# 3.0 MODELING NATURAL HAZARDS

## 3.1 Introduction

In this chapter, guidelines are provided for how natural hazards can be modeled for the evaluation of water supply systems risks. This chapter covers two of the shaded boxes in Figures 1: "Identify Natural Hazard Events to be Considered" and "Evaluate Hazard at Each Component Site."

Emphasized again is the requirement that natural hazards are to be modeled using a complete suite of event scenarios with probabilities assigned to account for the true risk to a water utilities unit treated as a system, an interconnected set of geographically distributed components. Note that the word probabilistic is emphasized as opposed to deterministic. The problem with deterministic methods in evaluating water utilities units is that they involve only a few selected scenarios for this evaluation with no likelihood's assigned, and so do not yield estimates of risk.

For the evaluation of selected natural hazards that are not extensively geographically distributed (e.g., a small landslide, a site with potential soil collapse, a localized flood zone), one can construct intensity scenarios for the site of interest. Intensity here represents the natural hazard effects at a single site. The term "site" is represented by some localized region (e.g., a zip code, a township section, a clearly identified lot). For such geographically concentrated natural hazards, the two shaded boxes in Figure 1, namely "Identify Natural Hazard Events to be Considered" and "Evaluate Hazard at Each Component Site," can converge.

However, for hazards that are extensively distributed geographically (e.g., hurricanes, earthquakes, great floods), the natural hazard must be treated separately from its local site intensity modification effects. Geographically large water utility systems require that initiating events be modeled first, followed by the modification of intensity (however physically measured) for the various sites within the water utility system. Hence, to comprehensively cover the topic of modeling natural hazards for water system risks, modeling efforts must consider both (1) how to model sources of natural hazards and then, as needed, (2) their attenuation or other intensity modification influences.

These guidelines cover only publicly available information and models, and not the many proprietary models and computer programs covering natural hazards. The public literature provides examples of four types of modeling methodologies ranging from fairly complete and rigorous to indicative of a hazard problem only. The modeling methods are variously described as: (A) relatively complete probabilistic modeling capability is available in data form in the literature, (B) only a partial probabilistic modeling capability is available in data form in the literature, (C) an approximate probabilistic modeling capability is available using data in the literature and (D) the data in the literature is only indicative of a possible problem with no associated probabilities. Each hazard is also described as either independently occurring (I) one from the other or dependently occurring as the result of an associated hazard (D).

For the rest of this Chapter, section 3.2 covers modeling ground movement hazards: gravity landslide (3.2.1), expansive soil (3.2.2), soil collapse (3.2.3), and frost heave (3.2.4).

Section 3.3 covers modeling flood hazards: riverine flood (3.3.1), and headwater flood (3.3.2).

Section 3.4 covers modeling windstorms: general severe wind (3.4.1), tornado (3.4.2), hurricane-tornado (3.4.3), hurricane-cyclone (3.4.4), hurricane-storm surge (combined with riverine flood and headwater flood) (3.4.5), and combining hurricane effects (3.4.6).

Section 3.5 covers modeling earthquakes: fault rupture (3.5.1), shaking (3.5.2), landslide (3.5.3), lurching and liquefaction (3.5.4), tsunami (3.5.5), seiche (3.5.6), and fire following (3.5.7).

Appendix C discusses more qualitatively the phenomenology of these natural hazards. The focus in this Chapter is on quantitative considerations in modeling natural hazards.

Tables 1 through 3 list the available computer programs, probabilistic hazard maps, indicative hazard maps, historic hazard data and hazard conditioning data that are readily available and can be used in modeling. Example reference sources available on the Internet and in the literature are also listed. The hazard and conditioning data can be used to develop coarse probabilistic models. Similar tables for more specific references are found in sections for ground movement hazards (3.2), flood hazards (3.3), windstorms (3.4), and earthquakes (3.5). Table 4 presents an overview of the judged current ability, as developed in this report, of available information and data to be used to model hazards probabilistically without a great deal of theoretical algorithm development.

## 3.2 Modeling Ground Movement Hazards

### 3.2.1 Gravity Landslide

Table 5 provides general references for quantitative modeling of landslide hazards. Appendix C provides an account of the phenomenology of landslides.

Natural Hazard Mechanism

Landslides can be identified by their geologic settings and topographic features based on: (1) field observations, (2) areal photograph interpretations and (3) topographic map interpretations. Features indicative of landslides are arch-shaped escarpments, ground cracks, ground hummocks, hillside benches, hillside ponds and disruptive drainages. Some landslides have had large displacements in historic time and are still near a critical state of stability. Others appear to have been dormant for a long period of time and may no longer be near a critical state of stability. Features are well-defined on recently active landslides, but with time and no further movements they become subdued due to weathering and erosion.

A method for estimating how long a landslide has been dormant based on surface features has been proposed for landslide inventory mapping. It is advisable, however, that apparent age of landslide dormancy not be relied on solely when assessing the current stability state of an existent landslide. For many landslides, judgement should be supported by: (1) subsurface exploration results, (2) slope movement and ground water assessment and monitoring and (3) stability modeling studies to give more accurate assessments of slide probability.

*Table 1: Types of Publicly Available Models and Data for Creating Probabilistic Models of Natural Hazards Data*

**A. Computer Models of Natural Hazards Intensity**

- Storm surge (SLOSH)
- Earthquake (HAZUS)
  - Faulting
  - Shaking
  - Landslide
  - Lurching-Liquefaction
  - Tsunami*
  - Seiche*
  - Fire Following
- Hurricane (HAZUS—under development)
- Flood (HAZUS—under development)

**B. Probabilistic Natural Hazard Maps**

- Tsunami
- Severe Wind
- Hurricane Wind
- Storm Surge-River/Headwater Flood
- Earthquake-Shake

**C. Indicative Natural Hazard Maps**

- Landslide
- Expansive Soils
- Soil Collapse-Earth Subsidence
- Frost Heave

**D. Historic Hazard Initiation Data**

- Hurricane (size, track, pressure, speed, date)
- Tornado (size, track length, width, date, time, location)
- Air Temperature (location, date, time)
- Rainfall Amounts (location, date)
- Wind Speeds (location, date)
- Earthquakes (location, magnitude, depth, date)
- Major Floods (location, date, duration)
- Tsunamis (location, source quake, run-up, date)
- Active Faults (name, slip rate, location, length, characteristic magnitude, dip, width, return period, G/B A-value, b-values)
- Costly Landslides (location)

**E. Hazard Conditioning Data**

- Earth Material Types and Thickness (location)
- Elevation (location)
- Water Table Depth (location)
- Lake and Embayment Parameters (location)
- Conflagration Parameters (location)
- Earthquake Shake Attenuation (location)
- Hurricane Wind Configuration (location)

*Table 2: Organizations Supplying Pertinent Models, Maps, or Data for Modeling Natural Hazards Probabilistically*

| U.S. Government | Item or Data Supplied |
|---|---|
| • Natural Resources Conservation Service (NRCS)<br>• National Oceanic and Atmospheric Administration (NOAA)<br>• National Weather Service (NWSS)<br>• National Hurricane Center (NHC)<br>• National Climatic Data Center (NCDC) | • National Atlas<br>• Earth materials maps<br>• SLOSH (storm surge computer program)<br>• Severe wind data and maps<br>• Hurricane data and maps<br>• Storm surge data and maps<br>• Air temperature data<br>• Tornado data<br>• Rainfall data<br>• Wind speed data<br>• Flood data<br>• Hurricane wind configuration data |
| • U.S. Corps of Engineers (USCE) | • Flood maps<br>• Storm surge maps<br>• Expansive soils maps |
| • Federal Emergency Management Agency (FEMA) | • HAZUS (earthquake hazard computer program)<br>• SLOSH (storm surge computer program)<br>• Flood maps |
| • U.S. Department of the Interior (USDOI) | • Tsunami maps and data |
| • U.S. Geological Survey (USGS) | • Earthquake maps and data<br>• Landslide maps and data<br>• Expansive soil map and data<br>• Soil collapse data<br>• Active fault data<br>• Earth materials data<br>• Elevation data<br>• Water table data<br>• Earthquake shake attenuation |
| **Private and State Organizations** | |
| • J. H. Wiggins Company (JHW) | • Expansive soils map |
| • Thomas P. Grazulis (TPG) | • Tornado data |
| • Lockshell Corporation (LC) | • FEMA flood maps, digitized |
| • Bergey Windpower (BW) | • Wind maps, average annual wind speed |
| • North Carolina State University (NCSU) | • Hazard data |
| • Various State Geologists (SG) | • Earth materials, local hazard maps, water table data |
| • Environmental Systems Research Institute, Inc. (ESRI) | • National hurricane, tornado, flood, earthquake, wind, hail intensities |

*Table 3: Sample General References for Data and Models for Developing Probabilistic Models of Natural Hazards*

| **Climate History** | **What is supplied?** |
|---|---|
| • http://www.nws.noaa.gov/oh/hdsc/max_precip/maxprecp.htm | Data for maximum rainfall throughout the world recorded in time periods ranging from 1 minute to 2 years. To be used with average annual rainfall. |
| • http://www.nedi.gov | The National Environmental Data Index (NEDI) provides direct access to environmental data and information descriptions, and thereby, improves awareness of and facilitates access to data and information holdings. |
| • http://www.nws.noaa.gov/oh/hdsc/noaatlas2.htm | 2 yr 6 hr, 2 yr 24 hr, 100 yr 6 hr and 100 yr 24 hr rainfall in the 11 western states. |
| • http://www.srh.noaa.gov/lub/wx/precip_freq/intor_rtside.htm | 1 yr, 2 yr, 5 yr, 10 yr, 25 yr,50 yr, 100 yr (30 min, 1 hr, 2 hr, 3 hr, 6 hr, 12 hr, 24 hr) rainfall in the states east of the 11 western states. |
| • http://www.wrcc.dri.edu/pcpnfreq.html | Western U.S. precipitation frequency maps (see site above for the eastern states). |
| • http://www.publicaffairs.noaa.gov/releases2000/dec00/noaa00084.html | Temperature, precipitation, wind, hail, tornado tracks. |
| • http://lwf.ncdc.noaa.gov/oa/documentlibrary/freezefrost/frostfreemaps.html | Risk maps for freeze free, spring freeze and fall freeze occurrence. |
| **Earth Materials and Terrain** | **What is supplied?** |
| • http://tapestry.usgs.gov/two/two.html | Includes all State Geologist websites. |
| **Atlas of Hazards Locations** | **What is supplied?** |
| • http://www.esri.com/hazards/makemap.html | Flood, recent earthquakes, historic earthquakes, historic hail storms, historic hurricanes, historic tornadoes, historic wind storms. |
| • http://www.nationalatlas.gov | Maps of many facts including: annual average rainfall, landfalling hurricanes and tropical storms, abandoned coal mines, coal fields, costly landslide events, costly regional landslide events, geologic map, landslide overview map, shaded relief, significant earthquakes. |
| • http://www.ngdc.noaa.gov/seg/hazard/resource/geohaz | (Call Paula Dunbar: (303) 497-6084 or pkd@ngdc.noaa.gov) Hazard index: seismic, geotech, landslide, software for same, sinkhole, tsunami. |
| • http://www.lib.ncsu.edu/stacks/gis/themes/term0240.html | GIS lookup—Natural Hazards: seismic, hurricanes, flood zones, fire, drought, tornadoes, landslides |
| • http://www.lib.ncsu.edu/stacks/gis/hazus.html | HAZUS: utility systems, SLOSH basin maps (hurricane maps), FEMA Q3 flood data. |
| • http://rsd.gsfc.nasa.gov/goes/text/interesting.servers.html | Websites for all types of ancillary information |

*Table 4: Natural Hazards That Can be Probabilistically Modeling Using Available Data and Published or Easily Developed Methodologies (Our Judgement)*

| Natural Hazard | Relative Geographic Area Affected | Modeling Capability |
|---|---|---|
| Gravity Landslide (I) | S | D |
| Expansive Soil (I) | L | D |
| Soil Collapse (I) | M | D |
| Frost Heave (I) | L | D-- |
| Riverine Flood (I & DEP) | L | A |
| Headwater Flood (I) | L | A |
| General Severe Wind (I) | L | B |
| Tornado (I) | L | A |
| Hurricane-Cyclone (I) | S | A |
| Hurricane-Tornado (DEP) | S | - |
| Hurricane-Storm Surge (DEP) | S | A |
| Hurricane-Headwater Flood (DEP) | L | See ratings for headwater flood and storm surge |
| Hurricane-Riverine Flood (DEP) | L | See ratings for riverine flood and storm surge |
| Earthquake-Fault Rupture (I) | S | A |
| Earthquake-Shaking (DEP) | L | A |
| Earthquake-Landslide (DEP) | S | D (possible A) |
| Earthquake-Lurching (DEP) | S-M | D |
| Earthquake-Liquefaction (DEP) | S-M | C (absent boring log data) |
| Earthquake-Tsunami (DEP) | S | A |
| Earthquake-Seiche (DEP) | S | - |
| Earthquake-Fire Following (DEP) | M | D-- |

I = Independently Occurring Natural Hazard
DEP = Natural Hazard Occurrence is Dependent on Another Natural Hazard Occurring
S = Small-affects only local areas, usually smaller than 2 square miles (5.2 sq km).
M = Medium-affects moderately sized areas, between 2 and 30 square miles (5.2 and 78 sq km).
L = Large-affects an entire system, even very large ones over 30 square miles (78 sq km).
A = Data is available to model the hazard fairly completely. Conditioning data is spotty. Estimates for large return period events are questionable.
B = Much better than D but of lower quality than A. Only partial modeling capability is possible without a great deal of additional theoretical modeling and data, especially conditioning data.
C = Better than D but worse than B. Much higher quality and quantity of data and a lot of work developing theory is required to approach A.
D = Method only indicates the possible presence or absence of a problem. Probabilities are estimated only coarsely.

*Table 5: Sample General References for Data and Models for Developing Probabilistic Models of Landslides*

| Landslides | What is supplied? |
|---|---|
| • http://www.ngdc.noaa.gov/seg/hazard/resource/geohaz/ldslhaz.html | Gateway to landslide information. Maps |
| • http://landslides.usgs.gov/html | Landslide maps |
| • http://landslides.usgs.gov/html_files/landslides/nationalmap/legend.html | Landslide maps |
| • http://cindi.usgs.gov/hazard/landslide.html | Landslide maps |
| • http://landslides.usgs.gov/html_files/nlicsun.html | Landslide maps |
| • http://edcwww.cr.usgs.gov/glis/hyper/guide/usgs_dem | Landslide maps |
| • http://cascade.lcsc.ed/terrain/metadata/generic_dem.htm | Landslide maps |
| • http://lwf.ncdc.noaa.gov/oa/ncdc.html | Landslide maps |

Precipitation and associated ground water changes have a preeminent influence on landslide stability. For example, landslide activity is reported to have increased during the period 1983 through 1987 as a result of higher than normal annual precipitation in Colorado. Precipitation change has apparently occurred in Colorado during the past five hundred years. Studies in the upper Colorado River drainage basin show that since the early 1500's wet cycles with an average duration of ten years have occurred about every 22 years. Long-term monitoring of a steep, colluvial slope in western Colorado has shown a correlation between winter precipitation (November through May) and annual slope creep. Most of the creep occurs during the spring snow pack melt. Consequently, gravity landslide propensity and, therefore, frequency depends largely upon the rainfall frequency-severity (inches per unit of time) of the region in question.

Landslides can be classified in many ways, each having some usefulness in emphasizing features pertinent to recognition and reduction of losses from landslides. Two criteria, (a) types of movement and (b) types of material, are typically used. Types of movement include falls, topples, slides, spreads, flows, and combinations of two or more of these five types. Types of material involved with a slide include two classes–bedrock and soils, with soils being divided into debris and earth materials (see Table 6).

All slides involve the failure of earth materials under shear stress. The initiation of the process can, therefore, be thought of in terms of the factors that contribute to increased shear stress and the factors that increase stress directly (load) and those that reduce shear strength (resistance). Although a single action, such as the addition of water to a slope, may contribute to both an increase in load and a decrease in strength, it is helpful to separate the various physical results of such actions.

*Table 6: Classifications and Definitions of Slope Movements*
*(See Figure 4 for Examples)*

| | **Type of Material** | | |
|---|---|---|---|
| | | **Soils (Earth Materials)** | |
| **Type of Movement** | **Bedrock** | **Coarse-grained (debris)** | **Fine-grained (earth)** |
| Falls | Rock fall | Debris fall | Earth fall |
| Topples | Rock topple | Debris topple | Earth topple |
| Slides | Rock-block slide | Debris-block slide | Earth-block slide |
| Rotational | Rock slump | Debris slump | Earth slump |
| Translational | Rock slide | Debris slide | Earth slide |
| Lateral spreads | Rock spread | Debris spread | Earth spread |
| Flows | Rock flow | Debris flow | Earth flow |
| Complex | Combination of two or more of the above | | |

The principal factors contributing to increased shear stress (load) are:

- Removal of lateral support by such means as erosion by streams and rivers, glaciers, or waves and longshore or tidal currents at the toe of a potential slide; previous slope failure; and results of adjacent construction, especially where cuts, quarries, pits, and canals are established, retaining walls and sheet piling are removed, or lakes and reservoirs are created and their levels altered.

- Loading by natural or human means provided by weight of rain water, hail, snow; accumulation of loose rock fragments or accumulated volcanic material; new stockpiles of ore or rock; new waste piles; and weight of new buildings and other structures.

Vibrations from earthquakes, blasting, machinery and traffic trigger an incipient slide (to be discussed further in a later section).

The principal factors contributing to a reduction in shear strength include:

- Inherent deterioration and weakening characteristics of the parent material–its composition, texture, structure, slope geometry.
- Weathering and other physicochemical reactions of the materials which tend to weaken them.
- Increases in water content and pore pressure in the soil structure.

## Probabilistic Analysis

A map of landsliding in the conterminous United States (Figure 5) provides an overview of the distribution and relative severity of landslide hazards. The map shows two aspects of landsliding–incidence and susceptibility. Incidence of landsliding refers to areas where landslides have actually occurred. For example, areas of high incidence contain more than 15 percent of discovered past slope failures. Areas of moderate incidence contain 1.5 to 15 percent of failed slopes in historic time. Susceptibility to landsliding refers to the strength of the earth materials in the area. Areas of high susceptibility are underlain by very weak or fractured materials.

Although not shown on the map, parts of Alaska and Hawaii also are severely affected by landslides.

There are no known truly probabilistic analysis models available for landslides in all parts of the United States. There is only the map, rather coarse in nature. It has been produced by the USGS and cited in the “natural hazards template”, Table 7 (an attempt to summarize the hazard intensity data and intensity modification factors on one page).

The landslide “probability” descriptors for the USGS map shown in Figure 6 are difficult to quantify. It is suggested that the Geological Survey office for the state in question be consulted for landslide likelihood information about specific areas. Further, the general

statement in the map that the loads may be produced by “natural or artificial cutting or loading of slopes, or to anomalously high precipitation” raises many questions. The cutting referred to is local in nature and is not included in a national mapping perspective. Only the rainfall can be evaluated as one of the driving forces that may activate a landslide. However, what constitutes an “anomalous high precipitation?” 1 in 50 years? 1 in 100 years? Other?

The map is quite general as is shown in a blowup of the Los Angeles County area (Figure 7). This figure shows some of the critical colors described in Figure 6. All of the Palos Verdes peninsula is colored red which is labeled High (greater than 15% of area involved). However, all of the red area is not steep (a slope is necessary for gravity to activate a slide). Thus, some modification of this area is required by overlaying an elevation contour map on top of the same area. See Tables 3 and 5 for websites providing elevations for all regions of the country. Finally, the only parameter of any significance that provides probabilistic data that is nationally available is rainfall incidence, on an hourly, daily, monthly and annual basis. Websites are also available for this information.

As an example, the National Weather Service has recorded rainfall for the Los Angeles area since 1878 (124 years). (Please note that the Palos Verdes station has only been in operation since 1931 or 72 years). The annual mean is 13.51 inches (34.32cm) with the 1 ó, 2 ó, and 3 ó annual amounts being 21.71 inches (55.14cm), 34.89 inches (88.62cm) and 56.08 inches (142.44cm), respectively. (σ refers to the standard deviation). Since the highest rainfall amount recorded in the 124 year time span is 40.29 inches (102.33cm) and since significant landsliding has been noted in the 124

*Table 7: A Template for Modeling Gravity Landslide Intensities*
*(Measure of Hazard Intensity inches/inch or cms/cm)*

**Principal effects of the hazard on water utility systems:** Fracture underground lines. Fail foundations of structures on the surface. Debris flow into above-ground structures.

| Principal Activating Parameters | Data Location | Data Quality | Data Quantity? | Data Gaps? | Data Condition? |
|---|---|---|---|---|---|
| • Removal of lateral support | (?) | NA | NA | NA | NA |
| • New weight added (eg. water) | Rainfall (NOAA) | Good | Virtually all | ± 100 yrs | Good |
| • Vibrations | Earthquake (USGS) | Good | Virtually all | ± 100 yrs | Good |

| Principal Conditioning Parameters: | Data Location? | Data Quality? | Data Quantity? | Data Gaps? | Data Condition? |
|---|---|---|---|---|---|
| • Slope (grade) | USD0I | Good | Good | None | Good |
| • Earth materials | USGS/State Geologist | Not local | Spotty to poor—in most cases | (?) | (?) |
| • Weathering of materials | (?) | (?) | (?) | (?) | (?) |
| • Pore water pressure increase | NOAA | Good | Good | ~ 100 yrs | Good |

**Websites or References Containing Data:** See references and websites in Table 3 labeled “Climate History,” “Earthquake Materials and Terrain” in Table 5 for “Landslides.”

**Available Probabilistic Models:** None to our knowledge.

year time frame, a 2 ó or a 2.27% chance of occurring in any one year is arbitrarily assigned to define the red, high incidence area. Possibly a 3 ó (0.135%) and a 4 ó (0.00385%) can be arbitrarily assigned to represent the moderate incidence and low incidence areas respectively. The susceptibility areas are not addressed for an arbitrary assignment of probabilities.

The assignment of the 2 ó to 4 ó probability values to the various colored areas is strictly arbitrary. An in-depth study of the history, gradient, rainfall and other factors is required to develop a reasonable likelihood of land failure in areas covered by a specific water supply facilities district. For these reasons, this procedure is rated a “D” as indicated in Table 4.

### 3.2.1 Expansive Soil

The phenomenology for expansive soil is found in Appendix C. The template for modeling expansive soil intensity likelihoods is shown in Table 8. No general, national models are known to be publicly available. The only known maps are those published in 1978 by the J.H. Wiggins Company (Figure 8), the map published by the USGS shown in Figure 9 and the map published in 1977 by the US Corps of Engineers, Waterways Experiment Station in Technical Manual 5-818-7 (Figure 10). All three maps differ, one from the other. All are based on coarse and general geological information associated with certain areas that is judged to contain montmorillonite minerals. It is suggested that each state Geologist be consulted about expansive soils details at specific sites.

The legends for “High” refer to soils containing large amounts of montmorillonite and clay (COLE >6%); “Medium” refers to soils containing moderate amounts of clay with some montmorillonite (3%   COLE   6%) and; “Low” refers to soils containing some clay but of the low swelling type (COLE < 3%). Ratings correspond to the modified shrink-swell (COLE) categories of the National Resources Conservation Service (NRCS) of the U.S. Department of Agriculture.

The only hazard initiating parameter that would affect the intensity of differential movement of the clays in the soil is rainfall amount. Again, the question of what level of probability to use to trigger various amounts or degrees of differential movement and therefore intensity of the hazard is open to expert judgement. Further, both drought and excessive amounts of rainfall above and below the norm for an area can trigger the differential movement of clay rich soils. In contrast, landslide only needs excessive rainfall for a trigger. Drought is not a problem, usually.

Again, it is suggested that an annual rainfall amount of ± 2ó be used to activate differential movement in “high” susceptibility areas and ± 3ó be used as the probability for severe movement in “medium” susceptibility areas of whichever map is chosen as an expansive soil reference. These maps are presented in very small scale. Consequently, a “D” must be assigned to this method of probabilistic modeling without a much better idea of the soils character, thickness, and depth being known.

*Table 8: A Template for Modeling Expansive Soils*
*(Measure of Hazard Intensity: inches/inch or cms/cm)*

**Principal effects of the hazard on water utility systems:** (1) Differential movement of surface structure foundations and (2) differential movement of buried pipelines and other structures.

| Principal Activating Parameters | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • Excessive water | NOAA | Good | Good | ± 100 years | Good |
| • Drought | NOAA | Good | Good | ± 100 years | Good |
| • Presence of montmorillonite | USGS | Poor | Poor | Poor | Poor |

| Principal Conditioning Parameters: | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • Depth of clays | State Geologists (See presence of montmorillonite) | | | | |
| • Amount and thickness of clay layers | State Geologists (See presence of montmorillonite) | | | | |

**Websites or References Containing Data:**

- Wiggins, John H. et al, 1978, Natural Hazards: Earthquake, Landslides, Expansive Soils, J. H. Wiggins Company, NSF Grant #ERS-75-09998-AOI, AEN-74-23992
- See references and websites in Table 3 labeled "Climate History" and "Earth Materials and Terrain." State Geologists may also have pertinent maps.

**Available Probabilistic Models:** None are known.

### 3.2.2 Soil Collapse

Soil collapse is broken down into three categories: (a) hydrocompaction, (b) natural subsidence and (c) man-induced subsidence. The phenomenology for these types of soil collapse is found in Appendix C.

Areas susceptible to hydrocompaction and natural subsidence are usually known by the geological survey professionals for each state. It is suggested that they be consulted about details at specific sites. No nationally available maps for hydrocompaction is known. For karst topography only Figures 11 and 12 are known. An example of a state geologist's knowledge of local collapse potential is exhibited by the state of Illinois. It has developed a map of karst areas in that state (Figure 13). Tables 9 and 10 list templates for modeling these hazards.

Rainfall amounts, though important properties which may initiate or trigger a sink hole collapse by adding load to an already weak "land bridge", do not directly act as an undermining mechanism. Thus, no natural probabilistic load is known, short of the coarse use of rainfall amounts.

*Table 9: A Template for Modeling Soil Collapse-Hydrocompaction*
*(Measure of Hazard Intensity: inches/inch or cms/cm)*

**Principal effects of the hazard on water utility systems:** (1) Differential movement of surface structure foundations and (2) differential movement of buried pipelines and other structures.

| Principal Activating Parameters | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| Addition of water by | | | | | |
| • Rainfall | NOAA | Good | Good | ± 100 years | Good |
| • Other local sources | (?) | (?) | (?) | (?) | (?) |

| Principal Conditioning Parameters: | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • Soil moisture | State Geologists | (?) | (?) | (?) | (?) |
| • Soil composition | State Geologists | (?) | (?) | (?) | (?) |
| • Plasticity index | State Geologists | (?) | (?) | (?) | (?) |

**Websites or References Containing Data:** See references and websites in Table 3 labeled “Climate History” and “Earth Materials and Terrain”.

**Available Probabilistic Models:** None to our knowledge.

Collapse by hydrocompaction can be influenced strongly by heavy rainfall. Thus, those areas that are identified by each state geologist as having hydrocompaction potential of “High” to “Moderate” can be associated with rainfall amounts and probabilistically addressed in a manner similar to landslide and expansive soil. For the above reasons, this method is classified as a “D”.

*Table 10: A Template for Modeling Soil Collapse—Natural Subsidence (Measure of Intensity inches/inch or cms/cm)*

**Principal effects of the hazard on water utility systems:** (1) Differential movement of surface structure foundations and (2) differential movement of buried pipelines and other structures

| Principal Activating Parameters | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • Underground water | (?) | (?) | (?) | (?) | (?) |
| • Excessive rainfall | NOAA | Good | Good | ± 100 years | Good |

| Principal Conditioning Parameters: | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • Karst topography | USGS and State Geological Offices | (?) | (?) | (?) | (?) |

**Websites or References Containing Data:** See references and websites in Table 3 labeled "Climate History" and "Earth Materials and Terrain".

**Available Probabilistic Models:** None to our knowledge

### 3.2.3 Frost Heave

The phenomenology for frost heave is found in Appendix C. The potential intensity of ice segregation in a soil depends largely on the size of the void space and may be expressed as an empirical function of grain size. Inorganic soils containing 3 percent or more by weight of grains finer than 0.02 mm (0.0004 in.) in diameter are generally considered frost susceptible. Frost-susceptible soils are classified as: F-1, F-2, F-3, and F-4. They are listed approximately in the order of increasing susceptibility to frost heave from both ice formation or collapse from frost melting (Table 11).

The freezing index value should be computed from NOAA provided daily air temperature data (See Figure 14). Differences in elevations, topographical positions, and proximity to cities, bodies of water, or other sources of heat may cause variations in freezing indexes over short distances. Therefore, the air temperatures should be obtained from a weather station located as close as possible to the water system facilities of interest.

*Table 11: Frost-Susceptible Soil Groups*

| Frost Group | Susceptibility | Kind of Soil | Percentage Finer Than 0.02 mm (0.0004 in.) by Weight |
|---|---|---|---|
| F-1 | Low | Gravelly soils | 6 to 10 |
| F-2 | Moderate | Gravelly soils | 10 to 20 |
| | | Sands | 6 to 15 |
| F-3 | High | Gravelly soils | Over 20 |
| | | Sands (except very fine silty sands) | Over 15 |
| | | Clays, PI* > 12 | -- |
| F-4 | Very High | All silts | -- |
| | | Very fine silty sands and | Over 15 |
| | | Clays, PI* > 12 | -- |
| | | Varved clays and other very fine-grained, banded sediments | -- |

* PI – Plasticity Index

The depth to which freezing temperatures penetrate below the surface depends principally on the magnitude and duration of below-freezing air temperatures and on the amount of water present in the earth materials. A potentially troublesome water supply for ice segregation is present if the highest groundwater at any time of the year is within 5 feet (1.5m) of the proposed subgrade surface or the top of any frost-susceptible earth materials. When the depth to the uppermost water table is in excess of 10 feet (3m) throughout the year, a source of water for substantial ice segregation is not likely to be present unless the soil contains a high percentage of silt. In homogeneous clay soils, the water content that the clay subgrade will attain is usually sufficient to provide water for some ice segregation even with a deeper water table, however.

There are no known probabilistic models of frost heave intensities for the nation. It is recommended that the State Geologists in the area under study be consulted about their local knowledge and experience with frost heave conditions. NOAA has published a freeze probability map for (a) freeze free period, 90% probability, (b) spring freeze occurrence, 10% probability and (c) fall freeze occurrence, 10% probability. The latter map is shown in Figure 15. References and pertinent websites are indicated in Table 12.

Areas that have (1) high water tables, (2) susceptible soil grain sizes, and (3) freezing index characteristics that are undesirable are to be included in any model, among other factors. Probably the central parts of the Midwest which are subject to many freeze-thaw circumstances during a fall-spring episode, as described in the earlier text, are the more susceptible areas of the country. However, without specific site information the modeling capability of this hazard must be rated at a “D-.”

*Table 12: A Template for Modeling Frost Heave (Measure of Hazard Intensity: inches/inch or cms/cm)*

**Principal effects of the hazard on water utility systems:** (1) fracture underground lines and structures and (2) fail foundations of structures on the surface.

| Principal Activating Parameters | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • Upward water migration | (?) | NA | NA | NA | NA |
| • Downward water migration | (?) | NA | NA | NA | NA |
| • Unfavorable freeze-thaw conditions | (NWS) | Good | Virtually all | ± 100 years | Good |
| • (Freezing index) | | | | | |
| | | | | | |
| **Principal Conditioning Parameters:** | **Data Location** | **Data Quality** | **Data Quantity** | **Data Gaps** | **Data Condition** |
| • Freezing index | NWS | Good | Good | ± 100 years | Good |
| • Water table depth | (?) | NA | NA | NA | NA |
| • Earth materials, F value | (?) | NA | NA | NA | NA |
| • Snow cover duration | NWS | Good | Good | ± 100 years | Good |
| • Rain fall | NWS | Good | Good | ± 100 years | Good |

**Websites or References Containing Data:** See references and websites in Table 3 labeled “Climate History” and “Earth Materials and Terrain”.

**Available Probabilistic Models:** None to our knowledge

## 3.3 Flood

### 3.3.1 Riverine Flood

The phenomenology for riverine floods is found in Appendix C. Table 13 provides data sources for flood in general. Table 14 provides the template for modeling riverine flood. However, FEMA has developed flood extent maps, which include riverine flood for about 20,000 communities. These maps provide the 100 year and 500 year return period of riverine, headwater and storm surge flooding extent. Maps may be purchased whether in paper map form or in digital form on disks. The Internet can also be

*Table 13: Sample references for Modeling Floods Probabilistically*

| Floods | What is supplied? |
|---|---|
| • http://ks.water.usgs.gov/Kansas/pubs/fact-sheets/fs.024-00.html | USGS Flood Measurements<br>Significant Floods of the 20th Century<br>Regional Floods<br>Flash Floods<br>Ice-Jam Floods<br>Dam- and Levee-Failure Floods<br>Debris, Landslide, and Mudflow Floods<br>Flood Information on the Internet<br>Other Internet Sites |
| • http://www.nibs.org/hazus4c.htm | HAZUS Flood Loss Estimation model |
| • http://www.esri.com/data/online/fema/femadata.html | FEMA Q3 Flood Data |
| • http://www.lochsheil.com | Discs of digitized flood maps for FEMA can be purchased here. |
| • http://www.fema.gov/mit/tsd/ft_hydro.htm#4 | Discussion of modernizing FEMA's Flood Hazard Mapping Program |
| **Storm Surge** | **What is supplied?** |
| • http://www.lib.ncsu.edu/stacks/gis/themes/term0167.html | Hurricane storm surges. Inundation areas. |

accessed to obtain flood maps for any location in the United States (see Figure 16 as an example). In order to compute flood depth in addition to flood extent, a measure of flood intensity for rising waters, the FEMA flood maps must be overlain by elevation maps. These too are available on the web or in paper form at modest cost.

Because FEMA has spent billions in today's dollars to produce these very detailed maps we rate the use of FEMA flood maps for the two levels of risk an "A". FEMA plans to upgrade the maps at a budgeted figure of $800 million more.

### Headwater Flood

The phenomenology for headwater flood is found in Appendix C.

Table 14 shows the factors and data necessary to create probabilistic headwater flood maps. They are the same as those for riverine flood with the exception that the rainfall data of interest are those of the 24 hour to 48 hour nature. (See the riverine flooding discussion in 3.3.1 about the FEMA flood maps that are available for the 100 year and 500 year return periods which also applied to headwater flooding. These maps also include storm surge.)

*Table 14: A Template for Modeling Riverine Flood Hazards*
*(Measure of Intensity: feet (m) of water)*

**Principal effects of the hazard on water utility systems:** (1) fracture underground lines and structures, (2) fail foundations of structures on the surface, (3) disable equipment and other components sensitive to direct water damage.

| Principal Activating Parameters | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • Precipitation | NOAA | Good | Good | ± 100 years | Good |
| • Melting snow and ice | NOAA | Good | Good | ± 100 years | Good |

| Principal Conditioning Parameters: | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • Proximity to river banks | USGS/USACE/ FEMA | Good | Good | Few | Good |
| • Elevation above river banks | USGS/USACE/ FEMA | Good | Good | Few | Good |
| • Flow gradient | USGS/USACE/ FEMA | Good | Good | Few | Good |
| • Surface roughness | USGS/USACE/ FEMA | Good | Good | Few | Good |

**Websites or References Containing Data:** See references and websites in Table 3 labeled “Climate History” and “Atlas of Hazards Locations” and Table 13 for “Floods.”

**Available Probabilistic Models:** FEMA maps of about 20,000 communities and 1200 counties.

Another understanding of headwater flood likelihood for various areas of the nation can be gained from viewing Figure 17. This figure was constructed using seven NOAA probability maps of mean precipitation (see Figure 18) for the 24-hour rainfall time period. The mapped return periods are: 1 year, 2 year, 5 year, 10 year, 25 year, 50 year and 100 year. Applying a hypothetical standard for incipient headwater flooding such as 8 inches in a 24 hour time period, Chicago would not be vulnerable up to a return period of about 3000 years; Oklahoma City for 45 years and; Miami for 5.5 years. Of course, each area has its own drainage and runoff characteristics which influence the capability of the various areas to handle the sudden accumulation of water. This capability also causes the hypothetical standard to vary from area to area.

Figure 18 shows the average rainfall that can be expected in a given duration of time for 1% chance of occurrence. The world record in 24 hours is 72 inches on the island of Reunion in the Indian Ocean at about 21° south latitude. This island is subject to major typhoons (hurricanes) which deliver this kind of rainfall. Consequently, tropical storms are a serious source of headwater flooding. By converting all of the losses from twentieth century floods affecting the United States, it can be shown that tropical storm and hurricane generated flooding cause greater losses than flash or riverine floods generated by other weather systems.

Therefore, the gulf and eastern coastal areas of the U.S. and their attendant heavy 24 hour rains are affected by tropical storms and hurricanes which strike these coastline areas dropping much of their moisture in the process. (Note also, how closely the rainfall contour map in Figure 18 resembles the wind contour map discussed later in Figure 24)

Because FEMA maps discussed in the earlier section on riverine flood also include headwater flooding hazards, using them to evaluate headwater flooding as well as riverine flooding and storm surge combined is rated an “A”.

## 3.4 Wind

### 3.4.1 General Severe Wind

The natural hazard mechanism for general severe wind is found in Appendix C. Table 15 contains a reference for general severe wind.

*Table 15: General Reference for Modeling General Severe Wind Probabilistically*

| Severe Wind | What is supplied? |
|---|---|
| • http://www.bergey.com/wind_maps.htm | Maps of average annual wind speed produced for the Department of Energy for wind power. |

The wind speed data for any location can be obtained for any weather station and used directly as interpolated data, one station from another. Probabilistic wind maps have also been prepared by the American Society of Civil Engineers (Figure 19) which depicts the 50 year return period 3-second wind gust speed. An equation is presented for the computation of higher or lower probability wind speeds:

$$F = 0.36 + 0.1 \ln (12\,T) \qquad (1)$$

in which

$F$ = factor multiplied by the contour velocity

$T$ = return period.

Thus, for T=100 years and T=1000 years the factor F is respectively 1.069 and 1.299

The average 90 mile per hour (145 km/hr) 3-second gust wind speed is converted to 96mph (154 km/hr) for 100 year probability and 117mph (188 km/hr) for a 100 year return period likelihood. It must be noted that the equation is not recommended for use above the 500 year or below the 50 year return period levels of risk, however. A rough idea of sustained wind speed or fastest mile wind speed can be computed noting that the 3-second gust velocity is between 15% to 20% higher than sustained wind speed.

Because the data quality which produced the map is good and because the 90mph (145 km/hr) severe wind speed map for the 50 year return period has been developed over years by competent wind engineers, this probabilistic modeling method is rated an “A”.

### 3.4.1 Tornado

The phenomenology for tornado is found in Appendix C. Table 16 provides sample references for modeling tornadoes probabilistically. Table 17 differentiates tornadoes by the Fujita scale. Figure 20 shows the frequency of all tornadoes strikes for various regions of the country.

*Table 16: Sample References for Modeling Tornadoes Probabilistically*

| Tornadoes | What is supplied? |
|---|---|
| • Thomas P. Grazulis, 1993, Significant Tornadoes, 1680-1991, The Tornado Project of Environmental Films, P.O. Box 302, St. Johnsbury, VT 05819 | This lists all tornadoes by state, county, F-number, length of travel, width of track, time, date, deaths plus much more. |
| • http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dill?wwEvent~Storms | Listing of tornadoes |
| • www.medi.gov/ | Listing of tornadoes |

Wind speed experienced per year and therefore tornado class is the intensity parameter of interest. The area covered by the different wind speeds per 10,000 square miles/year (25,889 sq. km) is the risk parameter of interest. For example, Oklahoma has a return period for a strike by a tornado of any size of 1,300 years per square miles. However, by noting the area covered by mix of tornado classes in Table 17 the frequency of strike by these classes in Table 18, the likelihood of a point in Oklahoma being struck by any tornado is 1 in 2100 years. Table 19 summarizes tornado zones by State by > f2 Ranking per 10000 sq mi (or 25,889 sq. Km)/ year. For the really ferocious F4/F5 tornadoes the return period is 56,000 years per square mile (2.59 sq. Km) but they cover about 8.78 square miles (22.73 sq. Km). The chance of being struck by one of these is about 1 in 6300 years. These return periods are reduced for water systems that are spread out geographically.

The new data can be accessed either from the Grazulis hard copy reference listing all reported tornadoes from 1680-1991 or from the Internet which lists all tornado data from 01/01/1950 through 12/31/2001 by state and by county. Holes in the data exist. The last 40 to 50 years is probably complete. For example, since 01/01/1950 Dade County in Florida has experienced 71 F0 tornadoes (<72 mph or 116 km/hr wind speeds), 19 F1 tornadoes (73-112 mph, or 117-180 km/hr, wind speeds), 5 F2 tornadoes (113-157 mph, or 182-253 km/hr, wind speeds), 1 F3 tornado (158-206 mph, or 254-331 km/hr, wind speeds) and no F4 or F5 tornadoes.

The data can be theoretically and statistically enhanced to provide a reliable data base up to 100 years. If done, this modeling method using the data for each state or county (wind speed, direction of travel, length, width, etc.) can produce a competent probabilistic risk analysis model rated “A”. No template is provided for tornado.

*Table 17: The Fujita Scale for Tornadoes*

| **F Scale** | **Average Length** | **Average Width** | **Range of Wind Speed** | **Percent of Tornadoes in F Classification** |
|---|---|---|---|---|
| F0 | 1.11 mi (1.79 km) | 0.026 mi (0.042 km) | 40-72 mph (64-116 km/hr) | 19.9 |
| F1 | 2.59 mi (4.17 km) | 0.053 mi (0.085 km) | 73-112 mph (117-180 km/hr) | 44.0 |
| F2 | 5.66 mi (9.11 km) | 0.094 mi (0.151 km) | 113-157 mph (181-253 km/hr) | 26.6 |
| F3 | 12.08 mi (19.44 km) | 0.16 mi (0.29 km) | 158-206 mph (182-332 km/hr) | 7.2 |
| F4 | 22.42 mi (36.08 km) | 0.25 mi (0.40 km) | 207-260 mph (183-418 km/hr) | 2.1 |
| F5 | 34.17 mi (54.99 km) | 0.35 mi (0.56 km) | 261-318 mph (419-512 mph) | 0.2 |
| **All** | **3.81 mi (6.13 km)** | **0.071 mi (0.114 km)** | **88-126 mph (142—203 km/hr)** | **100** |

### 3.4.1 Hurricane–Tornado

The phenomenology for hurricane-tornado is found in Appendix C.

No special evaluation is provided for hurricane-tornado.

*Table 18: Tornadoes Per 10,000 Sq. Mi. (or 25,889 sq. km) Per Year by State by Rank*

| **All** | | | **≥F2** | | | **F4/F5** | | |
|---|---|---|---|---|---|---|---|---|
| 1 | Florida | 8.4 | 1 | Oklahoma | 2.4 | 1 | Oklahoma | 0.18 |
| 2 | Oklahoma | 7.5 | 2 | Indiana | 2.0 | 2 | Indiana | 0.16 |
| 3 | Delaware | 6.1 | 3 | Iowa | 1.9 | 3 | Iowa | 0.16 |
| 4 | Kansas | 5.8 | 4 | Mississippi | 1.9 | 4 | Kansas | 0.12 |
| 5 | Louisiana | 5.6 | 5 | Alabama | 1.8 | 5 | Illinois | 0.12 |
| 6 | Iowa | 5.5 | 6 | Arkansas | 1.7 | 6 | Missouri | 0.11 |
| 7 | Indiana | 5.4 | 7 | Louisiana | 1.6 | 7 | Arkansas | 0.10 |
| 8 | Mississippi | 5.0 | 8 | Illinois | 1.5 | 8 | Mississippi | 0.08 |
| 9 | Nebraska | 4.8 | 9 | Kansas | 1.4 | 9 | Alabama | 0.08 |
| 10 | Illinois | 4.7 | 10 | Delaware | 1.3 | 10 | Nebraska | 0.08 |
| 11 | Texas | 4.7 | 11 | Wisconsin | 1.2 | 11 | Tennessee | 0.08 |
| 12 | Alabama | 4.0 | 12 | Florida | 1.2 | 12 | Wisconsin | 0.07 |
| 13 | Missouri | 3.8 | 13 | Texas | 1.1 | 13 | Kentucky | 0.07 |
| 14 | Massachusetts | 3.8 | 14 | Missouri | 1.1 | 14 | Ohio | 0.06 |
| 15 | Arkansas | 3.7 | 15 | Tennessee | 1.1 | 15 | Minnesota | 0.06 |
| 16 | Maryland | 3.7 | 16 | Ohio | 1.1 | 16 | Michigan | 0.05 |
| 17 | Ohio | 3.5 | 17 | Connecticut | 1.1 | 17 | Georgia | 0.04 |
| 18 | Georgia | 3.4 | 18 | Massachusetts | 1.1 | 18 | Connecticut | 0.04 |
| 19 | South Carolina | 3.4 | 19 | Georgia | 1.0 | 19 | Louisiana | 0.04 |
| 20 | New Jersey | 3.4 | 20 | Nebraska | 0.9 | 20 | Texas | 0.04 |
| 21 | Wisconsin | 3.4 | 21 | Kentucky | 0.9 | 21 | South Carolina | 0.03 |
| 22 | South Dakota | 3.3 | 22 | Michigan | 0.9 | 22 | South Dakota | 0.03 |
| 23 | Tennessee | 2.9 | 23 | South Carolina | 0.9 | 23 | North Carolina | 0.02 |
| 24 | Michigan | 2.8 | 24 | South Dakota | 0.7 | 24 | Massachusetts | 0.02 |
| 25 | North Carolina | 2.8 | 25 | North Carolina | 0.7 | 25 | Pennsylvania | 0.02 |
| 26 | Connecticut | 2.8 | 26 | Pennsylvania | 0.7 | 26 | North Dakota | 0.02 |
| 27 | North Dakota | 2.5 | 27 | New Jersey | 0.7 | 27 | Maryland | 0.01 |
| 28 | Colorado | 2.4 | 28 | Maryland | 0.6 | 28 | West Virginia | 0.01 |
| 29 | Minnesota | 2.4 | 29 | Minnesota | 0.5 | 29 | Colorado | 0.01 |
| 30 | Kentucky | 2.2 | 30 | Virginia | 0.5 | 30 | New York | 0.00 |
| 31 | Pennsylvania | 2.2 | 31 | North Dakota | 0.4 | 31 | Virginia | 0.00 |
| 32 | New Hampshire | 1.8 | 32 | New Hampshire | 0.4 | 32 | Wyoming | 0.00 |
| 33 | Rhode Island | 1.7 | 33 | Vermont | 0.3 | 33 | Florida | 0.00 |
| 34 | Virginia | 1.6 | 34 | Colorado | 0.2 | 34 | New Jersey | 0.00 |
| 35 | New York | 1.2 | 35 | West Virginia | 0.2 | 35 | Vermont | 0.00 |
| 36 | Wyoming | 1.0 | 36 | New York | 0.2 | 36 | California | 0.00 |
| 37 | Hawaii | 0.9 | 37 | Rhode Island | 0.2 | 37 | Rhode Island | 0.00 |
| 38 | Vermont | 0.8 | 38 | Hawaii | 0.1 | 38 | New Mexico | 0.00 |
| 39 | New Mexico | 0.7 | 39 | Wyoming | 0.1 | 39 | Maine | 0.00 |
| 40 | West Virginia | 0.7 | 40 | New Mexico | 0.1 | 40 | Montana | 0.00 |
| 41 | Maine | 0.6 | 41 | Maine | 0.1 | 41 | Idaho | 0.00 |
| 42 | Montana | 0.4 | 42 | Montana | 0.1 | 42 | Arizona | 0.00 |
| 43 | California | 0.3 | 43 | California | 0.0 | 43 | Washington | 0.00 |
| 44 | Idaho | 0.3 | 44 | Idaho | 0.0 | 44 | Utah | 0.00 |
| 45 | Arizona | 0.3 | 45 | Arizona | 0.0 | 45 | Oregon | 0.00 |
| 46 | Washington | 0.2 | 46 | Washington | 0.0 | 46 | Nevada | 0.00 |
| 47 | Utah | 0.2 | 47 | Utah | 0.0 | 47 | Alaska | 0.00 |
| 48 | Oregon | 0.1 | 48 | Oregon | 0.0 | 48 | Hawaii | 0.00 |
| 49 | Nevada | 0.1 | 49 | Nevada | 0.0 | 49 | New Hampshire | 0.00 |
| 50 | Alaska | 0.0 | 50 | Alaska | 0.0 | 50 | Delaware | 0.00 |

*Table 19: Tornado Zones By State By > F2 Ranking/10,000 Sq Mi (or 25,889 Sqkm)/Year*

| Zone (number per 10,000sq mi/yr) | Farwest | Midwest | East Coast |
|---|---|---|---|
| 0 (0.0) | CA, ID, AZ, WA, UT, OR, NV, AK | -- | -- |
| 1 (0.1-0.5) | HI, WY, NM, MT | MN, ND, CO | VI, NH, VT, WV, NY, RI, ME |
| 2 (0.6-1.0) | -- | NB, KY, MI, SD | GA, SC, NC, PA, NJ, MD |
| 3 | -- | IL, KS, WI, TX, TN, OH | DE, FL, CT, MA |
| 4 (1.6-2.0) | -- | IN, IA, AL, AR, LA, MS | -- |
| 5 2.1-2.5) | -- | OK | -- |

### 3.4.1 Hurricane-Cyclone

The phenomenology for hurricane-cyclone is found in Appendix C. Table 20 provides sample reference for hurricane-cyclone.

*Table 20: Sample References for Modeling Hurricane-Cyclone Probabilistically*

| Hurricane – General | What is supplied? |
|---|---|
| • http://www.eglin.af.mil/weather/hurricanes/history.html | Discusses the history of hurricanes in the western Florida Panhandle 1559-1999. |
| • http://www.fema.gov/hu97/hmag.htm | 5% probability of landfalling hurricane by category in the conterminous U.S. |
| • http://www.lib.ncsu.edu/stacks/gis/data12/data1229.html | HAZUS: inland wind decay maps (hurricane maps) |
| • http://www.fema.gov/hazus/wd_main.htm | HAZUS: wind loss estimation models to be released in 2002 |

The likelihood of occurrence of storms having varying strength as expressed on the Saffir-Simpson scale can be treated in several ways. First the landfall probabilities in various mainland gulf and Atlantic coastal states can be expressed by the top figure in Figure 21 which separates the major category 3-5 hurricanes from all hurricanes. A smoothed strike frequency can be constructed from this data for all tropical storms (see the lower figure in Figure 22).

Strike frequency by category has also been addressed by FEMA in Figure 21. A somewhat different inference is gained from this figure compared with those in Figure 23. Essentially, the amount of data that has been obtained since 1886, when tropical storm reporting was first formally instituted, is uncertain, have holes. This causes different investigators to interpret the available data and its quality lack differently, depending largely on their individual judgments.

Three methods are suggested for evaluating this hazard probabilistically, all of which will produce different probabilistic outcomes thus illustrating the uncertainties.

### Method 1-

The American Society of Civil Engineers in 2000 released a map (Figure 23) of gust iso- wind velocity for the gulf and east coast of the United States and for Puerto Rico and Hawaii. Designed to show the Gulf and Atlantic areas better, this map is an enlarged version of Figure 19. The return period shown for the constant velocity wind contours is 50 years. To compute other return period velocities the authors of the map suggest a formula for raising or lowering the wind gust velocities as a function of return period. We repeat equation (1) for ease of reference:

$$F=0.36 + 0.1 \ln (12T) \qquad (1)$$

in which

$F$ = a factor multiplied by the contour velocity

$T$ = return period

This equation has the same limitations as stated in section 3.4.1. However, the mean tropical storm wind velocity is suggested as 45 mph (72 km/hr). This is the gust velocity for the smallest tropical storm.

The wind map was prepared by a committee of wind engineers. It does not exactly represent the history of tropical storm winds that have struck the United States, since records were first kept in 1896, however. Further, the quality of the data is questionable from 1886 to about 1930; it is much better from 1931 to about 1980; and is quite good from 1981 onward. Thus, a great deal of judgement must be used when incorporating older data from tropical storms to forecast wind speeds with any reliable probability. However, this map and the equation can be used directly to estimate probabilistic wind speeds assuming the most critical direction of wind travel for each above ground unit in a water facility.

### Method 2-

An alternative way of constructing probabilistic wind speeds at a site is to use Figure 24 for sustained wind speeds experienced at the coast together with the lower figure in Figure 22 showing strike likelihood. This figure is yet another way of interpreting the raw hurricane occurrence data to draw conclusions about storm likelihood and strength. Attenuation of sustained wind speed inland can be determined by interpolating speeds noted in Figure 23. Gust wind speed is roughly 1.15x sustained wind speed.

### Method 3-

A third procedure for constructing a set of realistic storms that replicate the hurricane hazard is to sweep by the site or region in question all of the historic storm tracks including tropical depressions and tropical storms that come within, say 80 miles (129 km). These may be obtained from the National Hurricane Center's website on the Internet.

1. To each of these a wind speed can be assigned based on the 50 year wind speed contours shown in the map (Figure 21) for the region in question together with the F formula noted above to make up a random set of storms.

2. A radius of maximum wind, RMW, must also be assigned in order to compute wind velocity at a particular site for each storm. An average value of 20 miles (32 km) is suggested, though RMW's ranging from as low as 10 miles to 50 miles (16 to 81 km) have been observed.

3. An average travel speed of 12 mph (19 km/hr) south of the northern border of North Carolina and 30 mph (48 km/hr) north of that border is also suggested. However, this parameter also has a great deal of variability and uncertainty.

4. Decay of wind speed on either side of the storm center from the eye wall to the 60 mph (97 km/hr) zone beyond which little damage is expected randomly varies like all other parameters that describe the characteristics of a storm. It is suggested that on the right side of the storm that the equation for decay from the eye wall perpendicular to the direction of travel is:

   $$V=V_o^{c(1-K)} \quad \text{.......................................} \quad (2)$$

   in which

   $V_o$ = the peak eye wall storm gust wind speed, mph

   $C$ = 0.2 for RMW ≈ 10 miles

   $C$ = 0.1 for RMW ≈ 20 miles

   $K$ = x/RMW with x RMW

   $x$ = lateral distance from the storm center, miles

5. The rate of decay perpendicular to the direction of travel on the left side of the storm beginning at the eye wall is the same as equation (2) above except that $V_o$ is now replaced by $V_o - 2S$, where S is the forward speed of the storm.

Using each historical storm path noted and the perpendicular distance from each storm path to the site in question a set of maximum wind speeds for that site can be computed. For example, if a particular location experiences one tropical or greater storm every 20 years (see Figure 22), then 500 various wind velocities can be randomly simulated and computed from Figure 24 for each water system component site over a hypothetical 10,000 year time period. A mean peak gust velocity and $C_V$ can then be computed for each component site from these 500 data points.

### 3.4.3 Hurricane-Storm Surge (Combined with River Flood and Headwater Flood)

The phenomenology for hurricane-storm surge (combined with riverine flood and headwater flood) is found in Appendix C. Table 13 contains a key reference for probabilistic modeling.

The U.S. Army Corps of Engineers has prepared a probabilistic analysis of storm surge heights on an open beach area. This is shown in Figure 25 together with some estimates by NOAA from Brownsville, Texas to Elizabeth City, North Carolina. Note the differences in the estimates. For Miami, the 100-year return period event is about 12 feet (3.7 m) using the U.S. Army Corps of Engineers estimate whereas the NOAA estimate is about 7 feet (2.1 m). Hurricane Andrew in 1992 produced a 17 ft. (5.2m) maximum run up height as a comparison. Andrew was about a 200 year return period storm, which would more closely match the Corps of Engineers estimate.

Figure 26 shows an example of the principally storm surge map created by FEMA showing the extent of the 100 year and 500 year storm surge and headwater flood, run up extent for Brazoria County, Texas. Run up can extend 5+ miles (8 + km) inland. Figure 27 shows the storm surge and headwater flooding extent for the Miami, Florida area. Storm surge extent is extremely small compared with headwater flooding extent. No template is required for storm surge.

Because FEMA has developed the flood maps which include storm surge this method of extent and depth estimate (combining the use of elevation data with flood extent) is considered an “A” grade for probabilistic modeling.

### 3.4.4 Combining Hurricane Effects

A hurricane can cause high winds, tornadoes, storm surges, riverine floods and headwater floods from the same storm all at the same time. Combining the likelihoods of hurricane winds, tornadic winds and the three flood sources along the storm’s path by estimating the probability of the individual hazard occurrence and then computing the intensities of each hazard using that storm likelihood is incorrect, except for storm surge and hurricane wind which are interdependent. Riverine and headwater floods can be caused by rains generated by other severe weather events. Tornadoes also can be caused by frontal systems as explained earlier.

To incorporate all the hazards probabilistically with each given hurricane event, the history associated with each past storm over its entire path length must be examined. What was the wind velocity and rainfall associated with each storm at each location along its travel path? What was the run up at each site for the storm in question? These are the questions that can be addressed for historic storms. But is the ~100 years of data sufficient?

The data so derived must be combined for each of the 58 wind zones shown at the top of Figure 22 for each storm. Wind speeds will probably be missing from the NOAA data for most of the storms. Thus, they must be theoretically estimated using the forward speed of the storm and the pressure drop which can be correlated with wind velocity. Likewise, RMW must be obtained from the data or theoretically or statistically estimated in order to compute wind field velocities.

At the same time rainfall and tornado occurrence data for all sites along the path of a storm must be obtained and correlated with wind velocity or some other normalizing parameter. To repeat, this must be done for the entire storm path, since riverine flood and headwater flood can be severe inland, even though wind velocities have diminished. Rainfall data considered alone is not enough to compute flooding extent, unless this data is available, as well. The basins used to model the 100-year and 500- year return period FEMA flood maps must also be made available so that flood extent and elevation can be computed.

Obviously, this is a monumental task to perform, even with all the data. Even when the probabilistic analysis project is completed only about 100 years of data will have been accumulated. Therefore, higher risk probabilities will require a great deal of judgement and theoretical development in order to compute total hurricane loss outcomes which include cyclonic wind, tornado wind, storm surge, riverine flood and headwater flood hazards. This is the subject that proprietary risk models address.

No rating on this sketchy method of total hurricane risk is assigned.

## 3.5 Earthquakes

### 3.5.1 Earthquake—General

Table 20 provides general references for modeling earthquakes probabilistically. Here, it must be repeated that most probabilistic modeling of earthquakes (as for other natural hazards) is focused on sites rather than on geographically distributed systems. Hence, for probabilistic modeling, it is necessary to disaggregate information and models used elsewhere in order to model initiating events (earthquake scenarios) randomly. This is true of such maps, for instance, as those found in Figure 28, a probabilistic ground motion map for the United States. The disaggregated information used to develop this map is much more pertinent to the probabilistic evaluation of water utilities—except for those that are very small in areal extent.

Non-probabilistic modeling is also common, and there are many sources listed that provide pre-specified earthquake scenarios, scenarios not randomly selected. These can be used for intermediate or operations evaluations of water systems to the extent that other pertinent hazard elements (especially estimates of ground failures) are reasonable.

*Table 20: Sample References for Modeling Earthquakes Probabilistically*

| **Earthquake – General** | **What is supplied?** |
|---|---|
| http://www.trinet.org/shake/archive/scenario.html | Earthquake scenarios in California with leads to many other sites, some dealing with probabilistic earthquake modeling. |
| Earthquake – Faulting | What is supplied? |
| http://geohazards.cr.usgs.gov/eq/faults/fsrpage01.html | Listing of 441 active faults used to construct shake maps. 39% are in California and 29% are in Nevada. (Note also that various State Geologists may have maps of surface faults, and that these are very detailed in California) |
| Earthquake – Shake | What is supplied? |
| http://mac.usgs.gov/mac/isb/pubs/forms/eqmaps.html | Probabilistic maps and epicentral maps of earthquakes. |
| http://geohazards.cr.usgs.gov/eq/index.html | Detailed probabilistic maps for earthquake shake. |
| Earthquake – Landslide | What is supplied? |
| http://geohazards.cr.usgs.gov/pubs/ofr/98-113/ofr98-113.html | Probabilistic seismic landslide hazard maps. |
| http://cvfeller.cv.ic.ac.uk/carlos.html | Earthquake induced landslide hazards |
| Earthquake – Seiche | What is supplied? |
| http://www.coastal.udel.edu/faculty/rad/seiche.html | Seiche calculator |

### 3.5.2 Earthquake-Fault Rupture

The phenomenology for fault rupture is found in Appendix D. Figure 29 provides a map of young surface faulting zones in the conterminous United States.

The USGS has published on the Internet a listing of all the faults that are considered active and can break ground. Data given are:

- State
- Name of fault
- Slip rate (mm/yr)
- Fault end points (lat/long)
- Fault length (km)
- Fault dip (degrees)
- Fault width (km)

- Characteristic magnitude (M- moment magnitude)
- Rate at which the characteristic magnitude might be expected (number/year N)
- Gutenberg/Richter A-value for use in the equation log N=A-bM
- b-value in the above equation

For evaluating prospective permanent ground displacements within a specific region of faults, such references as Wells and Coppersmith (1993) may provide estimates of maximum displacement given the magnitude of an event. Randomization must occur along the fault segment in order to determine the extent of the fault rupture zone. And finally, a distribution must be used to simulate how the displacements at various points compare with the maximum displacement.

Table 21 is the template for this hazard. With the USGS data, this method of probabilistic modeling is rated an “A”.

### 3.5.3 Earthquake-Shaking

The phenomenology for earthquake strong ground motion is discussed in Appendix C.

Modeling specific earthquake occurrences may start with historic events. These are some problems, however. (1) There is considerable uncertainty in the locations of previous earthquakes. (2) Estimates of earthquake magnitudes becomes more uncertain as the earthquake occurrences date farther back in time, before the advent of and continuing development of seismograph stations and even before the advent of large numbers of historic records of the earthquakes. (3) Considering the problem of pre-instrumental earthquakes, the time-span of recorded earthquake occurrences is very short in the United States as contrasted to the time-span of the geologic processes that produce them. For this reason, over the past twenty-five years, investigators have been developing pertinent paleoseismic data from fault trenching and liquefaction-displacement studies in order to provide scientific perspectives on these geologic processes and rates of occurrences of earthquakes in diverse regions throughout the United States. Current investigators thus typically use models that combine scientific (paleoseismic) perspectives along with the historic record. The USGS data developed for faults mentioned in Table 20 are an example.

To date, the development of earthquake scenarios that represent the full range of possible locations and magnitudes has been rare in the published literature, although widespread among proprietary models—especially those used in catastrophe insurance and reinsurance modeling.

*Table 21: A Template for Modeling Fault Rupture Hazards (Measure of Intensity: inches/inch or cms/cm)*

**Principal effects of the hazard on water utility systems:** Damage or destruction of construction both above and below ground

| Principal Activating Parameters | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • USGS parameters noted in Appendix D | USGS/State geologists | Good | Good | All local faults | Good |

| Principal Conditioning Parameters: | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • Likelihood of ground breakage (M) | Model used for frequency of fault rupture, randomization along fault | Uncertainty | +/- 100 yrs | Some | Good |
| • Fault displacement (M) | Available models (see also Appendix D) | Uncertainty | +/- 100 yrs | Some | Good |
| • Fault length (and width) (M) | Available models | Uncertainty | +/- 100 yrs | Some | Good |

**Websites or References Containing Data:** See references and websites in Table 3 labeled "Atlas of Hazard Location" and "Earth Materials-Terrain" and Table 20 for "Earthquake-General," and "Earthquake-Faulting."

**Available Probabilistic Models:** derivative of general models alluded to

Various methods have evolved for generating a representative set of earthquakes. At a beginning level, one may merely use USGS and other catalogs of previous earthquake occurrences, and replicate those. More sophisticated levels assume a weighting for these events plus a consideration of paleoseismic information. Sample methods that combine historic methods with paleoseismic methods are found in Toro and Silva (d.u.), Anderson et al. (2002). A method that disaggregates basic models used by USGS and recombines them to develop a representative suite of scenarios is found in Taylor et al. (2001).

Table 18 provides a template for earthquake-shaking. A rating of "B" to "A" will depend on the credibility of data and models used.

*Table 22: A Template for Modeling Earthquake-Shaking Hazards*
*(Measures of Intensity: peak ground acceleration; spectral acceleration, peak ground velocity, duration of shaking, time-histories)*

**Principal effects of the hazard on water utility systems:** inertial loads damage surface structures

| Principal Activating Parameters | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • Earthquake faulting | USGS | Good | Good | yes | Good |
| • Earthquake history | USGS | Good to fair | Good | Yes | Good to fair |

| Principal Conditioning Parameters: | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • Faulting depths | USGS | Good | Good | Some | Good |
| • Faulting azimuth | USGS | Good | Good | Some | Good |
| • Basement rock | USGS | ? | ? | ? | ? |
| • Site soil conditions | State geologists | Good | Fair | Some | Fair |
| • Attenuation characteristics | USGS/various | Varied | Varied | Many locations | N/A |

**Websites or References Containing Data:** See references and websites in Table 3 labeled "Atlas of Hazards Locations," and "Earth Material-Terrain" and Table 20 for "Earthquake-Shake," "Earthquake-General," and "Earthquake-Faulting."

**Available Probabilistic Models:** Public models only applicable to small water utility systems

### 3.5.4 Earthquake-Landslide

Section 3.2.1 and Appendix C describe the factors involved with a landslide. The sudden impact or trigger caused by an earthquake adds load over that which gravity provides. There are two references that address the likelihood of landsliding in two, very different ways. These are discussed below as probabilistic analysis procedures.

The first procedure is developed in Keeney et al. 1978. The authors conclude that an analysis of earthquake induced slides is greatly complicated by uncertainties about earthquake occurrence and about the interpretation of slope stability analyses. Due to these uncertainties, a probabilistic analysis is the most useful way of investigating the problem and presenting the results. The report illustrates a probabilistic model which incorporates both statistical analyses of earthquake occurrence and subjective probability assessments of sliding potential developed by a group of landslide experts. The subjective probability assessments provide a systematic procedure to quantify and communicate an engineer's professional knowledge. The concept of subjective probability can be useful in any situation where an engineer must integrate his knowledge about a site, results of various field tests, and his experience.

The second is Jibson et al, 1998, and parallels that of Keefer et al., 1978. . The authors model the dynamic performance of slopes using the permanent-displacement analysis developed by Newmark. Using Newmark's method to model the dynamic behavior of landslides on natural slopes yields reasonable and useful results. Newmark's method models a landslide as a rigid block that slides on an inclined plane. The block has a known critical (or yield) acceleration, ac, which is simply the threshold base acceleration required to overcome shear resistance and initiate sliding. The analysis calculates the cumulative permanent displacement of the block relative to its base as it is subjected to the effects of an earthquake acceleration-time history.

In the analysis, an acceleration-time history is selected, and the critical acceleration of the slope to be modeled is superimposed. Accelerations below this level cause no permanent displacement of the block. Those portions of the record that exceed the critical acceleration are integrated once to obtain the velocity profile of the block; a second integration is performed to obtain the cumulative displacement history of the block. The user then judges the significance of the displacement. Newmark's method is based on a fairly simple model of rigid-body displacement, and thus it does not precisely predict measured landslide displacements in the field. Rather, Newmark displacement is a useful index of how a slope is likely to perform during seismic shaking.

Newmark showed that the critical acceleration of a potential landslide block is a simple function of the static factor of safety and the landslide geometry, expressed as:

$$\boldsymbol{a_c} = (FS-1) g \sin a \qquad (3)$$

in which

$a_c$ = the critical acceleration in terms of $g$, the acceleration of Earth's gravity;

$FS$ = the static factor of safety; and

$a$ = the angle from the horizontal that the center of mass of the potential landslide block first moves.

This can generally be approximated as the slope angle. Thus, conducting a Newmark analysis requires knowing the static factor of safety and the slope angle and selecting an earthquake strong-motion record at the site in question.

Given the set of earthquakes described in 3.5.3 and using either of the two methods generally described a likelihood of landslide occurrence can be computed. This area is fraught with uncertainties, however. It is difficult enough to estimate the likelihood of shaking let alone the likelihood of landslide given the ground shaking.

Because the latter Jibson et al. method correlated fairly well with the Northridge earthquake landslide incidence ( a known event) their method is rated a "B" to "D". Table 23 presents the template for earthquake-landslide.

*Table 23: A Template for Modeling Earthquake-Landslide Hazards*
*(Measures of Intensity: inches/inch or cms/cm)*

**Principal effects of the hazard on water utility systems:** (1) failure of structures situation on or in slide areas and (2) failure of structures below slide areas

| Principal Activating Parameters | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • Earthquake shaking scenarios | USGS | Good | Good | Yes | Good |

| Principal Conditioning Parameters: | Data Location | Data Quality | Data Quantity | Data Gaps | Data Condition |
|---|---|---|---|---|---|
| • Landslide conditions | USGS | Good | Good | Some | Good |

**Websites or References Containing Data:** See references and websites in Table 3 labeled “Atlas of Hazards Locations” and “Earth Material-Terrain” and Table 20 for ”Earthquake-Landslide,” “Earthquake-Shake,” “Earthquake-General,” and “Earthquake-Faulting.”

**Available Probabilistic Models:** USGS in “Earthquake-Landslide” website and HAZUS

### 3.5.6 Earthquake-Lurching and Liquefaction

Considerable efforts have been undertaken in the last decade to provide materials for evaluation of liquefaction hazards on a regional basis (See especially references to Bartlett and Youd, Youd, and J.P. Bardet et al.) To date, these efforts have primarily provided methods that can be applied for components which can be associated with existing boring log data. Modeling sites and locales for which boring log data are not clearly available or for which reasonable assumptions cannot be made on potential critical values of input parameters significantly increases the uncertainties involved.

For sites for which boring log data are available, displacements owing to liquefaction are a function of

(a) earthquake magnitude (moment magnitude),

(b) peak ground acceleration and/or the closest distance from the earthquake source to the site,

(c) slope and length of free-face,

(d) the thickness of saturated cohesionless soils with boring log blow counts $(N1)_{60}$ less than 15 derived from boring log data for each layer evaluated,

(e) the average fines content (percent finer than 75 µm) derived from all sub-layers, and

(f) the average $D_{50}$ grain size in the thickness of saturated cohensionless soils, derived from sub-layers.

This data-intensive approach has recently been simplified. The development of data on average fines content and average D50 grain size within the thickness of the saturated cohesionless soils, derived from all sub-layers is not required.

This method does not meet the need to evaluate sites for which boring log data are absent. In particular, for sites for which boring log data are absent, scenario estimates can be made of the moment magnitude, the peak ground acceleration, and the closest distance from the earthquake source to the site. Information on slope and length of free-face as well as on the thickness of saturated cohesionless soils with blow counts less than 15 would need to be surmised or else alternative methods would need to be used.

Where sufficient boring log data is available, finite different codes such as Itasca's FLAC *(Fast Lagrangian Analysis of Continua)* can provide relatively good estimates of permanent ground displacement. It should be noted, however, that the calculated displacements are subject to significant uncertainties—in excess of those found by systematic variation of input parameters.

Simplified methods where little data is available do not provide estimates of the extent (in measured quantities such as centimeters) of permanent ground displacement. Likewise, liquefaction susceptibility maps that have been developed largely for landuse planning purposes have not been defined either in a uniform fashion for all regions of the United States nor for use in developing unbiased risk statistics. For landuse planning purposes, for instance, the region labeled "High" liquefaction susceptibility may include many regions that contain predominantly low liquefaction susceptibility sites whereas a region labeled "Moderate" liquefaction susceptibility may include some site that has a high liquefaction susceptibility. The terms "high," "medium," and "low" may have different, undisclosed meanings according to the investigators and the region of the country that has been evaluated.

Thus, evaluation of liquefaction severities in specific earthquake scenarios has improved considerably in the past decade for sites which may be associated with boring log data. However, for other sites, makeshift methods must currently be employed, with clearly specified assumptions with many uncertainties involved. Hence, for sites with boring log data, the methods are currently rated an "A" whereas for sites without boring log data—absent current research focuses, the methods are currently rated a "D."

### 3.5.7 Earthquake-Tsunami

The phenomenology of earthquake-tsunamis is discussed in Appendix C

Land-use zoning of coastal areas is another way used to reduce losses from tsunamis. Such zoning is based on the heights of tsunami waves expected for exposure times of 20, 50, and 100 years. Tsunami hazard maps, such as shown in Figure 30 for the island of Hawaii and Figure 31 for southern California are used in zoning and may be used for probabilistic analysis.

Areas not addressed, namely Alaska, the remaining Hawaiian Islands, northern California and Washington and Oregon coastlines need to be treated in like manner using all tsunami data for those regions. Maps are not yet available, however, the data needed to produce them are. No template is given for this hazard.

### 3.5.8 Earthquake Seiche

The phenomenology earthquake-seiche is discussed in Appendix C. No discussion of probabilistic evaluation is developed here.

### 3.5.9 Earthquake-Fire Following

All major contributions to fire loss result from the fire spread or conflagration process, which is essentially modeled using a geometric growth rate procedure. There are two ways in which geometric growth rate produces large loss estimates:

(a) A "large fire" is created when the initial growth is such that it has exceeded the capacity of suppression (fire-fighting) resources when those resources have reached the fire scene.

(b) A "conflagration" is created when a large fire subsequently spreads resulting from fire growth, crossing fire breaks and burning for days.

In modeling fire loss, these conditions of geometric growth are driven by two initial conditions:

(1) The number of ignitions (the demand) exceeds the available "units" of fire suppression resources (the supply), thereby producing conditions for large fires.

(2) The precise initial condition at any fire is influenced by the reporting delay and engine travel time. This overall delay is an offset in the initial condition applied to the geometric growth of the individual fire. The resulting fire loss is dependent upon the estimation of a non-linear (geometric growth) process and upon the estimation of the initial conditions to it. Any error (such as a bias) in estimating parameters will produce tremendous changes in the predicted loss. Sensitivity analyses show that the mathematics are "poorly conditioned" (highly non-linear) in that small changes in initial conditions drastically alter the losses computed.

There are several elements in any model that develop the fire loss summation situation. These are:

(a) Earthquake Source Zone – This is the line or area of faulting from which the earthquake shaking emanates.

(b) Earthquake Shaking Activity Attenuation – The manner in which the earthquake shaking attenuates from source to site and the manner in which the site amplifies the shaking intensity is related to the number of fire ignitions that might take place.

(c) The Fire Ignition Rate – The ignition rate is an important factor.

(d) Individual Fire Growth Rate – The fire might ignite, however, it might not grow. A small ignition might actually cause an explosion which can grow extremely rapidly.

(e) Fire Discovery Time – If the fire is left for a long period of time prior to it's discovery then the difficulty in suppression is generally increased.

(f) Fire Department Contact Time – After the fire is discovered there will be some time during which the fire could grow before the fire department is contacted and alerted to the situation.

(g) Fire Engine Arrival Time – After the fire department is contacted it takes time for the fire engine to travel the streets and arrive at the site.

(h) Water Supply Availability – If the water supply lines have been broken by permanent earth movement or even shaking activity then the presence of the fire crew makes little difference to the fire suppression system.

(i) Initial Fire Suppression Time – The time to suppress each individual fire is a parameter which influences the overall fire loss summation process.

(j) Fire Spread Rate – Many factors including wind speed and direction, dryness of the area, fire breaks, etc. influence the rate of fire spread.

(k) Final Fire Suppression Time – If a fire has spread to more than one structure, the time to suppress a large fire may be different from that for an individual structure.

(l) Fire Loss Summation – All of the individual and multiple structure fires must be summed in order to determine the total loss.

All of the above influence the total fire loss after an earthquake. Each parameter is important in effecting the sum total. Each has a great deal of uncertainty.

No probabilistic method is proposed in this document.