Chapter 9
Induced Damage Models - Inundation

9.1 Introduction

Flood-induced damage in an earthquake can result from tsunamis (seismic sea waves), seiches (sloshing effects in lakes and bays) or dam or levee failure. Especially in the case of dams and levees, a single structure's failure could result in large losses, which implies that a site-specific analysis should be done rather than using the methodology, which is designed to estimate losses based on probabilities of performance across large inventories. Therefore, the potential exposure to earthquake-caused inundation is computed in the methodology, while prediction of losses or the likelihood of losses is excluded. Figure 9.1 illustrates the relationship of the inundation module to other modules in the methodology.

9.1.1 Scope

The purpose of this module provides the methods for assessing inundation loss potential due to dam and levee failure, tsunami and seiche. For each of these hazards, various levels of results can be obtained according to the complexity of the evaluation, data requirements, and the use of expert assistance to perform the assessment.

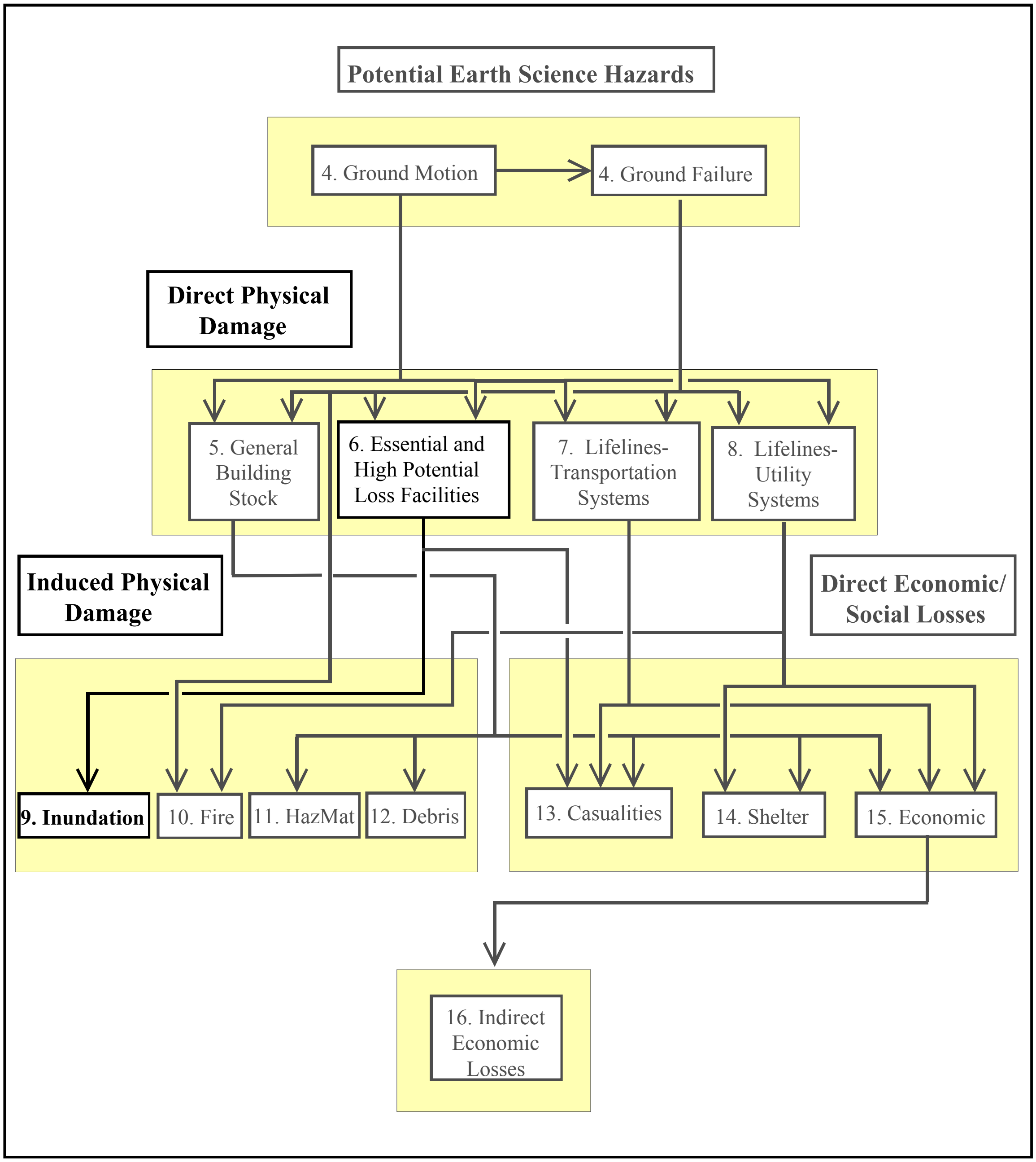
The purpose of this module is to identify the potential sources of flooding in a study area and overlays existing inundation maps with other data to identify the potential exposure. If existing inundation maps are not available, creating inundation maps will require the involvement of experts to perform sophisticated evaluations.

9.1.2 Form of Inundation Estimate

In using existing inundation maps care must be taken in interpreting the results. These maps usually are based on worst-case assumptions, such as a dam being completely full and failing catastrophically, and rarely is such a scenario tied to a specific earthquake scenario.

In general, a complete characterization of flood hazard includes an assessment of:

- Area of inundation
- Depth and velocity of flooding
- Arrival time of the flood following the occurrence of the earthquake, such as in the case of a dam or levee failure or tsunami
- Probability of the above described event



Flowchart 9.1: Relationship of inundation Module to other Modules in the Earthquake Loss Estimation Methodology

The information on inundation that is reported will vary from analysis to analysis. Only in a detailed engineering analysis, as described above, is a complete characterization of the inundation provided.

For each source of flooding (dam or levee failure, tsunami and seiche), the primary format for the presentation of the hazard will be an inundation map. An inundation map identifies the bounds of the area that will be inundated. The bounds can be used to evaluate the population and economic values in the affected area. When digitized for entry into a GIS system, the area of inundation could be overlaid with a topographic map to infer the depth of flooding. However, in the current methodology, this capability does not exist. Figure 9.1 provides an example of an inundation map.

9.1.3 Input Requirements and Output Information

This subsection defines the input requirements and output information for the induced damage inundation module. Subsection 9.1.3.1 describes the input requirements, followed by subsection 9.1.3.2 providing the output information.

9.1.3.1 Input Requirements

9.1.3.1.1 Dam Failure

The input information comes from a default database developed from the National Inventory of Dams database (NATDAM) [FEMA, 1993]. The database identifies all dams in the United States that satisfy the minimum size or hazard criteria given in Table 9.1. For each dam, the database contains multiple fields of information related to the dam and the body of water impounded by the dam. Hazard classifications are found in Section 9.1.3.2.1. Where they exist, inundation maps can be collected. The availability of inundation maps can be determined by contacting the following organizations:

- State or federal dam safety or water resources regulatory agencies
- State office of emergency services
- Local emergency services, law enforcement, or fire protection agencies
- Dam owner (which may be a private individual or organization or public agency such as the U.S. Army Corps of Engineers or Bureau of Reclamation).

Table 9.1 National Inventory of Dam - Size and Hazard Criteria

Category	Criterion	Excluded
Dam Height	Structural Height (H) $\geq$ 25 ft.	C $\leq$ 15 acre-feet maximum capacity regardless of dam height
Reservoir Size	Reservoir Impoundment Capacity (C) $\geq$ 50 acre-feet	H $\leq$ 6 feet regardless of reservoir capacity
Hazard	Any dam that poses a "significant" threat to human life or property in the event of its failure.	

9.1.3.1.2 Levee Failure

Unlike dams, a national inventory for levees does not exist. The user must contact local sources to identify levees in the study region. Possible sources include United States Army Corps of Engineers district offices, local flood, reclamation, or levee maintenance control districts, the United States Soil Conservation Service, and municipal or county authorities. The user must provide the geographical location of the levees (represented in the methodology software as polylines). Additional information that should be included in the levee inventory includes the levee design basis (e.g., 100 year flood), the levee crest elevations, normal water level elevation, and levee owner/operator.

Since most levees and in some locations floodwalls are designed to provide protection during periods of flooding, they are typically dry (i.e., do not impound/retain water) at the majority of the time. As a result, seismic failure of a levee during non-flood conditions does not pose an inundation hazard. As part of the process of identifying levees in the study region, the user should also obtain information as to whether the levee is dry the majority of the year (e.g. greater than 75% of the time). If this is the case, the levee might be screened out from further consideration, unless a study of the worst-case scenario is desired

Existing levee inundation maps are used to identify areas that may be flooded in the case of a failure. It is unlikely that an existing levee inundation study will be available. If a study is available, it should be reviewed to determine whether the water level used is consistent with the level that can be expected when an earthquake occurs.

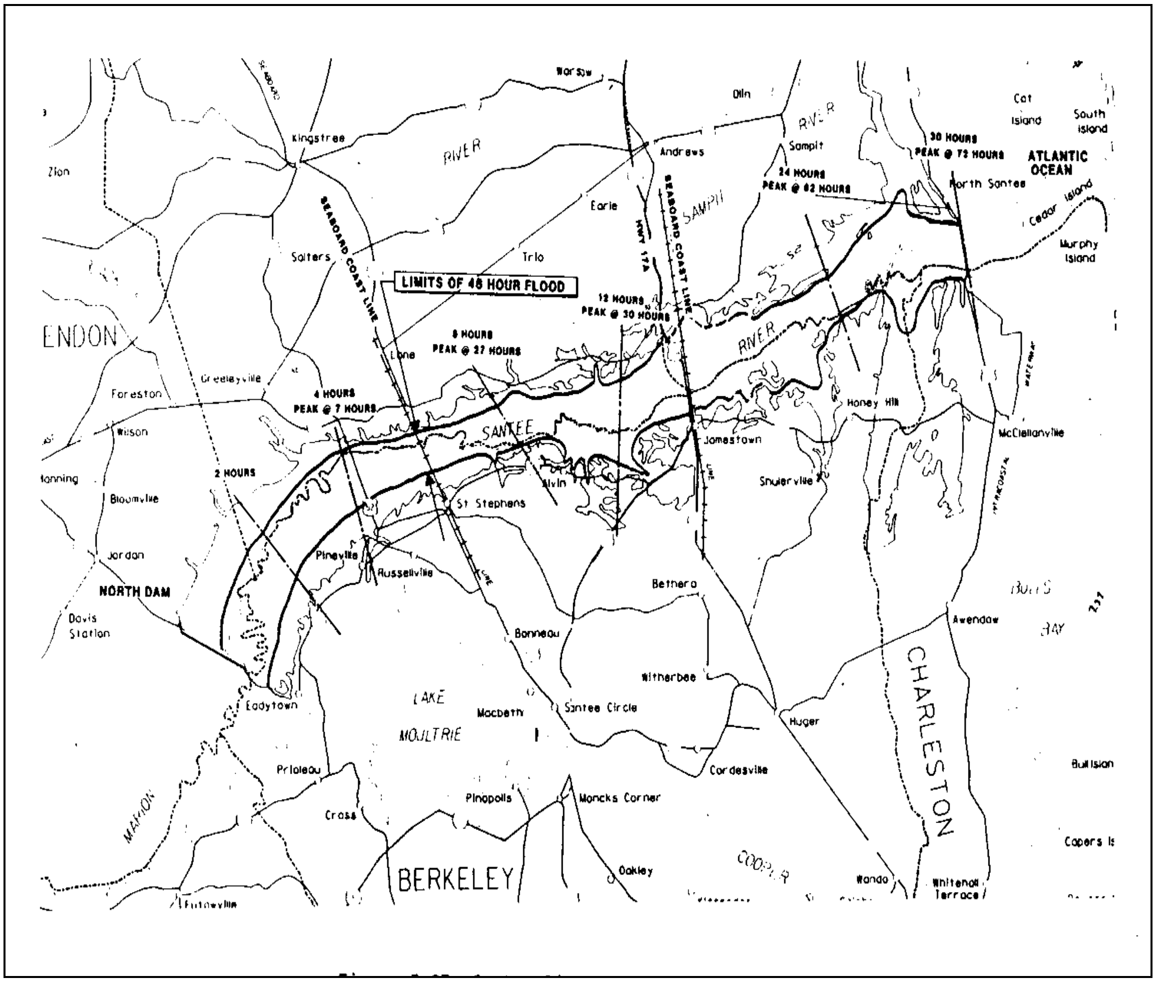


Figure 9.1 Dam failure inundation map.

9.1.3.1.3 Input Requirements - Tsunami

The first objective in the analysis of tsunami is to simply identify whether a tsunami hazard exists. To accomplish this, the following information is needed.

- Location of the earthquake (on-shore or off-shore event)
- Type of faulting

If the earthquake source is on-shore there is no tsunami hazard. The same is true if an offshore event occurs that involves primarily strike-slip movement. Alternatively, if the earthquake occurs offshore and significant vertical displacement of the seafloor occurs and a tsunami exists. The assessment of tsunami inundation in the methodology is for nearby seismic events only. Tsunami inundation maps based on distant events should not be combined with the study region scenarios. For example, a tsunami affecting the West Coast generated by and earthquake in Alaska should not be combined with the study of losses occurring from an earthquake in Los Angeles.

The user should determine the size and location of the earthquake that was assumed to estimate the tsunami inundation or, if specified, the mean return period of the tsunami. This will provide a basis to judge whether the existing inundation map conservatively or un-conservatively estimates the inundation that would be produced by the study earthquake. In cases where a scenario earthquake would generate a tsunami, the probability basis of the tsunami inundation map should match that of the scenario earthquake. For example, if an existing tsunami inundation map based on wave run-ups caused by local earthquake that have a mean return period of 500 years for a study region in Alaska, then the scenario earthquake selected for use with the methodology should also have a 500 year return period. Otherwise, the tsunami and the earthquake loss outputs should not be combined because this would describe different events.

9.1.3.1.4 Input Requirements - Seiche

To first step in seiche analysis is to identify natural or man-made bodies of water where a seiche may be generated. The default database of dams can be used to identify the man-made bodies of water (see Section 9.1.3.1.1) while the user must generate an inventory of natural water bodies in the study region. The following criteria can be used to identify bodies of water that should be considered in the assessment:

- The lake volume must be greater than 500,000 acre-feet
- There must be an existing population and/or property located in proximity to the lake shore that could be inundated

If these criteria are not met, lakes should not be considered for assessment. Existing seiche inundation maps are used to identify areas subject to flooding. Sources of existing seiche inundation studies include state and federal agencies that regulate dams, dam or lake owners, and state office of emergency services. The availability of such studies is very limited.

9.1.3.2 Output Information

The output of the dam failure inundation module consists of an inventory of the dams located in the study region divided into three groups corresponding to the hazard classifications provided in the database. The hazard classification system is shown in the Table 9.2 below.

Table 9.2 Dam Hazard Classifications

Hazard	Urban Development	Economic Loss
Low	No permanent structures for human habitation	Minimal (undeveloped to occasional structures or agriculture)
Significant	Urban development and no more than a small number of inhabitable structures	Appreciable (notable agriculture, industry)
High	Urban development with more than a small number of inhabitable structures	Serious (extensive community, industry or agriculture)

In addition to the inventory of dams located in the study region, the analysis will utilize existing digital dam inundation maps to identify the population and property at risk due to the dam failure.

The output of levees analysis is an inventory of the levees in the study region whose failure could lead to flooding. In addition to the inventory of levees located in the study region, analysis can use existing digital levee, tsunami, and seiche inundation maps (limited availability) to quantify the population and property at risk due to the failure of levees.

9.2 Description of Methodology

9.2.1 Dam Failure

This subsection describes the approach used to perform analyses for inundation due to dam failure. To start the analysis of dams, the dams that are located in the study region have to be identified. To do this, a geographic search through the default dam database is conducted. Based on the dam hazard classification, a list of the Low, Significant and High Hazard dams can generated. Note that “hazard” here means the danger posed if the dam fails, and is not a description of the probability of such failure. Next, an analysis using existing digital inundation maps is conducted to estimate the potential population and economic value impacted by a dam failure.

9.2.2 Levee Failure

The tasks and analysis tools are similar to those required for dam failure. An inventory of levees located in the study region is generated by contacting local, state and federal agencies. The inventory should typically include levees that act as water barriers greater than 10 percent of the time. This excludes from the inventory levees that remain dry except during short periods of flooding, because of the small probability the earthquake will coincide with a time of high water level. Existing levee failure inundation studies are used to identify areas that may be impacted by levee failure. When using existing inundation studies, the following should be considered:

- Existing inundation studies must be reviewed to determine assumptions regarding water levels
- The analyst should identify areas where levee failure will have the most severe impact; existing studies may not have used this approach

9.2.3 Tsunami

This subsection describes the approach to perform evaluations for inundation due to tsunami. Existing tsunami studies may include inundation maps for the scenario earthquake. However, they should be reviewed to verify the assumptions on which the tsunami was based. As explained above, tsunami inundation maps developed for distant earthquakes should not be used in combination with a local scenario event. However, the methodology can be used to independently estimate the population and building value at risk from a distant event tsunami simply by using a representative inundation map in which case these results would not be combined with those of a local earthquake scenario.

9.2.4 Seiche

This subsection describes the approach to perform evaluations for inundation due to seiche. Existing seiche inundation studies are used to identify the areas where flooding may occur. However, in most cases such studies do not exist. In some cases the results of a seiche analysis may be available that did not produce an inundation map. In this case, the user could transfer the results to a topographic map of the lakeshore area to determine the bounds of inundation.

9.3 Guidance for Expert-Generated Estimates

Losses that might be caused by earthquake-caused flooding are not calculated within the methodology, because of the facility-specific evaluation by experts that is necessary. The information in this section is not intended to supplant the need for experts when a loss study is extended into these induced hazards, but rather to provide these civil engineering, hydrological, and geotechnical experts guidance to standardize their analyses.

9.3.1 Dam Failure

The greatest uncertainty lies in the likely cause, mode, degree and time sequence of failure. Another uncertainty involves flood routing and limits of inundation downstream of the failed dams. Although several historical dam failures have been documented, very few have provided an exact description of the hydraulics of the failure flood.

The hydraulic characteristics of a surge released from a dam failure depends on the size, shape and position of the breach, volume of water stored behind the dam, the dam height, width and length of the reservoir, and the reservoir inflow and tailwater condition at the time of the failure. To provide uniformity in the evaluation of the effects of dam failure during a seismic event, the following guidelines are provided. These guidelines should be followed unless deviations are appropriate in the opinion of an expert analyst.

Antecedent Conditions - Reservoir levels generally predictably related to the purpose of the reservoir. Whereas a seismic event can occur anytime during the year, the following guidance is provided:

1. Reservoir Conditions - It should be assumed that the reservoir is at the average operational level for the season when water levels are highest. If the average operational level is not known, the maximum normal depth of water should be used.
2. Antecedent Flow - Unless a dam has failed due to failure of an upstream dam, the antecedent stream flow into the reservoir is assumed equivalent to the mean monthly flow for the season assumed for the scenario. If the failure is assumed to occur during the flood season, then the mean annual flood for the month is assumed. This antecedent flow can also be applied as the base flow downstream of the dam.

Tailwater Condition - No assumption on the varying tailwater condition is necessary when using DAMBRK, a program developed by the National Weather Service (NWS), because the model automatically calculates the tailwater elevation based on the base flow and outflow from the spillway or breach formation. The model does appropriate correction for submergence automatically.

River Cross-Section - For the purpose of representing the river channel in the DAMBRK model (see Figure 9.2), cross-sections of the river at selected critical stations are normally taken from U.S.G.S. 7 1/2 minute topographic maps. Since only 8 elevation-top-widths data points can be accepted by DAMBRK, care should be used in selecting cross-section data for the stations along the river or valleys to assure accurate estimates of flood elevations.

Mode of Failure - A conservative estimate of flooding due to a dam failure would assume complete disappearance of the dam. For small concrete dams, such an assumption may be reasonable. However, for large concrete gravity dams, it is more reasonable to assume partial breach with some parts of the dam remaining intact. For example, embankment dams will generally fail by erosion.

Shape and Size of Failure - Breach shapes are assumed to follow regular geometrical shapes such as a triangle, rectangle, trapezoid, or parabolic figure. Failure depth is always assumed equal to the total height of the dam unless there is a high tailwater. Table 9.3 gives guidance on the various parameters that could be assumed for a given breach shape and size.

Time to Maximum Failure - This is one of the most unpredictable parameters in dam break modeling. To facilitate the adoption of reasonable values of time to maximum failure, Table 9.3 gives recommended values for various types of dams.

Expansion and Contraction Coefficients - The manual for DAMBRK recommends values of cross-section contraction/expansion coefficients for the contraction or expansion of the downstream reach's cross-sectional geometry. Contraction values generally vary from 0.1 to 0.3 while expansion values usually vary from -1.0 to -0.1. If contraction-expansion effects are negligible, a value of 0.1 is used.

Table 9.3 Suggested Breach Characteristics (see Figure 9.3)
(Fread, 1982)

Parameter	Value	Type of Dam
Average Breach Width (BR)	W = Crest Length H = Dam Height BR = Width of 1 or more monoliths, usually BR ≤ 0.50W	Arch Masonry, Gravity
	HD < BR ≤ 5HD (usually between 2HD and 4HD)	Earthen, Rockfill, Timber Crib
	BR > 0.8 Crest Length	Slag, Refuse
Horizontal Component of the Side Slope of Breach (Z)	0<Z≤ Slope of the Valley Walls	Arch
	Z = 0	Masonry, Gravity, Timber Crib
	1/4 < Z ≤ 1	Earthen (engineered compacted)
	1 < Z ≤ 2	Slag, Refuse (non-engineered)
Time to Failure (TFH) (hours)	TFH < 0.10	Arch
	0.1 < TFH ≤ 0.3	Masonry, Gravity
	0.1 < TFH ≤ 1.0	Earthen (engineered compacted), Timber Crib
	0.1 < TFH ≤ 0.5	Earthen (non-engineered, poor construction)
	0.1 < TFH ≤ 0.3	Slag, Refuse

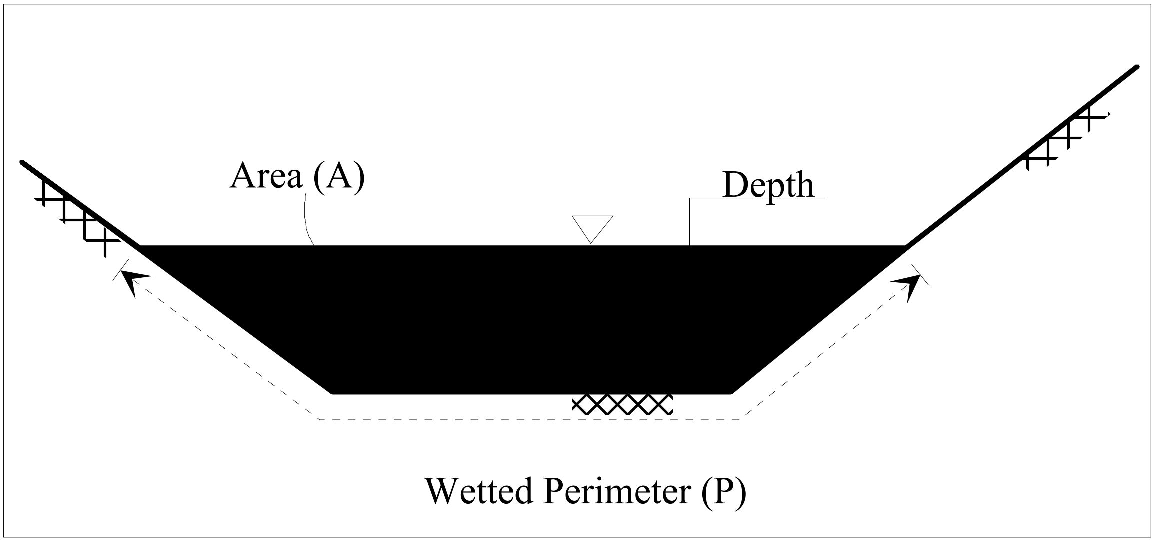


Figure 9.2 Illustration of a channel cross-section.

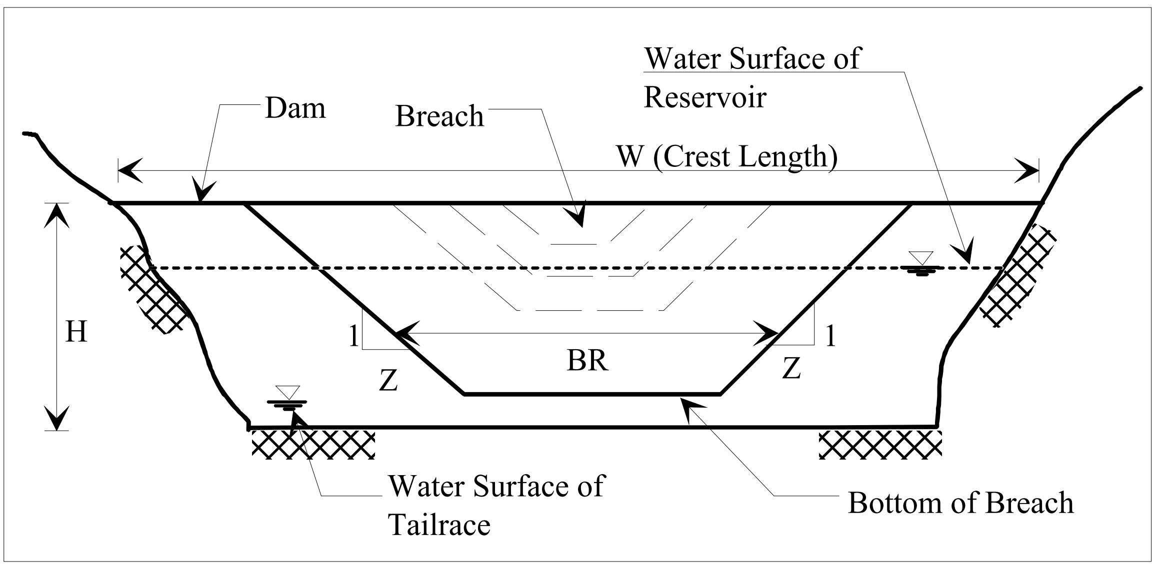


Figure 9.3 Definition sketch of the breach parameters.

Roughness Coefficients - Manning's "n" which represents the roughness of the river channel is the most indeterminate variable in dam break modeling. Calibrated values from high-water marks cannot really be used to represent those expected under a dam failure flood. Published data such as those from the U.S.G.S. can only be used to approximate the expected value from the hypothetical flooding. Therefore, it is necessary that relatively reasonable values be assumed or considered before a flood plain analysis is started. In most cases, these assumed values are varied through the modeling effort in order to resolve non-convergence problems with DAMBRK.

Table 9.4 Recommended Values of Manning's n
(US Dept. of Transportation, 1980)

Channel Type	n Values
1. Fairly regular section	
a. Some grass and weeds, little or no brush	0.30-0.035
b. Dense growth of weeds, depth of flow materially greater than weed height	0.35-0.05
c. Some weeds, light brush on banks	0.35-0.05
d. Some weeds, heavy brush on banks	0.05-0.07
e. Some weeds, dense willows on banks	0.06-0.08
f. For trees within channel, with branches submerged at high stage, increase all above values by	0.01-0.02
2. Irregular sections, with pools, slight channel meander; <u>increase</u> values given above about	0.01-0.02
3. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stage:	
a. Bottom of gravel, cobbles, and few boulders	0.04-0.05
b. Bottom of cobbles, with large boulders	0.05-0.07

Routing - Generally the flood wave from a hypothetical dam break flood should be routed downstream to the point where the failure will no longer constitute a threat to human life or property. The results of the routing should be plotted on inundation maps with the dam break flood wave travel time and flood depths indicated at critical downstream locations.

9.3.2 Levee Failure

The guidance for expert generated inundation due to levee failure is essentially the same as the guidance for dam failures. The NWS DAMBRK software is used to determine the flooding due to levee failure. However, in the case of levee failure the analyst should consider multiple locations for levee failure based on a consideration of the locations where the levee may be most vulnerable and where the impact of flooding in the study area would be greatest.

9.3.3 Tsunami

The most detailed work on inundation map preparation from tsunami has been conducted for Hawaii, though sophisticated analyses have also been conducted for areas of the West Coast. Therefore, most guidelines refer to the work in this state. However, it should be noted that even though the following guidelines have been applied to Hawaii, the same procedures and assumptions could be adapted to other coastlines of the country that would be subject to tsunami flooding.

Tsunami inundation maps that have been produced are based on computer programs that are considered state-of-the-art. However, these programs are still short of the accuracy attainable by hurricane and storm-surge simulation programs. A two-dimensional model is recommended for modeling of tsunami for inundation studies. The available two-dimensional models solve the non-linear shallow water long wave equation using different methods of finite difference solution. A complete description of the available and verified models in the United Sates is provided in Bernard and Gonzalez, 1994. Numeric models are used to make scenario specific tsunami assessments. Inputs required for this assessment include detailed information on the location of earthquake and fault movement that is expected to occur on the ocean floor. In addition, information is needed regarding the bathymetry of the ocean floor, shoreline geometry, topographic data and tide information. Good quality bathymetric and topographic data are essential for accurate inundation model results.

9.3.4 Seiche

A detailed assessment is performed to estimate the seiche hazard at natural and man-made bodies of water. Input to this assessment includes the length, width and depth of each body of water and rim topographic and geologic information required to assess landslide potential and wave run-up. The length and width of the lake or reservoir correspond to the average dimensions of the body of water where wave generation is evaluated. The user may have to consider a number of different wave geometries to determine the critical dimensions that generate the largest estimated wave height. At a minimum, geologic maps of the lake or reservoir rim or landslide potential maps should be obtained. In addition, for earthquakes that occur on faults along or within bodies of water, the location of the event and the magnitude of vertical fault displacement is required.

A simple calculation is performed to determine the maximum wave height that would be generated by an earthquake. The following relationship can be used to estimate the peak wave height.

$$H = \sqrt{\frac{A}{L(\pi f)^2}} \qquad (9\text{-}1)$$

where:

H = peak wave height (cm)
A = peak ground acceleration (in g's)
f = frequency of the lake (Hz)
L = Wavelength $= 5.12 / f^2$

The above approach is a simplified method to estimate the peak wave height of a seiche generated by seismic motion at the lake. As part of this assessment the analyst must consider the occurrence of waves along alternative axes in the lake. Since the natural period of the lake is based on its shape, the period will be different on different axes.

Oscillations of water bodies above and below their mean level have a natural period depending upon the physical features of the water body. A disturbing force with the same period of oscillation as the lake or pool builds up the seiche to the point where the energy dissipated by friction equals the rate of application of energy. When the force causing the displacement ceases or changes in intensity, a series of pulsations follow at the natural frequency until damped by frictional forces. Standing waves of large amplitude are likely to be generated when the causative forces which sets the water basin in motion is periodic in character, especially if the period of these forces is the same as, or is in resonance with, the natural or free oscillation period of the basin.

The period of the seiche is dependent on the geometry of the basin. This period can be estimated with Merian's equation.

$$T_n = \frac{2l_b}{n\sqrt{gd}} \tag{9-2}$$

where:

T_n = period in seconds
l_b = length of the basin
n = number of nodes 1,2,3,...
g = gravitational acceleration
d = depth of water

For the fundamental and maximum period (T_n for n=1),

$$T_1 = \frac{2l_b}{\sqrt{gd}} \tag{9-3}$$

However, the preceding equation is based on the assumption of uniform and constant cross-section in the basin. In a basin of irregular section, the period is given by integrating equation 9-4. The frequency of the basin is the reciprocal of the period.

$$T = 2\int_0^{l_b} \frac{dx}{\sqrt{gd}} \tag{9-4}$$

where dx = finite increment of l_b.

9.4 Inundation References

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