DELTA RISK MANAGEMENT STRATEGY

INITIAL TECHNICAL FRAMEWORK PAPER

LEVEE FRAGILITY

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Levee Fragility

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Foreword

The purpose of the Delta Risk Management Strategy (DRMS) Initial Technical Framework (ITF) is to guide the analysis of specific technical topics as they relate to assessing potential risks to Delta levees and assets resulting from various potential impacts (e.g., floods, earthquakes, subsidence, and climate change). These ITFs are considered “starting points” for the work that is to proceed on each topic. As the work is developed, improvements or modifications to the methodology presented in this ITF may occur.

The scope of this ITF paper addresses levee fragility analysis under various stress events. These events are normal (static) conditions, floods, and seismic events, and the effects of climate change and subsidence on these events. Subsidence of an island is mainly a result of oxidation of the surficial soft peat. The direct effect of subsidence can be considered with the levee configuration that will be used in the fragility analysis. Climate change may result in sea level rise and may also increase the frequency and the magnitude of flooding. The effects of climate change will be integrated into the model that predicts the flooding in the delta and associated flood stages in various areas of the Delta. This ITF paper describes the methodology for analyzing the fragility of the Delta levees under these stress events, the inputs required to perform the analysis, the expected output, and a work plan to complete the analysis.

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1.0 INTRODUCTION

Levee fragility is one of several topical area methodology Initial Technical Framework (ITF) papers prepared for the Delta Risk Management Strategy (DRMS) project. The overall objectives of the DRMS project are to evaluate the risk of failure of the Delta levees under present as well as foreseeable future conditions and to develop a risk management strategy to reduce and manage the risk.

The Delta has approximately 1,100 miles of levees of significant height (up to 25 feet) continuously impounding sloughs and river waters and protecting agriculture and urban areas within islands and tracts. The islands' floor in the central and western Delta is below sea level by several feet as a result of farming-induced oxido-reduction of organic and peaty soils. The Suisun Marsh has over 220 miles of exterior levee that protect over 50,000 acres of managed wetland habitats, delta water quality, and Suisun public and private infrastructure. These levees are primarily privately maintained and considerably smaller in height and width than those levees in the legal boundary of the Delta. Due to the Suisun Marsh's geographic location in the estuary, the channel water salinities are higher and more seasonally variable than those of the Delta. Historical land use in the Suisun Marsh has preserved the peat soils and has resulted in less significant subsidence in comparison to land in the Sacramento–San Joaquin Delta. The term "Delta" as it appears in this ITF is taken to include the Sacramento–San Joaquin Delta area and the Suisun Marsh area. The primary purpose of each ITF paper is to describe the methodology and its input and output characteristics to perform a probabilistic analysis of a specific topical area in a manner that is consistent with the overall DRMS risk analysis framework.

The scope of this ITF paper addresses the levee fragility analysis under various stress events. These events are normal (static) conditions, floods, and seismic events, and the effects of climate change and subsidence on these events. Subsidence of an island is mainly a result of oxidation of the surficial soft peat. The direct effect of subsidence can be considered with the levee configuration that will be used in the fragility analysis. Climate change may result in sea level rise and may also increase the frequency and the magnitude of flooding. The effects of climate change will be integrated into the model that predicts the flooding in the delta and associated flood stages in various areas of the Delta. This ITF paper describes the methodology for analyzing the fragility of the Delta levees under these stress events, the inputs required to perform the analysis, the expected output, and a work plan to complete the analysis.

There have been 162 Delta failures leading to island inundations since construction of levees a century ago. No reports could be found to indicate that seismic shaking had ever induced significant damage. However, the lack of historic damage should not be used to conclude that Delta levees are not vulnerable to earthquake shaking. The present day Delta levees have never been significantly tested under moderate to high seismic shaking since the levees have been at their current size (CALFED 2000).

2.0 OBJECTIVE

The objective of the levee fragility analysis is to evaluate the probability of failure of levee reaches for each stressing event, considering for all modes of failures that may occur during the event. A fragility curve expresses the probability of levee failure in a particular mode caused by a stressing event, for example, seismic loading. As part of the assessment of levee vulnerability, the aleatory and epistemic uncertainties in the analysis will also be evaluated.

3.0 PHYSICAL SYSTEM

The system of levees in the Delta study area will be divided into *vulnerability classes* using factors that differentiate the performance of the levees when subjected to the same stressing event. The following factors are considered to be a starting point to define levee vulnerability classes:

- Levee fill material (properties and thickness of peat and soil)
- Foundation material (material and thickness of peat, potentially liquefiable soil, pervious substrata)
- Levee geometry (levee width at mid height and height of levee)
- Performance history, maintenance and current maintenance practices

Because most levees in the Delta have generally been formed under similar depositional environments and similar construction processes, the variety of levee configurations can be simplified into two basic parameters: height of levee (H_i) and nominal widths of levee (L_1, L_2), which can be represented by single shape factors such as L_i/H_i, as shown in Figure 1. However, when the analysis model allows, typical cross sections will be developed for each class rather than shape factors, as described in Section 5.1.

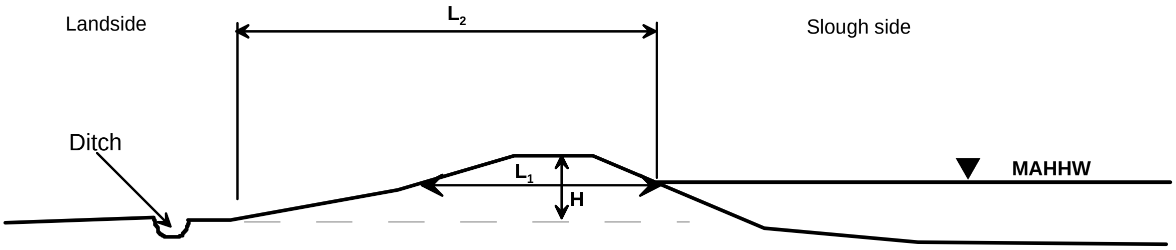


Figure 1: Typical Levee Configuration

The first step in assessing the risk of failure is to gather and review the available information (e.g., soil borings, past performance, maintenance history, etc.) and use this information to develop a GIS-based Delta levee catalogue that provides data regarding the spatial and temporal variation in conditions. This catalogue can then be used to develop typical cross sections (e.g., Figure 2) based on a shape factor and materials. Systematic variations in levee conditions over the study area will be analyzed to define distinct levee vulnerability classes. Based on the GIS-based Delta levee catalogue, individual reaches of levees will be assigned to their respective vulnerability classes.

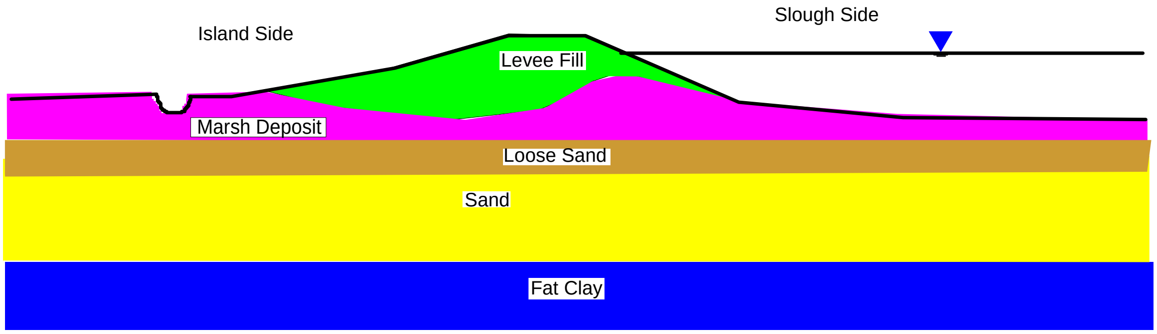


Figure 2: Typical Levee Cross Section (For illustrative purposes only)

4.0 ENGINEERING OR SCIENTIFIC MODELS

Three stressing events identified for the study are: normal “sunny weather” condition, (steady-state seepage, ongoing piping, settlement, lateral spreading, borrowing animals etc.), flooding, and seismic loading. The vulnerability of levees at various times in the future to each stressing event will be evaluated taking into account the expected time dependent changes (climate change, subsidence, structural integrity). The expected trends in these time-dependent variables are shown in Figure 3. The following levee failure modes will be considered:

- Levee through-seepage and/or under-seepage (for various flood stages)
- Wave-induced erosion on both water and landside slopes (in the event of an island flooding)
- Flood-induced overtopping
- Current-induced erosion
- Static instability
- Levee instability due to sudden drawdown in a slough that may occur as a result of levee failures and island flooding
- Seismic-induced failures (deformation due to liquefaction and inertial loading of non-liquefiable materials).

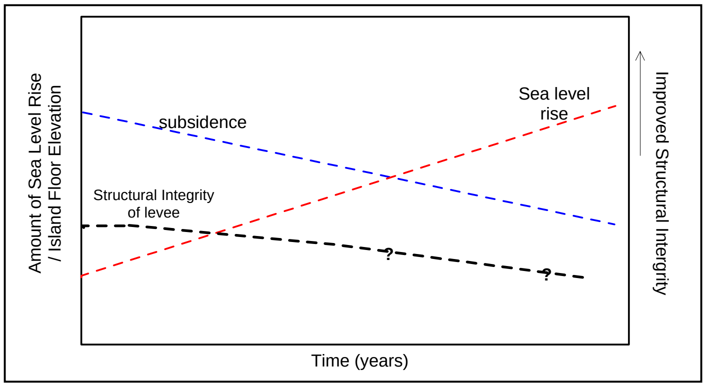


Figure 3: Time Dependent Changes

The engineering analyses will be performed using well-established approaches and numerical models as summarized in Table 1.

Table 1
Summary of Engineering Models

Failure Modes	Basis of Prediction	Models and Parameters	Input from Others	Uncertainties (Aleatory and Epistemic)
Through and/or under seepage	Levee class, Maintenance, Height of water and duration	Seepage analysis numerical models (e.g., SEEP/W), gradients	Height of water and duration	Model, Geometry, Material properties
Wave-induced erosion	Levee class, Maintenance, Wave size, Riprap size	Wave height versus riprap, Weight or D_{50} for F.S. of ½,1, 2	Wave size, (hydrologists)	Model, Geometry, Levee fill, Riprap
Flood-induced overtopping	Levee class, Height of water, Duration, Width of levee, Paved?	Height of water and duration over crest	Height of water and duration	Model, Geometry, Material properties
Current-induced erosion	Levee class, Riprap, Velocity	Velocity, Riprap,	Velocity (hydrologists)	Model, Geometry, Material properties
Static instability	Levee class, Height of water	Slope stability analysis	Height of water	Model, geometry, Material properties
Levee instability due to sudden drawdown	Levee class, amount of drawdown	UTEXAS-3, Levee fill properties	Amount of drawdown (gulp)	Variation around the mean drawdown value ( )
Seismic-induced deformation or liquefaction	Estimate deformation	Deformation analysis (simplified and QUAD4M-Newmark)	PGA, Mw Acceleration time history, response spectra	Model, geometry, Dynamic material properties

The engineering or scientific models are further described in Section 5.0.

5.0 PROBABILISTIC APPROACH

The probabilistic evaluation of levee fragility will involve an assessment of the probability distribution of the damage state of each levee reach under each stressing event defined by the hazard teams. These results will then be used in the risk quantification module to define multiple realizations of the spatial distribution of damaged levees reaches For this study, two distinct damage states will be defined for a given levee reach: (1) a breach; and (2) damage, but no breach.

The effect of a given stressing event will vary spatially and this variability will exhibit aleatory uncertainty. For brevity, we will use the term “snapshot” to define a particular realization of the spatial distribution of the effect over the study area. Thus, for example, a “ground motion snapshot” will be a particular realization of the spatial distribution of ground motion under a seismic event of specified magnitude and location. Many such ground motion snapshots (i.e., realizations of spatial distribution of ground motion) are plausible. They would be generated by sampling the spatial variability in the attenuation of ground motion for the specified seismic event.

A particular combination of a stressing event and a resulting effect snapshot will define a “stressing event set”. For example, for seismic hazard, a specific event may be defined to be a magnitude-7 earthquake on the southern segment of the Hayward fault. For this event, the variability of the ground attenuation may be sampled to produce multiple ground motion snapshots over the study area. This specific event and a specific ground motion snapshot together will define one particular stressing event set for the seismic hazard.

Given a particular stressing event set, the probabilistic evaluation of levee fragility will be performed using the following steps:

1. Analyze the probability distribution of the damage state of a representative levee section in each vulnerability class under each stressing event set.
2. Develop levee damage snapshots (i.e., multiple realizations of the spatial distribution of damaged levee reaches) under each stressing event set.

Details of these steps follow.

5.1 Models for Analyzing the Probability Distribution of the Damage State of Levee Reaches Under a Given Stressing Event Set

Levee fragility will be analyzed under normal, seismic, and flooding events. The following sections describe the failure/damage modes under each type of event and the specific engineering models and model parameters that will be used to analyze the probability of failure/damage under each mode.

Normal Conditions

Modes of failure/damage state for the normal condition include piping through cracks or animal burrows in the levees, piping due to through-seepage or under-seepage, and slope instability (though the latter has a very low probability compared to other failure modes). The analyses will consist of slope stability analysis using limit equilibrium methods (using the computer program UTEXAS (Wright 1991) and seepage analysis using two-dimensional cross-sectional finite element analysis (using the computer program, SEEP/W (GEO-SLOPE International 2004). The aleatory uncertainties associated with subsurface material properties (e.g., c, ϕ, S_u, permeability values, etc.) will be considered in developing the levee fragility curve for each vulnerability class. Calibrations against past and current water surface elevations in the sloughs versus groundwater levels on the landside will be used to validate the model and material properties.

Seismic Condition

The method proposed to develop the levee seismic fragility functions will consider estimating the earthquake-induced permanent deformation for various event sets following the logic trees presented in Figure 4. The earthquake-induced levee deformations can result either in liquefaction-induced flow slides or inertia-induced seismic deformation in non-liquefied case.

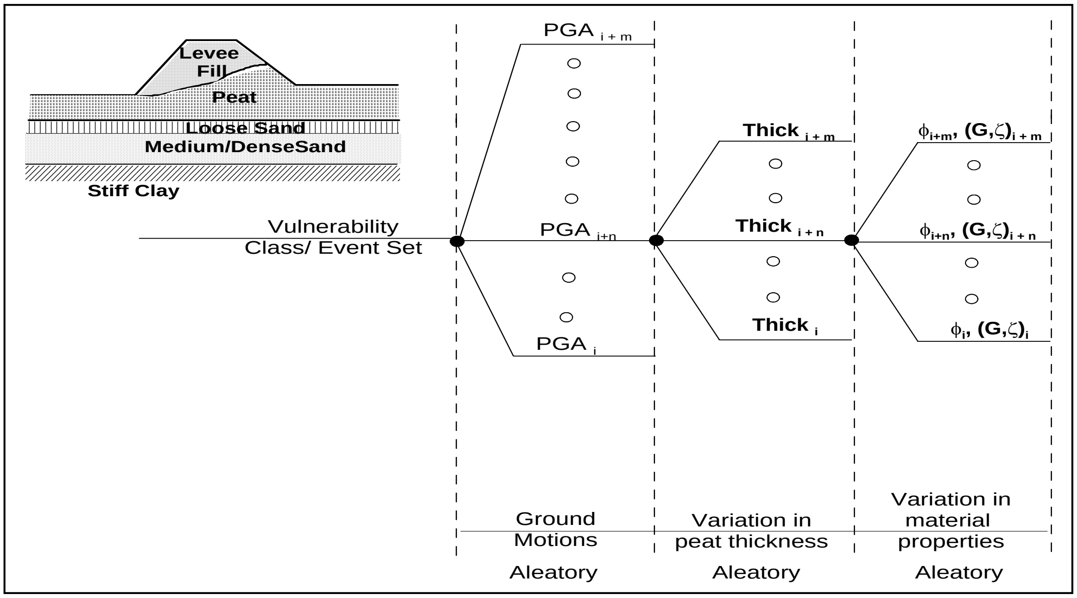


Figure 4: Logic Tree Approach to Estimate Deformation under Seismic Loading

Non-liquefied case: The dynamic site response of the levee and foundation is greatly influenced by the levee-foundation interaction due to the presence of softer marsh deposits in the foundation. It is therefore necessary to perform 2-D site response analysis to capture this interaction and better estimate the seismic-induced displacements and deformations. The 2-D site response analysis will be performed using the computer program QUAD4M (Hudson et al. 1994). A limited validation runs will be conducted using the time domain non-linear computer model FLAC (Itasca 2000). The seismic hazard work group will develop stiff outcropping soil motions (peak ground accelerations [PGAs] and time histories), which will be used as input motion to the QUAD4M model (Figure 5). The seismic-induced displacements and deformations will then be estimated using the Newmark type approach (1965) which requires the output from QUAD4M (i.e., average acceleration along a pre-defined potential sliding mass) and yield acceleration from limit equilibrium analysis.

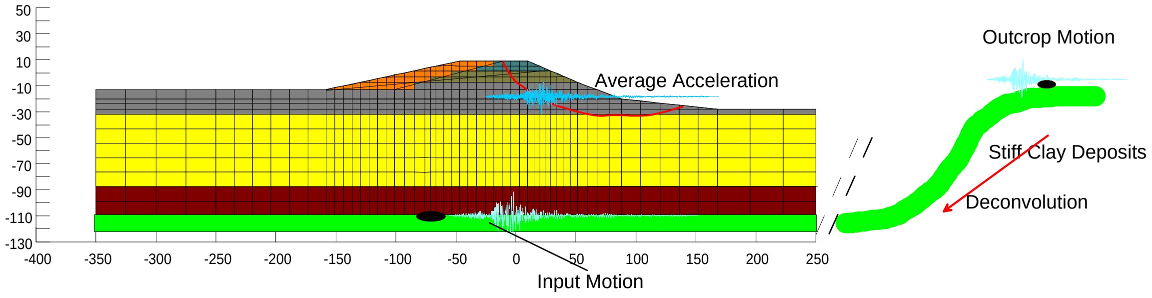


Figure 5: Typical QUAD4M Model and Schematic Illustration of Deconvolution Procedure

Liquefaction Case: The liquefaction potential of saturated loose, cohesionless, sandy and silty layers will be evaluated using the available penetration test data and the more recent correlation relationships developed at U.C. Berkeley (Cetin et al. 2004). The post-liquefaction shear strength will be estimated using the correlation relationships developed by Seed and Harder (1990). The computer program FLAC will be used to evaluate the post-seismic static slumping (when a full time domain analysis is not conducted). However, when a full characterization of flow failure and lateral sliding are required, a time-domain non-linear analysis will be performed (Salah-Mars et al. 2004).

Since there are no reports available to indicate that seismic shaking had ever induced significant damage in the Delta, the levee fragility team will review past performances of levees/dams under seismic loading. Such example may include: the dams that suffered liquefaction-induced slumping during the 2001 Bhuj (India) Earthquake (Seed et al. 2002), the miles of liquefied and slumped levees during the 1999 Chi-Chi (Taiwan) Earthquake (Stewart et al. 2001), and the levee failures during the 1995 Kobe (Japan) Earthquake (Akai et al. 1995).

The aleatory uncertainties associated with the dynamic properties of the levee and foundation soils (e.g., modulus reduction and damping as a function of shear strain, shear wave velocity, c, ϕ, $S_{u,}$ unit weight) will be considered in developing the levee fragility curves. The available results from the ongoing research on dynamic properties of peat at U.C. Davis (Kishida et al. 2006) including the aleatory uncertainty around mean values will be used in this study. The levee fragility under seismic loading will be developed as depicted in Figure 6.

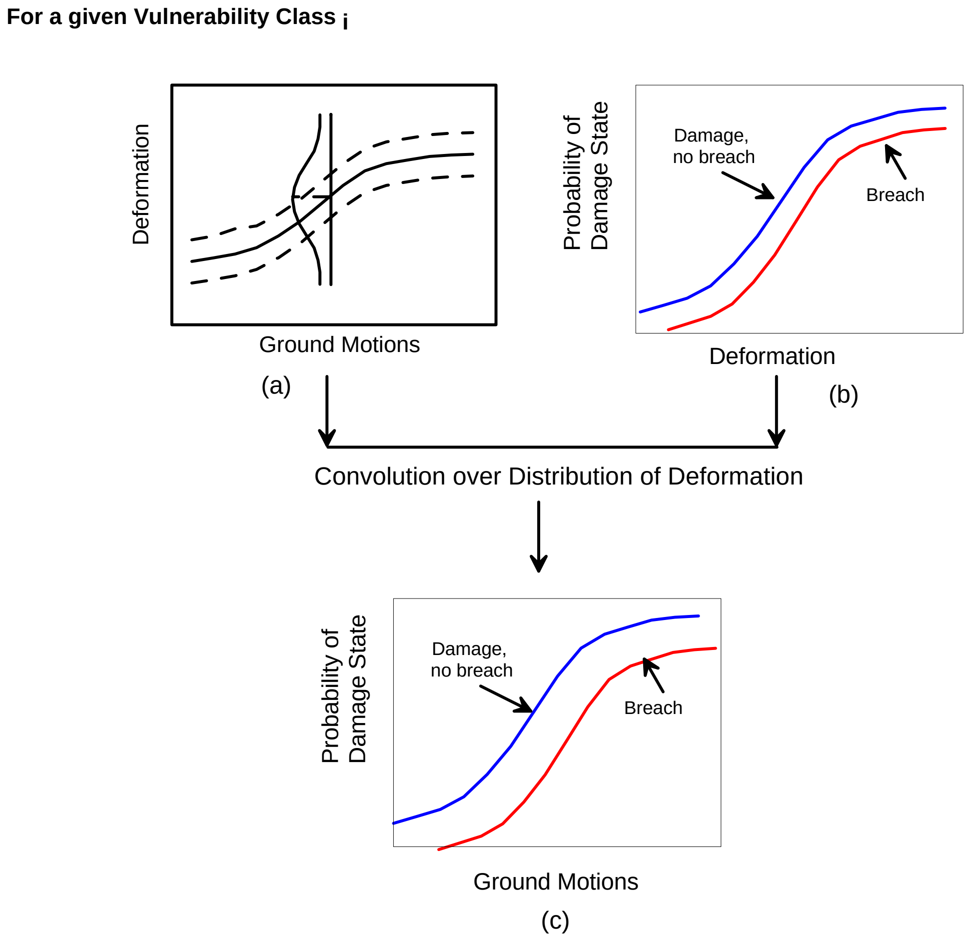


Figure 6: Development of Seismic Levee Fragility Curves under Seismic Events

The model representing the relationship between levee deformation and probability of damage state will be based on known freeboard for that levee class and published correlation relationship between expected damage from deformation and probability of failure (CALFED 2000; Wu et al. 2003), and case histories mentioned earlier. Figure 6 shows how the deformation under a range of ground motions (illustration a in Figure 6) is combined with the probability of damage state (illustration b in Figure 6) to produce the probability of failure as a function of ground motions (illustration c in Figure 6).

Flood Condition

Three modes of failure will be used to assess the probability of a levee failure under flood loading for various water stages.

The **first** mode will consist of estimating the internal and exit gradients for through-seepage and under-seepage on a typical cross section of a reach in a given vulnerability class as a function of flood stage level. To simulate seepage conditions in the Delta for evaluating seepage gradients, a limited number of two-dimensional cross-sectional finite element analyses will be performed (e.g., Figure 7 shows a typical SEEP/W mesh) in combination with simplified procedures that the levee fragility work group will develop. In addition to the basic geometry of the levee and surrounding ground elevations and the water stage elevation, the cross-sectional model will also consider all pertinent features of the physical system (far-field groundwater conditions, local drainage ditches, irregularity of the geometry of the aquifer, slough bottom silt deposits, etc.)

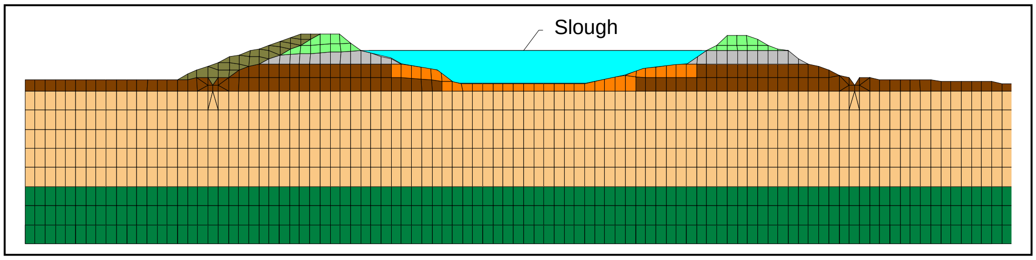


Figure 7: A Typical 2-D Finite Element Mesh for Calculating Seepage Gradients

The **second** mode will consist of estimating the probability of a failure due to overtopping for a typical reach in each vulnerability class. The estimation of the probability of failure will follow the logic-tree approach discussed above in the seismic section.

The **third** mode will consist of estimating the potential failure by erosion process due to wind, wind set-up and wave action for each vulnerability class. As a subset of the third mode of failure, chain-events such as erosion of the interior levee slopes as a result of flooding of an island will be considered.

The probability of levee failure will be correlated to the values of internal and exit gradients following generally accepted criteria for critical gradients and onset of internal erosion and piping. The aleatory uncertainties associated with subsurface material properties, in particular permeability values of pervious soil strata will be considered in developing the levee fragility curve for each vulnerability class as shown in Figure 8.

Failure due to overtopping will be compared to the expected flood stage plus wind set-up and wave action to the levee crest elevation. Similarly, standard published manuals on coastal engineering (USACE 2002) for erosion of waterfront structures, levees, and dikes will be used to estimate the potential for an erosion-induced levee failure (see wind-wave erosion ITF paper).

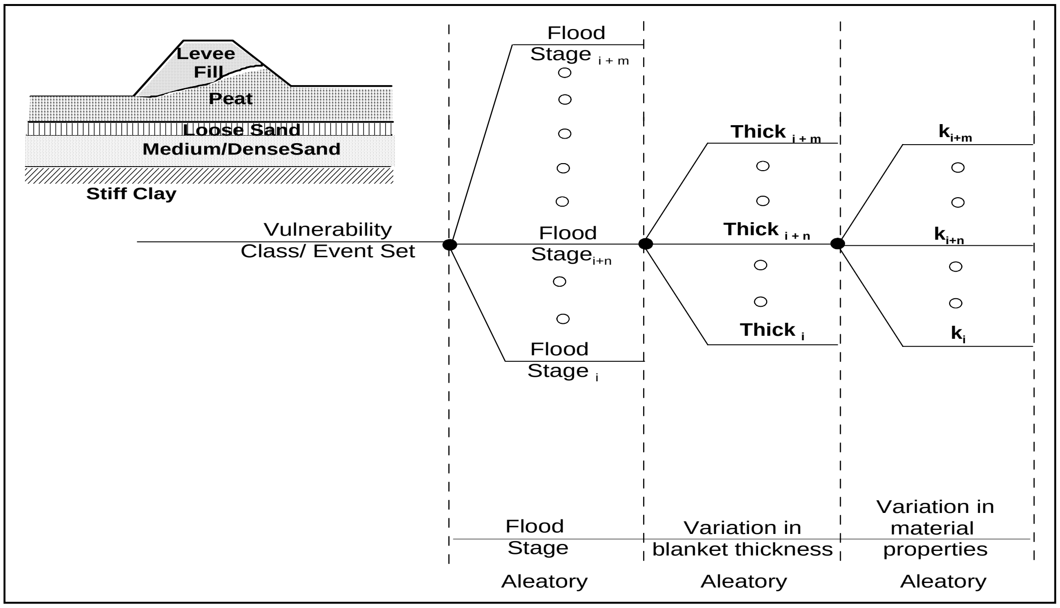
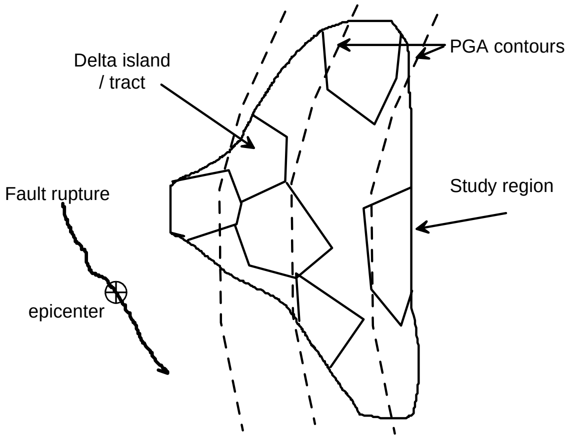


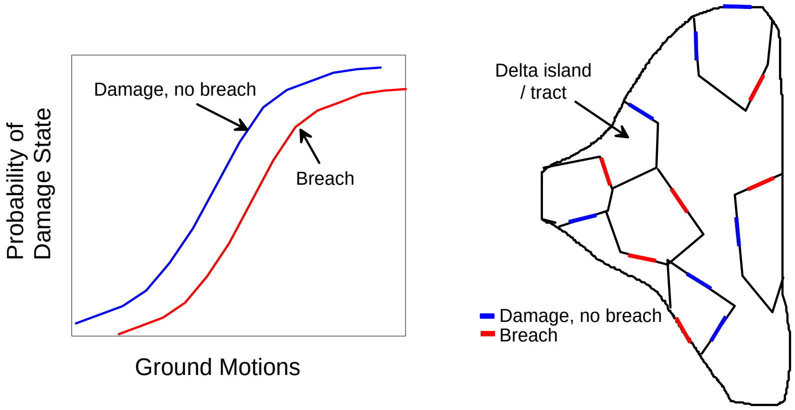
Figure 8: Logic Tree Approach to Estimate Seepage Gradients Under Flooding

5.2 Model for Developing Plausible Levee Damage Snapshots for Each Stressing Event Set

As defined previously, a levee damage snapshot will be a particular realization of the spatial distribution of the damaged levee reaches in the study area under a specified stressing even set (i.e., a given combination of a stressing event and a resulting effect snapshot). The levee fragility analysis will assess the probability distribution of the damage state of each individual levee reach under a given stressing event set. These probability distributions then could be sampled using a statistically valid sampling method (such as Monte Carlo simulation) to generate multiple levee damage states (i.e., realizations of the spatial distribution of the damage states of the levee reaches) in the study area. Figure 9 illustrates the process for developing a levee damage snapshot. The development of levee damage snapshots will be a part of the risk quantification module.



(a) Seismic Event and Resulting Ground Motion Snapshot



(b) Probability of Damage State as a Function of Ground Motion

(c) Levee Damage Snapshot

Figure 9: Development of a Levee Damage Snapshot

5.3 Treatment of Uncertainties

The probabilistic evaluation of levee fragility requires quantifying uncertainties in levee characteristics, engineering models, and model parameters. A distinction is made between two types of uncertainties – “aleatory” and “epistemic”.

Aleatory uncertainties are a reflection of randomness or small-scale natural variability in the input variables for a given engineering model. In principle, the aleatory uncertainties cannot be reduced with additional data collection.

Epistemic uncertainties, on the other hand, are a reflection of limited information about the models or model parameters. Professional judgment may be used in conjunction with available information to estimate model parameters and associated epistemic uncertainties. When information is limited, epistemic uncertainty will be evaluated by assessing the credibility of each plausible hypothesis based on its consistency with data, experience, and consensus within the scientific community.

For the present analysis, epistemic uncertainties will be represented in terms of alternative parameter sets. These uncertainties acknowledge the fact that alternative values of the parameters are plausible. Factors that may be considered in defining alternative parameter sets in the evaluation of levee fragility under a given stressing event include:

- The length of a reach of a levee such that different reaches can be assumed to respond independently to a given loading.
- Miles of levee reaches with liquefiable soils in the foundation.
- Miles of levee reaches with peat.
- Miles of levee reaches that are well designed and maintained.
- Estimates of mean values of input parameters.

For each selected factor, alternative plausible values will be defined and the credibility of each value will be assessed using the expert interpretation of geotechnical engineers familiar with Delta levees and with the performance of levees under a given stressing event.

The probabilistic analysis will quantify aleatory uncertainties in key geotechnical and hydrological variables (such as peat thickness, dynamic soil properties, and permeability values) by defining their probability distributions. The probability distributions will be based on a statistical analysis of available field data and published results of previous studies.

For each parameter set, the aleatory uncertainties will be quantified in terms of appropriate probability distributions. These uncertainties will then be propagated to estimate the probability distribution of levee damage. The next section presents a mathematical formulation of the probabilistic models that will be used for the levee fragility analysis.

5.4 Mathematical Framework for Levee Fragility Analysis

As stated previously, appropriate geotechnical factors will be used to define different levee vulnerability classes. Individual levee reaches will be assigned to the appropriate vulnerability class based on available information. The objective of the levee fragility analysis will be to develop models to assess the probability distribution of the damage state of a representative levee section within each vulnerability class as a function of loading from a given stressing event set.

A mathematical framework of the anticipated models is described in this section for seismic events. A similar framework will be applicable for other stressing events.

For seismic events, the loading may be defined in terms of PGA and earthquake magnitude. Levee response to the loading may be characterized in terms of permanent deformation. Thus, the levee fragility analysis for seismic events can be performed in the following steps:

1. Assess the deformation in each vulnerability class as a function of ground motion (PGA and earthquake magnitude);

2. Assess the probability distribution of levee damage state in each vulnerability class as a function of deformation; and
3. Combine the results of the first steps to develop the probability distribution of levee damage state in each vulnerability class as a function of ground motion.

The probability models for these steps are described below.

Probability Model to Assess Levee Response as a Function of Loading

An engineering model (QUAD4M or similar) will be first used to estimate the mean log deformation (*d*) on a representative levee section in each vulnerability class as a function of PGA and magnitude. Mean values of the input variables will be used in applying the engineering model. A regression equation will be fitted to the resulting curve between the mean log deformation and ground motion for each vulnerability class. Let this relationship be represented as:

$$\text{Mean } (\log d) = \text{empirical function of (PGA and magnitude} \qquad (1)$$

To quantify the aleatory uncertainty in the calculated deformation, a Monte Carlo simulation model will be used to generate many plausible realizations of deformation for representative PGA values. In this model, input variables are randomly sampled from their respective probability distributions and processed to estimate deformation for a given PGA and magnitude. This process is repeated a large number of times and the results are used to define the probability distribution of deformation for a given PGA and magnitude.

For the present analysis, the results of the Monte Carlo trials will be used to estimate the standard deviation of log deformation in each vulnerability class when subjected to each of the selected PGA values for a given magnitude.

The regression equation developed from the results of the engineering model can be used to estimate the mean logarithmic deformation as a function of PGA (and magnitude) in each vulnerability class. A lognormal distribution is commonly assumed for an engineering response parameter such as deformation. The log of deformation then can be assumed to follow normal distribution. The normal distribution may be defined by two parameters – the mean and standard deviation of log deformation. The mean log deformation obtained from the regression equation along with the logarithmic standard deviation estimated from the Monte Carlo simulation will completely characterize a normal distribution of log deformation in each vulnerability class at any PGA value for a given earthquake magnitude. Thus, the probability distribution of log deformation can be represented as:

$$Log\ d = \text{Normal (mean of log } d, \sigma \text{ of log } d) \qquad (2)$$

A similar process will be used for other stressing events to characterize the probability distribution of levee response to loading resulting from each event.

If the application of the engineering model to estimate deformation is time consuming, this could put a constraint on the practical number of Monte Carlo simulation runs that could be made. In that case, alternative approaches to Monte Carlo simulation will be considered; for example, Latin Hypercube sampling or a first-order, second-moment method of uncertainty propagation may be used.

Probability Model to Assess Probability Distribution of Levee Damage State as a Function of Levee Response

As defined previously, two distinct levee damage states will be analyzed – breach and damage, but no breach. Fragility curves will be developed to model the relationship between probability of each damage state and deformation. The published relationship between the probability of levee failure and deformation in the CALFED study (CALFED 2000) will be extended to define curves to assess the probabilities of the two damage states (breach, and damage, but no breach) as a function of deformation. A mathematical function will be fitted to each curve, which will provide the means to estimate the probability of a damage state given (log) deformation, *P*[Damage State *i*/log *d*].

Probability Model to Assess Probability Distribution of Levee Damage State as a Function of Ground Motion

The levee fragility curves defined in Step 2 will be combined with the probability distribution of deformation for a given ground motion, defined in Step 1, to obtain the probability of each damage state as a function of ground motion for a given earthquake magnitude. Mathematically, the probability of each damage state can be calculated from the following equation:

$$P\left[\text{Damage State } i \middle| \text{ground motion}\right] = \int_{\log d} P\left[\text{Damage State } i \middle| \log d\right] \times f\left(\log d \middle| \text{ground motion}\right) d\left(\log d\right), \qquad (3)$$

in which, $f\left(\log d \middle| \text{ground motion}\right)$ is the normal probability distribution function of log deformation for a given ground motion defined by the parameters in Equation 2.

6.0 ASSUMPTIONS, CONSTRAINTS, AND LIMITATIONS

The following are some of the assumptions that will be made in our analyses:

- Maintenance continues at present levels.
- Known and expected emergency responses will be considered in the post-failure or flood fight conditions.
- Freeboard is maintained at present levels (keeps pace with water level rise due to climate change, and settlement).
- Assumptions and constraints related to simplified engineering or scientific models.
- Available data satisfactorily represents the existing conditions; no new explorations are planned for this study.

7.0 INFORMATION REQUIREMENTS

This section describes the data needs that are required to implement the methodology described above. This section also describes the information that is required from other risk analysis groups.

The key data requirements are:

- Geometry – topography and bathymetry
- Soils - stratigraphy and spatial variability structure of engineering properties
- Static and dynamic material properties of natural soils and fill materials
- Slough water levels (operational, non-flood related) gage readings
- Groundwater regime in levees and interiors of islands, and groundwater operation including piezometers readings
- Consolidation, rate of settlement, and lateral deformation of the levees
- Island-specific subsidence rate (oxidation)
- Detailed account or data of historic levee failures
- Levee maintenance records, observations during flood fights, rate of erosion and sedimentation
- Riprap size and weight

Information from other risk groups:

- Flood height and duration in sloughs
- Velocity of slough water
- Height of waves
- Earthquake magnitude, PGA, and acceleration time histories
- Emergency response practices in the Delta

8.0 ANTICIPATED OUTPUT OR PRODUCTS

The primary output of the analysis will be the probability distribution of the damage state for each levee reach for each stressing event set defined by the hazard teams. This output will be generated for each parameter set defined in the levee fragility analysis. In addition, the probability ("relative credibility") of each parameter set will also be assessed using expert judgment. The results will be used in the risk quantification module to develop multiple levee damage snapshots.

9.0 RESOURCE REQUIREMENTS

The following are some of the required resources to implement the proposed methodology:

- A project-specific GIS map with overlays of various data, including soil borings,
- Erosion and overtopping specialty hydrologists,
- Geomorphologic changes of Delta levees and sloughs.

10.0 PROJECT TASKS

The specific project tasks for this analysis module will be as follows:

- **Task 1: Data Collection and Analysis**
  In this task, the project team will compile the available data required to support the analyses described in this ITF paper. Most of the data compiled for this study will be built into a data base system for use GIS displays. Data gaps, if any, and methods to deal with gaps will be identified.
- **Task 2: Define Vulnerability Classes and Assign to Levee Reaches**
  In this task, the project team will apply the predefined parameter sets for identifying and delineating the vulnerability classes for levees and foundation conditions. The mapping of the various classes will heavily rely on the GIS displays and integration of the various sets of data layers. Judgment and experience will be used to define the final set of vulnerability classes.
- **Task 3: Refine Model Development**
  In this task, the project team will refine the analysis models by running a define number of cases to calibrate the models (dynamic response and deformation, seepage modeling, etc.) against past and observed responses when available. Furthermore, key model runs will be performed to bracket the range of expected responses of the seepage and deformation models.
- **Task 4: Develop Fragility Curves for Levees in Different Vulnerability Classes**
  In this task, the project team will analyze the typical cross sections of a levee segment in each vulnerability class and assess their probability distribution of damage states as a function of the stressing event (e.g., ground motion, hydraulic head, etc.). In light of the key runs performed in Task 3, simplified interpolation functions will be developed to represent the large number of conditions associated with the variation of material geometry and material properties for each vulnerability class.
- **Task 5: Summarize Results of Analysis**
  In this task, the project team will summarize the results of the analysis for each parameter set and each stressing event set and for each hazard. For each stressing event set, the probability distribution of levee damage state will be defined for individual reaches in the study area.
- **Task 6: Compile Report**
  In this task, the project team will describe the methodology and summarize the results of the analysis in a draft topical memorandum and submit to DWR for review.

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