

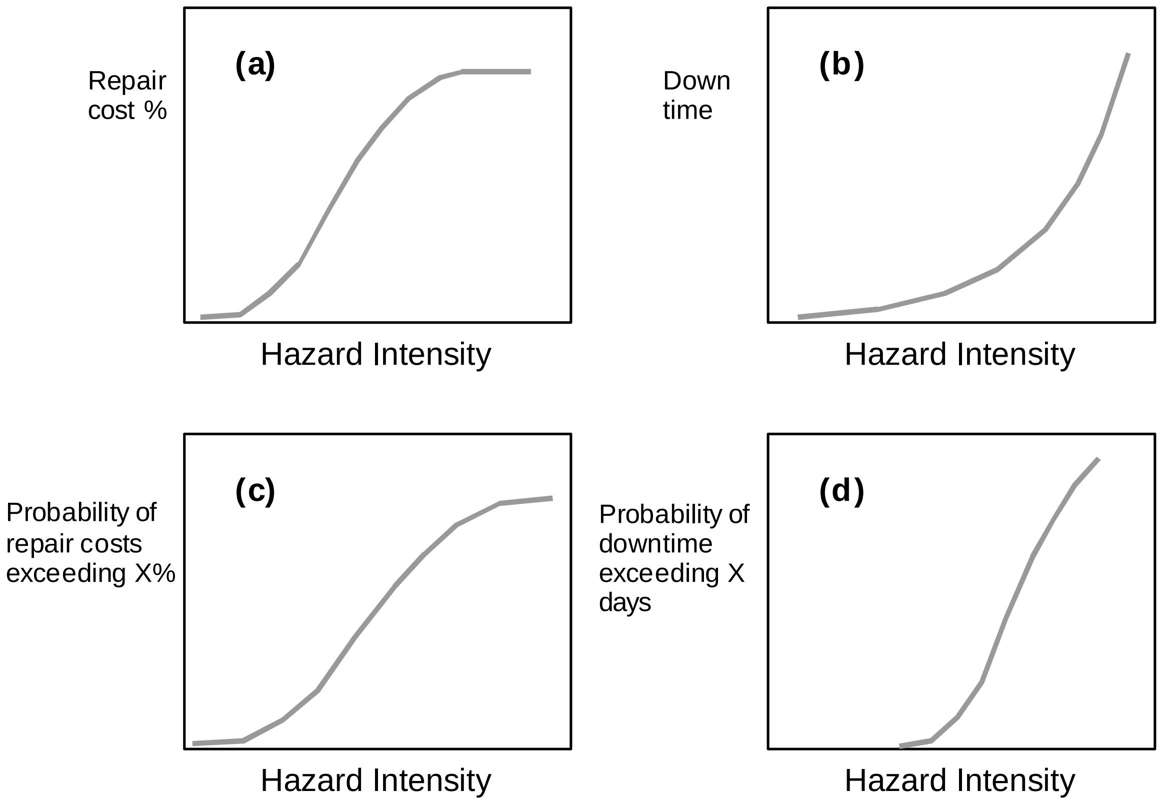

Figure 32: Types of Component Vulnerability Models

4.2.2 General Types of Methods

Under ideal conditions, component vulnerability models for water systems would be drawn from a large database, spanning all types of components, under the full range of levels for each hazard. With enough samples, the data would define the statistical distributions of damage, functionality and repair time for each level, for each hazard. For new components, or for hazards not covered by the database, analysis or testing (experiment) would extend the models as needed, with the results reviewed and applied by experts. Visual inspections would be conducted to assess conditions and confirm the system and component data contained on as-built documents.

Unfortunately, loss experience databases for water system component vulnerability exist for only a few major structures or components (buildings, underground piping, water reservoirs, electrical cabinets, pumps, etc.), for mostly low levels of certain hazards (e.g., ground shaking, wind, corrosion, etc.). (See ALA, 2001, which summarizes many of these data collection activities that bear on water system risk evaluations). Often, the hazard level at which damage or failure occurred must be estimated from hazard models, since few components are instrumented. Damage reconnaissance reports help to indicate the components having the greatest vulnerability to particular hazards. Test data (IEEE) from the nuclear industry helps to extend the existing databases.

Where damage statistics or experimental data lack, visual inspection and rating methods provide a risk profile, narrowing the focus to a manageable number of major components. Analysis and expert judgment may then be used to construct the needed vulnerability models.

In summary, methods for developing vulnerability models include (a) empirical, (b) visual inspection and rating, (c) analytical, (d) experimental, and (e) heuristic (expert judgment). Further, the integration of these five types of methods has been disappointing for natural hazards generally. For these reasons and also for economic reasons, we therefore currently recommend for most water agencies the application of visual inspection and rating methods supplemented by empirical and judgmental methods for assessing the vulnerability of pipelines. In some cases, analytical models may be combined with limited statistics to inform heuristic models. In rare cases, dependent on the decision context, the stage of the investigation, and the size of the water utility, more specialized methods may be applied (see, for instance, Der Kiureghian, 2002, and Werner and Taylor, 2002, for illustrative methods that could be applied in more specialized cases).

4.2.3 Qualitative Risk Models

Qualitative models can be used with visual inspection and rating techniques in preliminary risk assessment phases, as a means of screening the risks, deciding which natural hazards are material to water agency risks, and which components or subsystems may need further evaluation and/or mitigation.

Once the severity and spatial distribution of natural hazards within the water system is evaluated, the agency can decide which of the hazards present substantial risk, and to which components. These components can then be judgmentally rated by experienced engineers for:

- vulnerability (low, moderate, high, very high) to damage in each defined, relevant hazard
- operational importance (preliminary judgment, subject to considerations in Chapter 5)
- life-safety implications of failure

These judgmental, relative rankings of risk can be used to identify components with high or very high rankings in a number of categories, so that further investigation can be done. The visual surveys can also identify specific weaknesses (e.g., poor or missing anchorage, configuration, support), which can be corrected without further analysis. System modeling can reflect vulnerability either before such judgment-based lower-cost mitigations or after these mitigations are undertaken.

4.2.4 Analysis of Structural and Mechanical Components

Analytical models for structural and mechanical/electrical components range from the simple to the very complex. Due to the cost and effort involved, such models are generally employed only for the components found to be most critical or susceptible under each defined hazard, as identified by initial screening surveys. Often, the mechanical or structural failure of the component will imply failure of the component to function, but this is not always the case, as where structural redundancy requires multiple component failure prior to loss of function.

Simple manual calculations may be sufficient in many cases to estimate the forces, accelerations or displacements that will cause mechanical or structural failure in a particular critical component. An example would be the seismic evaluation of anchorage bolt adequacy for a pump or electrical transformer, where anchorage is the key ‘weak link’ controlling failure of the equipment. The loads are obtained by multiplying the weight of the equipment by the acceleration (in ‘g’ units) for the equipment mounting point (i.e., the foundation or floor to which it is anchored) under the selected earthquake scenario. A similar calculation would be made for an electrical cabinet exposed to hurricane wind forces, where the wind velocity at the cabinet is used, together with the shape of the cabinet, to estimate the applied pressures. In either case, bolt shear and tension forces are computed for the forces and overturning moments, for comparison with the bolts’ capacity. Mean tested bolt capacities would be used to estimate the state of the anchorage relative to anchor failure, rather than design values. The variability of anchor failure values from test would provide a lower-bounds estimate of the failure uncertainty.

Well-developed finite element software exists for buildings, for aboveground piping, and for mechanical elements. Used by skilled engineers, finite element software packages typically permit analysis for gravity loads in conjunction with temperature changes, temperature differences, pressure loadings, inertia loadings specified as static accelerations, base-motion spectra or acceleration time histories. Some packages will allow analysis for independently specified support displacements. Familiarity with the program and skill in modeling are generally required. The output from the models are typically given as stresses, displacements, accelerations, and many of these packages compare these output parameters with those permitted under relevant design codes. A knowledgeable engineer must reinterpret the analysis results for their implications in terms of damage, cost to repair and functionality. To be used effectively, structural or mechanical models must be used in conjunction with engineering judgment (expert opinion), and simple structural models are often used to inform expert opinion in the development of heuristic damage models.

4.2.5 Analysis of Underground Components

Underground water system elements include piping, tanks, basins, tunnels, vaults, building basements and foundations. Finite element and finite difference analysis methods can be used to assess the effects of interaction of these components with the surrounding soils. Nonlinear, large-displacement finite difference programs (such as Itasca’s FLAC, *Fast Lagrangian Analysis of Continua*), may be used to assess the forces and displacements imposed upon underground components with the occurrence of hazards such as liquefaction or slope instability. In these analyses, the water system component (e.g., tank, basin, tunnel, etc.) is represented by finite elements within the soil continuum, and the soil pressures and displacements computed. These tractions may then be imposed as loadings in separate, detailed finite element models of the individual water system components, to evaluate damage and potential loss of function.

4.2.6 Modeling Component Repair Costs

As a secondary consideration in this document, component vulnerability models for component repair cost can be used directly to estimate system-wide direct damage. These repair cost estimates are valuable in the immediate aftermath of disasters in order to provide FEMA with estimated "capped" losses (a conservative estimate of losses). These simple damage models can also help in estimating the size and siting of repair inventories.

There are many published sources for water system component direct damage models. These include: ALA, 2001; ATC-13, Applied Technology Council, 1985; ATC-25, Applied Technology Council, 1991; HAZUS [FEMA/National Institute of Buildings and Standards]; Cassaro et al., 1993; and Taylor, ed., 1991. The damage models are based on heuristic, analytical, and empirical methods – or a combination of these methods.

As suggested previously, various techniques are available to derive or adapt such repair cost models. Appendix D discusses the use of a “power” function (as in ALA, 2001) for vulnerability models (with or without uncertainties attached) and the use of a triangular distribution for the development of fragility models (vulnerability models expressed in probabilistic terms). These types of modeling forms are easy to use in initial stages of component vulnerability modeling—with considerable resulting coarseness in the estimates.

4.2.7 Modeling the Functionality of Components

The functionality of a water system component may have some degree of correlation — rarely perfect — with its repair costs. For instance, repair costs for a damaged outlet connection at a water storage reservoir may be small by comparison to other repair costs but may lead to significant functionality problems. In contrast, other damages to the water storage reservoir may be costly to repair (e.g., sloshing wave damage to the roof), but may not impair the functioning of the reservoir.

Many repair cost models assume a perfect degree of correlation between repair costs and functionality. Such models may be used for an initial evaluation of component functionality although improvements are desirable with respect to the definition of various component failure modes and their implications for component functionality.

For a more accurate but more extensive evaluation of component functionality, one should improve the definitions of damage descriptors:

> An improved basis for defining damage states for component vulnerability modeling purposes is physically-based damage descriptors for the component’s structural elements. These descriptors consist of limit-state forces, deformations, etc., associated

with various modes of damage to structural elements or components. If demand values of these parameters exceed any of the limit-state values for any element, the damage mode associated with that damage state is assumed to occur for that element. After repeating this for all elements in the component, an overall damage state for the component is developed in terms of these damage descriptors. Then, repair procedures established from these improved damage state descriptions can be used to provide more rational estimates of component repair costs and functionality during repair. [Werner and Taylor, 2002]

4.2.8 Modeling Component Restoration Time

As important as functionality modeling, restoration modeling for individual components yields critical information on when the water system will be fully restored, and what countermeasures are needed to offset potentially long downtimes for critical water system components.

In this section, we discuss only how to evaluate the restoration times for individual components. Challenges of strategies for repair many components concurrently or through prioritization—in the case of a major natural disaster—are discussed in Chapter 5.

Repair costs and downtimes vary regionally and over time, reflecting differences in construction practice, labor rates, etc. Water agency managers and their technical staffs are often the best sources for realistic current data, based on:

- construction of new components and systems,
- repair or replacement of existing systems under normal conditions, and in some cases
- repair and replacement of existing systems under previous upset (post event) conditions.

This experience must be adapted to represent the post-event conditions for each hazard under consideration.

More complex modeling techniques are needed where component or subsystem configurations are non-standard, where hazards (and consequently risks) are high, and where post-event function is critical. Advanced models may also be needed where simplified models cannot represent the complex behaviors leading to damage or failure.

Generally, preliminary, lower-bound estimates of component repair times will require a number of simplifying assumptions:

- repair inventories are available and undamaged
- trained and capable repair crews are available
- repair crews, equipment and materials can reach the damaged site
- repair times are greater than or equal to repair times for similar components under normal conditions

One practical way to estimate downtime is to apply the same methods as used in construction project estimation. The restoration process is divided into a number of phases, and each phase subdivided into tasks. Work crews are sized and the duration of individual repairs estimated based on assumed worker productivity. The availability of replacement components including equipment is checked against inventories of spares, and time allotted for ordering from vendors, with requisite lead-times, where needed. Design lead time, inspections and tests are allotted. Reasonable repair production downtime is included.

Using the above approach, a generic timeline can be developed for each component or subsystem type, to repair a given system for the damage that occurs in a given hazard. The process can then be automated and incorporated into recovery algorithms. Repair parts inventories including equipment can be tracked, and the algorithms written to account for finite inventories and work crews, bringing some of the event-specific correlations into natural hazard recovery simulations.

Increases in post-disaster repair times and costs typically occur as a result of systems features. For instance, continuing hazard, limited access, labor, material and the like can lead to increased costs on an aggregated basis. These systemic considerations are discussed especially in section 5.3.

4.2.9 Uncertainty in Component Vulnerability Modeling

The uncertainty in component vulnerability modeling is a major issue. For instance, if visual inspection and rating methods are used, there is a high degree of uncertainty. Because there has generally been a lack of integration of empirical, visual inspection and rating, analytic, and experimental methods, significant uncertainties remain for component vulnerability modeling. However, in modeling the vulnerability of components, it is essential to distinguish between the uncertainty of the natural hazard intensity and the uncertainty of the response of the component to that hazard. These uncertainties should be tracked separately through the risk analysis. Otherwise, the overall uncertainty in the process may be exaggerated. (See Der Kiureghian, 2002 and Werner and Taylor, 2002, for diverse treatments of this subject.)

4.3 Steel and Concrete Water Storage Reservoirs

Concrete and steel storage reservoirs are commonly damaged by earthquake ground motions, ground or slope failures, extreme winds and floods. Interestingly, reservoirs are most vulnerable to earthquake motions when full, but most susceptible to wind and flood damage when empty or at a reduced fill height.

Where ground or slope failures are modeled, tank foundations are the key element to examine. Deep foundations may help to mitigate liquefaction-related ground failures (although deep foundations may support only the ring footing, and not the center of the tank). Tank losses may be severe (but otherwise very difficult to quantify) where surface fault rupture, rock-slides, storm surge or tsunami occur.

Above-Ground Steel Tanks. Water tanks are vulnerable to earthquake ground motions, particularly when full. Large inertia forces are generated by the fluid moving in phase with the tank shell (impulsive mass) as well as the sloshing mass (convective mass). Failure modes for anchored tanks include foundation or anchorage failures, and shell compressive failures. Failure modes for unanchored tanks include uplift, compressive buckling ("elephant's foot"), failure of the tank bottom plate, and shell tensile failures. Other failure modes include shell yielding, and damage from impact of the sloshing wave on a fixed roof, or dislocation of a floating roof.

Seismic and wind analysis guidelines (oriented towards the design of new tanks) are provided by AWWA Standard D100. Damage functions for earthquake analysis are provided by ALA, 2001 and ATC-13. Alternative evaluation procedures include the Modified Manos analysis (empirical) and iterative uplift analysis (analytical) [Bureau, 1995].

In earthquake modeling, the connection of inlet and outlet piping, drain lines and other appurtenances often cause failures, when tank uplift occurs in unanchored tanks. If the piping connections are rigid, they may be ruptured, resulting in loss of the tank contents. Visual survey can be used to estimate the degree of relative tank/foundation motion that can be tolerated by the connections, and the probability and extent of uplift can be estimated analytically.

In modeling above-ground steel tanks for wind-related hazards, the roof of the tank is often the weak link. Loss of the roof may impair tank function and result in contamination of the water. Wind forces may be computed using code formulas, and structural analysis used to assess the roof capacity, relative to the wind demands.

Foundation failures occur from landslide, liquefaction, surface fault rupture, sink holes, etc. Freeze-thaw cycles may distress tank and piping as well. Failure of large reservoirs may generate a destructive water wave that damages structures and equipment that it encounters.

Above-Ground Concrete Tanks. These are similar to steel water storage reservoirs supported at ground surface, but with less vulnerability to compressive shell failures. Hoop stress failure is more common. Damage functions for earthquake analysis are provided by ALA, 2001 and ATC-13. Further evaluation of concrete tanks may utilize the seismic and wind requirements of AWWA Standard D110 or D115.

Underground and Partially-Embedded Concrete Tanks. Underground and partially embedded tanks are much less susceptible to damage from ground motion or wind-related forces. For earthquake forces, in stable and non-liquefiable soils, AWWA code-based analyses, which assume the that the tank is above-ground, are extremely conservative. Complex soil-structure interaction analyses may be needed to assess the intensity of earth pressures on the tank wall.

Elevated water storage reservoir.s In earthquake, an elevated tanks acts as an inverted pendulum, generating high overturning forces on the foundations. Similar force patterns occur in high wind. Modes of failure include cross bracing yielding, connection failure and buckling, tower leg buckling or yield, and foundation failures. Connecting piping may also fail at connections, due to structural movements. Flooding may cause weakening of soils supporting foundations. Freeze-thaw cycles may distress tank and piping as well.

4.4 Vulnerability of Mechanical and Electrical Equipment

4.4.1 Equipment Anchorage

Mechanical and electrical equipment are generally vulnerable to earthquake ground shaking hazards, and ground failure hazards (depending upon foundation conditions). For exposed equipment, wind hazards may be significant, especially for tall equipment, lightweight equipment and equipment presenting a large surface area to wind exposures. A key element of the vulnerability of equipment to earthquake or wind damage is the anchorage of the equipment.

Anchorage adequacy may be assessed by an experienced Civil or Structural Engineer. Factors to consider include equipment size, weight and configuration, as well as anchorage size, type, embedment and installation. Where anchorage appears to be inadequate, the adequacy of anchorage may be assessed using the requirements of the 1997 Uniform Building Code (UBC) as a guideline. Section 1634 of the UBC specifies design seismic forces, and Section 1923 specifies requirements for anchorage to concrete. Additional data on anchor capacity may be obtained from vendor catalogs and ICBO reports [International Conference of Building Officials, Whittier, California]. Equivalent provisions in the NEHRP guidelines and the International Building Code (IBC) may be used in lieu of the UBC.

4.4.2 Inundation of Equipment

For electrical and mechanical components subject to inundation hazards -- failure may be assumed when water levels are estimated to be above base of unit, with a relatively narrow uncertainty. In these models, it is most important to include the uncertainty in the hazard demand (i.e., the water height estimate at each equipment mounting location).

Equipment under consideration may be found in water treatment plants, booster pump stations, wells, diversion structures, etc., and includes:

- Mechanical equipment – pumps, filters, valves and valve operators
- Electrical equipment
  - switchgear, motor control centers, breaker panels, cabinets
  - transformers (on grade, in buildings, and pole supported)
- Transmission towers
- Electrical raceways and conduit
- Pressure vessels (surge tanks, etc.)
- Booster pumping stations

- Wells and sumps – pneumatic equipment, mechanical equipment, pumps
- Above-ground piping, pipe bridges, pipe supports, and pipeways
- Equipment for chemical storage and usage; chemical piping
- SCADA instrumentation and control equipment
- Instrumentation, chlorination control, surveillance
- Communications equipment (telephone, cellular, radio, etc.)
- Penstocks, Flumes, Vaults, Canals, Aqueducts and Tunnels

4.4.3 Loss of Power and Communications

Hurricanes, wind storms, flooding and earthquakes often result in power failures, as well as loss of telephone and data links. Damage to electrical power equipment and telecommunication equipment, and the resultant system impacts and loss of service may be modeled as a part of water system natural hazards modeling, or "postulated" as a part of the natural hazards scenario. Typically, direct damage is modest, but the impacts on operations and restoration of system function are significant, especially where adequate backup systems are not in place. Loss of power and communications are further discussed as a part of system modeling in Chapter 6.

4.4.4 Pressure Vessels (surge tanks, chlorine cylinders, etc.)

Vessels are generally steel shells, and may be cylindrical or (rarely) spherical. Cylindrical vessels with horizontal axes are often supported on saddles or legs. Vessels with vertical axes are supported at grade or on legs. Chemical gas cylinders may rest in cradles. Structural failures in earthquake include anchorage connectors, supporting legs, or sliding in saddles. Rupture at connections or objects penetrating the shell may generate "missile" hazard, if the tank can escape its structural attachment. Escaping contents can pose a health risk or an explosion risk.

In wind-related events, lateral forces can (more rarely) cause failures similar to those described for earthquake forces. Additionally, wind-generated missiles can penetrate pressure vessels, generating an additional missile hazard, as well as health risk or an explosion risk. Within an enclosed building, sudden vessel rupture or ignition of escaping flammable contents may present serious blast hazard to the building, its contents, other equipment and occupants. Escaping corrosive chemicals or oxidizers may attack vulnerable items nearby.

4.4.5 Pipe Bridges

Pipes may cross rivers, flood control channels, ravines or other obstructions on a highway or railroad bridge, or special pipe bridges may be used. Generally, failure of the bridge or excessive bridge movements can cause failure of the pipeline. Failures often occur at abutments, where differential movements may be large.

4.5 Vulnerability Models for Underground Piping

4.5.1 Introduction

For most decisions, empirical or categorization methods for underground piping are enough to provide a sound basis for a subsequent systems evaluation of the water system. In a few cases, especially those involving the construction of new pipelines, more detailed analytic methods may be desirable. This section, however, emphasizes only the majority of cases in which empirical or categorization methods are adequate.

Systematically collected data for estimating vulnerabilities of underground piping are found principally for earthquake strong ground motion and permanent ground deformation hazards. These will first be presented. Some data have been collected locally to estimate the response of buried pipelines for frost heave hazards. These will next be presented briefly. Finally, for other natural hazards potentially damaging buried pipelines, the basic suggestion—absent systematically collected data—is to extrapolate from data collected in regions of permanent ground deformation as a result of earthquakes.

4.5.2 A Brief Summary of Empirical or Categorization Methods for Earthquake Hazards

The most comprehensive summary of earthquake damage data for pipelines is found in ALA, 2001. This discussion will cover only some of the main details of that discussion.

In the first place, ALA, 2001 summarizes data for two types of earthquake hazards: strong ground motions expressed as peak ground velocity (PGV) and permanent ground deformation (PGD). The basic rates are expressed as repairs per 1000 lineal feet of piping repair rate (RR). Distinctions are generally made among diverse types of pipeline material (e.g., cast iron, asbestos cement, welded steel, polyvinyl chloride, and ductile iron) and diverse types of joint (lead or cement-caulked, rubber gasket, arc-welded, riveted, screwed). Further distinctions cover corrosive versus non-corrosive soils, and large versus small diameter pipelines. Discussion of repairs made for breaks and repairs made for leaks are beyond the scope of this document, although many of the repairs needed will likely be for leaks. (See Cassaro et al., 1992 for one detailed discussion of how to analyze repair, to separate them into breaks and leaks). Furthermore, leaks unnoticed at the time of the earthquake may become exposed at significant periods after a damaging earthquake.

For estimating pipeline damage rates, the following two equations are basic:

$$Ln\ (RR) = \text{Ln}\ (K_1{*}0.00187{*}PGV) + 1.15{*}\varepsilon \qquad (4)$$

$$Ln\ (RR) = \text{Ln}\ (K_2{*}1.06{*}PGD^{0.319}) + 0.74{*}\varepsilon \qquad (5)$$

in which:

* means multiplied by

L*n* is the natural logarithm,
RR = repairs per 1000 lineal feet of pipeline,
K_1, K_2 are coefficients dependent on such factors as pipeline material, joint type, corrosivity of soils (see Table 24 for illustrative values),
PGV = peak ground velocity (measured in inches/second),
PGD = peak ground deformation (measured in inches),
e is a normally distributed uncertainty factor with a mean (and median) of zero, a standard deviation of 1

The above equations have an upper limit for PGV of about 50 inches/sec and upper limit of about 100 inches of PGD. (ALA, 2001)

The above equations are used in the summary owing to the emphasis in this document on the uncertainties in modeling water system response to natural hazards. The uncertainties in the above equations are very large. If a robust simulation method is used, then these uncertainties can be modeled through the use of many simulations. Methods for simulating a normal distribution with a mean and median of zero and a standard deviation of unity are found in many works. (See, for instance, Law and Kelton, 1991)

It should be mentioned that equation (5) has a form that is more suitable for the evaluation of repair rates. Owing to practical and physical limitations, one should not expect over a certain number of repairs for 1000 lineal feet of pipe. For instance, on practical grounds, one may divide 1000 lineal feet of pipe into 18- or 20-feet sections and arrive at a practical limit of approximately 50-56 breaks. Even in the worst case, when 1000 lineal feet of pipeline have been severely damaged, replacement of the pipeline would lead to some such upper bound. Worst cases on record have been approximately 12 breaks per 1000 lineal feet of pipeline. The linear form of the equation can in principle (and has for some alternative models) lead to estimates of numbers of breaks far in excess of 50-56 at higher estimates of strong ground shaking. This will not be the case for the first equation above only as a result of the low coefficients used (although for three standard deviations, some estimates may be, say, 4 repairs per 1000 lineal feet of pipeline).

For many applications, it may be desirable to simplify the above equations through the omission of the uncertainty terms. In particular, one may let

$$RR = K_1 * 0.00187 * PGV \qquad (6)$$

$$RR = K_2 * 1.06 * PGD^{0.319} \qquad (7)$$

The use of these simplified equations will basically yield median values of repair rates. These median values of repair rates will be significantly below the mean values of repair rates. As a result, the evaluation using these median values will underestimate the overall expected water system losses resulting from earthquake hazards. Nonetheless, these simplified equations may be very suitable in many applications.

The values of K1 and K2 will only be illustrated in this document, with the anticipation that the more detailed discussion in ALA, 2001 will be used as needed. Table 24 summarizes some of these values and shows how the baseline cases tend to be small cast iron pipelines, with varying coefficients for those pipelines depending on their estimated degree of seismic vulnerability.

Table 24: Illustrative Values of K1 and K2 in Pipeline Seismic Vulnerability Models (ALA, 2001, pp. 38, 39)

Pipe Material	Joint Type	Illustrative K_1	Illustrative K_2
Cast Iron (or Asbestos Cement)	Cement	1.0	1.0
Ductile Iron	Rubber gasket	0.5	0.5
Large Diameter Welded Steel	Lap—Arc welded	0.15	0.15
Polyvinyl Chloride (PVC)	Rubber gasket	0.5	0.8

ALA further contains methods for estimating the probability of some pipe break, and further distinguishes between the above methods for various ground deformations and fault rupture deformations.

Generally speaking, a poisson process may be used to estimate whether or not a specific pipeline has suffered one or more breaks. In general, the probability, P, of n repairs can be established according to the following equation (ALA, 2001):

$$P(x=n) = (RR*L)^n e^{-RR*L}/n!$$

in which

n is the number of repairs,

RR is the repair rate per 1000 lineal feet as determined by previous equations, and

L is the length of pipe (divided by 1000 lineal feet)

This equation will thus permit one to estimate whether or not 0, 1, 2, or more repairs are expected for a specific length of pipeline. In a full simulation, one can use a uniform random generator to estimate for each simulation how many repairs are needed on the pipe segment being evaluated. For instance, if (RR*L) = 0.6, then P(x=0) = 0.549, P(x=1) = 0.329, and so on. If the uniform random generator yields a value of below 0.549, then zero repairs may be simulated. If the uniform random generator is above 0.549 but below 0.878, then one repair may be simulated, and so on.

For fault crossing hazards, ALA, 2001 provides heuristic models:

> For segmented pipelines, no failure occurs if PGD is less than 1 inch, the probability of failure is 0.5 for PGD from 1 to 12 inches, 0.8 for PGD from 13 to 24 inches, and 0.95 for PGD over 24 inches.

For continuous welded-steel pipelines, the probability of failure is less than 0.95 and determined otherwise by the equation 0.70*PGD/60.

These and other models in ALA, 2001 are currently under review in an ASTM (American Society of Testing and Materials) standards committee.

4.5.3 Vulnerability of Pipelines from Frost Heave

As indicated in Chapter 4, estimating frost heave depends principally on grain size (grain sizes with 3% or more by weight less than 0.02mm or 0.0004inches), temperatures or freezing values, and groundwater within 5 feet (1.5 m) at any time of the year.

Since generalized models of pipeline repairs owing to frost heave are unavailable, it is suggested that local water utilities affected by frost heave hazards develop their own empirical data on breaks and leaks. Following Cassaro et al. (1992), the local water utility can develop longitudinal estimates of pipe repairs first as a function of temperature. These estimates can be further broken down by soil type, water table depth, installation period (if pertinent), joint construction, and pipe material.

4.5.4 Vulnerability of Pipelines from Other Natural Hazards

Other natural hazard events that may lead to pipeline damage include gravity landslide, expansive soils, soil collapse, riverine flood and scour, headwater flood and scour, hurricane—storm surge and scour, hurricane—headwater flood and scour, and hurricane—riverine flood and scour.

The authors do not know of systematically collected data on pipeline damage from these natural hazards events, although local flood control districts and FEMA may have data , for instance, on pipeline damage based on watercourse hazards. In the absence of data, estimates of PGD from an evaluation of natural hazards may yield reasonable but very coarse estimates of damage as based on models developed for earthquake permanent ground deformations. The state-of-the-art in assessing pipeline damages from these natural hazards (e.g., gravity landslide, expansive soils, and so on) is here assumed to be very wanting. Since very little exists in the form of generic pipeline vulnerability relationships for many hazards (e.g., ground movement), these vulnerability relationships can be treated by analytical methods for site-specific assessments. This is appropriate for critical components and hazards that are typically very localized, such as landslides and zones of soil expansion or settlement.

4.6 Vulnerability of Buildings

4.6.1 Introduction

Buildings are considered in this document insofar as they are essential to water system operations. Water agency buildings may include:

- the water district office, the headquarters building, and Emergency Operations Centers

- shelter structures for pump stations and water treatment plants
- the maintenance yard and garage structures
- warehouse (parts, stock, and equipment)

Buildings house and protect critical control equipment and personnel from weather-related phenomena and hazards.

4.6.2 Building Damage in Natural Hazards

Buildings may be damaged by most of the other natural hazards under consideration:

- Earthquakes produce inertial forces by ground shaking, and damaging differential ground deformations associated with soil liquefaction, surface fault rupture, and landslide.
- Winds (hurricane, tornado or other) cause differential pressures, and transport debris (including wind-generated missiles). Wind pressures may damage roof, window, door damage, leading to loss of integrity of the building envelope, with wind and water-related damage to internal nonstructural walls, ceilings and floors, equipment and other contents. The sudden change in pressure from violating the building envelope can also lead to general structural failure.
- Floods, tsunami or seiche (damage from immersion, and force of flowing water, as appropriate) or storm surge can inundate structures, causing damage to damage to wood framing, drywall, ceilings, contents, stored data, and damage to electrical, mechanical and other equipment.
- Slope failures can damage building foundations, or lead to total collapse of the structure.
- Expansive soils and freeze/thaw cycles can damage building foundations and other exposed elements.
- Susceptibility of buildings to wildfire hazards depend upon clear space between surrounding trees or brush and the building perimeter, as well as the flammability of exterior building materials.

4.6.3 Assessing Building Vulnerability for Earthquakes

In earthquake, damage can occur to contents or contained equipment, to architectural elements (nonstructural damage), or to the lateral force resisting system. Damage to building elements such as contents, storage racks, suspended ceilings or piping (e.g., a water quality laboratory) may result from in-structure accelerations, which tend to be amplified over the building height. Damage to building structural elements may occur due to excessive displacement demands related to interstory drift, or from overstress, or from connection weaknesses. The strength and toughness (ductility) of the structural and nonstructural elements depend upon the materials used (steel, masonry, wood, concrete) and design detailing. Overall building vulnerability may be increased by nonductile (brittle) elements or connections, interruptions to the load path, poor configurations (plan or vertical irregularity), low redundancy, or low strength.

The assessment of building vulnerability for earthquake hazards has benefited from the efforts of many individuals and institutions, culminating in documents produced under FEMA's National Earthquake Hazard Reduction Program (NEHRP):

FEMA 154 - Rapid Visual Screening of Buildings for Potential Seismic Hazards [1988]

FEMA 310 - Guidelines for Seismic Evaluation of Existing Buildings

FEMA 273 (now FEMA 356) - Guidelines for Seismic Rehabilitation of Buildings

In preliminary studies, the rapid screening techniques are particularly useful. In subsequent phases of study, the more detailed techniques of FEMA 310 may be useful. Where weaknesses are found and mitigation is required to meet water system life-safety or performance objectives, FEMA 356 may be employed.

One weakness of these methods in the current context is that they were not developed specifically for water agency buildings. Neither do they provide models that are easily adapted for use in water system modeling. They provide methods to evaluate the critical weaknesses of a building and predict its general damage states (meeting or not meeting particular performance objectives) for a given level of earthquake hazards. A building may be evaluated at several hazard levels to develop a model that directly relates ground motion and related earthquake hazards directly to a damage state. The earthquake performance levels in FEMA 356 are described as follows:

Table 25: Structural Performance Levels in FEMA 356

(S-1) Immediate Occupancy Structural Performance Level	The post-earthquake damage state that remains safe to occupy, essentially retains the pre-earthquake design strength and stiffness of the structure, and is in compliance with the acceptance criteria ...
(S-2) Damage Control Structural Performance Range	The continuous range of damage states between the Life Safety Structural Performance Level (S-3) and the Immediate Occupancy Structural Performance Level (S-1).
(S-3) Life Safety Structural Performance Level	The post-earthquake damage state that includes damage to structural components but retains a margin against onset of partial or total collapse in compliance with the acceptance criteria specified in this standard for this Structural Performance Level.
(S-4) Limited Safety Structural Performance Range	The continuous range of damage states between the Life Safety Structural Performance Level (S-3) and the Collapse Prevention Structural Performance Level (S-5).

(S-5) Collapse Prevention Structural Performance Level	The post-earthquake damage state that includes damage to structural components such that the structure continues to support gravity loads but retains no margin against collapse in compliance with the acceptance criteria …

[Adapted from Section 1.5.1, FEMA 356]

FEMA 356 provides thorough description of the damage states for the elements of each defined type of building structure to achieve the selected earthquake performance level.

Buildings designed and constructed without special criteria, energy dissipation or seismic isolation systems will generally not meet the objectives of the Immediate Occupancy Performance Level (S-1) under the earthquake hazard levels specified in FEMA 356. This does not necessarily imply failure to function under the presumed earthquake hazard level. Judgment is needed to adapt the Rehabilitation Guidelines into useful relationships for building damage, functionality or restoration time.

Simple damage functions for buildings are provided by other sources, such as ATC-13, models by Karl Steinbrugge, models by J.H. Wiggins, and models developed as a part of FEMA's HAZUS software [Kircher et al]. These predict repair costs and/or damage states for classes of building construction.

For instance, damage relationships are often derived from ATC-13 [Applied Technology Council, 1985], a widely-used and intended for coastal California construction, designed for the equivalent Uniform Building Code Seismic Zone 4. ATC-13 provides damage functions to estimate repair costs as a fraction of building replacement value, for 40 building types. Outside of California, these relationships may need to be adjusted to account for local design and construction practice. This is usually done through engineering judgment. One hypothesis that can serve as a basis for adjustment of building damage functions is that buildings designed for Zone 3, when exposed to Zone 3 ground motions (i.e., having a peak ground acceleration of 0.3g), will experience damage levels similar to Seismic Zone 4 construction subjected to Zone 4 ground motions (i.e., having a peak ground acceleration of 0.4g).

4.6.4 Assessing Building Vulnerability – Windstorm

Unlike earthquake damage where the building frame itself can sustain a high degree of damage, damage to buildings associated with wind forces (hurricanes and other extreme winds) is usually caused by failures of the building envelope, including the roof cover, windows and doors. Exceptions to this occur for small buildings, where the entire building may be displaced from its foundation, and for the most extreme winds (e.g., tornadoes) where complete structural failure may occur.

Many water agency buildings are of light-metal construction. These may be open shelters or enclosed buildings, and damage may include loss of exterior wall or roof sheathing, sliding or lifting of the entire structure. Damage to the shelter may lead to high levels of damage to the associated equipment.

Where walls are constructed of concrete, brick masonry or concrete block, the most vulnerable portions of the building are generally the windows and doors, as well as the wood or metal roof deck. During a severe wind event, doors or windows may fail inwards, precipitating an increase in pressure inside that section of the building, which loads the underside of the roof deck, significantly increasing the net upward load on the building. Since the roof deck is usually designed assuming an enclosed space (i.e. no change in internal pressures), the increase in internal pressure can easily exceed design loads and cause roof system failure. Another source of wind-related failure comes from wind-borne debris, from gravel to large, heavy objects, which can break windows, or even penetrate the building shell.

For important buildings, vulnerability models may use a load and resistance modeling approach, where simulated winds are passed by the building, with the wind speed and wind direction varied, and maximum force demands tracked. A direction-dependent vulnerability model may be used in conjunction with a directional wind loading model used to estimate the loads at any point on the building at any point in time. Given the wind load demands acting on the exterior of the building, the loads are compared to the modeled resistance of the relevant building components. The component is assumed to fail when the load exceeds the resistance. This analysis can be performed in a deterministic manner, or with probability distributions for the component failures. Once an envelope component fails, the change in internal pressures is computed, and other internal components are examined for the increased load.

More approximate building damage models may be developed through judgment, based on visual survey and review of the design documents. Design documents often state the design assumptions used, such as basic wind speed. Visual survey can indicate whether significant modifications have been made since original construction, and whether preexisting damage or deterioration has undermined capacity of the existing building. The visual survey should also focus on exterior elements that may fail and violate the building envelope. Relevant codes for hurricane winds include ASCE-7 and the Southern Building Code (SBC). Local and national wind design regulations have changed significantly over time, especially after milestone storms (e.g., Hurricane Andrew, etc.).

4.6.5 Assessing Building Damage in Floods

Building damage in floods is largely a function of the level to which flood waters rise. A simple model may assume that, if the flood occurs, the entire building may be lost, together with the contents on each floor subject to inundation. Hence, the focus is on the probability of occurrence of the flood event, and on the maximum flood height, rather than on models to quantify the degree of building damage.

With partial inundation, the basic frame of a steel, masonry or concrete building may survive inundation. A wood-frame building may be a total loss. The nonstructural elements, including electrical power and electronic systems, communication systems, etc., may need to be replaced.

A water treatment plant may suffer serious contamination in flooding. Water inventory may be lost, and more water used in decontamination.

4.6.6 Assessing Building Damage in Landslides

A simple model may assume that, if the landslide occurs, the entire building is lost, together with its contents. Hence, the focus is on the probability of occurrence of the landslide event, rather than on models to quantify the degree of building damage.

4.6.7 Assessing Building Damage in Fires

A simple model may assume that, if a wildfire occurs affecting the building site, the entire building is lost, together with its contents. Fire breaks and fire-resistant building exteriors may reduce the likelihood of loss, and a probability distribution can be constructed, relating fire intensity and duration to the probability of total building loss. Active fire suppression (i.e., by the fire department) may reduce or eliminate losses, but the availability of these resources may be limited in a large or wide-spread fire.

For fires occurring within the structure due to storm-induced electrical short-circuits or earthquake-induced ignitions, automatic fire sprinkler systems may limit structural and nonstructural losses to the area where the fire initiates. In the case of earthquake-initiated fires, the post-earthquake operability of the fire sprinkler system, or the availability of water at adequate pressure and flow rates, may also come into question.

4.6.8 Modeling Buildings within Natural Hazards Risk Assessment

<u>Economic Damage</u>

The estimation of repair costs for the building itself requires the use of a damage function. These relate damage to hazard intensity (wind speed, ground acceleration, water depth, etc.), generally as a fraction of building replacement value. Hence, an accurate prediction of repair costs requires good replacement value data for large, important buildings. More approximate replacement values may be derived from Means Cost Data or other sources, and such approximate methods may be appropriate for smaller buildings.

<u>Collateral damage to contents and equipment</u>

There is a correlation of building distortion (drift) and the degree of damage that occurs to contents and equipment, especially equipment that is rigidly connected to more than one structural member. In the most extreme case, structural collapse may destroy all contents and equipment within. In a more limited case, damage to a building wall may precipitate damage to the supported equipment.

There are correlations of acceleration and damage to contents and equipment, as in earthquake shaking. Building structures amplify ground motions, so the seismic environment at the actual mounting point must be considered. Contents may be highly damaged by loss of building envelope integrity in winds.

The inventories needed for water system repair following a natural hazard event may themselves be damaged in the event. As an example, in the M6 Whittier-Narrows earthquake in 1987, sewer system components were damaged due to poor storage practice in sanitation district yard in Whittier.

Damage resulting in loss of occupancy (for occupied structures, such as an office, Emergency Operations Center, etc.)

At a certain damage level or damage state, post-earthquake damage inspections may determine that the building is unsafe to occupy (i.e., it may be red-tagged or yellow-tagged). The duration of vacancy to effect repairs is a complex function of the degree of damage, the type of construction, the resources of the water agency, and the availability of engineering and construction (repair) resources. The period of vacancy is subject to a limit -- either the time required to relocate the critical functions, or the time for complete reconstruction. Non-occupied buildings are an exception.

Water System Functional Impacts

In modeling water system impacts from building damage, the role and function of the building must be defined within the water system. What functions are carried out in the building? Are key water agency personnel housed within it, and would injury or loss of life impair agency response and recovery? Is the building an Emergency Operations Center, does it house SCADA systems, or does it serve as a communications hub? What are the system-wide consequences of the loss of these functions at this location? How would water agency personnel resume functions elsewhere?

4.7 Interdependence of Water System Facility Damage and Other Damage

Other structures, such as highway or railway bridges, often support pipelines. Movements of a bridge structure with respect to its abutments may damage the pipeline. Collapse of the bridge will destroy the pipeline segment. If the bridge collapses, repair of the pipeline may require extensive and expensive temporary pipe bridge or other means, pending repair or replacement of the bridge. Meaningful assessment of the bridge's vulnerability, and its potential relative movements (structure versus abutments) requires a high level of effort and significant expertise. Often, the local, state or federal highway department may be able to provide assistance in this modeling, related to the design criteria used for the bridge, typical design margins with respect to defined hazards, past performance of similar structures in the vicinity, or even specific analyses performed for the hazard of interest.

Examples of adjacent structures include a standpipe whose damage could lead to damage both to a fire station and a communication tower. (A. Alfi, written comm., 6/02)

Other examples of interdependence include the collapse of an enclosure building that destroys a chlorination system, or an Emergency Operations Center that is destroyed by flooding, taking with it the enclosed SCADA equipment.