Final

COST- BENEFIT STUDY OF REMEDIATING WEST SACRAMENTO LEVEES FOR SEISMIC HAZARD

West Sacramento Study Area

Urban Levee Evaluations Project
Contract 4600008101

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Acronyms and Abbreviations

Term	Description
AACE	Association for the Advancement of Cost Engineering
B/C	Benefit to Cost
City	City of West Sacramento
CVFPP	Central Valley Flood Protection Plan
DRMS	Delta Risk Management Strategy
DSM	deep-soil mixing
DWR	Department of Water Resources
EAD	expected annual damage
GER	Geotechnical Evaluation Report
HEC-FDA	Hydrologic Engineering Center – Flood Damage Assessment
HEC-RAS	Hydrologic Engineering Center – River Analysis System
ICB	Independent Consultant Board
M	magnitude
MLR	multi-linear regression
NAVD	North American Vertical Datum
NCEER	National Center for Earthquake Engineering Research
NSF	National Science Foundation
PCET	parametric cost estimate template
PHA	peak horizontal acceleration
PSHA	probabilistic seismic hazard
R_u	Excess pore pressure ratio
SC	stone columns
SDWSC	Sacramento Deep Water Ship Channel
ULE	Urban Levee Geotechnical Evaluations
URS	URS Corporation
USACE	U.S. Army Corps of Engineers

EXECUTIVE SUMMARY

The City of West Sacramento (City) is surrounded by levees, which protect the city against flooding from the Sacramento River, the Sacramento Bypass, the Sacramento Deep Water Ship Channel (SDWSC), and the Yolo Bypass. Recent levee investigations by the City, the Department of Water Resources (DWR), and the U.S. Army Corps of Engineers revealed both static and seismic deficiencies in the levees. The City has launched the West Sacramento Levee Improvement Program to rehabilitate and strengthen the levees to reduce the risk of flooding from a 200-year flood (an annual exceedance probability of 0.005).

A seismic hazard study was initiated by DWR to better understand seismic deficiencies of the urban levees. Specifically, the study presented in this report focuses on assessing the benefit of seismically remediating “high” seismic vulnerability levee segments. The primary focus of the cost-benefit study is to understand the differences in benefits of investing in a seismic fix now versus repairing (i.e., no seismic fix now) to pre-earthquake conditions after a seismic event occurs.

The cost-benefit study was formulated to better understand those differences in benefits and involved the following key steps:

- Dividing the study region into two impact zones
- Estimating the magnitude and frequency of the loading functions for the seismic and the flood events
- Defining analyses cases for performing seismic deformation analyses
- Estimating the conditional probability of flooding the landside of the levee functions for various cases (commonly referred to as seismic fragility functions curves)
- Estimating the seismic remediation and post-earthquake repair costs
- Estimating the expected annual damage (an economic measure) and cost-benefit ratios for various scenarios

Impact Zones

The study area was divided into two impact zones. For each zone, an index point (or analysis location) was selected for aggregating and representing the system performance of the respective zone. The selected impact zones are north (Zone 1) and south (Zone 2) of the Port of West Sacramento.

Magnitude and Frequency of Loading Functions

Seismic Load. A probabilistic seismic hazard analysis was performed for the Urban Levee Geotechnical Evaluations region. This analysis incorporated the latest geologic and seismologic information on seismic sources in northern and central California and recently developed ground-motion prediction models (URS 2012b). The peak horizontal accelerations and the dominant magnitudes and distances of the controlling seismic sources were computed using the results from the probabilistic seismic hazard analysis at the selected analysis zones.

Flood Load. The annual probability of water surface in the river (exterior) exceeding a specified elevation (stage) was updated using the recent DWR's Central Valley Flood Protection Plan (CVFPP) development study results.

Note that, **the probability for a flood (say 100-year or higher) and an earthquake events occurring simultaneously has a very low probability**. The risk analysis considers this low probability of occurrence in the cost- benefit evaluations for different scenarios.

Analysis Cases

The purpose of selecting analysis cases is to develop seismic fragility curve for each case that would then be used in the risk analysis to address the benefit questions discussed above. Three analysis cases were selected as discussed below:

<u>Analysis Case 1:</u> Without-project (i.e., no seismic fixes). This case represents levee segments that have no static deficiencies (and therefore no need for a static fix) or levee segments in which the static fix is already in-place or would be implemented. For each analysis water level (varied from toe of levee to top of levee), seismic-induced deformation values corresponding to 25-, 50-, 100-, 200-, and 500-year events were estimated. The probability of flooding the landside (probability of failure) for each analysis water level was estimated using expert elicitation considering the deformed levee for a given earthquake event. Note that, the amount of vertical deformation (estimated using the computer program FLAC) was a key parameter used in the development of seismic fragility function for this case.

<u>Analysis Case 2:</u> Without-project with post-earthquake repairs. This case assumes a seismic event occurs, the levee sustains damage, and then it is repaired back to the original without-project conditions within 2-years (i.e., repair window is 2 years). It also assumes that the damaged levee meets the ULDC's criterion for 10-year flood. In the event, if the earthquake resulted in significant damages to the levee preventing it from providing 10-year flood protection (i.e., crest should be higher than 10-year flood level plus 3 feet) to the City (DWR, 2012), then the damaged levee would be restored within 8 weeks to provide at least 10-year flood protection per ULDC guidelines. The risk analysis assumes that only one seismic event occurs in the 50-year life cycle (i.e., after levee sustains damage due to the first earthquake, then within the 2-year repair window it assumes a second earthquake will not occur). The seismic fragility curves for this case were developed by adjusting those representing Analysis Case 1. The Analysis Case 1 seismic fragility curve for each seismic event was shifted to the left by the anticipated amount of crest settlement (estimated in Analysis case 1) corresponding to respective seismic event.

<u>Analysis Case 3:</u> With-project (i.e., seismic fixes to high seismic vulnerability levee segments). This case represents levee segments that are seismically remediated beyond the level of the static remediation. The objective of the seismic remediation is to bring the remediated levee reach into the low-seismic-vulnerability class. The seismic performance of the remediated section is judged adequate or not based on its performance during a 200-year return period ground motion with river stage at winter level. No seismic deformation analysis was performed based on Independent Consulting Board (ICB) comments. The post seismic slope stability analysis was used to select the minimum level of seismic improvement

(depth and extent of treatment). A minimum acceptable factor of safety for post-seismic slope stability condition is to be equal to or greater than 1.3.

Conditional Probability of Flooding

In this study, the probability of flooding (or failure) the landside (commonly referred to as fragility functions) was estimated considering both seismic and water loads. The fragility functions expressed conditional probability because of number of assumptions and loading conditions used in this study. The key assumptions used include the followings:

- Simultaneous occurrence of earthquake and flooding
- Main failure mode considered is overtopping as a result of seismic-induced crest settlement. Note that other failure modes such as piping through the cracks and levee instability because of excessive deformations are not considered as the primary mode of failure
- The material properties were not modeled as random variables (note that the selected material properties though considered the inherent variability but only one set of properties were assigned for each soil type).
- Assumes only one earthquake would occur within a 50-year life cycle
- No human intervention

An expert panel meeting was arranged to obtain seismic expert's opinion on probability of flooding for West Sacramento levee. During the meeting, the project team made a series of presentations covering various topics including brief project background, objective of the meeting, available data, analysis methods, assumptions, and results. After the group discussions, the expert panel members offered their opinion of the probability of failure for different analysis cases.

Seismic Remediation and Post-Earthquake Costs

The construction cost of a seismic remediation alternative is the incremental cost of the seismic fix beyond the cost of the required static fix (i.e., the cost of the static fix is not included in the construction cost). The costs for these alternatives were estimated using the parametric cost estimate template, which was developed as part of Task Order U02 (URS 2014b). The estimated costs are Class 4 estimates as defined by the Association for the Advancement of Cost Engineering (AACE 2011). Class 4 cost estimates are typically performed for detailed strategic planning, project screening, alternative scheme analysis, confirmation of financial or technical feasibility, and preliminary budget approval. The estimated incremental seismic remediation costs for Zones 1 and 2 are $398 million (2014 dollar) and $507 million, totaling approximately $905 million for the study area.

The costs of repair for restoring the damaged levee segments to the pre-earthquake conditions (i.e., again, no seismic fix, without-project) are approximately $30 million and $36 million for Zones 1 and 2, respectively.

Expected Annual Damage and Cost-Benefit Ratios

The risk analysis approach for this study was developed in a way that enables use of the computer program HEC-FDA, Version 1.2.4a (USACE, 2008). The risk analysis was formulated around calculating the incremental benefit of two action plans: 1) repair the levee after a seismic event occurs, and 2) invest the money now for seismically remediating the high-vulnerability levee segments. The direct comparison of annual damages and costs of these two action plans enables us to seek an answer to the following benefit-cost question: what is the benefit of seismically fixing the levees now versus repairing the damaged levees after the occurrence of an earthquake?

The input collected for the analysis includes river water surface elevation, probability of water surface exceeding a specified stage (exterior), water surface elevation in the floodplain (interior), seismic fragility curves for different scenarios, and repair and construction costs. The HEC-FDA program was used to compute structure (residential, commercial, public, and industrial) damage, content damage, automobile damage, and temporary housing and displacement costs. The expected annual damage (EAD) **does not include life loss**.

The results from the analysis are summarized in Table ES-1:

Table ES-1 Expected Annual Damage and Benefit-Cost Ratios

Scenario	EAD ($1,000)	B/C ratio[1]
Zone 1		
Without-project, levee repair	1,860	—
With project	1,098	0.03
Zone 2		
Without-project, levee repair	4,873	—
With project	1,710	0.10
[1] B/C ratio = present value benefit / project costs — = not applicable		

The results presented in Table ES-1 indicates that the costs of investing in a seismic fix today versus repairing after a seismic event outweighs the benefits at both index points. The benefit-cost ratio is well below 1.0 for the without project with levee repair versus with project, but the important point to realize is that the risk analysis only considered a single seismic event occurring in the 50-year project life.

Conclusion

In reviewing the results of this Planning-level Cost-Benefit Study of remediating the Urban West Sacramento Levees for seismic hazard and comparing them to the results of DWR’s ULE screening-level studies complete for remediation of existing static levee deficiencies (seepage, stability, erosion, freeboard), it is concluded:

1) Seismic remediation is quite costly compared to remediation for static deficiencies,
2) Given the seismic environment of the Central Valley of California, the economic benefit cost of seismic remediation is quite low, and

3) Priority of available remediation funds should be given to remediating the static deficiencies

It is noted that loss of life has not been addressed by this study. However, other than the extremely low probability of the design or greater earthquake occurring simultaneously with the design flood, flooding following seismic damage to the levees could be easily forecast and the population warned and evacuated.

This report is one of multiple documents describing work completed in the West Sacramento Study Area. This report should not to be used as the basis for design, construction or remedial action; nor should it be used as a basis for major capital spending decisions.

1.0 INTRODUCTION

The City of West Sacramento (City) is surrounded by levees, which protect the city against flooding from the Sacramento River, the Sacramento Bypass, the Sacramento Deep Water Ship Channel (SDWSC), and the Yolo Bypass. Recent levee investigations by the City, the Department of Water Resources (DWR), and the U.S. Army Corps of Engineers revealed both static and seismic deficiencies in the levees. The City has launched the West Sacramento Levee Improvement Program (City, 2010) to rehabilitate and strengthen the levees to reduce the risk of flooding from a 200-year flood (an annual exceedance probability of 0.005).

A seismic hazard study was initiated by DWR to better understand seismic deficiencies of the West Sacramento levees. Specifically, the study presented in this report focusses on assessing the benefit of seismically remediating “high” seismic vulnerability levee segments. This study also assesses the cost-benefit ratios for repairing the liquefaction-induced damaged levees back to the pre-earthquake conditions.

1.1 Project Background

This Task Order (U13) was performed in general compliance with the scope of work outlined in Exhibit A of Master Agreement 4600008101 between the Department of Water Resources (DWR) and URS Corporation (URS), dated May 1, 2008. The DWR Urban Levee Geotechnical Evaluations (ULE) Project evaluates levee systems estimated to protect communities of more than 10,000 people. The ULE Project, through investigation and planning-level analyses, evaluates levees relative to U.S. Army Corps of Engineers (USACE) levee design criteria for seepage and slope stability, DWR’s Urban Levee design Criteria (ULDC) (DWR, 2012), and additional guidelines as developed based on the recommendations of URS and DWR’s Independent Consultant Board (ICB), along with input from DWR, its consultants, and USACE, as described in the *Guidance Document for Geotechnical Analyses* (URS 2014a). The results from these analyses are used to:

- Identify potential static levee deficiencies and recommended improvements.
- Identify potential levee repair alternatives and their associated costs.

These screening-level analyses were performed to identify whether geotechnical evaluation criteria are met; the analyses are not design-level analyses. The results of these screening-level analyses for West Sacramento study area are presented in a Geotechnical Evaluation Report (GER) (URS 2012a). The GER presents the results of freeboard, erosion, seepage, stability, and seismic vulnerability assessments. The GER identifies levee reaches that do not meet the evaluation criteria and that may require remediation (GER Volume 1, Existing Conditions) and discusses the feasible conceptual repair alternatives, estimated costs, and seismic vulnerability assessment for such levee reaches (GER Volume 2, Remedial Measures).

The results from the West Sacramento levee seismic vulnerability assessment presented in Volume 2 of the GER were used to develop appropriate seismic remediation alternatives for levee segments that have been designated as having high seismic vulnerability. The selected seismic remediation alternatives and their conceptual cost estimates for each of the levee segments in the study area that do not meet the evaluation criteria are presented in a separate report as part of Task Order U02 (URS 2014b). The work performed under this Task Order focused on a cost-benefit analysis with regard to seismic hazard for the West Sacramento Levee Region.

A draft report for this Task Order was submitted to Seismic Review Panel (SRP) review in June 2013. Based on recommendation received from the SRP, URS developed new sets of seismic fragility curves that better represent conditions expected for the West Sacramento levees. Additionally, this final report includes revisions to the hydrologic and hydraulic analysis at the request of DWR. As part of DWR's Central Valley Flood Protection Plan (CVFPP) development, DWR produced HEC-RAS channel hydraulic models of major Central Valley streams and FLO-2D overland flow models of their associated floodplains.

1.2 Scope of Work

The scope of work for accomplishing the project objectives consists of the following four main tasks:

- Task U13-1: Characterize seismic hazard for West Sacramento levees. This task involved developing ground motions using the probabilistic seismic hazard analysis corresponding to three return periods 100 years, 200 years, and 500 years.
- Task U13-2: Estimate conditional failure probability. This task involved developing the conditional probability of failure of levees using simplified procedures. The main mode of failure considered was overtopping as a result of expected large vertical deformations.
- Task U13-3: Compute annual damage and economic benefits. This task involved performing flood-risk analysis to estimate the expected annual damage for three different scenarios. The economic benefit of each scenario was also estimated.
- Task U13-4: Report preparation. An earlier draft and this final report were prepared as part of this task to summarize the results of tasks U13-1 through U13-3. The draft report was submitted to DWR and SRP for review and comments. This final report is being issued after incorporating the review comments.

1.3 Report Organization

After this introductory section, this report is organized as follows:

- Section 2 discusses the seismic hazard evaluation performed as part of Task Order 38 and the development of peak horizontal accelerations for Task Order U13.
- Section 3 discusses the approach used to develop conditional failure probability curves.
- Section 4 discusses levee remediation costs.
- Section 5 discusses the approach used to compute annual damages and economic benefits and the results of the computations.
- Section 6 presents discussion and main conclusions derived from each subtask performed for this Task Order.

- Section 7 provides the acknowledgments and discusses the limitations of the analysis.
- Section 8 lists the references used to prepare this report.
- Appendix A presents the meeting notes from the expert panel meeting.
- Appendix B presents the report that was prepared as part of the calculation of annual damages and economic benefits (Task U13-3) by David Ford Consulting Engineers, Inc
- Appendix C presents our responses to comments received on the draft report

2.0 SEISMIC HAZARD EVALUATION

This section discusses the probabilistic seismic hazard analysis and the peak horizontal accelerations used in the evaluation.

2.1 Probabilistic Seismic Hazard Analysis

In 2007, as part of the Delta Risk Management Strategy (DRMS) Project, probabilistic seismic hazard maps for peak horizontal ground acceleration (PGA) for the return periods of 100, 200, and 500 years were developed for the Delta region (URS 2007). At the request of DWR as part the ULE under the Task Order 38, the 200-year return period PGA hazard map for the Delta region was expanded to the north to include the northern ULE region, resulting in a hazard map for the entire ULE study region. The same approach used to develop the Delta probabilistic hazard maps was used to develop the ULE map. The hazard for the Delta portion of the map was not recalculated.

Probabilistic seismic hazard analysis (PSHA) was performed for the northern ULE region to incorporate the latest geologic and seismologic information on seismic sources in northern and central California and recently developed ground motion prediction models. In the PSHA, all available data were used to evaluate and characterize potential seismic sources, the likelihood of earthquakes of various magnitudes occurring on those sources, and the likelihood that the earthquakes would produce ground motions greater than a specified level.

The details of the PSHA approach, the seismic source models, and the ground-motion prediction models were presented in a memorandum titled “Development of a 200-Year Return Period Seismic Hazard Map for the Urban Levee Evaluations Program Region,” dated February 24, 2012 (URS 2012b).

2.2 Peak Horizontal Accelerations

For the purpose of cost-benefit analysis, the study area is divided into two impact zones, and for each zone an index point (or analysis location) is selected to aggregate and represent system performance in that zone (Figure 2-1). Index points are selected locations that represent the hydrologic, hydraulic, and geotechnical characteristics of a reach of a stream. The part of the study area that is north of the Port of West Sacramento is in Zone 1. The part of the study area south of the port is in Zone 2.

The peak horizontal accelerations (PHAs) for Zones 1 and 2 were calculated using the results from the PSHA analysis for multiple return periods (see Table 2-1). At these selected return periods, the PHA hazard is dominated by events in the magnitude range of magnitude (M) 6.4 to 7.0 at distances of less than 95 kilometers.

3.0 CONDITIONAL FAILURE PROBABILITY FUNCTIONS

In general, levee fragility functions express the probability of failure or breach of levee condition on the degree of loading it experiences (often referred to as “conditional probability of failure functions”). In this study, the probability of flooding (or failure) the landside was estimated considering both seismic and water loads. The fragility functions expressed conditional probability because of number of assumptions and loading conditions used in this study. The key assumptions used include the followings:

- Simultaneous occurrence of earthquake and flooding (note that, the risk analysis considered the low probability for this simultaneous occurrence of two extreme events)
- Main failure mode considered is overtopping as a result of seismic-induced crest settlement. Note that other failure modes such as piping through the cracks and levee instability because of excessive deformations are not considered as the primary mode of failure
- Assumes only one earthquake would occur within a 50-year life cycle
- No human intervention

The conditional failure probability functions (flooding) for the Zones 1 and 2 were developed using simplified seismic deformation analysis methods as discussed in this Section. The conditional probability of failure was estimated only for the levee segments that have been categorized as being in the high-seismic-vulnerability class. The conditional failure probability was calculated for three analysis cases.

3.1 Analysis Approach

The analysis approach used to develop the conditional failure probability functions for each zone involved six interrelated steps:

- Step 1: Select representative analysis sections.
- Step 2: Define analysis water surface elevations.
- Step 3: Develop material properties.
- Step 4: Perform seismic analysis.
- Step 5: Develop the conditional failure probability function for each zone.

3.2 Seismic Vulnerability Class

The seismic vulnerability assessment consists of liquefaction potential, slope stability, and simplified seismic deformation analyses. This assessment was performed as part of Volume 2 of the West Sacramento Levee GER (URS 2012a). The main purpose of the seismic vulnerability assessment was to assign a vulnerability class to each levee reach in the study area. The seismic vulnerability class was defined based on the amount of vertical deformation, the remaining freeboard, and the degree of potential damage to internal structures during an earthquake. Three vulnerability classes listed from least vulnerable (low) to most vulnerable (high) are defined in Table 3-1. Figure 3-1 shows the designated vulnerability classes for levee reaches in the West Sacramento levee region. In general, levee reaches that are considered to have high seismic vulnerability are on the east side of both Zone 1 and Zone 2. The remaining levee reaches are considered to be in a low seismic vulnerability class. There are no levee reaches in the study area that are considered to be in the medium vulnerability class.

For the purpose of the cost-benefit study, West Sacramento levee has been divided into four seismic levee segments as shown in Figure 3-1. The cost-benefit analysis only considered levee segments that have been assigned a high-seismic-vulnerability class.

3.3 Analysis Cases

The levee and foundation materials properties used in the seismic deformation analyses were previously selected as part of the GER. The material properties were not modeled as random variables in this cost-benefit study (note that, the selected material properties considered the inherent variability but only one set of properties were assigned for each soil type).

The primary focus of the cost-benefit study is to understand the differences in benefits of investing in a seismic fix now and repairing (i.e., no seismic fix now) after a seismic event occurs. To understand the differences in benefits, three analysis cases: no seismic fix (commonly referred to as without-project), repair case (no seismic fix now but repair after a seismic event), and seismic fix (commonly referred to as with-project) were developed to estimate the seismic fragility functions.

The seismic deformation analyses for each analysis cases considered water levels varying from toe of the levee to the top of levee. For each analysis water level, seismic deformations were estimated for a suite of earthquake loadings (e.g., 25-, 50-, 100-, 200-, and 500-year return period events). The analyses cases are further described below:

Analysis Case 1: Without-project (i.e., no seismic fixes). This case represents levee segments that have no static deficiencies (and therefore no need for a static fix) or levee segments in which the static fix has been already implemented or will be implemented. For each analysis water level, a total of 5 seismic-induced deformation values corresponding to 25-, 50-, 100-, 200-, and 500-year events were estimated.

The probability of flooding the landside (probability of failure) for each analysis water level was estimated using expert elicitation considering the deformed levee for a given earthquake event (Section 3.4.5). Note that, the amount of vertical deformation was a key parameter used in the development of seismic fragility function for this case. This study assumes that the flooding (or failure) is mainly initiated by overtopping. Note that, other failure modes such as piping through the cracks formed as a result of seismic deformation can also lead to failure.

Analysis Case 2: Without-project with post-earthquake repairs. This case assumes a seismic event occurs, the levee sustains damage, and then it is repaired back to the original without-project conditions within 2-years (i.e., repair window is 2 years). It also assumes that the damaged levee meets the ULDC's criterion for 10-year flood. In the event, if the earthquake resulted in significant damages to the levee preventing it from providing 10-year flood protection (i.e., crest should be higher than 10-year flood level plus 3 feet) to the City (DWR, 2012), it assumes that the damaged levee would be restored within 8 weeks to provide at least 10-year flood protection per ULDC guidelines.

Analysis Case 3: With-project (i.e., seismic fixes to high vulnerability levee segments). This case represents levee segments that are seismically remediated beyond the level of the static remediation. The objective of the seismic remediation is to bring the remediated levee reach into the low-seismic-vulnerability class. The seismic performance of the remediated section is judged adequate or not based on its performance during a 200-year return period ground motion with river stage at winter level.

As discussed in Section 5, risk analysis assumes that only one seismic event occurs in the 50-year life cycle (i.e., after levee sustains damage due to the first earthquake, then within the 2-year repair window it assumes a second earthquake will not occur). It assumes that the damaged levee sustained crest settlement as estimated in the Analysis Case 1 for corresponding seismic event and other damages which can also lead to failure are not considered (e.g., cracking, piping etc.,). The seismic fragility curves for this case were developed by adjusting those representing Analysis Case 1. The Analysis Case 1 seismic fragility curve for each seismic event was shifted to the left by the anticipated amount of crest settlement corresponding to respective seismic event.

3.4 Analysis to Develop Conditional Probability of Failure

3.4.1 Step 1: Select Representative Analysis Cross Sections

Four typical analysis cross sections representing the high-seismic-vulnerability levee segments were selected for the analysis. These sections were previously developed as part of the GER for West Sacramento Study Area (URS 2012a). The typical cross section was selected based on the levee geometry attributes, in particular the height and side slopes, the thickness of the potentially liquefiable soil, and the corrected SPT blowcount data. Table 3-2 presents the analysis cross sections for each zone, the locations of the analysis cross sections, the anticipated critical slopes, and the reasons for the selection. The selected cross sections are also shown on Figures 3-2 through 3-5.

3.4.2 Step 2: Analysis Water Surface Elevations

The water surface elevations considered in the analysis are summarized in Table 3-3. The multiple analysis water surface elevations presented in the table are obtained from the GER for the West Sacramento Study Area (URS 2012a).

3.4.3 Step 3: Develop Material Properties

The material properties used for the seismic hazard analysis are the same as those used in the GER (URS 2012a), with the following exceptions:

- The residual shear strengths of liquefiable materials correspond to the 25-, 50-, 100-, and 500-year return periods. The residual shear strengths presented in the GER (URS 2012a) correspond to liquefaction triggering due to a seismic event with a 200-year return period.

- The composite shear strength of seismically improved areas is different. The composite strengths of areas treated with either stone columns (SC) or deep-soil mixing (DSM) were estimated based on the ratio of the SC (or DSM) area to the total plan area. These in situ treatments were considered to be the most cost-effective and feasible seismic remediation alternatives for the West Sacramento Study Area (URS 2014c).

The residual shear strengths of the liquefiable soils for earthquake events corresponding to return periods of 25, 50, 100, and 500 years were estimated using the procedure outlined in the Guidance Document for Geotechnical Analyses (URS 2014a). A set of liquefaction triggering analyses was performed for borings at locations of selected analysis sections using events with a 25-, 50-, 100-, and 500-year return period.

For the purpose of the seismic deformation analysis, it was assumed that the SCs will be installed using vibro-replacement methods. The vibrations created during the installation of SCs densify the soils around the columns. However, the composite shear strengths of the improved areas were estimated based on the replacement ratio, ignoring the increased shear strength of the soils surrounding the columns, but considering that the soil does not liquefy.

The seismic deformation analysis assumed that the soil-cement walls (using DSM) will be installed in a grid pattern. The use of a grid pattern is most effective due to its function of embodying the entire treated area as a unit for full mobilization of the compressive strength soil-cement and the rigidity of the treated ground. The shear strength of the treated zone was estimated by ignoring the contribution of the liquefiable soil within the soil-cement grid.

The estimated residual shear strengths and composite strengths of treated areas for the selected analysis sections are presented in Tables 3-4 through 3-7.

3.4.4 Step 4: Perform Seismic Analysis

The seismic vulnerability analysis performed as part of the GER for the West Sacramento Study Area indicated the presence of potential liquefiable soils in the levee and the foundation in some areas (URS 2012a). Therefore, the earthquake shaking may trigger liquefaction in saturated liquefiable soils and result in large deformations. The estimation of these deformations is a key step in developing conditional probability of failure curves. Several methods are available in the literature to estimate the liquefaction-induced seismic deformations; these methods range from a simplified Newmark-type analysis to a sophisticated nonlinear finite-element analysis.

For the Analysis Case 1, the liquefaction-induced seismic deformation analysis was estimated using the following steps:

- Perform a post-seismic slope stability analysis that models liquefiable soils using the residual shear strength values discussed in Section 3.4.3, above. Use the results from this analysis expressed in terms of factor of safety to judge whether a given levee reach would be unstable after an earthquake. If the calculated factor of safety is less than 1.0, assume that the given levee reach will sustain large deformations (flow slides may be expected). For this analysis, assume that the seismic deformation of such a levee reach can be estimated using available methods to calculate lateral spreading.

- If the calculated factor of safety from the post-seismic slope stability analysis discussed above is greater than 1.0, estimate the seismic deformation of such a levee reach using the deformation analysis approach presented in the Guidance Document (URS 2014a). However, the results from the post-seismic slope stability for all high vulnerability levee segments in West Sacramento indicated instability. Therefore, the Newmark-type deformation analysis was not performed for this analysis case.

Several empirical formulas are available to estimate the seismic deformation in cases where lateral spreading is expected to take place. Therefore, a second analysis approach was used to verify the deformations estimated using the empirical formulas. In the second approach, the levee and foundation zones identified as susceptible to liquefaction are explicitly represented in the analysis model. Fully non-linear finite-difference methods that track the development of excess pore pressures and strength loss in the liquefaction-susceptible zones and the cyclic strength degradation of non-susceptible soils are used to calculate the dynamic response and seismic deformations of the levee. In those analyses, the calculations of dynamic response, excess pore pressures and strength loss, and earthquake-induced deformations are coupled in a single analysis.

For the Analysis Case 2, no separate seismic analysis was performed. The seismic deformation estimated for the Analysis Case1 was used in developing the seismic fragility curves for this case.

For the Analysis Case 3, based on recommendation from the SRP, no seismic deformation analysis was performed. The level of improvement (depth and extent of treatment) for remediating seismic vulnerability of a high seismic levee segment was selected to increase the factor of safety for the post-seismic slope stability condition to be equal to or greater than 1.3.

3.4.4.1 Lateral Spreading Analysis

As discussed above, the lateral spreading analysis was used to estimate the liquefaction-induced deformation for conditions when the calculated factor of safety for the post-seismic slope stability is less than 1.0. When the post-seismic factor of safety is less than 1.0, liquefaction-induced flow failures are often anticipated to occur. Estimation of the deformation produced by liquefaction-induced flow failure is difficult; only a handful of procedures are available. The estimated ground motions for the West Sacramento Study Area are less likely to produce flow failures (or, in other words, the liquefiable soil is less likely to reach its residual shear strength from the onset of earthquake shaking), and therefore the project team judged that the lateral spreading analysis is reasonable to estimate the liquefaction-induced deformations.

Several empirical relationships are available in the literature to relate the permanent ground displacement due to lateral spreading to geotechnical, topographic, and earthquake parameters (e.g., Baska 2002, Faris et al. 2006, Hamada et al. 1986, Idriss and Boulanger 2008, Kramer and Baska 2007, Youd et al. 2002, Zhang et al. 2004). For this analysis, the project team selected the procedures proposed by Hamada et al. (1986), Youd et al. (2002), and Kramer and Baska (2007) to estimate the permanent displacements due to lateral spreading. Because the cost-benefit analysis is performed in a probabilistic framework, the project team judged that the average of the three estimated deformations would be reasonable to address the uncertainty in the model predictions (i.e., the epistemic uncertainty).

Hamada et al. (1986) considered the effects of geotechnical and topographic conditions on the permanent ground displacements observed in uniform sands of medium grain size in the 1964 Niigata (M = 7.5), 1971 San Fernando (M = 7.1), and 1983 Nihonkai-Chubu (M = 7.7) earthquakes. Permanent ground displacement was found to be mainly a function of the thickness of the liquefied layer and the slopes of the ground surface and lower boundary of the liquefied zone. The permanent ground displacement, *D*, can be expressed empirically as:

$$\mathrm{D} = 0.75\ \mathrm{H}^{\frac{1}{2}}\ \theta^{\frac{1}{3}} \qquad (1)$$

where,

D = permanent ground displacement, in meters

H = thickness of the liquefied layer, in meters

θ = larger of the ground surface slope or the slope of the lower boundary of the liquefied zone in percent

Youd et al. (2002) developed a multi-linear regression (MLR) model to estimate the lateral displacements through MLR of a large database of lateral spreading case histories from Japan and the western United States. The recommended MLR models for free-face and gently sloping ground conditions are provided below.

Equation 2 is applied to free-face conditions:

$$\begin{aligned}\log D_H = & -16.713 + 1.532M - 1.406 \log R^* - 0.012R + 0.592 \log W \\ & + 0.540 \log T_{15} + 3.413 \log (100 - F_{15}) \\ & - 0.795 \log (D50_{15} + 0.1\ \mathrm{mm}) \qquad (2)\end{aligned}$$

Equation 3 is applied to gently sloping ground conditions:

$$\log D_H = -16.713 + 1.532M - 1.406 \log R^* - 0.012R + 0.338 \log S$$
$$+ 0.540 \log T_{15} + 3.413 \log (100 - F_{15})$$
$$- 0.795 \log (D50_{15} + 0.1 \text{ mm}) \quad (3)$$

where,

$R^* = R + R_o$

$R_o = 10^{(0.89M - 5.64)}$

R = horizontal or mapped distance from the site in question to the nearest bound of the seismic energy source, in kilometers

R_o = a distance factor that is a function of earthquake magnitude, M, and R* = a modified source distance value

D_H = the estimated lateral ground displacement, in meters

M = the moment magnitude of the earthquake

T_{15} = the cumulative thickness of saturated granular layers with corrected blowcounts, $(N_1)_{60}$, less than 15, in meters

F_{15} = the average fines content (fraction of sediment sample passing a No 200 sieve for granular materials included within T_{15}, in percent

$D50_{15}$ = the average mean grain size for granular materials within T_{15}, in millimeters

S = the ground slope, in percent

W = the free-face ratio defined as the height (H) of the free face divided by the distance (L) from the base of the free face to the point in question, in percent.

Kramer and Baska (2007) method is developed using combination of a series of nonlinear analyses using advanced constitutive model to represent behavior of liquefiable soil and comparison and adjustment of the analysis models to represent the available case histories. The median lateral spreading displacement is expressed as:

$$D_H = \begin{Bmatrix} 0 & for\ \sqrt{D_{H1}} \leq 0 \\ (\sqrt{D_{H1}})^2 & for\ \sqrt{D_{H1}} \geq 0 \end{Bmatrix} \quad (4)$$

Where,

$$\sqrt{D_{H1}} = \frac{\beta_1 + \beta_2 T_{gs}^* + \beta_3 T_{ff}^* + 1.231M - 1.151 logR^* - 0.01R + \beta_4\sqrt{S} + \beta_5 logW}{1 + 0.0223(\beta_2/T_{gs}^*)^2 + 0.0135(\beta_3/T_{ff}^*)^2}$$

Where,

$R^* = R + 10^{0.89Mw-5.64}$

$N_i = (N_1)_{60,cs}$ (as calculated using the fines correction of Youd et al. (2002)) for the i^{th} sublayer

t_i = sublayer thickness (limited to a maximum value of 1 m)

The model-specific β coefficients are as indicated below:

Model	β_1	β_2	β_3	β_4	β_5
Ground Slope	-7.207	0.067	0.0	0.544	0.0
Free Face	-7.518	0.0	0.086	0.0	1.007

3.4.4.2 FLAC Deformation Analysis

In cases where lateral spreading is expected to take place (i.e., post-seismic factor of safety is less than 1.0), a second approach utilizing the software FLAC 6.0 (Itasca 2008) was used for the following reasons:

- To independently evaluate the lateral deformation estimated using available empirical formulas (there are several of them available in the literature)
- To reasonably estimate the vertical deformation. Estimation of vertical deformation based on estimated lateral displacement is extremely difficult because no procedures are available in the literature. After reviewing some of the case histories involving lateral spreading, the project team estimated that vertical deformation may be approximately half of the lateral displacement. The results from the FLAC analyses were useful in supporting this approximation.
- To assess the impact of different levels of ground motions in the lateral spreading deformations. The empirical formulas are limited in that ground motion is represented by magnitude and distance of the controlling fault.

FLAC is a two-dimensional, finite-difference code that models the behavior of soil with nonlinear constitutive models. The analyses were performed using the Mohr-Coulomb constitutive model in the basic FLAC code. The failure envelope for that model uses a Mohr-Coulomb shear criterion with a tension cutoff. The program calculates stresses and strains incrementally, using elastic properties until the failure envelope is reached. At that point, a plastic correction is used to estimate the behavior of the material at yield.

The zones of expected liquefaction were represented explicitly in the FLAC analysis models. The analysis mesh is shown on Figure 3-6 for the analysis section at Station 1279+50 in Reach L. To establish the state of stress in the levee and foundation before the earthquake, a static initial stress analysis was first performed. The static initial stress analysis was performed by applying gravity in a single load stage using assumed elastic moduli for the materials corresponding to 10 percent of the small-strain dynamic moduli values. That gravity turn-on analysis was done with pore pressures and hydrostatic loads in place. The hydrostatic loads were computed with water at two levels: the 200-year flood elevation and the winter water elevation. The gravity turn-on analysis was then repeated using the Mohr-Coulomb constitutive model with drained strengths for all materials. The resulting state of stress in the levee and foundation served as the initial stress state for the dynamic analyses.

The initial static stresses were used to calculate all of the stress-dependent properties used in the dynamic analysis. For the static initial stress analysis, horizontal and vertical displacements were fixed at the base of the mesh. Also, the horizontal displacements were fixed at the landside and waterside of the mesh (the sides are free to displace vertically).

The dynamic analysis was run in large-strain mode, which updates the mesh geometry continuously during the analysis. Free-field boundaries were used along the land and water sides of the foundation model. The base of the model used a quiet boundary to prevent waves from reflecting off the base of the model. The height of the elements was selected such that frequencies of up to 15 to 25 hertz could be included in the analysis. Non-liquefiable soils were modeled using the built-in Mohr Coulomb model. Liquefiable materials were modeled using the URS pore pressure generation model.

The constitutive model used for the liquefiable materials incorporates the pore-pressure generation procedure illustrated on Figure 3-7, which is based on the cyclic stress approach proposed by Seed (1979). In this procedure, pore pressure is continuously accumulated for each element in response to shear stress cycles, and the effective stresses and corresponding drained shear strength decrease with increasing pore pressure. The model incorporates the post-liquefaction residual strength of the material by using a bi-linear failure envelope, as shown on Figure 3-8. When pore pressure increases to the point that the strength of an element drops to the residual strength, that strength is used for the element thereafter. A separate post-earthquake analysis is not needed. The cyclic resistance of the soil is modeled using relationships such as those shown on Figure 3-9. In the current version of the URS model, K_α is computed using the procedure recommended by Idriss and Boulanger (2008), where K_α is a function of the static stress ratio *α,* the relative density, and the overburden stress, σ'_v. The correction factor for overburden stress, K_σ, is computed using the recommendations of the 1996 NCEER and 1998 NCEER/NSF workshops (Youd et al. 2001).

A Rayleigh damping formulation is used to simulate small-strain viscous damping for all materials (2 percent at center frequency of 2 hertz). Hysteretic damping is implicitly included in the nonlinear stress-strain behavior of the Mohr-Coulomb model, as the materials yield during ground shaking. The input motion was applied as a traction history at the base of the model per Mejia and Dawson (2006).

The material properties used in the FLAC analysis are summarized in Table 3-8. Because FLAC analysis requires acceleration time histories for the dynamic analysis, previously developed time histories from the DRMS project were used. The modified 1987 Superstition Hills earthquake record (Station: 5052 Plaster City) was scaled to match PHAs corresponding to a 200-year return period and a 500-year return period motions. The input time histories used for the 200-year return period analysis in FLAC analyses are shown on Figure 3-10.

<u>Results of the Seismic Analyses</u>

Analysis Case 1: The lateral spreading analysis was performed for multiple levels of water surface elevations (post-seismic factor of safety < 1.0). The estimated lateral deformations are conservative, but are considered reasonable for this screening-level study. The vertical deformations were estimated using the FLAC analysis results presented below. Note that, Table 3-1 indicates that the vertical crest displacement can be estimated at 0.7 times the displacement from simplified deformation analyses. However, based on limited FLAC analyses performed for this study it appears the vertical displacements are ½ of estimated lateral displacements. Therefore, this study assumes that vertical displacements are ½ of estimated lateral displacements. The liquefaction-induced volumetric compression of liquefiable soil was estimated using the procedure proposed by Tokimatsu and Seed (1984). This volumetric compression value was added to the estimated vertical deformation from lateral spreading analysis. The estimated average vertical displacements for Zone 1 and Zone 2 are presented in Figures 3-11 and 3-12, respectively. In general, the vertical deformation decreases with increase in water surface elevation when the seismic vulnerability is on the waterside slope and the opposite trend is observed when the seismic vulnerability is on the landside slope. The waterside slope is benefiting from the stabilizing effect of normal water pressure on the slope. The increase in water surface elevation has two major negative impacts on the landside slope: 1) increase the thickness of saturated liquefiable soils, and 2) reduce the effective stresses within the levee prism.

The results of the FLAC analysis performed for the analysis section at Station 1279+50 for the winter water level and the 200-year seismic event are presented in the following figures:

- Figure 3-13. Deformed geometry, seismic-induced shear strain, and displacement vectors at the end of shaking
- Figure 3-14. Contours of horizontal and vertical deformation at the end of shaking
- Figure 3-15. Contours of excess pore pressure ratio at end of shaking
- Figure 3-16. Time histories of displacements at the crest and levee toes
- Figures 3-17a and 3-17b. Time histories (set 1 and set 2) of excess pore pressure ratios within the liquefiable soil (refer to Figure 3-15 for output node locations)

Figures 3-18a and 3-18b show the contours of horizontal and vertical deformation at the end of shaking for the 200-year and 500-year return period motions, respectively. The comparison of calculated displacements (both vertical and horizontal) of 200-year and 500-year ground motions indicates that displacements are very similar. The vertical deformation estimated using FLAC appears to be approximately 0.5 times the lateral displacement.

Analysis Case 3: Figures 3-19 through 3-22 show the results for analysis case 3 for sections analyzed to represent proposed improved conditions with water surface elevation assumed at winter level for Zone 1. Figures 3-23 through 3-26 show the results for sections analyzed to represent the proposed improved conditions with water surface elevation at winter water level for Zone 2. The seismic deformation for this analysis case is expected to be small (less than 2 feet).

3.4.5 Step 5: Develop the Conditional Failure Probability Function for Each Zone

A meeting was held at the URS Sacramento Office on June 10, 2014 to obtain seismic expert's opinion on probability of flooding for West Sacramento levee subject to various seismic and water loadings. Prior to the meeting, a document summarizing project background, the type of analyses performed for various seismic and water loads, general framework for developing seismic fragility curves and objective of the meeting was sent out to expert panel members. The Meeting Notes from this expert panel is presented in Appendix A. During the meeting, project team made a series of presentations to provide additional information including a brief project background, objective of the meeting, available data, analysis methods, assumptions, and results. The meeting group discussed the strategy for developing the conditional probability of failure (flooding). After the group discussion, the expert panel members offered their opinion of probability of failure assuming no human intervention.

Analysis Case 1: The expert panel mainly focused on results from FLAC analyses to make their judgment regarding the probability of flooding the landside. For a given seismic event, the estimated crest settlements for various water surface elevations were reviewed by the panel members. Each member was asked to provide an estimate for the probability of flooding the landside for a given crest settlement (corresponding to a given water surface elevation and seismic event). Note that, this analysis case does not include any seismic fix. The resulting seismic fragility curves for zones 1 and 2 are shown in Figures 3-27 and 3-28, respectively.**Analysis Case 2**: The seismic fragility for this case was developed by shifting the seismic fragility curves developed for analysis case 1 by the assumed crest settlement. The resulting seismic fragility curves for zones 1 and 2 are shown in Figures 3-29 and 3-30, respectively.

Analysis Case 3: Similar approach as analysis case 1 was taken for this case. This case assumed the high vulnerability levee segments received seismic fix. The resulting seismic fragility curves for zones 1 and 2 are shown in Figures 3-31 and 3-32, respectively.

4.0 SEISMIC REMEDIATION AND POST-EARTHQUAKE REPAIR COSTS

The construction costs of the selected seismic remediation alternatives and post-earthquake repair costs are required for the cost-benefit analysis presented in Section 5. The construction costs of the seismic remediation alternatives for the West Sacramento Study Area were developed as part of a separate task order (Task Order U02) and are presented in a memorandum (URS 2014c). The construction costs only include the cost associated with the seismic remediation and assume it is done independently from static remediation.

4.1 Remediation Alternatives

A total four seismic remediation alternatives: grading (several alternatives considered under a general grading alternative), SC, DSM and dynamic compaction were considered as recommended in the report "Conceptual Seismic Levee Remediation Alternatives and Cost Estimating Templates" (URS 2014b). The grading and dynamic compaction alternatives were considered not feasible for the West Sacramento study area. The grading was mainly not feasible because the critical slope condition was on the waterside slope and therefore seismic fixes on the waterside would have environmental impacts and constructability issues. The deep dynamic compaction is not feasible because application of this method would require degrading the levee which would be impractical and high cost. Both SC and DSM were considered feasible alternatives but SC was preferred to DSM because of cost consideration.

4.2 Post-Earthquake Repair Costs for Case 2

As discussed in Section 3, Case 2 assumes that no seismic fixes are made to the levees but that the damaged (as a result of earthquake) levees would be repaired to restore them back to pre-earthquake conditions. Therefore, only the repair cost is considered in the cost-benefit analysis. For the cost estimate, the following assumptions were made:

- The levees sustained damage during an earthquake and the crest settled several feet (but still can provide 10-year flood protection or levee restored to provide 10-year flood protection within 8 weeks of the occurrence of an earthquake).
- Damaged levees would be repaired within 2 years of the occurrence of the earthquake that caused the damage.
- The repairs to the levees would not include any seismic fixes.

Table 4-1 summarizes the estimated repair costs for Case 2.

4.3 Remediation Costs for Case 3

As discussed in Section 3, the case 3 assumes static and seismic fixes to levees. The remediation costs for the SCs and DSM with cement walls in grid for both Zones 1 and 2 were estimated using the parametric cost estimate template (PCET), which was developed as part of Task Order U02. These costs are Class 4 estimates as defined by the Association for the Advancement of Cost Engineering (AACE). The accuracy of cost estimates under this classification ranges from -15 percent to -30 percent on the low side and from +20 percent to +50 percent on the high side. This level of cost estimating is typically performed for detailed strategic planning, project screening, alternative scheme analysis, confirmation of financial or technical feasibility, and preliminary budget approval.

Figure 3-19, 3-21, and 3-25 show typical SC layouts; these layouts were used to develop cost estimates for Levee Reaches D, L, and S. In general, installation of proposed stone columns requires partial degradation of the existing levee and construction of a level working pad. The degraded levee material may be used to construct the working pad. The construction costs associated with the installation of SCs for the various reaches considered in the two study zones are listed in Table 4-2.

Figure 3-23 shows a typical DSM layout; this layout was used to develop a cost estimate for Levee Reach P. SC was not selected for this reach because it would have to be installed to great depths to meet the performance criteria. DSM was considered for reach P because SC does not meet the performance requirement. As in the case of SCs, installation of DSM grids requires degradation of levee and construction of a working pad. The construction costs associated with the installation DSM grids for various reaches considered in the two study zones are listed in Table 4-2.

5.0 ANNUAL DAMAGE AND ECONOMIC BENEFITS

The incremental benefit and expected annual damage (EAD) of the seismic fixes and the levee repairs were calculated using conditional probability functions developed in Section 3 for different analysis cases, construction costs for the selected seismic remediation alternatives, and repair costs for the damaged levees. The economic benefits and EAD were computed using the computer program HEC-FDA, Version 1.2.5.a (USACE 2008). This section presents a brief summary of the calculations; a detailed discussion of the procedures, input data, and results are presented in Appendix B

5.1 Analysis Scenarios

Multiple analysis scenarios were developed to estimate incremental benefits to essentially address two questions:

1. What is the incremental benefit of repairing the levee after a seismic event occurs?

2. What is the incremental benefit of investing in a seismic fix today, as opposed to not and then repairing the levee after a seismic event occurs?

To estimate the benefit of levee repair, the without-project, no action scenario was compared to the with levee repair scenario (defined as Task 1 as discussed in Appendix B). These scenarios consider a single seismic event occurring once over the 50-year analysis period. For comparing the incremental benefits of different scenarios, the without-project, no action scenario, assumes a seismic event occurs and no action is taken to repair it. Note that, this scenario is hypothetical in nature because if levee sustains damage during an earthquake, the damaged levee would be repaired. For the with levee repair scenario, a seismic event occurs, the levee sustains damage and then it is repaired back to the without-project condition within 2 years.

Task 2 was performed to determine the incremental benefit of a seismic fix over not investing in a fix but rather repair the levee after a seismic event. For Task 2 benefit computations, the without-project scenario is a scenario where the City would not invest in a seismic fix now, but instead wait for a seismic event to occur, then repair the levee back to its original condition.

5.2 Expected Annual Damage

To reasonably estimate EAD, the ability to predict flood flows years in advance would be preferred, but the random nature of flooding makes such predictions impossible. To calculate risk reduction and project benefits, the available literature suggests the use of the statistical average damage value (see DWR 2008; U.S. Water Resources Council 1983). This average is better known as the expected annual damage, EAD. In this report, the project team calculates and uses EAD as an index of risk reduction and project benefits. The annual probability of water surface in the river (exterior) exceeding a specified elevation (stage) was updated using the recent DWR's Central Valley Flood Protection Plan (CVFPP) development study results.

5.2.1 Analysis Tool and Input

The risk analysis approach for this study was developed in such a way that it enables the use of the HEC-FDA computer program. However, for this reason the risk analysis involves certain simplifications. The EAD for the West Sacramento Study Area was estimated using two index points and two impact zones (several sub-impact areas were considered within each Zone), as discussed in Section 2. The input collected for the analysis included information about river water surface elevations, the probability of the water surface exceeding a specified stage (exterior), the water surface elevations in the flood plain (interior), levee fragility curves for different scenarios, and repair and construction costs. The probability that the water surface elevation in a channel at an index point will equal or exceed a specified magnitude used for this study are based on the UNET unsteady open-channel flow model (USACE 2001), considering likely upstream conditions. The computer program HEC-FDA was used to compute damage to structures (residential, commercial, public, and industrial), content damage, automobile damage, and the costs of temporary housing and displacements.

For the without-project, two EAD values were estimated: 1) one estimate representing the levee prior to a seismic event, and 2) the other estimate representing the levee after the seismic event has occurred and it is damaged for two years prior to being repaired. The EAD prior to the seismic event was estimated using the seismic fragility representing Analysis Case 1 (curve set 1 as discussed in Table 5 in Appendix B). EAD was estimated for each seismic event, 0-, 25-, 50-, 100-, 200-, and 500-yr to develop probability-damage curve. To estimate project benefits, a single EAD for each scenario was needed which was accomplished by integrating the probability-damage curve and computing an average. This average EAD takes into account all seismic and flood return periods and combines damage values into a single value of EAD for the without-project, no action condition using fragility curve set 1 (i.e., Analysis Case 2, without-project). An average EAD was estimated similarly using seismic fragility curve set 2 (i.e., Analysis Case 2, without-project with repair). Average EADs were computed at index point 1 and index point 2. Note that these EADs are damages that have an equal likelihood of occurring in each year of the analysis period. We computed EAD for the without-project, with levee repair scenario and compared this to the with-project EAD.

5.3 Results

By comparing EAD results, the project team evaluated the incremental benefits of the seismic fixes to the City’s levees. The results of this comparison are shown in Table 5-1 for index points 1 and 2.

6.0 DISCUSSION AND CONCLUSIONS

DWR initiated this seismic hazard study of the West Sacramento levees to better understand seismic deficiencies of the levees. Specifically, this study assesses the incremental benefit of seismically remediating “high” seismic vulnerability levee segments beyond the static remediation for the 200-year flood level. This study also assesses the cost-benefit ratios for repairing the liquefaction-induced damaged levees back to the pre-earthquake conditions. The cost-benefit analysis was performed in a risk-based formulation using the computer program HEC-FDA.

6.1 Conditional Probability of Failure

The conditional probability of failure (flooding) curves for three analysis cases were developed using the expert’s opinions. The analysis cases included without-project, without-project with post-earthquake repair, and with-project. The conditional probability of failure curves are presented as a function of the water surface elevations for different seismic events.

6.2 Seismic Remediation Costs

The construction cost of the seismic remediation alternative is an incremental cost that corresponds to the cost of the seismic remediation beyond the cost of the required static fix (i.e., the cost of the static fix is not included in the construction cost of seismic remediation). After consideration of various factors (e.g., cost, effectiveness in reducing liquefaction-induced seismic deformation or potential for liquefaction, environmental impacts, available land, constructability), vibro-replacement with stone columns and cement deep-soil mixing were selected as the most appropriate remediation alternatives for the study area. The costs of these alternatives were estimated using the PCET, which was developed as part of Task Order U02. The estimated costs are Class 4 estimates as defined by AACE. This level of cost estimating is typically performed for detailed strategic planning, project screening, alternative scheme analysis, confirmation of financial or technical feasibility, and preliminary budget approval. The estimated project costs for Zones 1 and 2 are $398 million and $507 million, respectively.

The costs for levee repair are estimated by assuming that the levees are not seismically remediated but instead repaired within 2 years of the date of the earthquake that caused the damage. The damaged levee would be repaired to pre-earthquake conditions (again, no seismic fix). The costs of repair for Zones 1 and 2 are approximately $30 million and $36 million, respectively (2014 dollar value).

6.3 Estimating Expected Annual Damage and Cost-Benefit Ratios

The risk analysis approach for this study was developed in a way that enables use of the computer program HEC-FDA. The input collected for the analysis includes river water surface elevations, the probability of water surface exceeding a specified stage (exterior), water surface elevations in the floodplain (interior), levee fragility curves for different scenarios, and repair and construction costs. The HEC-FDA program was used to calculate structure (residential, commercial, public, and industrial) damage, content damage, automobile damage, and temporary housing and displacement costs. The results from the analysis are summarized in Table 5-1.

6.4 Conclusions

The results presented in Table 5-1 suggest that the seismic fix is economically not justified for the West Sacramento as the benefit-cost ratios are well below 1.0.

7.0 ACKNOWLEDGMENTS AND LIMITATIONS

7.1 Acknowledgments

The information presented in this report is based on the efforts of the ULE Program team. Team members who helped develop this cost-benefit study of the West Sacramento levees under seismic hazard are listed below.

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7.2 Limitations

This cost-benefit study was performed in accordance with the standard of care commonly used as the state of practice in the engineering profession. Standard of care is defined as the ordinary diligence exercised by fellow practitioners in this area performing the same services under similar circumstances during the same period.

The discussions of subsurface conditions summarized in this report are based on subsurface soil and groundwater conditions at limited exploration locations. Variations in subsurface conditions may exist between exploration locations, and the project team may not be able to disclose all adverse conditions in the levee and its foundation.

No warranty, either express or implied, is made in the furnishing of this report, which is the result of geotechnical evaluation services. URS makes no warranty, express or implied, that actual encountered site and subsurface conditions will exactly conform to the conditions described herein, nor that will this report's interpretations and recommendations be sufficient for all construction planning aspects of the work. The design engineer and/or contractor should perform a sufficient number of independent explorations and tests as they believe necessary to verify subsurface conditions rather than relying solely on the information presented in this report.

URS does not attest to the accuracy, completeness, or reliability of geotechnical borings and other subsurface data by others that are included in this report. URS has not performed independent validation or verification of data provided by others.

The data presented in this report are time sensitive in that they apply only to locations and conditions existing at the time of the exploration and preparation of this report. Data should not be applied to any other projects in or near the area of this study, nor should the data be applied at a future time without appropriate verification.

This report is one of multiple documents describing work completed in the West Sacramento Study Area. The report should not to be used as the basis for design, construction, or remedial action; nor should it be used as a basis for major capital spending decisions.

8.0 REFERENCES

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TABLES

Table 2-1. Computed PHA Values for Zones 1 and 2

Zone	PHA (g) [1]				
	25-Year Return Period	50-Year Return Period	100-Year Return Period	200-Year Return Period	500-Year Return Period
1	0.05	0.08	0.11	0.15	0.20
2	0.05	0.08	0.12	0.16	0.21

[1] Soil outcrop.

PHA = peak horizontal acceleration

Table 3-1. Criteria for Seismic Vulnerability Classifications[1]

Amount of Crest[2] Displacement Relative to Landside Levee Height (percent)	Potential for Significant Damage to Internal Structures (e.g., Cutoff Walls)	Remaining Freeboard[2] for Post Seismic Evaluation (10-Year Flood WSE +3 feet[3])	Vulnerability Class[4] (Post-Seismic Flood Protection Ability)
< 10	No	>0.3 m (1 foot)	Low Vulnerability
<20	Possibly	Between 0 and 0.3 m (1 foot)	Medium Vulnerability
≥20 (Flow Slide	Yes	None	High Vulnerability

Note:
[1] This table applies to intermittently loaded levees.
[2] Vertical crest displacements can be estimated at 0.7 times the deviatoric deformation from simplified deformation analysis (such as Newmark type displacement), and by adding volumetric displacement as applicable.
[3] Based on ULDC criteria for intermittently loaded levees (Section 7.7.1 of the ULDC [DWR, 2012]).
[4] Analyses results must pass each of the criteria in the first three columns of the table at a given vulnerability class (the last column), or the corresponding segment should be rated at the next higher vulnerability class.

Table 3-2. Summary of Selected Analysis Cross Sections

Zone	Critical Slope Condition	Cross-Section Location (ULE Station / Reach)	Reason for Selection
1	Landside	1091+21/ Reach D (seismic levee segment 1)*	- Factor of safety for post-earthquake landside stability was 0.95 in the GER. - Levee height is approximately 20 feet. - Foundation has potentially liquefiable layer (if saturated) at shallow depth.
	Waterside	1279+50 / Reach L (seismic levee segment 2)	- Factor of safety for post-earthquake waterside stability was 0.79 in the GER. - Waterside levee slope extends below the waterside levee toe and into the river bank. - Embankment and foundation have potentially liquefiable layers (if saturated).
2	Landside	1542+79 / Reach P (seismic levee segment 4)	- Factor of safety for post-earthquake landside stability was 0.16 in the GER. - Levee height is approximately 20 feet. - Embankment and foundation have potentially liquefiable layers (if saturated).
	Waterside	1670+94 / Reach S (seismic levee segment 3)	- Factor of safety for post-earthquake waterside stability was 0.36 in the GER. - Waterside levee slope extends below the waterside levee toe and into the river bank. - Embankment and foundation have potentially liquefiable layers (if saturated).

Notes: * seismic levee segments are shown on Figure 3-1

Table 3-3. Analysis Water Surface Elevations

Analysis Case	Water Surface Elevation (feet) [1]			
	Zone 1		Zone 2	
	1091+29/ Reach D	1279+50 / Reach L	1542+79 / Reach P	1670+94 / Reach S
Summer water level	9.1	7.9	7.4	7.2
Winter water level	14.6	13.3	12.3	11.9
Landside toe level	21	28.5	20.5	20.5
10-year flood level	30.3	30.7	28.8	27.7
200-year flood level	35.9	36.2	34.3	33.2
Top of levee	40	40	39	40.5

[1] North American Vertical Datum (NAVD) of 1988.

Table 3-4. Material Properties Used for Reach D Analyses

Material Layer	Total Unit Weight (pcf)	Drained Cohesion, c' (psf)	Drained Friction Angle, ϕ' (degree)	Undrained strength ratio, Su/σ_{v0}'	Residual Shear Strength of Liquefiable Layers (psf)
					100, 200, and 500 Year Return Period Event
Compacted Fill	120	150	32	0.76	-
CL(1)	110	0	30	-	-
SP-SM(3)	130	0	34	-	-
SP-SM(4)	130	0	32	-	425
ML(5)	120	0	27	0.5	120
CL(6)	110	0	30	0.31	-
CL(7)	110	0	27	0.25	-
SP-SM(8)	130	0	34	-	-
GW(9)	135	0	35	-	-
SM(10)	130	0	35	-	-
Stone Column Treated Zone (25% ARR)	130	0	35	-	-

Notes: (1) Reach D has no potential liquefiable layers under 25-year and 50-year return period events.

(2) $\phi_{\text{stone column treated zone}}$ = [ARR x $\phi_{\text{stone columns}}$ + (100-ARR) x ϕ_{soil}]/100, where $\phi_{\text{stone columns}}$ = 40 degrees and ARR in percent.

Table 3-5. Material Properties Used for Reach L Analyses

Material Layer	Total Unit Weight (pcf)	Drained Cohesion, c' (psf)	Drained Friction Angle, ϕ' (degree)	Undrained strength ratio, Su/σ_{v0}'	Residual Shear Strength of Liquefiable Layers (psf)
					100, 200, and 500 Year Return Period Event
Compacted Fill	120	150	32	0.76	-
SP-SM(1)	130	0	30	-	200
ML(2)	120	75	31	0.76	265
SM(3)	130	0	29	-	120
SP-SM(4)	130	0	34	-	290
GP-GM(5)	130	0	35	-	-
CL(6)	110	100	33	0.44	-
Stone Column Treated Zone (25% ARR)	130	0	33 [treated SP-SM(1), ML(2), and SM(3)]; 36 [treated SP-SM(4)]	-	-

Notes: (1) Reach L has no potential liquefiable layers under 25-year and 50-year return period events.

(2) $\phi_{\text{stone column treated zone}}$ = [ARR x $\phi_{\text{stone columns}}$ + (100-ARR) x ϕ_{soil}]/100, where $\phi_{\text{stone columns}}$ = 40 degrees and ARR in percent.

Table 3-6. Material Properties Used for Reach P Analyses

Material Layer	Total Unit Weight (pcf)	Drained Cohesion, c' (psf)	Drained Friction Angle, ϕ' (degree)	Undrained strength ratio, Su/σ_{v0}'	Residual Shear Strength of Liquefiable Layers (psf)	
					100, 200, and 500 Year Return Period Event	50 Year Return Period Event
Compacted Fill	120	150	32	0.76	-	-
SP-SM (1)	130	0	28	-	70	70
SP-SM (2)	130	0	28	-	130	130
ML (3)	120	0	34	0.3	390	-
ML (4)	120	0	31	-	145	145
SP-SM (5)	130	0	32	-	265	265
SM (6)	130	0	33	-	290	-
ML (7)	120	0	30	-	90	90
ML (7) (below Elevation -65 feet)	120	0	30	0.3	-	-
DSM Treated Area (25% ARR)	100	1800	-	-	-	-

Notes: (1) Reach P has no potential liquefiable layers under 25-year return period event.

(2) $S_{u,DSM\ treated\ area}$ = [ARR x $S_{u,DSM}$ + (100-ARR) x $S_{u,soil}$]/100, where $S_{U,DSM}$ = 50 psi, $S_{u,soil}$ = 0, and ARR in percent.

Table 3-7. Material Properties Used for Reach S Analyses

Material Layer	Total Unit Weight (pcf)	Drained Cohesion, c' (psf)	Drained Friction Angle, ϕ' (degree)	Undrained strength ratio, S_u/σ_{v0}'	Residual Shear Strength of Liquefiable Layers (psf)		
					100, 200, and 500 Year Return Period Event	50 Year Return Period Event	25 Year Return Period Event
Compacted Fill	120	150	32	0.76	-	-	-
SP (1)	130	0	30	-	220	-	-
CL (2)	110	100	31	0.76	-	-	-
ML (3)	120	100	30	0.50	130	130	130
SM (4)	130	0	30	-	220	220	-
SP (5)	130	0	35	-	600	-	-
GW (6)	135	0	35	-	-	-	-
ML (7)	120	75	34	0.76	-	-	-
Stone Column Treated Zone (25% ARR)	130	0	33	-	-	-	-

Notes: (1) The parts of the SM(4) and SM(5) layers were modeled as non-liquefiable/ less likely liquefiable.

(2) $\phi_{\text{stone column treated zone}}$ = [ARR x $\phi_{\text{stone columns}}$ + (100-ARR) x ϕ_{soil}]/100, where $\phi_{\text{stone columns}}$ = 40 degrees and ARR in percent.

Table 3-8: Material Properties Used in the FLAC Analysis

Materials	Saturated Density (pcf)	Friction (degrees)	Cohesion (psf)	Poisson's Ratio	Shear Wave Velocity	$(N_1)_{60\text{-}CS}$	$(S_u)_r$ (psf)	K_h (ft/day)	K_h/K_v	Porosity
Embankment Fill (EMB)	120	32	150	0.35	500	-	-	0.011	4	0.3
Embankment SP-SM (ESPSM)	130	30	0	0.35	700	9	200	56	4	0.45
Silt (ML)	120	31	75	0.35	550	10.5	265	0.03	1	0.35
Silty Sand (SM)	130	29	75	0.35	600	6.5	120	11	4	0.4
Sand with Silt (SPSM)	130	34	0	0.35	700	11	290	56	4	0.45
Gravel (GRAVEL)	130	35	0	0.35	1100	-	-	560	4	0.5

Table 4-1. Repair Costs for Analysis Case 2

Zone	Seismic Segment ID	River/ Channel	Static Reach ID	Static Reach Length (feet)	Conceptual Seismic Remediation Cost Estimate by Reach	Conceptual Seismic Remediation Cost Estimate by Segment
1	1	Sacramento Bypass	D	900	$1,200,000	$1,200,000
	2	Sacramento River	E	1,600	$2,000,000	$28,800,000
			F	2,700	$3,300,000	
			H	1,100	$1,300,000	
			J	3,500	$4,300,000	
			K2	2,000	$2,400,000	
			L	4,500	$5,500,000	
			M	8,200	$10,000,000	
2	3	Sacramento River	O	7,900	$9,600,000	$29,600,000
			R	3,200	$3,900,000	
			S	8,900	$11,000,000	
			T	4,200	$5,100,000	
	4	Sacramento River	P	2,500	$3,000,000	$6,400,000
			Q	2,800	$3,400,000	
					Total =	**$66,000,000**

Table 4-2. Remediation Costs for Analysis Case 3

Zone	Seismic Segment ID	River/ Channel	Static Reach ID	Static Reach Length (feet)	Analysis Section	Remedial Alternative Details	Treatment Depth from Levee Crest	Conceptual Seismic Remediation Cost Estimate by Reach	Conceptual Seismic Remediation Cost Estimate by Segment
1	1	Sacramento Bypass	D	900	1091+29	Stone Columns Target ARR: 25% Treatment Width: 135 feet	30 feet	$9,300,000	$9,300,000
	2	Sacramento River	E	1,600		Stone Columns Target ARR: 25% Treatment Width: 105 feet	35 feet	$14,000,000	$389,000,000
			F	2,700			50 feet	$36,000,000	
			H	1,100			75 feet	$23,000,000	
			J	3,500			80 feet	$74,000,000	
			K2	2,000			50 feet	$27,000,000	
			L	4,500	1279+50		75 feet	$95,000,000	
			M	8,200			55 feet	$120,000,000	
2	3	Sacramento River	O	7,900		Stone Columns Target ARR: 25% Treatment Width: 95 feet	70 feet	$145,000,000	$346,000,000
			R	3,200			45 feet	$37,000,000	
			S	8,900	1670+94		50 feet	$115,000,000	
			T[1]	4,200			40 feet	$49,000,000	
	4	Sacramento River	P	2,500	1542+79	DSM Target ARR: 25% Treatment Width: 105 feet	105 feet	$76,000,000	$161,000,000
			Q	2,800			105 feet	$85,000,000	
								Total =	**$905,300,000**

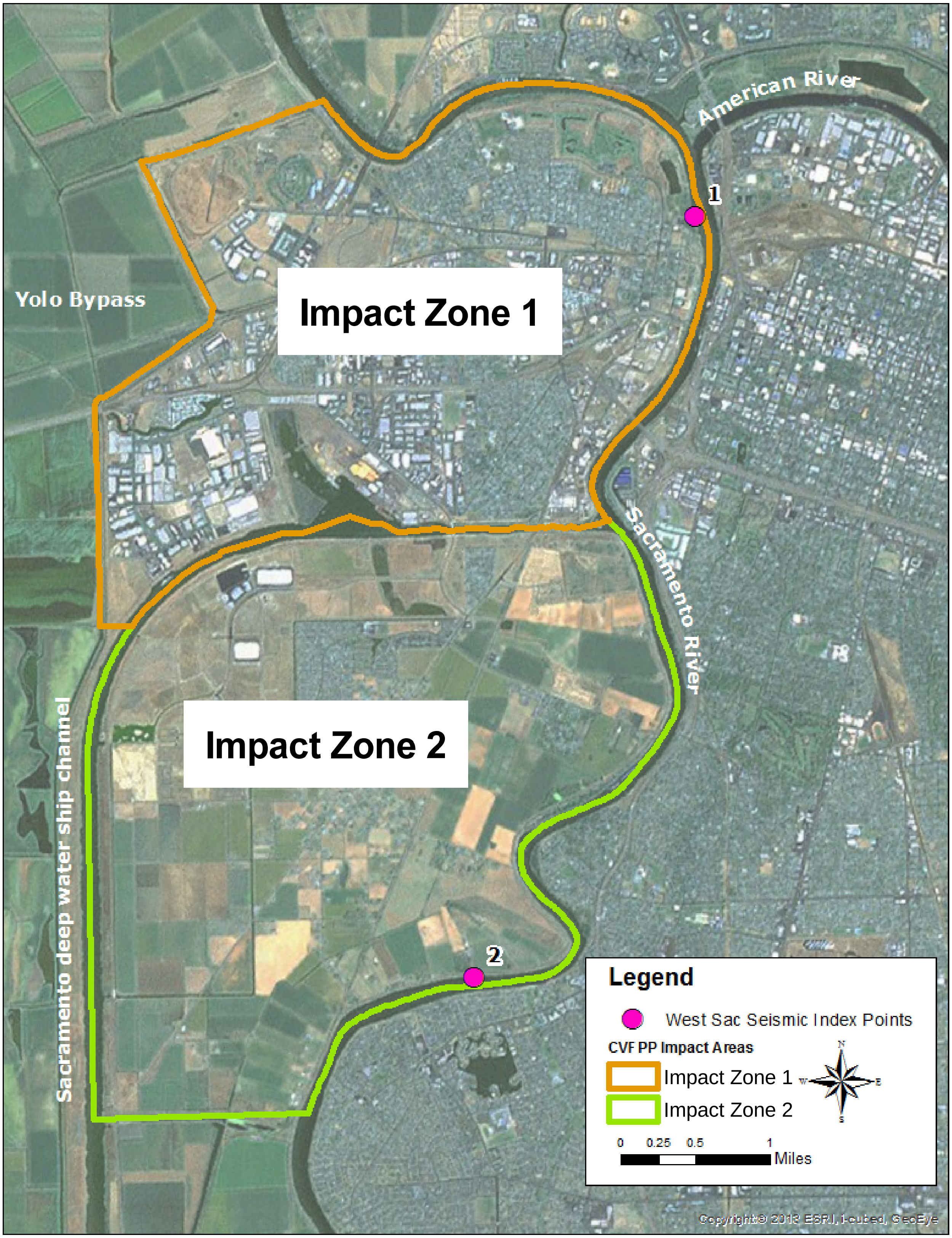
Notes:
ARR = average replacement ratio
[1]For Reach T, a shallow cutoff wall is included in the remediation cost estimate to address the potential for increased seepage associated with stone columns.

Table 5-1 Expected Annual Damage and Benefit-Cost Ratios

Scenario	EAD ($1,000)	Present Value Benefit ($1000)	Present Value Cost ($1000)	B/C ratio[2]
Zone 1				
Without-project, levee repair	1,860	767	9,174	—
With project	1,098	12,007	398,300	0.03
Zone 2				
Without-project, levee repair	4,873	1,764	11,009	—
With project	1,710	49,866	507,000	0.10

[1] Present value computed using the current DWR discount rate of 6% and a 50-year project life.
[2] B/C ratio = present value benefit / project costs
— = not applicable
EAD = expected annual damage

FIGURES



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IMPACT ZONES AND INDEX POINTS
COST-BENEFIT ANALYSES

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE 2-1

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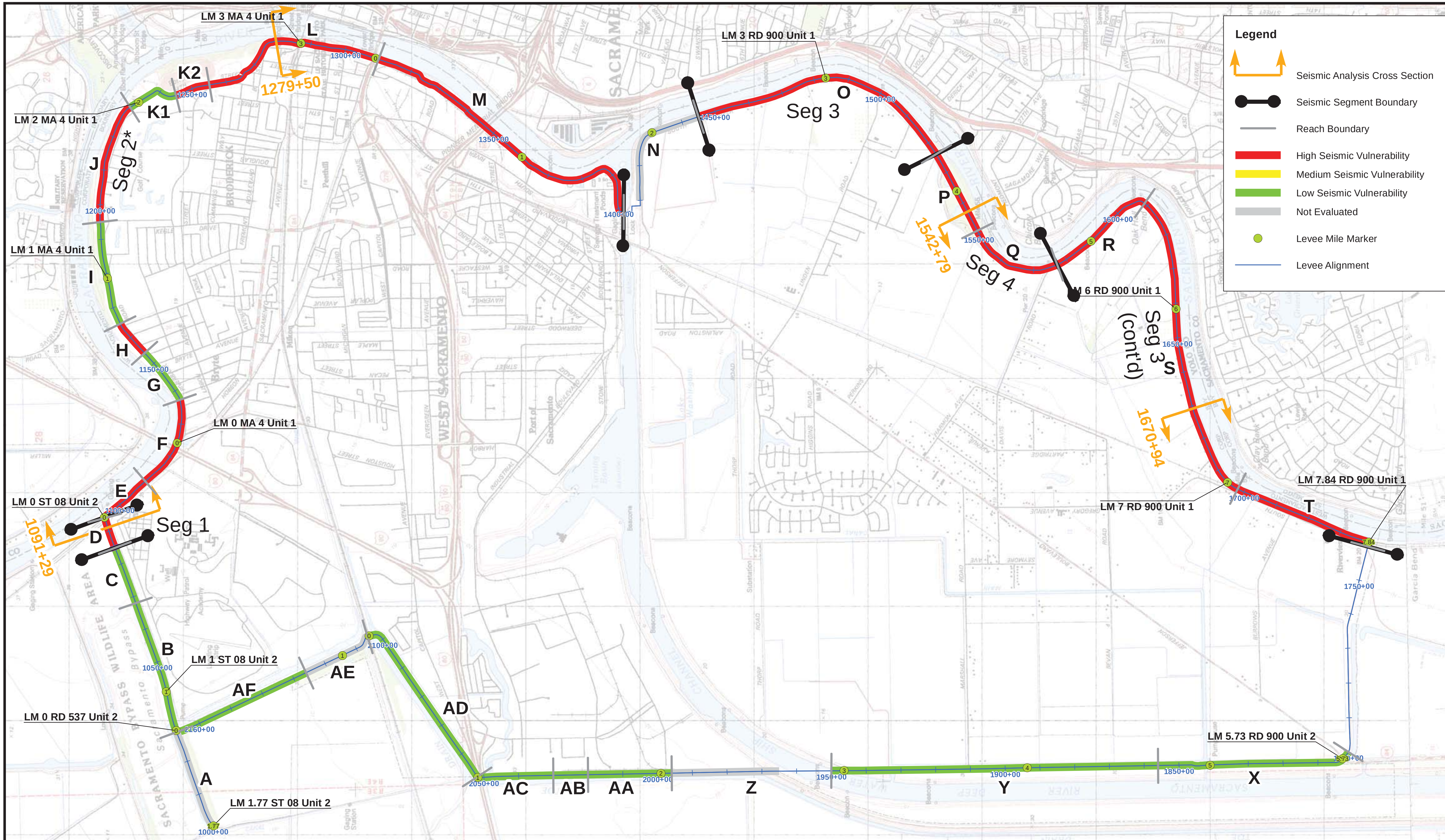

N

0 2,000 4,000
FEET

***Low vulternability areas were not included in Seg 2**

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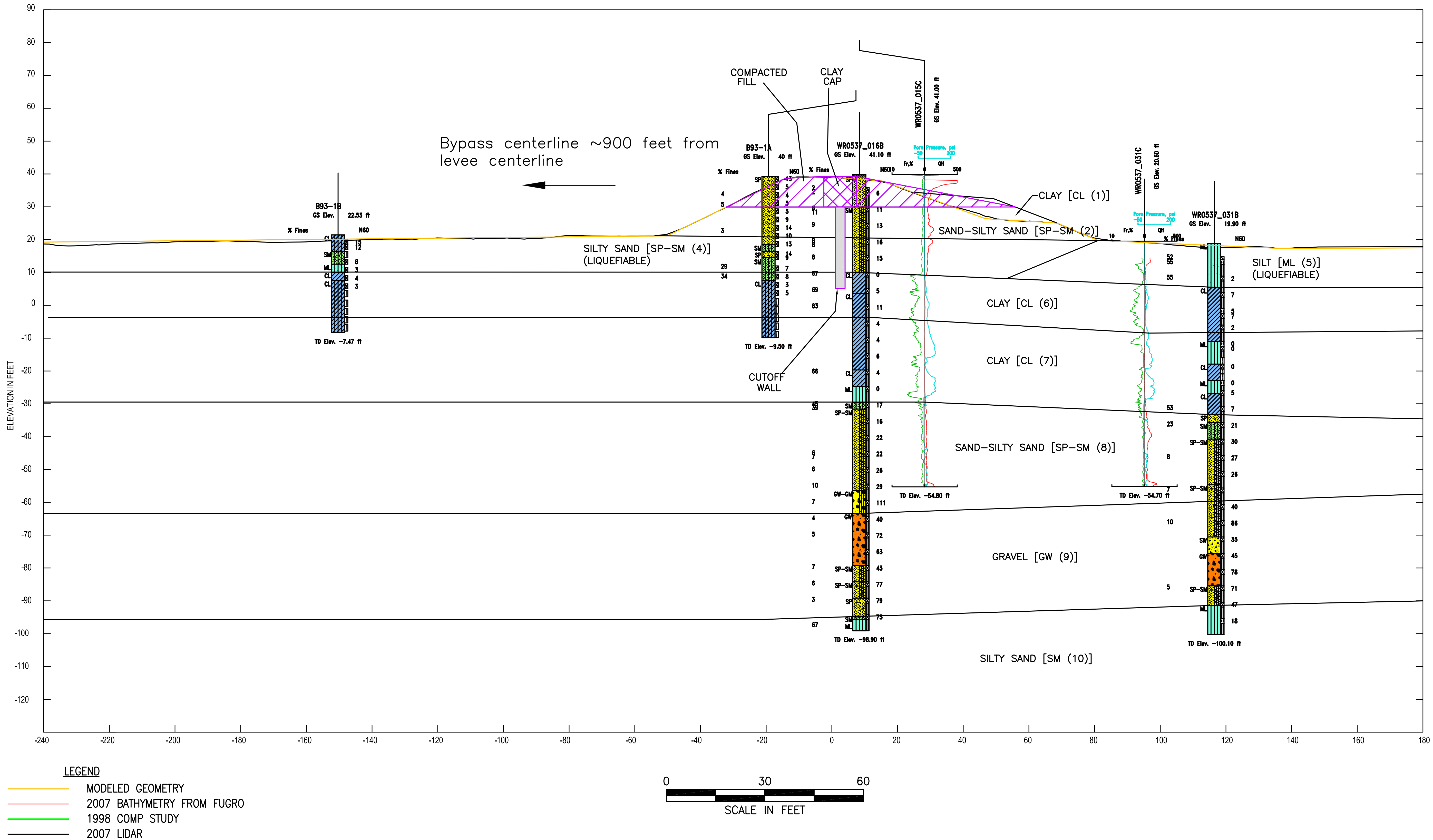
URS
in association with:
GEI Consultants
FUGRO

Seismic Vulnerability Classes
West Sacramento Study Area

URBAN LEVEE
GEOTECHNICAL EVALUATIONS PROGRAM

FIGURE
3-1



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ANALYSIS CROSS SECTION 1091+21
REACH D, ZONE 1

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE
3-2

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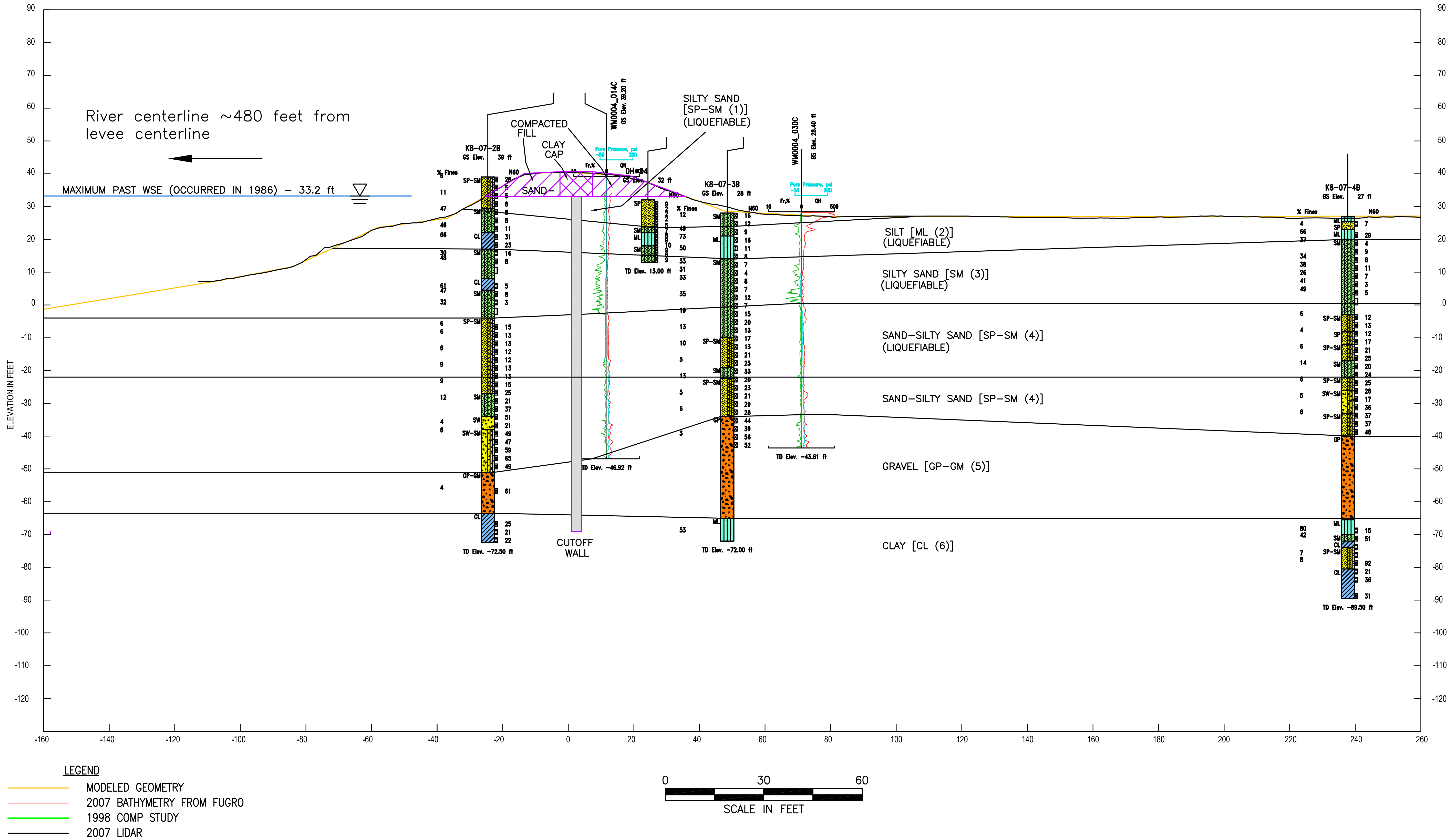

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ANALYSIS CROSS SECTION 1279+50
REACH L, ZONE 1

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE
3-3

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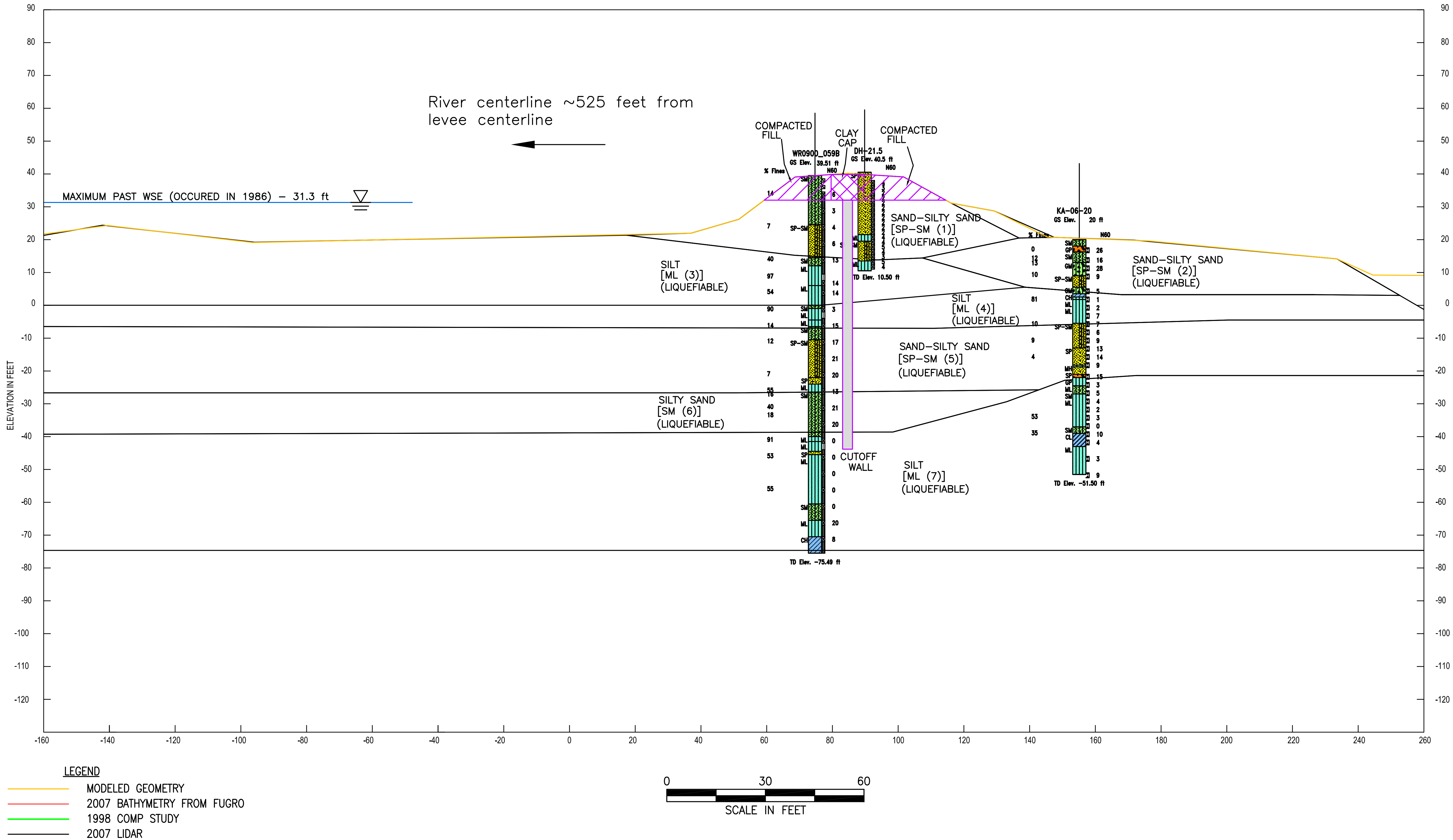

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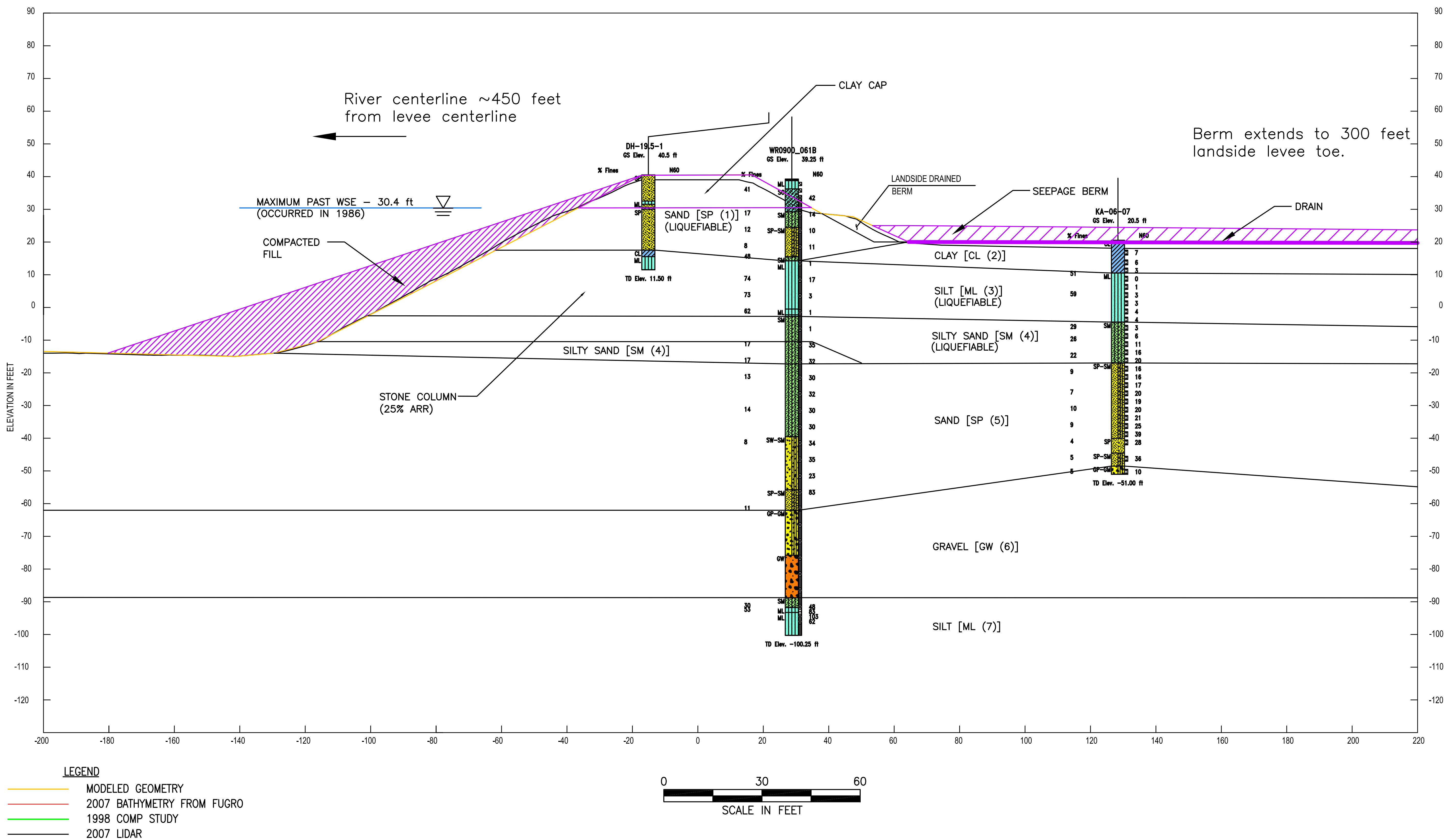
ANALYSIS CROSS SECTION 1542+79
REACH P, ZONE 2

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE 3-4



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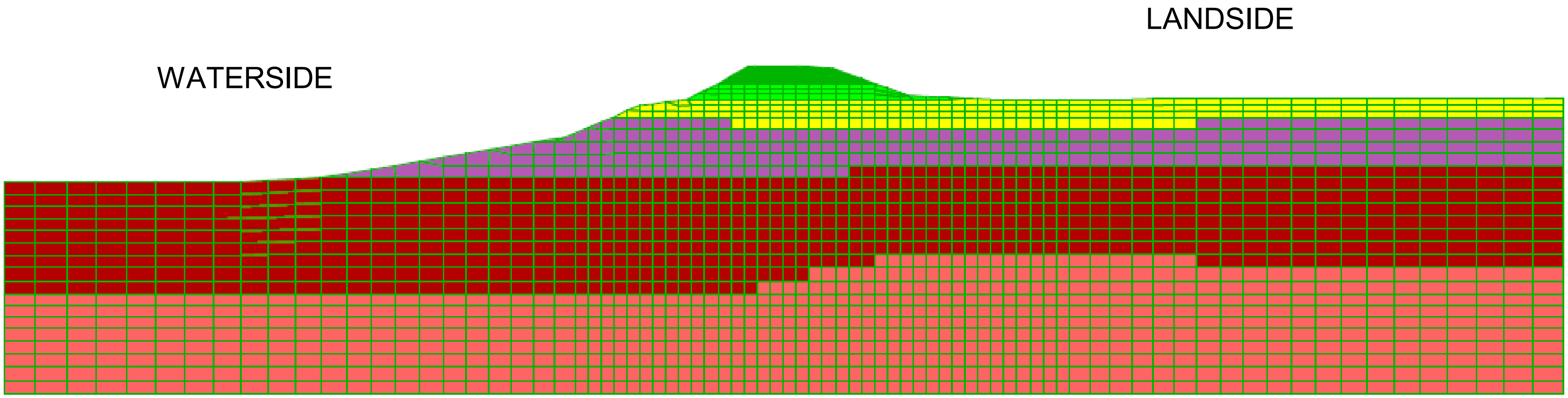
ANALYSIS CROSS SECTION 1670+94
REACH S, ZONE 2

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE
3-5



User-defined Groups

- GRAVEL
- SPSM
- SM
- ML
- ESPSM
- EMB

Note:
EMB- Embankment
ESPSM- SPSM in the Embankment

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Mesh of the Analysis Section 1279+50
Reach L, Zone 1

WEST SACRAMENTO STUDY AREA
URBAN LEVEE EVALUATIONS

FIGURE 3-6

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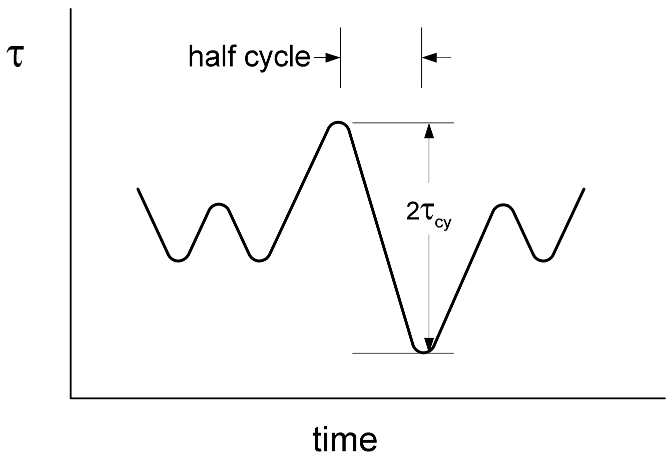
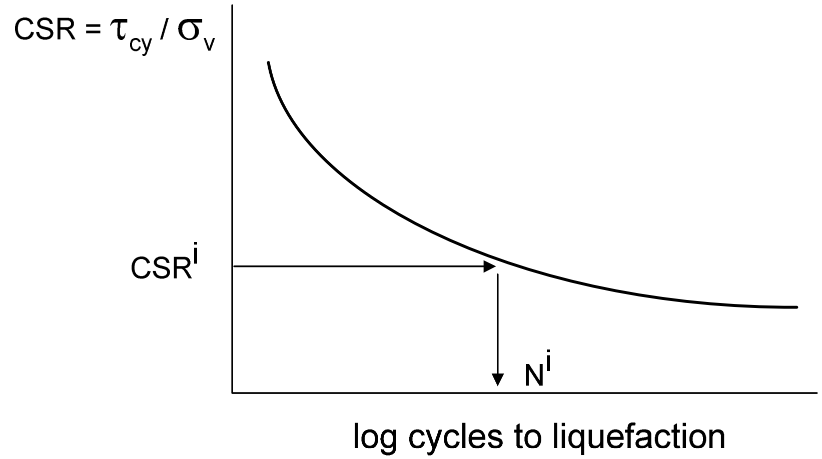
Shear Stress Time History



Cyclic Strength

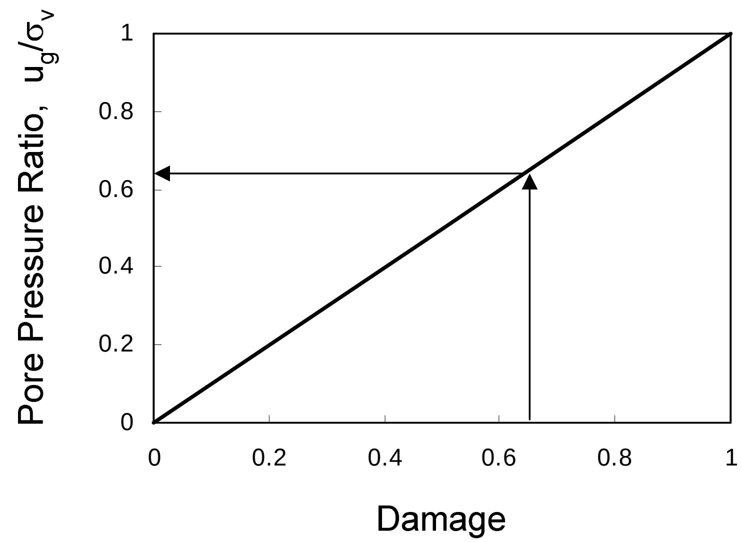


Damage Increment

$$\Delta D^i = 0.5 / N_L^i$$

Cumulative Damage

$$D = \sum \Delta D^i$$



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Seismic-Induced Pore Pressure Generation Scheme for Liquefiable Materials

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE 3-7

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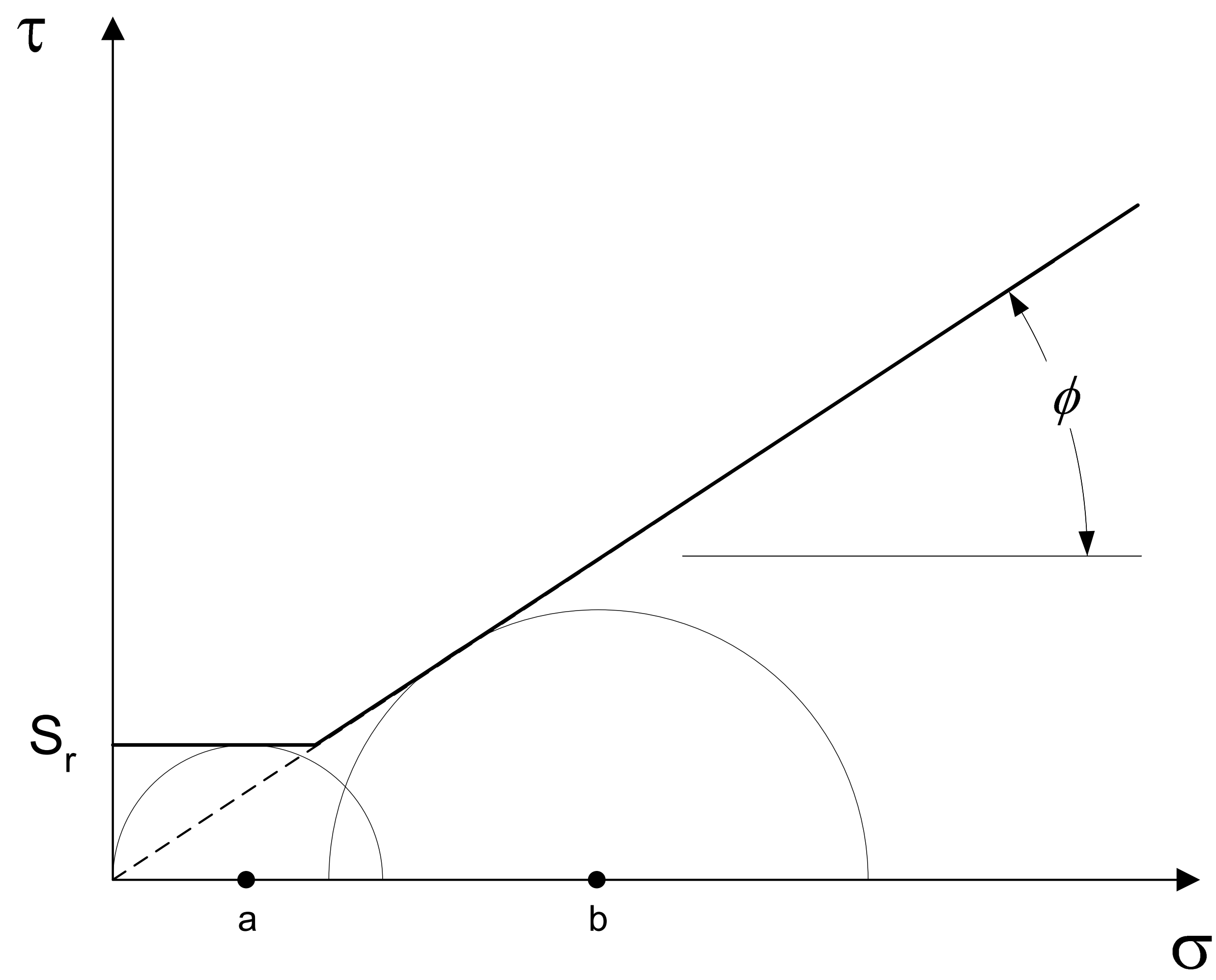

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Mohr-Coulomb and
Residual Strength Envelope
for Liquefiable Materials

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE

3-8

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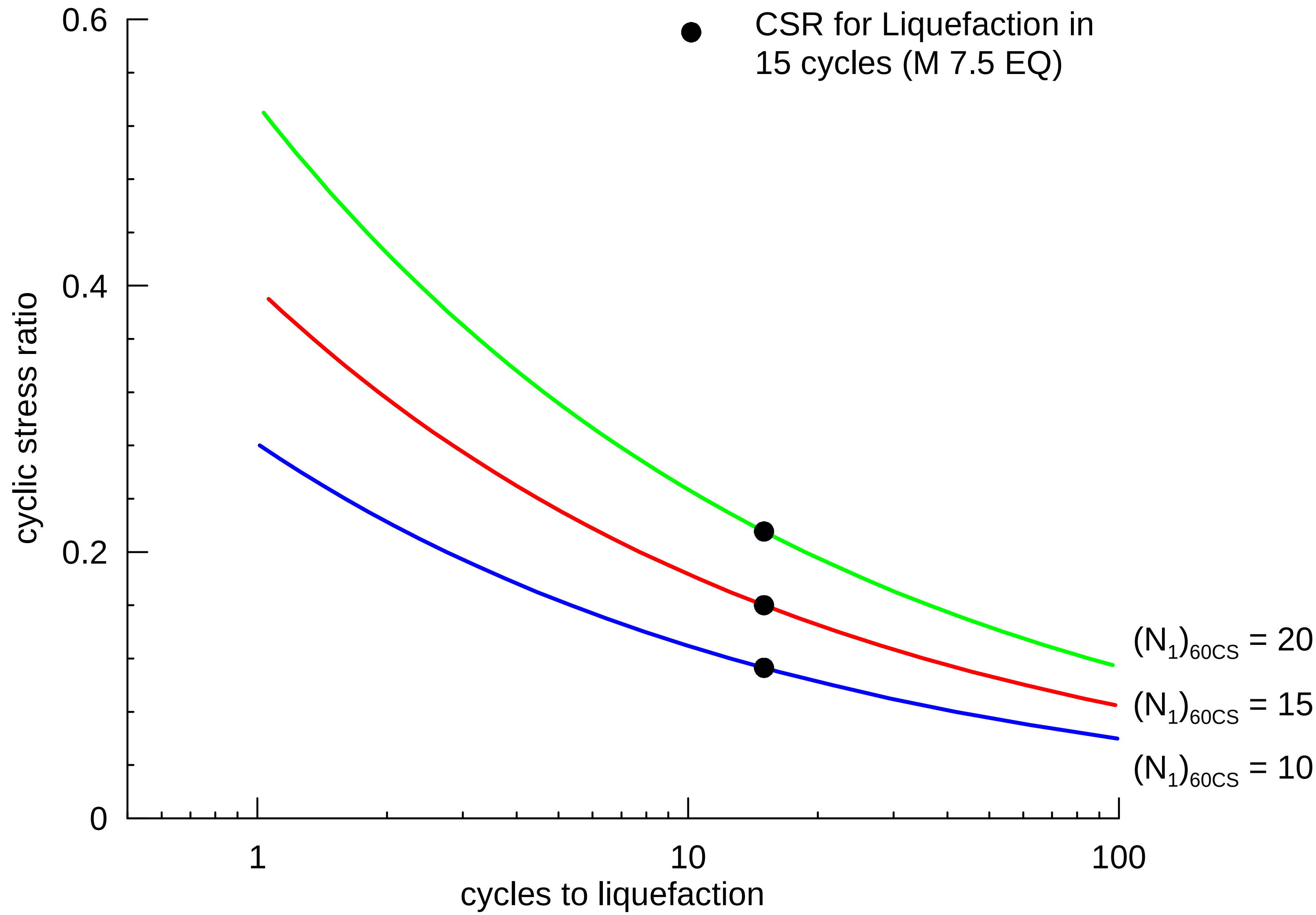

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Cyclic Strength of Saturated Liquefiable Materials

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE

3-9

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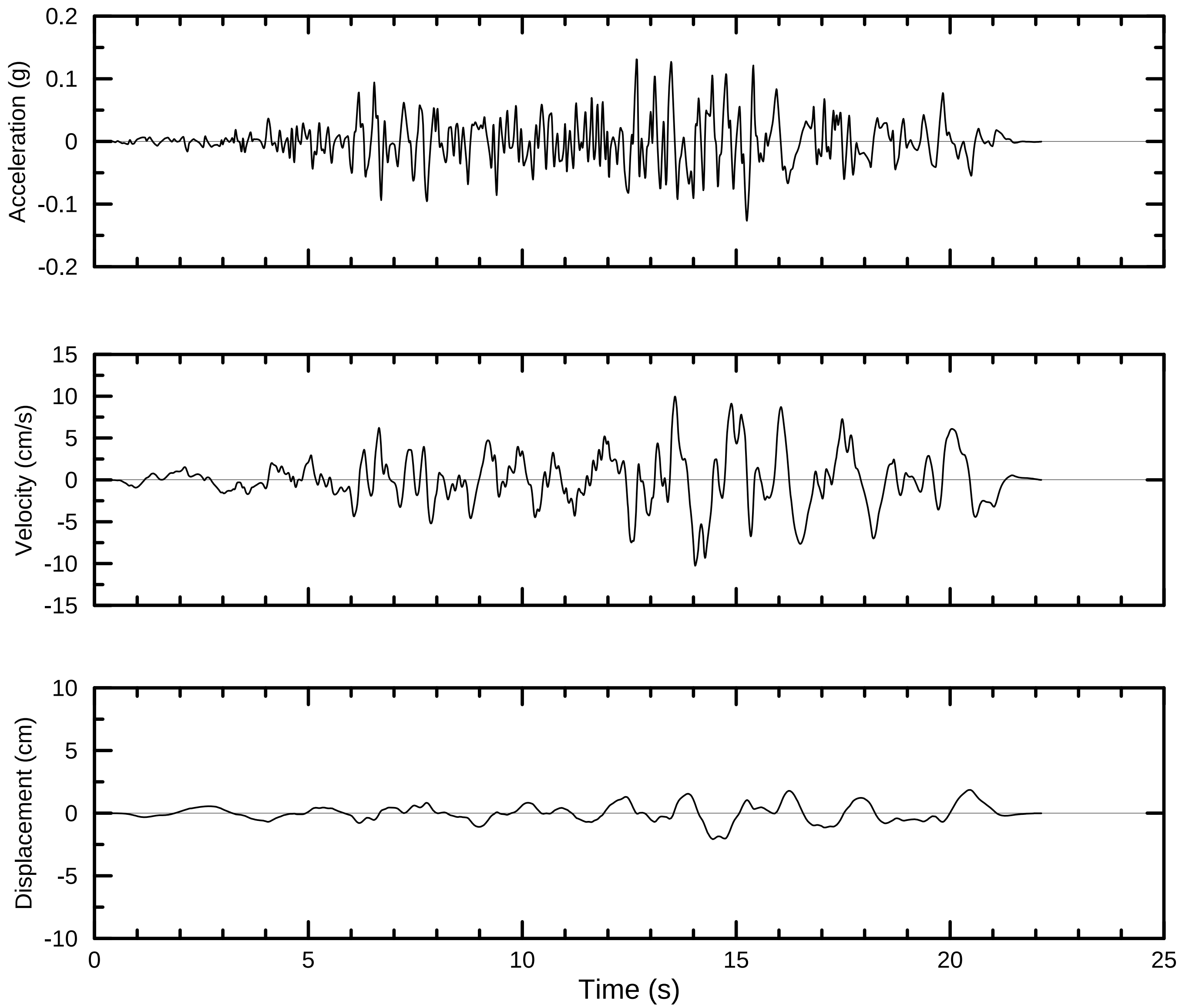

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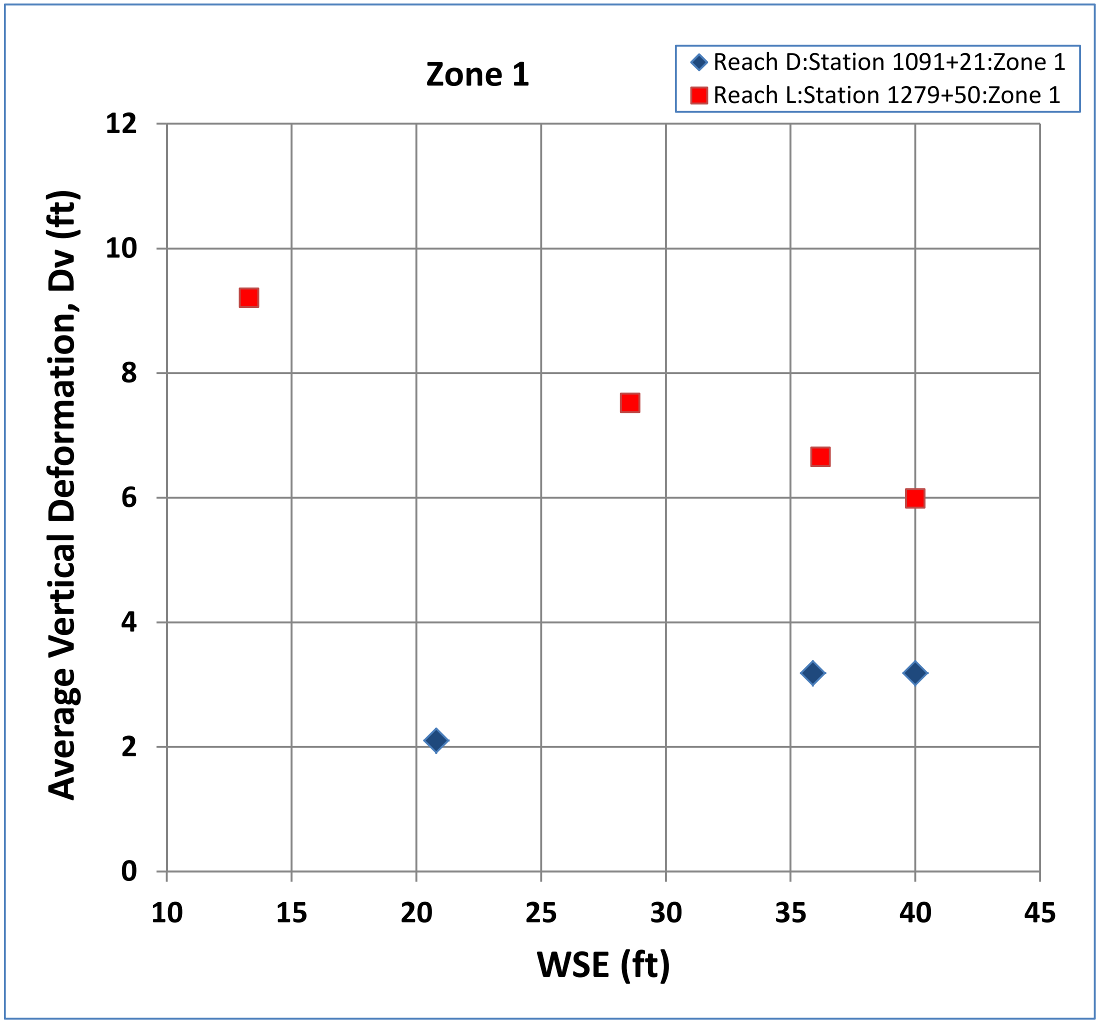
Input Time Histories Corresponding to 200 Year Return Period Seismic Event

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE 3-10



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LATERAL SPREADING ANALYSIS RESULTS FOR ZONE 1

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE 3-11

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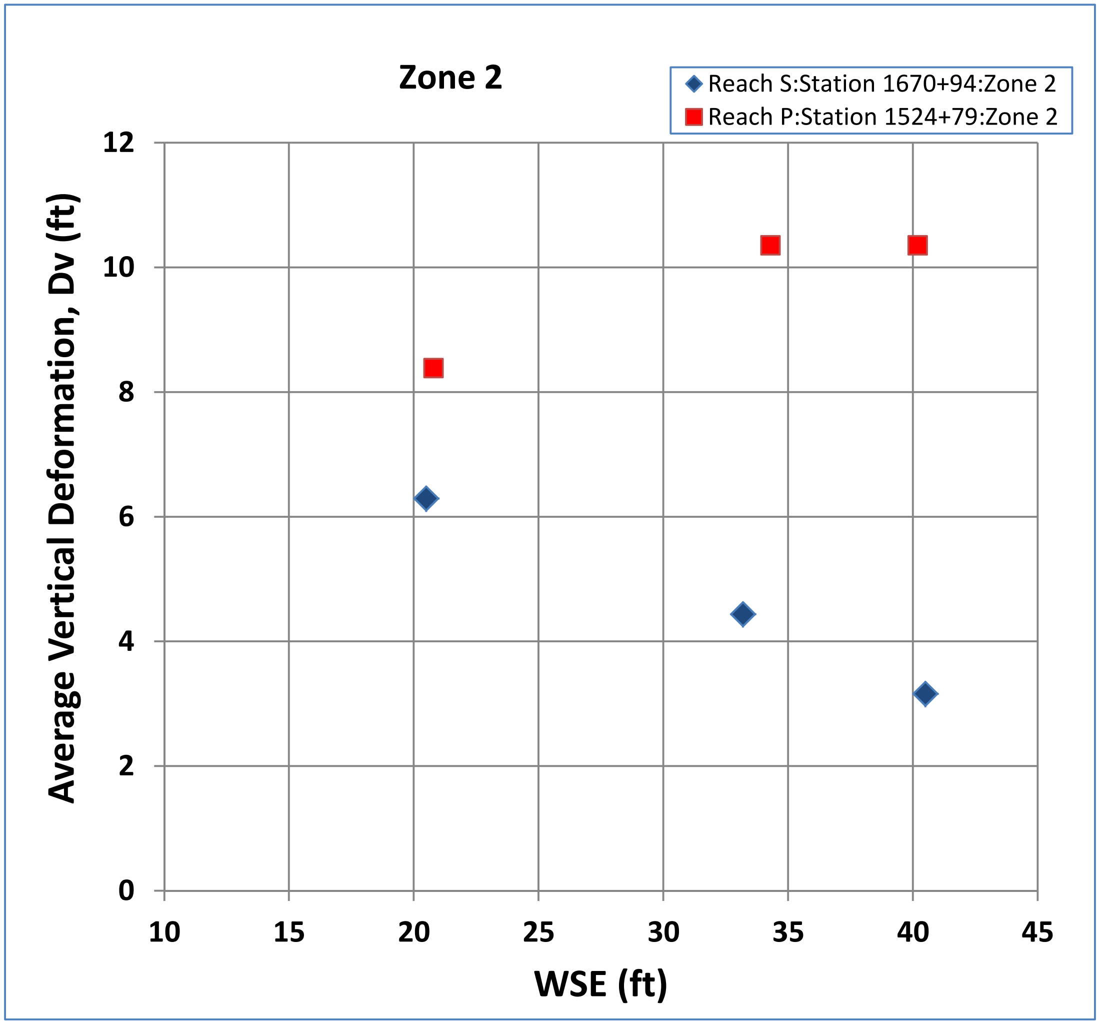
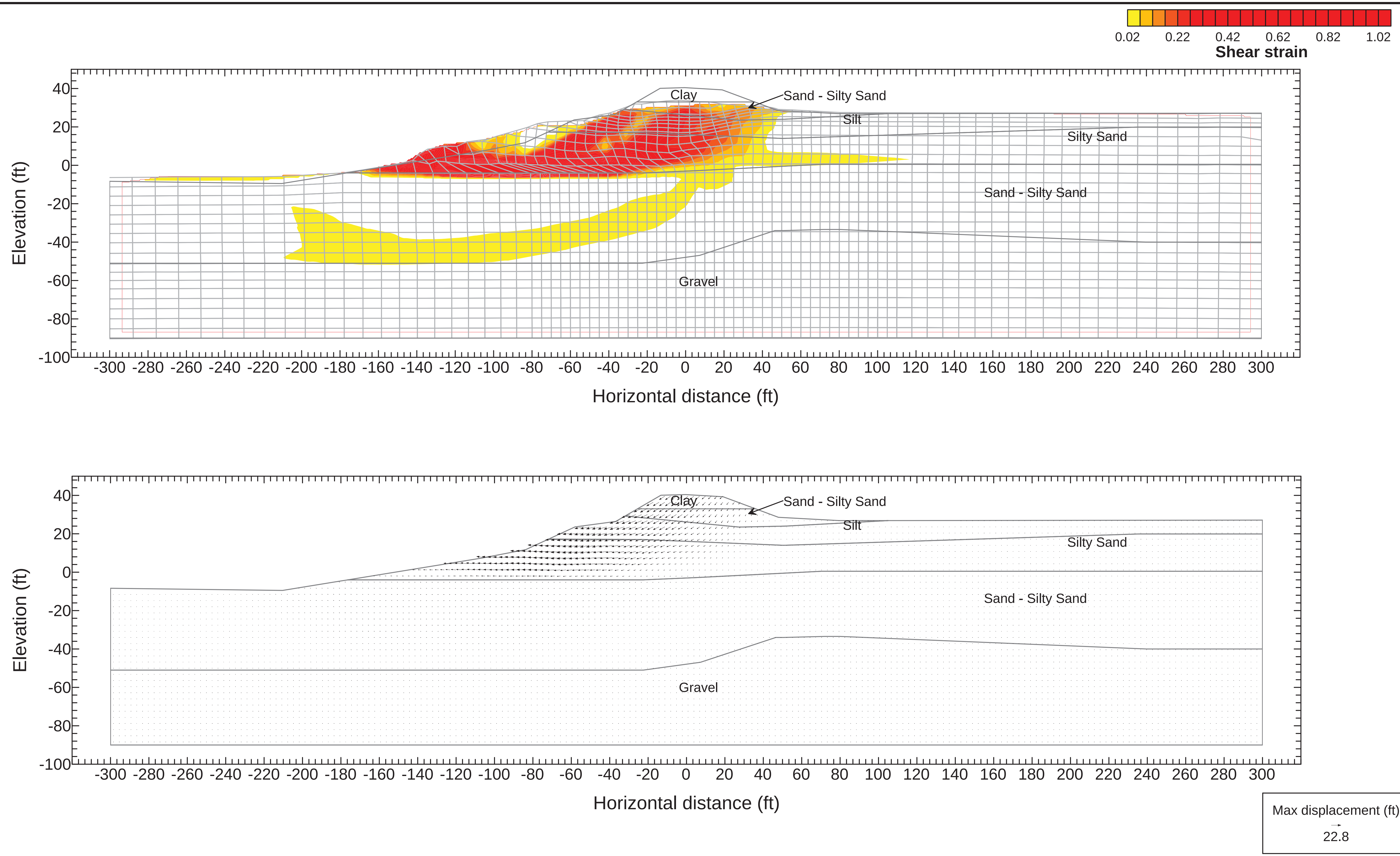


Department of Water Resources Divison of Flood Management Levee Evaluations Branch	URS	**LATERAL SPREADING ANALYSIS RESULTS FOR ZONE 2** WEST SACRAMENTO STUDY AREA URBAN LEVEE EVALUATIONS	FIGURE 3-12

P:\Task Orders\TO-U13 Seismic Risk\08 Task Groups\08_2014 Updates\05_Report\Figures\Originals\Figure 3-12 Lateral Spreading.grf



Department of Water Resources
Divison of Flood Management
Levee Evaluations Branch

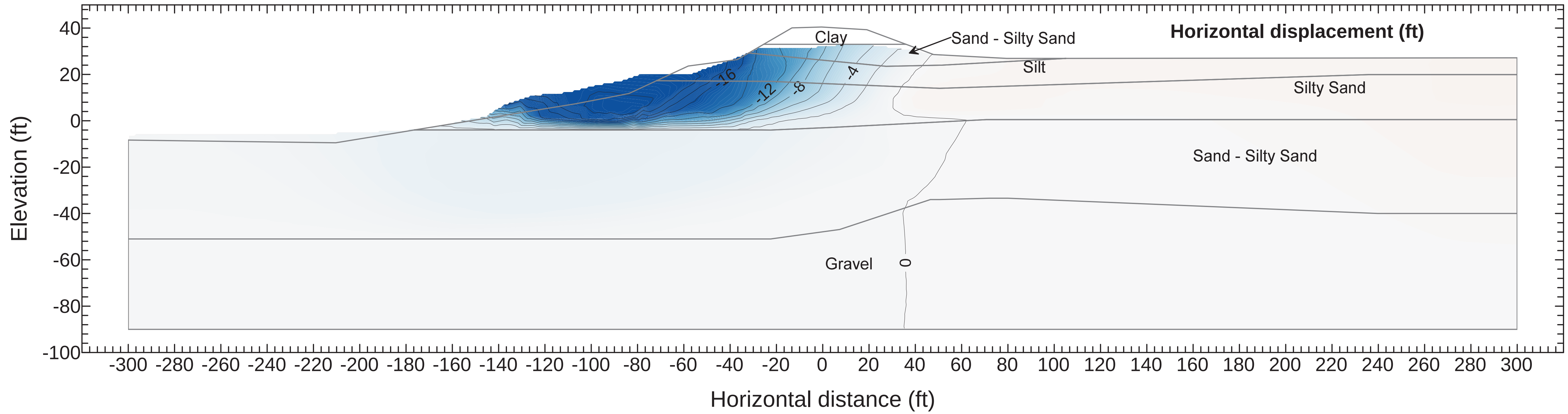
URS

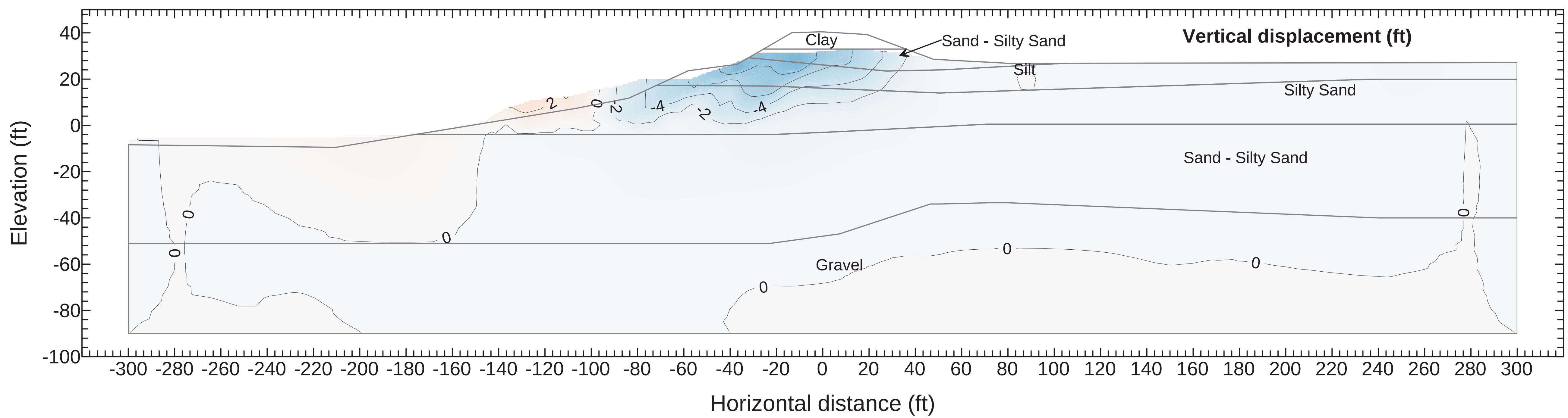
Deformed Shape, Shear Strain, Displacement Vectors
Analysis Section at 1279+50, Reach L, Zone1
Winter Water Level, 200 Year Motion

WEST SACRAMENTO STUDY AREA
URBAN LEVEE EVALUATIONS

FIGURE
3-13

//S021emc2/leveegeotecheval/Task Orders/TO-13 Seismic Vulnerability Assesment/Analysis/west sac model 1/FLAC/Analysis in Dec 2012/Winter WL





Department of Water Resources
Divison of Flood Management
Levee Evaluations Branch

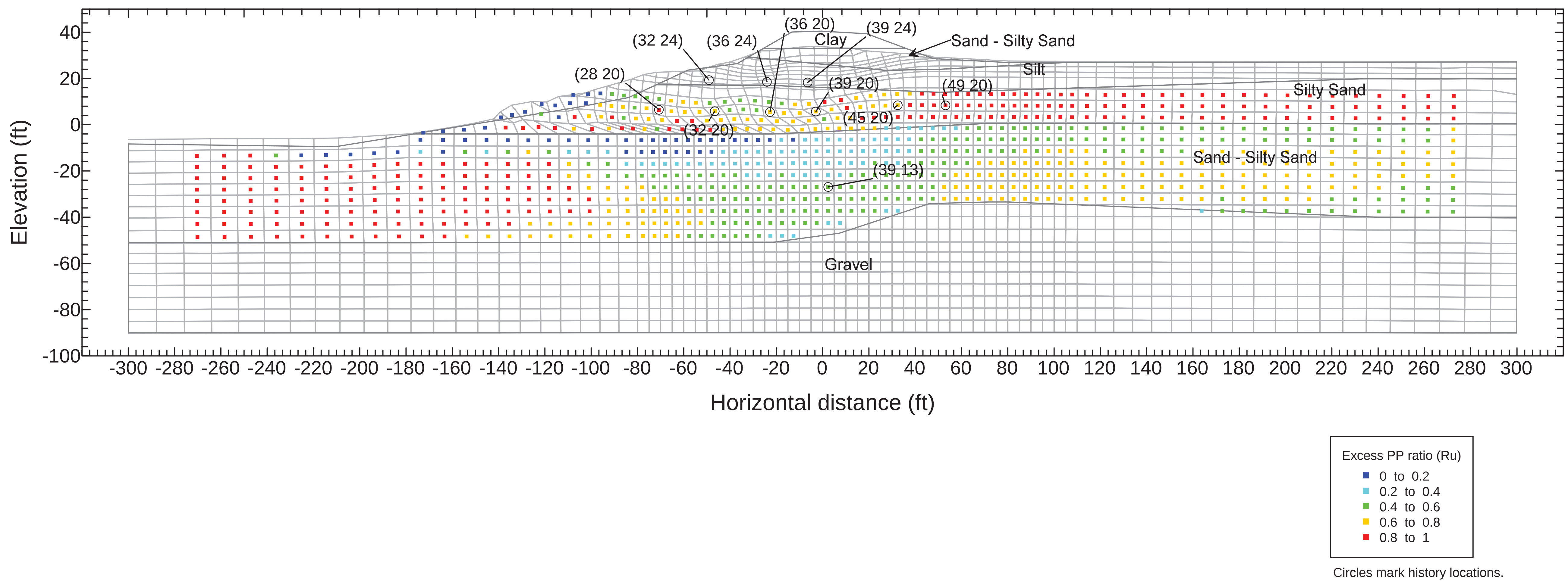
URS

Displacement Contours
Analysis Section at 1279+50, Reach L, Zone1
Winter Water Level, 200 Year Motion

WEST SACRAMENTO STUDY AREA
URBAN LEVEE EVALUATIONS

FIGURE
3-14

//S021emc2/leveegeotecheval/Task Orders/TO-13 Seismic Vulnerability Assesment/Analysis/west sac model 1/FLAC/Analysis in Dec 2012/Winter WL



Department of Water Resources
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Levee Evaluations Branch

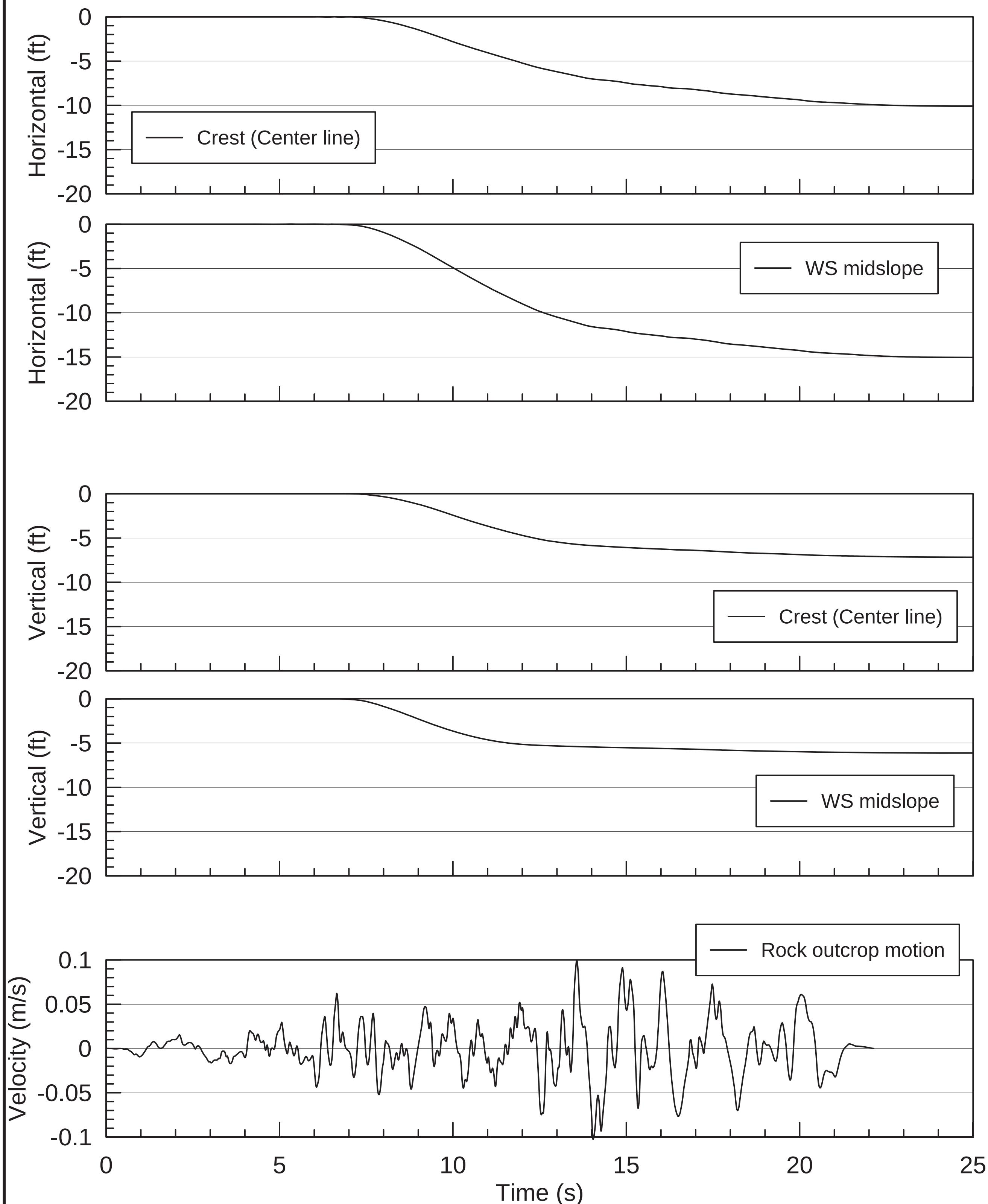
URS

Excess Pore Pressure Ratio
Analysis Section at 1279+50, Reach L, Zone1
Winter Water Level, 200 Year Motion

WEST SACRAMENTO STUDY AREA
URBAN LEVEE EVALUATIONS

FIGURE 3-15

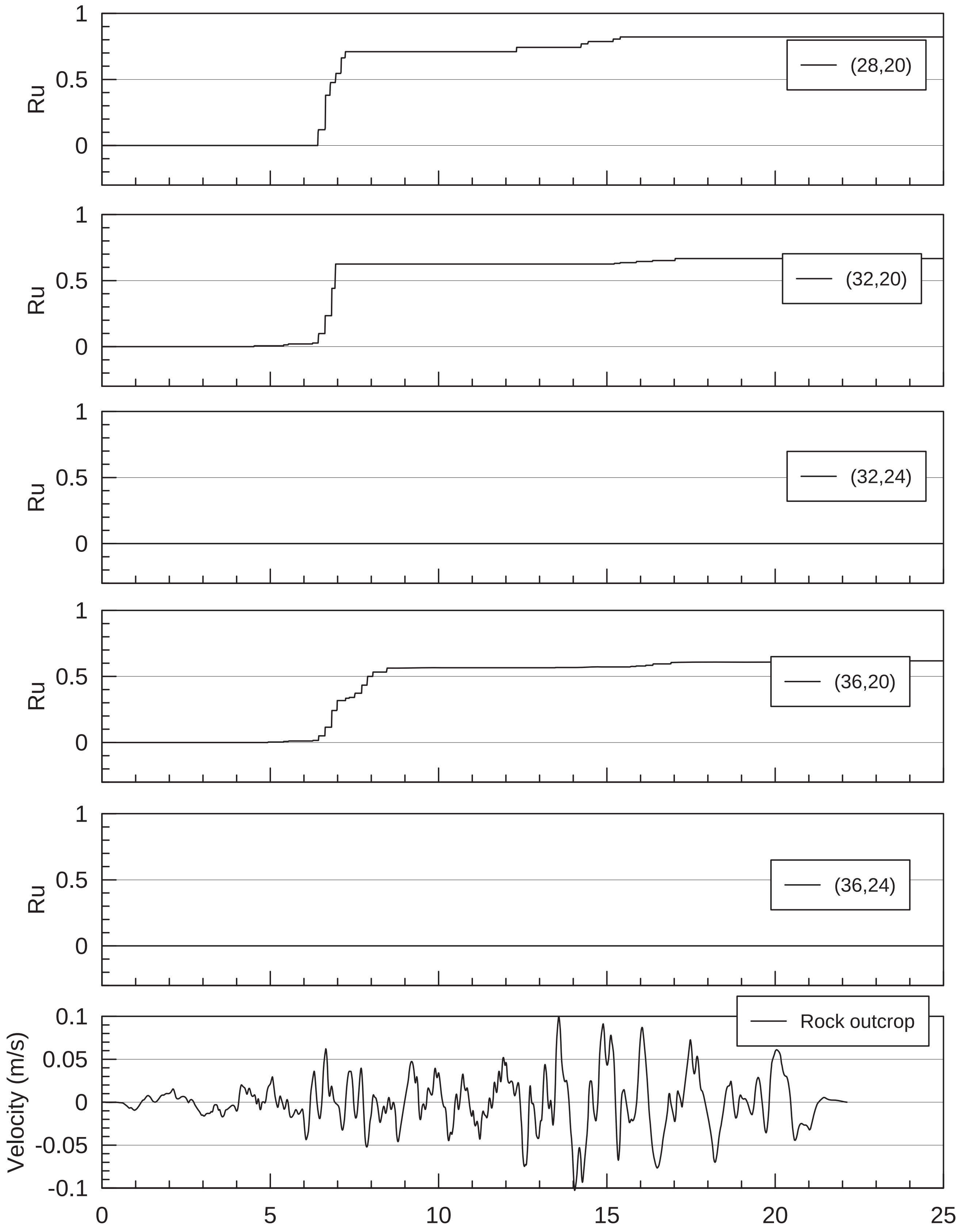
//S021emc2/leveegeotecheval/Task Orders/TO-13 Seismic Vulnerability Assesment/Analysis/west sac model 1/FLAC/Analysis in Dec 2012/Winter WL



Note: Winter Water Level, 200 Year Motion

Department of Water Resources Divison of Flood Management Levee Evaluations Branch	URS	**Calculated Displacements** **Section at 1279+50, Reach L, Zone1** WEST SACRAMENTO STUDY AREA URBAN LEVEE EVALUATIONS	FIGURE 3-16

\\S021emc2\leveegeotecheval\Task Orders\TO-13 Seismic Vulnerability Assesment\Analysis\west sac model 1\FLAC\Analysis in Dec 2012\Winter WL - Rev\Dynamic_200 Yr RP\Plots_



Note: Winter Water Level, 200 Year Motion

Department of Water Resources
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Levee Evaluations Branch

URS

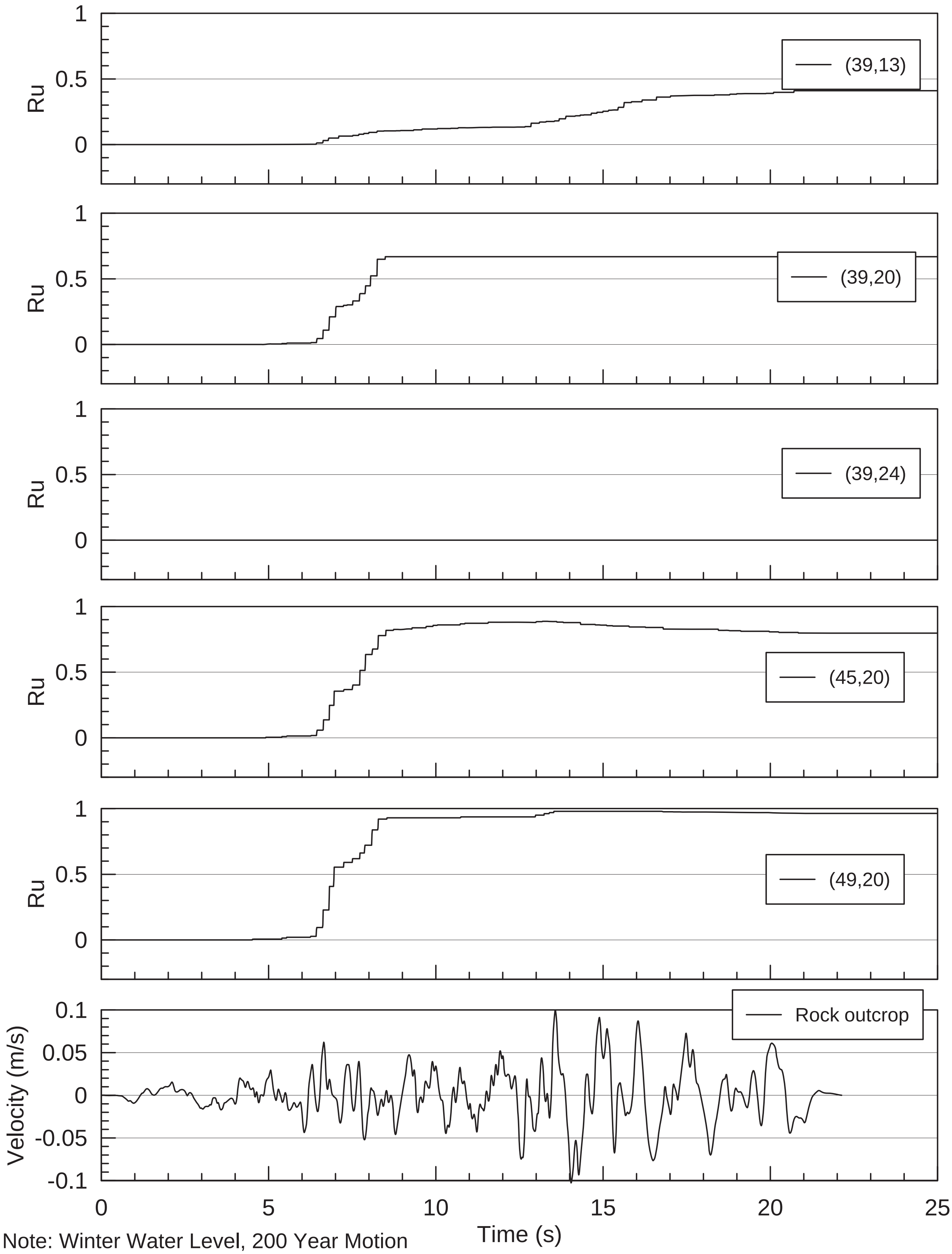
Excess PP Time Histories Set 1
Section at 1279+50, Reach L, Zone1

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE 3-17a

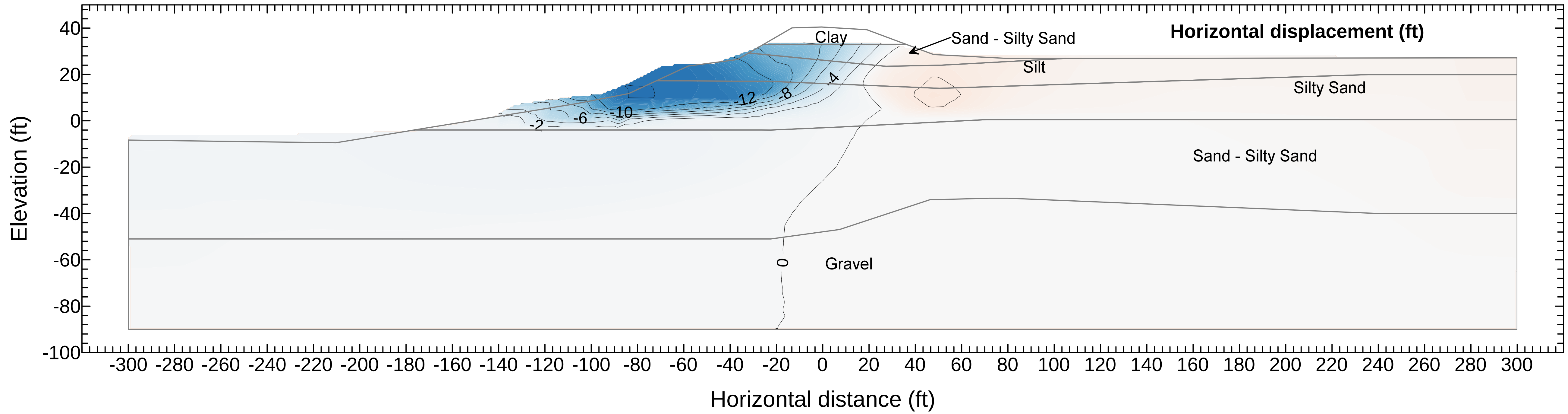
\\S021emc2\leveegeotecheval\Task Orders\TO-13 Seismic Vulnerability Assesment\Analysis\west sac model 1\FLAC\Analysis in Dec 2012\Winter WL - Rev\Dynamic_200 Yr RP\Plots_

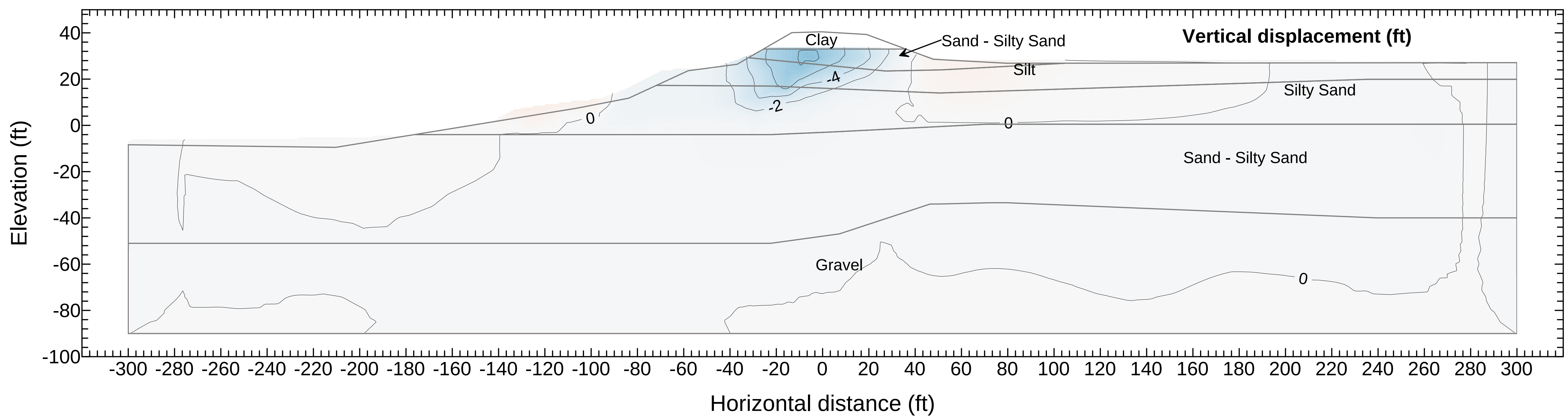


Note: Winter Water Level, 200 Year Motion

Department of Water Resources Divison of Flood Management Levee Evaluations Branch	URS	**Excess PP Time Histories Set 2** **Section at 1279+50, Reach L, Zone1** WEST SACRAMENTO STUDY AREA URBAN LEVEE EVALUATIONS	FIGURE 3-17b

\\S021emc2\leveegeotecheval\Task Orders\TO-13 Seismic Vulnerability Assesment\Analysis\west sac model 1\FLAC\Analysis in Dec 2012\Winter WL - Rev\Dynamic_200 Yr RP\Plots_





Department of Water Resources
Divison of Flood Management
Levee Evaluations Branch

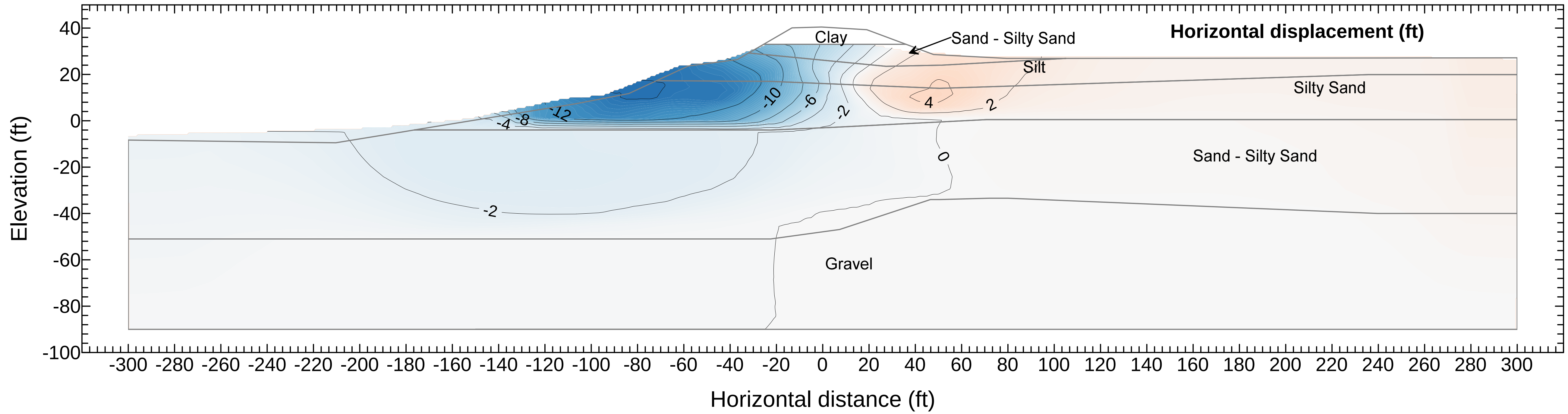
URS

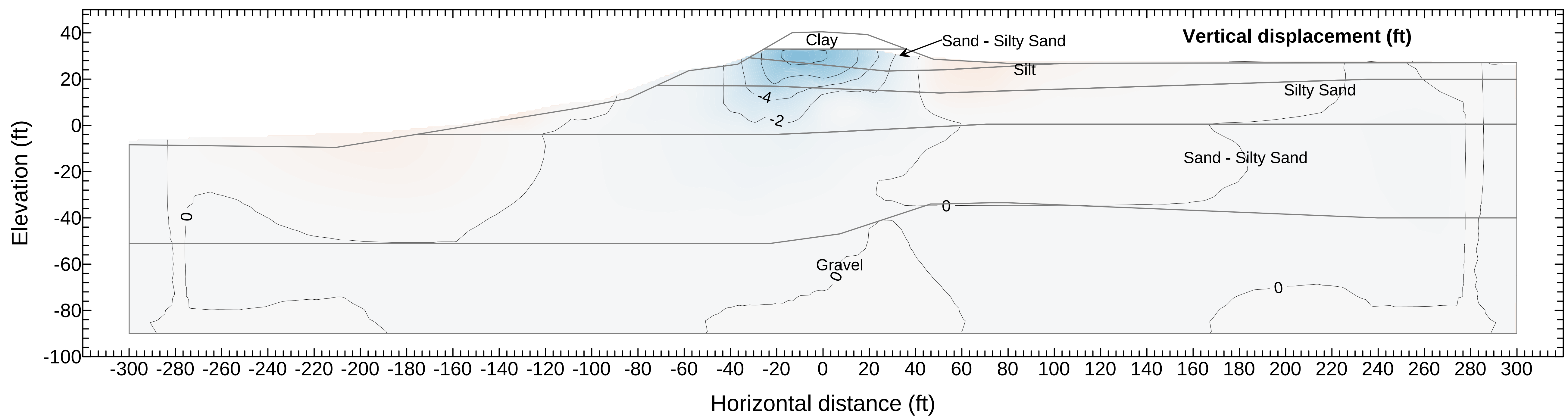
Displacement Contours
Analysis Section at 1279+50, Reach L, Zone1
200 Year Water Level, 200 Year Motion

WEST SACRAMENTO STUDY AREA
URBAN LEVEE EVALUATIONS

FIGURE 3-18a

//S021emc2/leveegeotecheval/Task Orders/TO-13 Seismic Vulnerability Assesment/Analysis/west sac model 1/FLAC/Analysis in Dec 2012/200 yr WL





Department of Water Resources
Divison of Flood Management
Levee Evaluations Branch

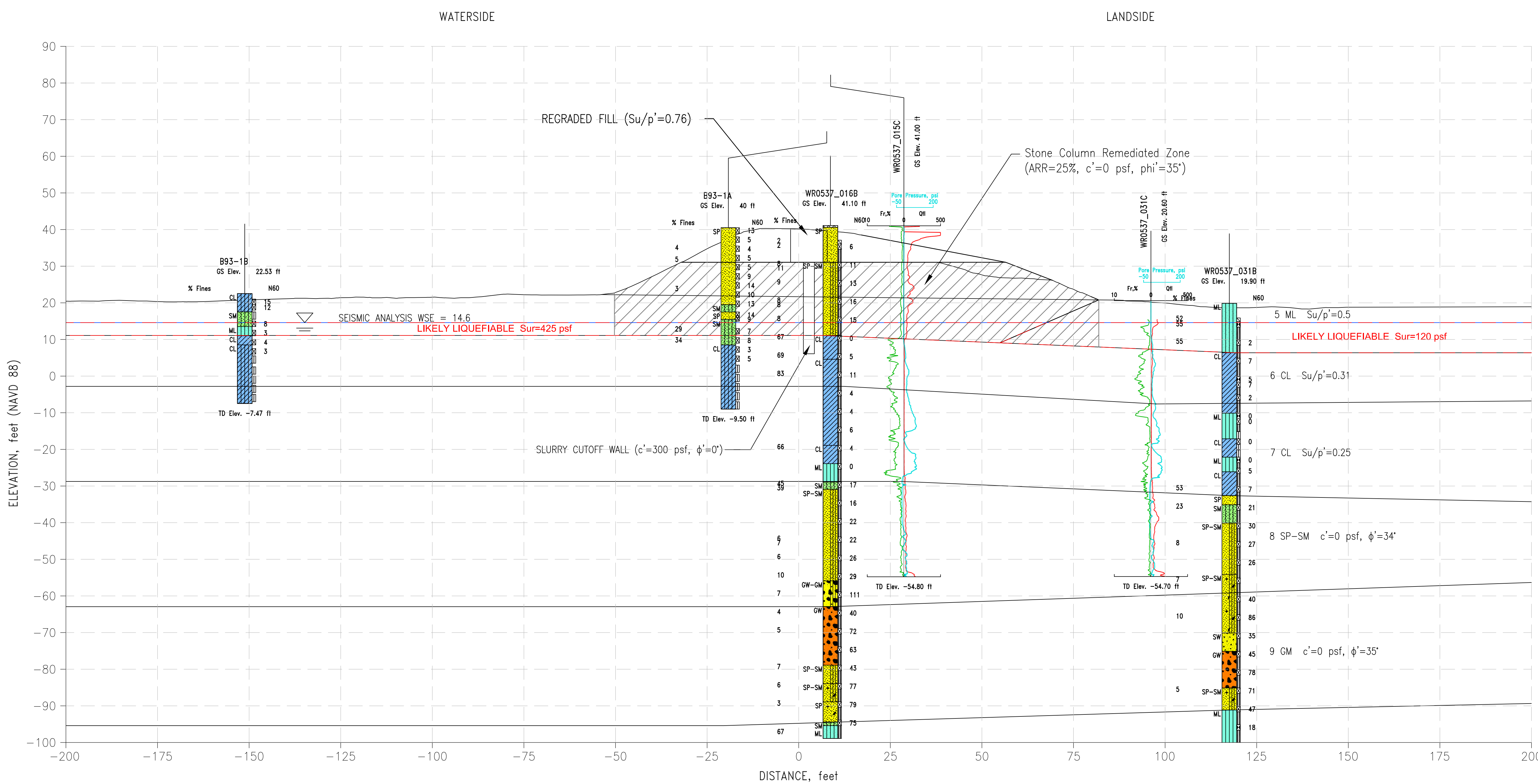
URS

Displacement Contours
Analysis Section at 1279+50, Reach L, Zone1
200 Year Water Level, 500 Year Motion

WEST SACRAMENTO STUDY AREA
URBAN LEVEE EVALUATIONS

FIGURE
3-18b

//S021emc2/leveegeotecheval/Task Orders/TO-13 Seismic Vulnerability Assesment/Analysis/west sac model 1/FLAC/Analysis in Dec 2012/200 yr WL



Department of Water Resources
Division of Flood Management

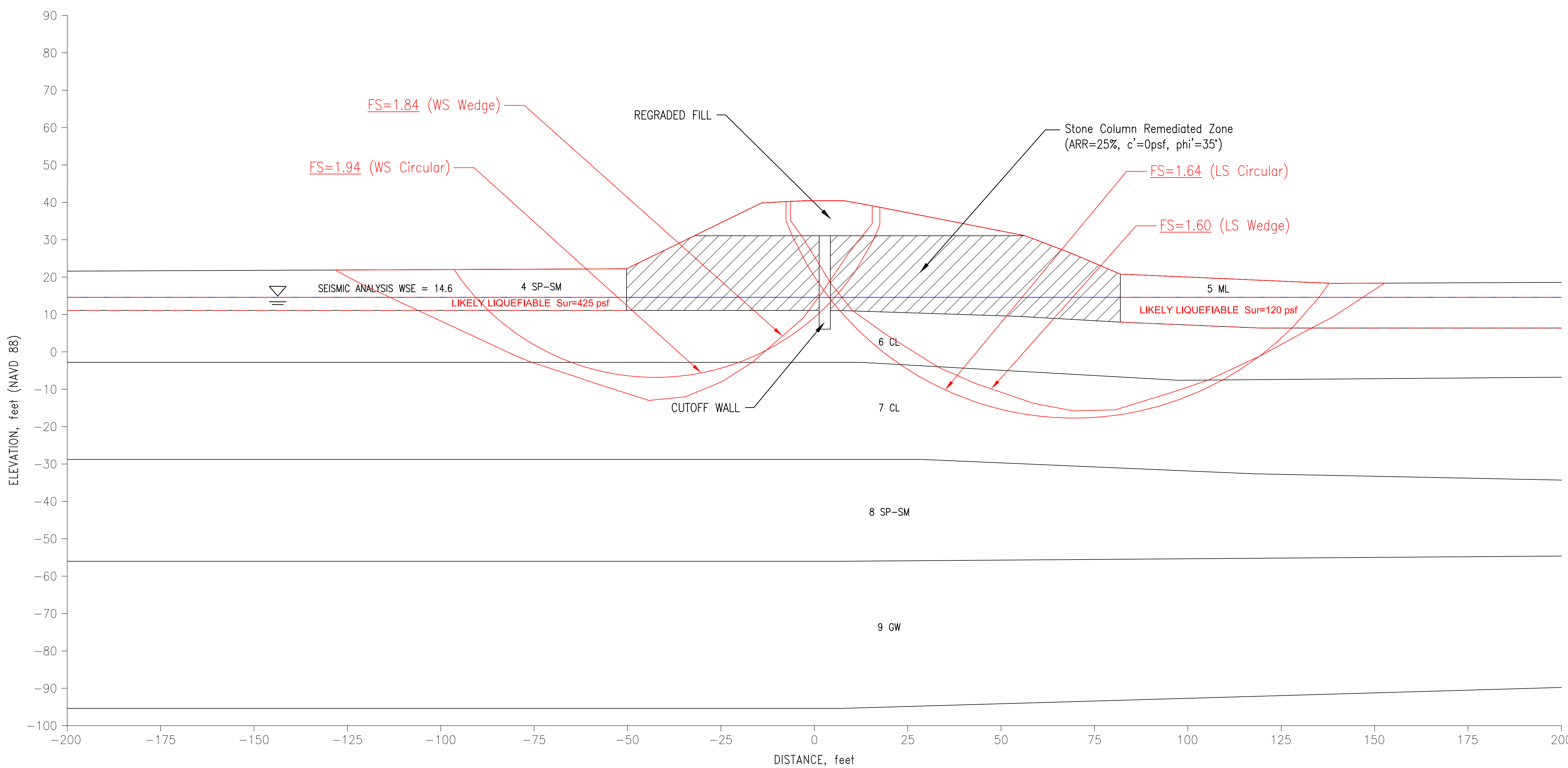
URS

CONTRACT NUMBER	PREPARED BY
4600008101	B. Choy
TASK ORDER	CHECKED BY
TO U13	K. Kanagalingam

WEST SACRAMENTO STUDY AREA
URBAN LEVEE EVALUATIONS

SEISMIC REMEDIATION
REACH D, ZONE 1
STATION 1091+29

FIGURE
3-19



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DRAWING: P:\Task Orders\TO-U02 Seismic Remediation\U02-2 Group 1 Assessment\W Sacramento\02 CADD\Drawings\04 Remediation Figures\FIGURE 3-20 Station 1091+29 TOU13.dwg

Department of Water Resources
Division of Flood Management

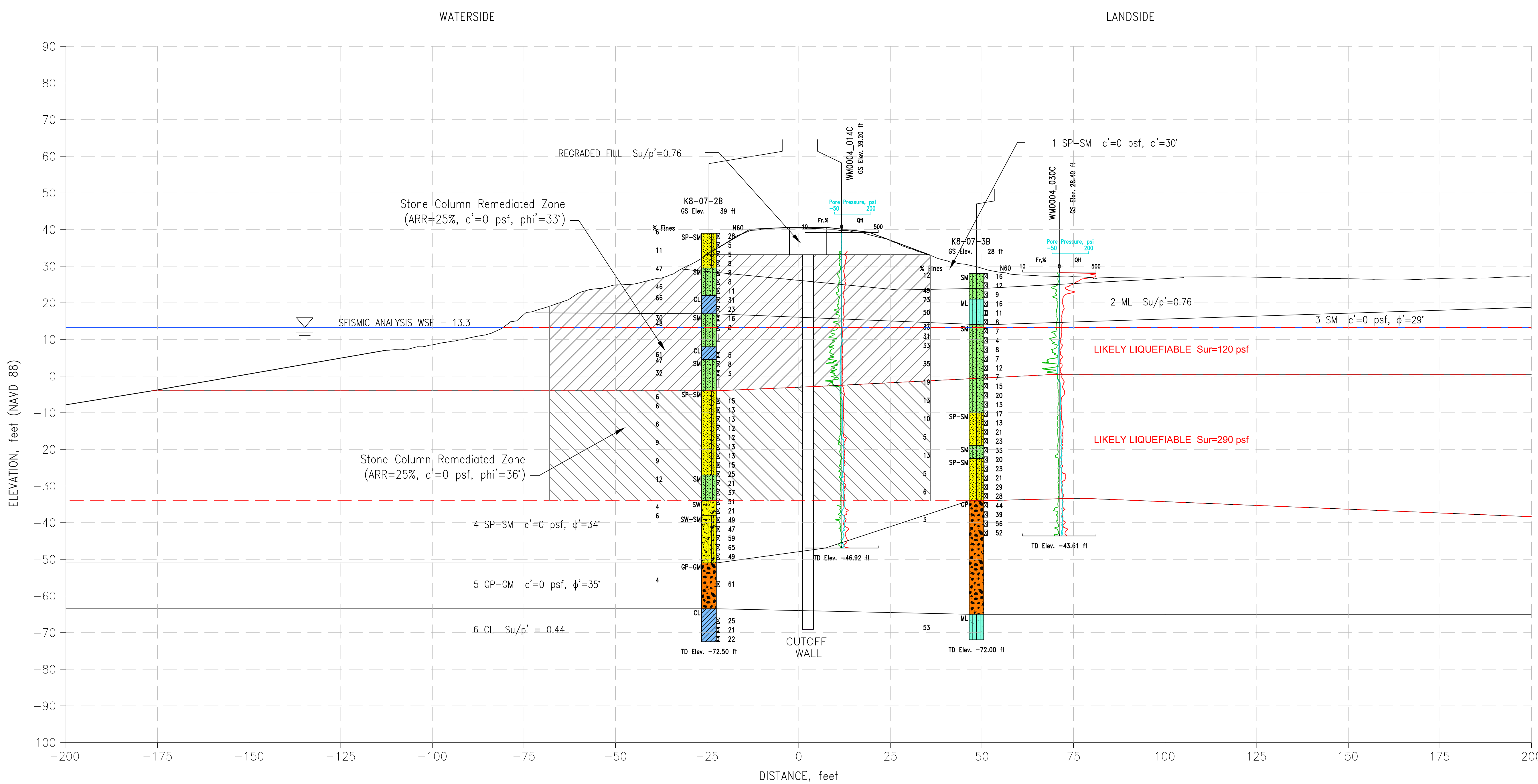
URS

CONTRACT NUMBER	PREPARED BY
4600008101	B. Choy
TASK ORDER	CHECKED BY
TO U13	K. Kanagalingam

WEST SACRAMENTO STUDY AREA
URBAN LEVEE EVALUATIONS

SEISMIC REMEDIATION ANALYSES RESULTS
REACH D, ZONE 1
STATION 1091+29

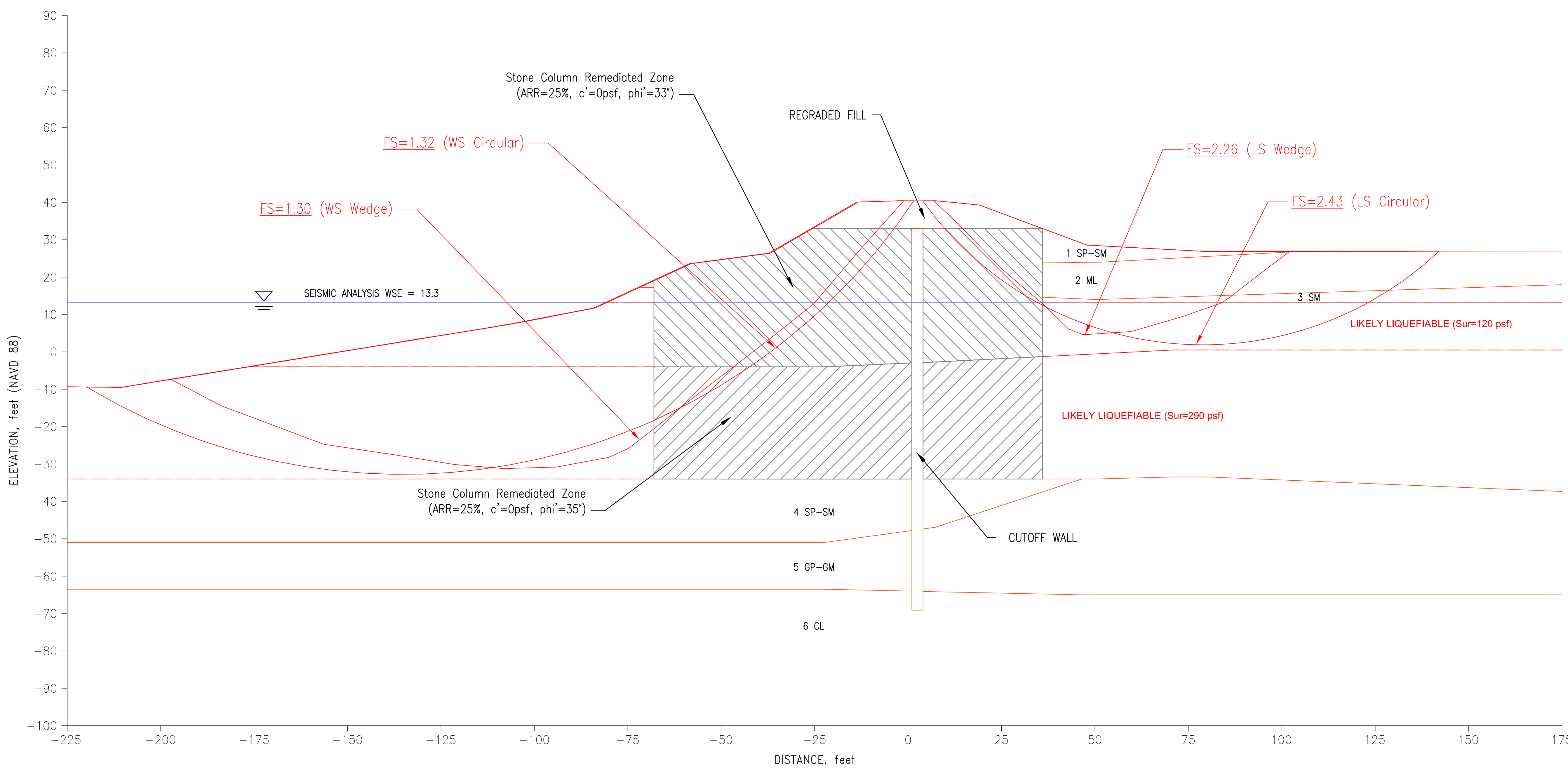
FIGURE
3-20



Department of Water Resources Division of Flood Management	URS	CONTRACT NUMBER 4600008101 TASK ORDER TO U13	PREPARED BY B. Choy CHECKED BY K. Kanagalingam	WEST SACRAMENTO STUDY AREA URBAN LEVEE EVALUATIONS	SEISMIC REMEDIATION REACH L, ZONE 1 STATION 1279+50

FIGURE
3-21

PLOT BY: KANAX_KANAGALINGAM - Nov 21, 2014 - 6:56:43pm
DRAWING: P:\Task Orders\TO-U02 Seismic Remediation\U02-2 Group 1 Assessment\W Sacramento\02 CADD\Drawings\04 Remediation Figures\FIGURE 3-22 Station 1279+50 TOU13.dwg



Department of Water Resources
Division of Flood Management

URS

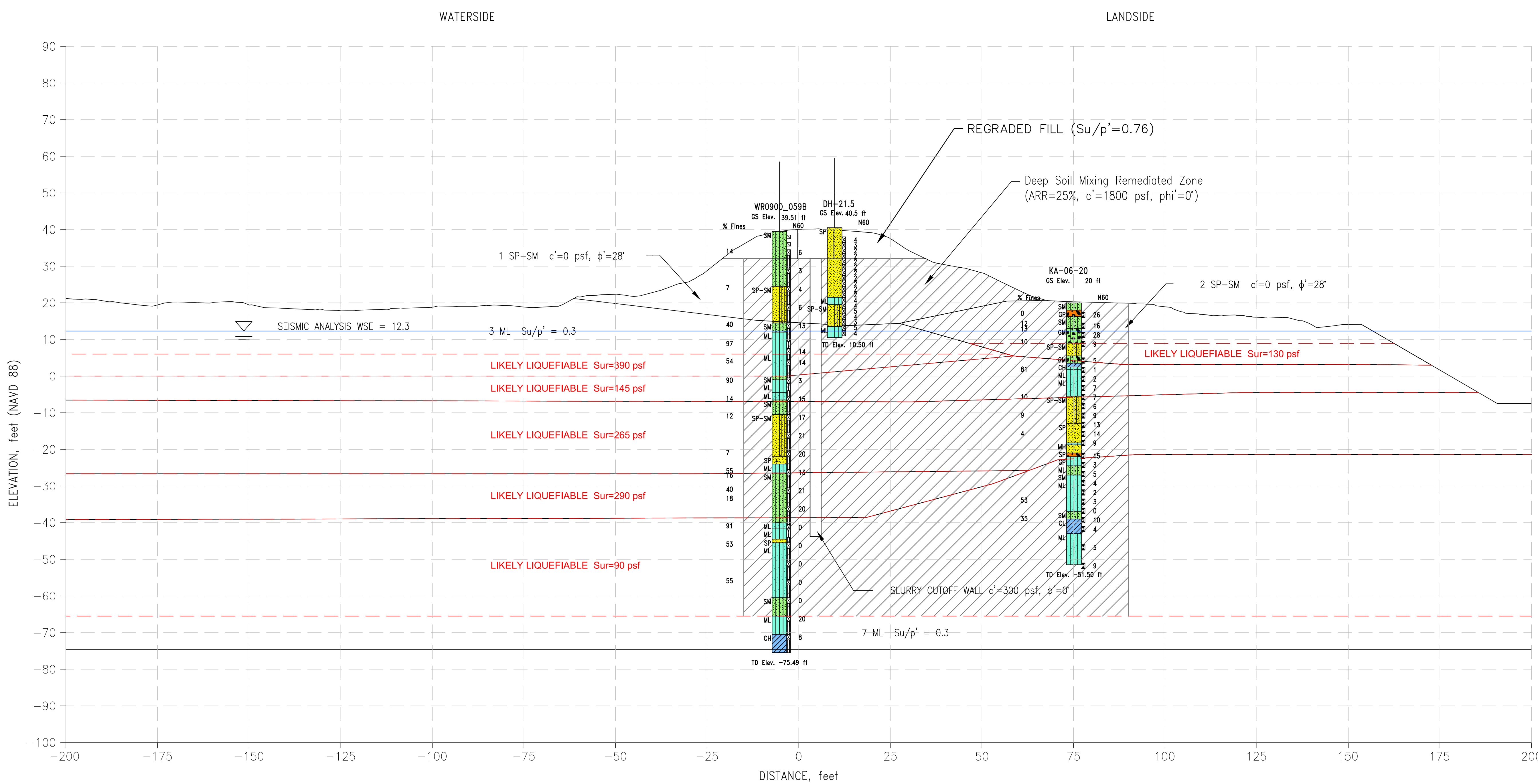
CONTRACT NUMBER 4600008101	PREPARED BY B. Choy
TASK ORDER TO U13	CHECKED BY K. Kanagalingam

WEST SACRAMENTO STUDY AREA
URBAN LEVEE EVALUATIONS

SEISMIC REMEDIATION ANALYSES RESULTS
REACH L, ZONE 1
STATION 1279+50

FIGURE
3-22

PLOT BY: KANAX_KANAGALINGAM - Nov 21, 2014 - 6:54:46pm
DRAWING: P:\Task Orders\TO-U02 Seismic Remediation\U02-2 Group 1 Assessment\W Sacramento\02 CADD\Drawings\01 Transverse X-sec\FIGURE 3-23 Station 1542+79 TOU13.dwg



Department of Water Resources
Division of Flood Management

URS

CONTRACT NUMBER 4600008101	PREPARED BY B. Choy
TASK ORDER TO U13	CHECKED BY K. Kanagalingam

WEST SACRAMENTO STUDY AREA
URBAN LEVEE EVALUATIONS

SEISMIC REMEDIATION
REACH P, ZONE 2
STATION 1542+79

FIGURE 3-23

PLOT BY: KANAX_KANAGALINGAM - Nov 21, 2014 - 6:58:48pm
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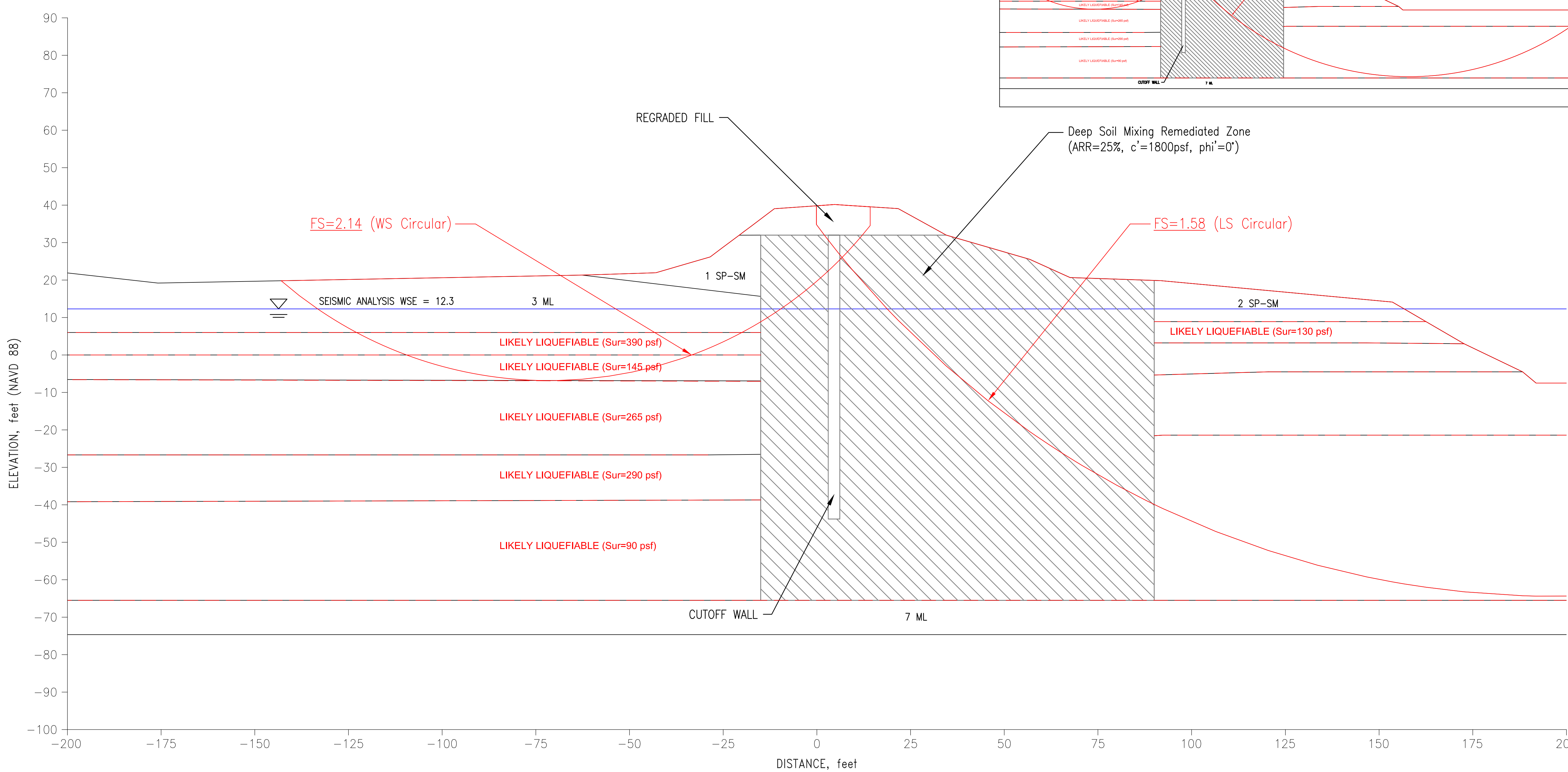
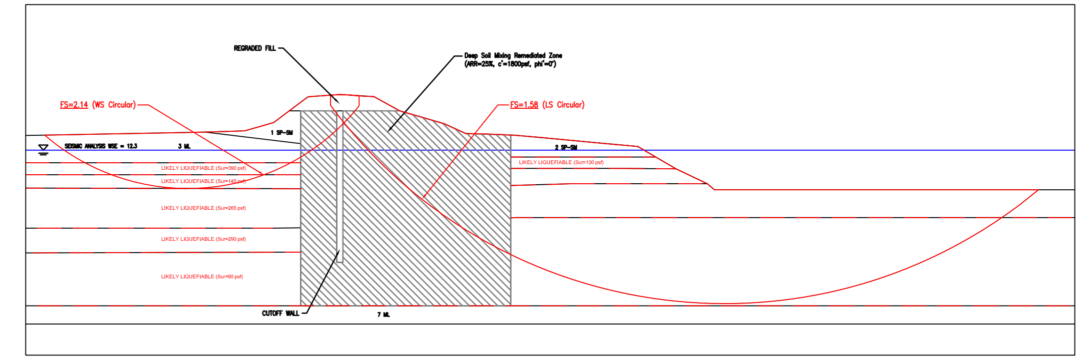




Department of Water Resources
Division of Flood Management

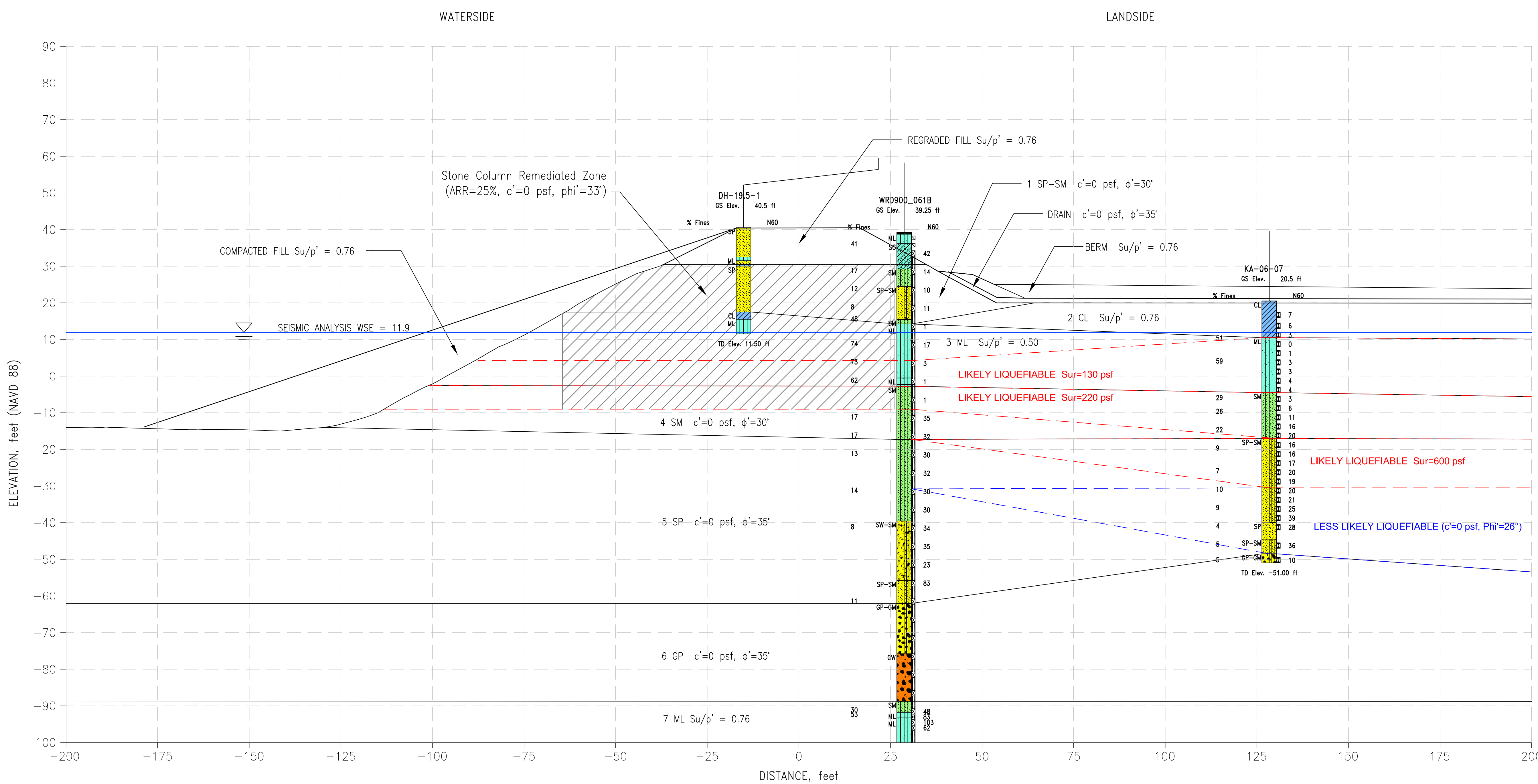
URS

CONTRACT NUMBER 4600008101	PREPARED BY B. Choy
TASK ORDER TO U13	CHECKED BY K. Kanagalingam

WEST SACRAMENTO STUDY AREA
URBAN LEVEE EVALUATIONS

SEISMIC REMEDIATION ANALYSES RESULTS
REACH P, ZONE 2
STATION 1542+79

FIGURE
3-24



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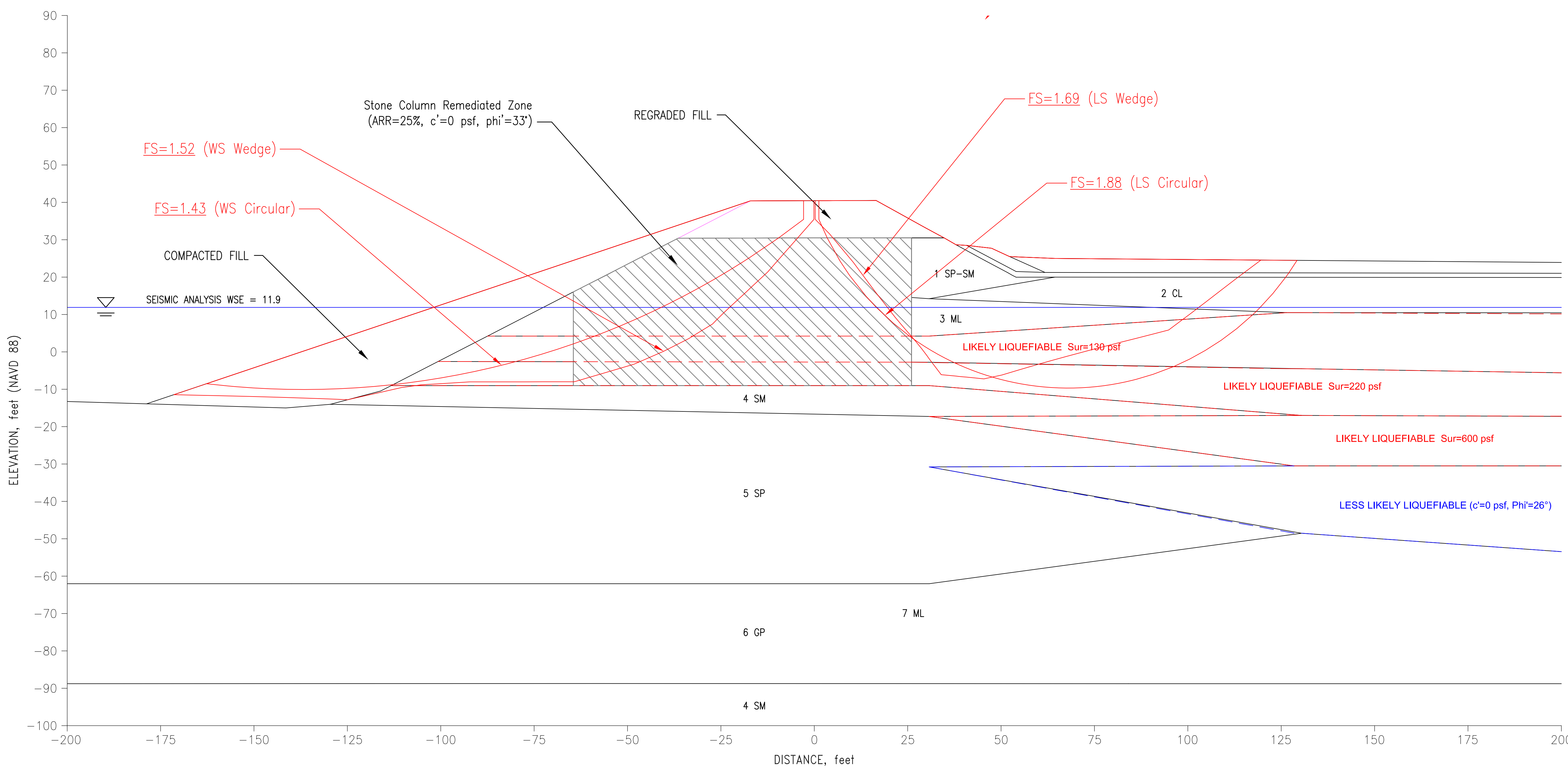
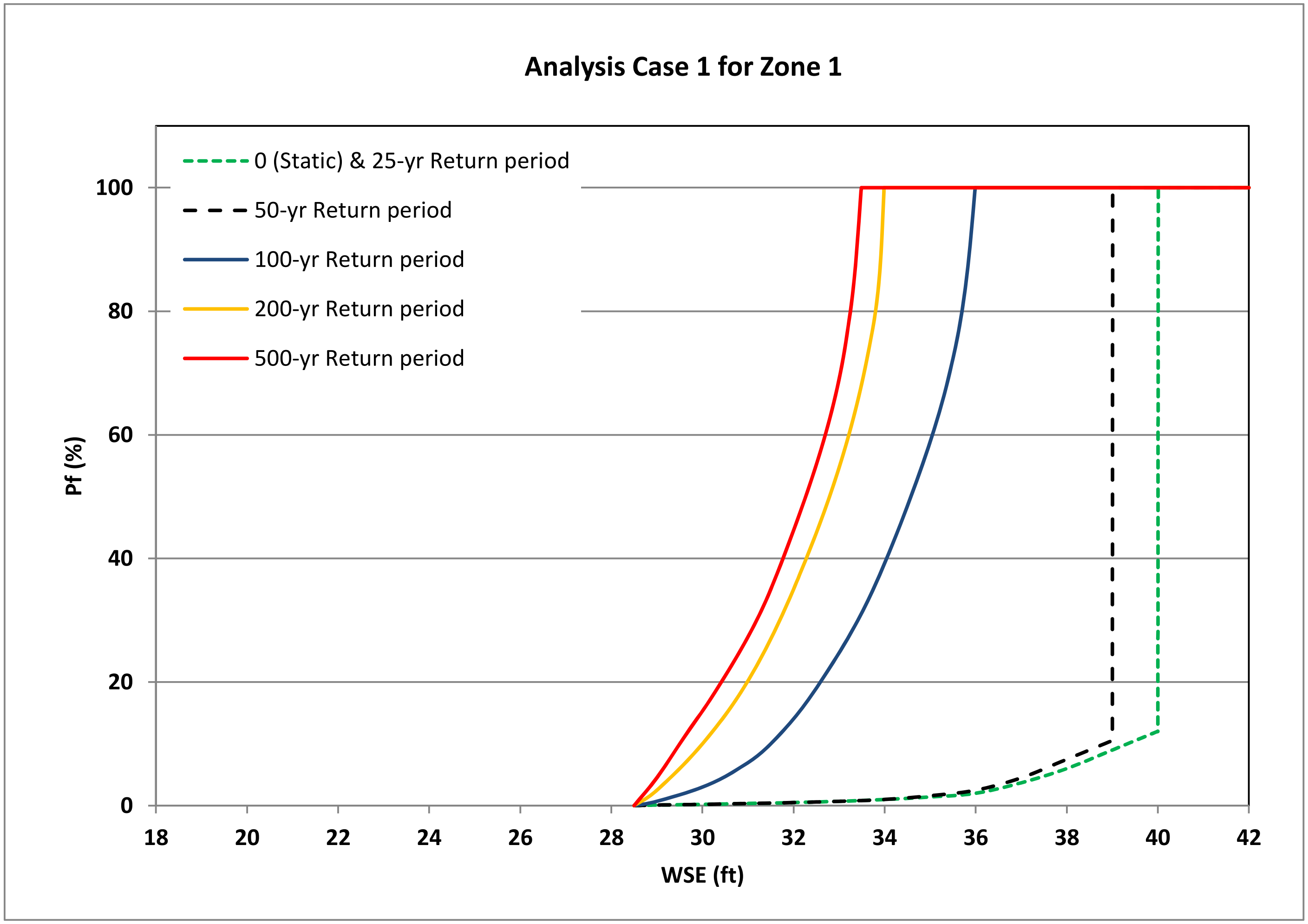
Department of Water Resources Division of Flood Management	URS	CONTRACT NUMBER 4600008101 TASK ORDER TO U13	PREPARED BY B. Choy CHECKED BY K. Kanagalingam	WEST SACRAMENTO STUDY AREA URBAN LEVEE EVALUATIONS	SEISMIC REMEDIATION REACH S, ZONE 2 STATION 1670+94

FIGURE
3-25

PLOT BY: KANAX_KANAGALINGAM - Nov 21, 2014 - 7:00:29pm
DRAWING: P:\Task Orders\TO-U02 Seismic Remediation\U02-2 Group 1 Assessment\W Sacramento\02 CADD\Drawings\04 Remediation Figures\FIGURE 3-26 Station 1670+94 TOU13.dwg



Department of Water Resources Division of Flood Management	URS	CONTRACT NUMBER 4600008101	PREPARED BY B. Choy	WEST SACRAMENTO STUDY AREA URBAN LEVEE EVALUATIONS	SEISMIC REMEDIATION ANALYSES RESULTS REACH S, ZONE 2 STATION 1670+94	FIGURE 3-26
		TASK ORDER TO U13	CHECKED BY K. Kanagalingam			



Department of Water Resources
Divison of Flood Management
Levee Evaluations Branch

URS

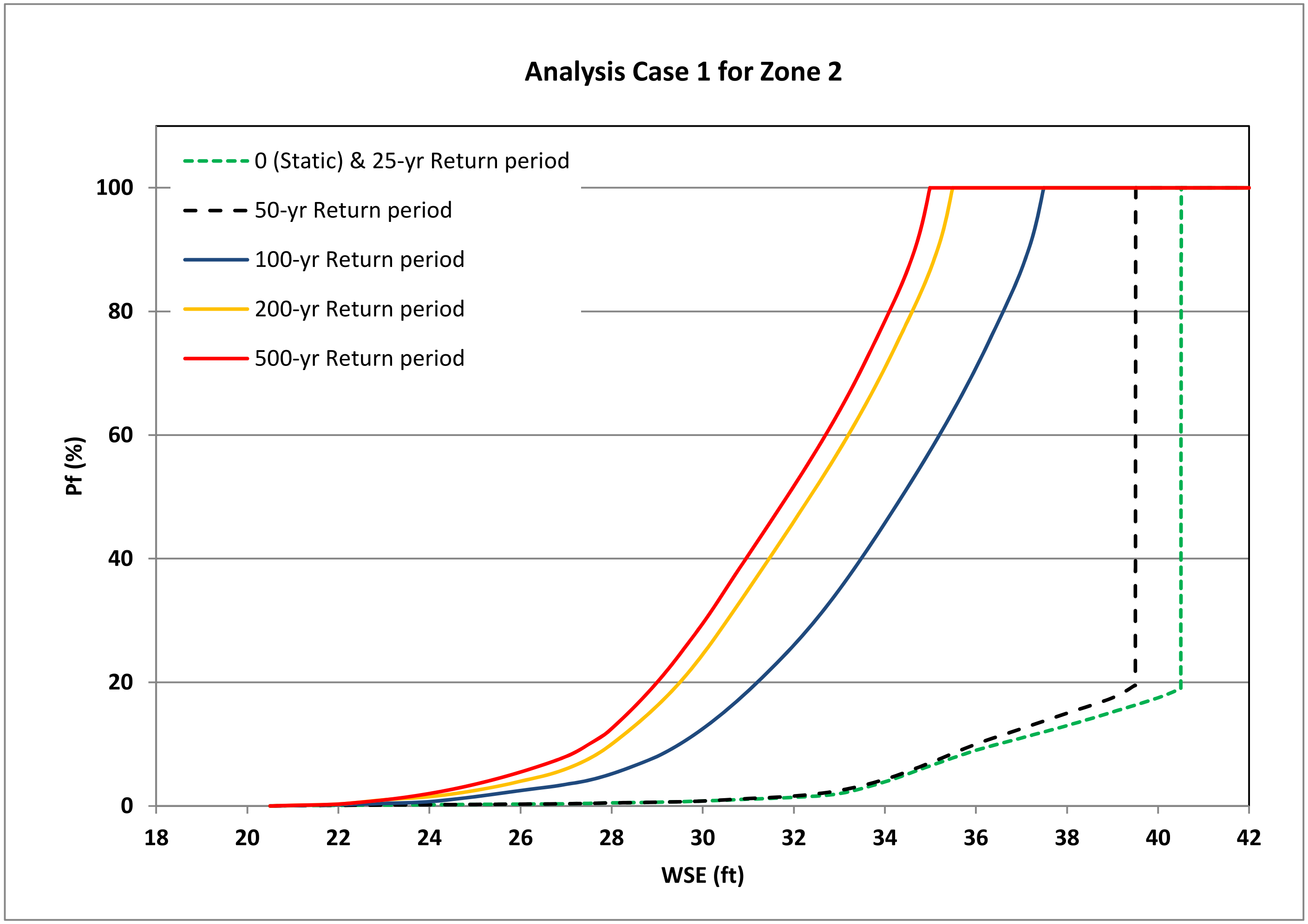
CONDITONAL PROBABILITY OF FAILURE (FLOODING) FUNCTION FOR ANALYSIS CASE 1
INDEX POINT 1, ZONE 1

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE 3-27

P:\Task Orders\TO-U13 Seismic Risk\08 Task Groups\08_2014 Updates\05_Report\post-ICB comments\Figures\Revised Originals\Figure 3-27 Zone 1 Analysis Case 1.grf



Department of Water Resources
Divison of Flood Management
Levee Evaluations Branch

URS

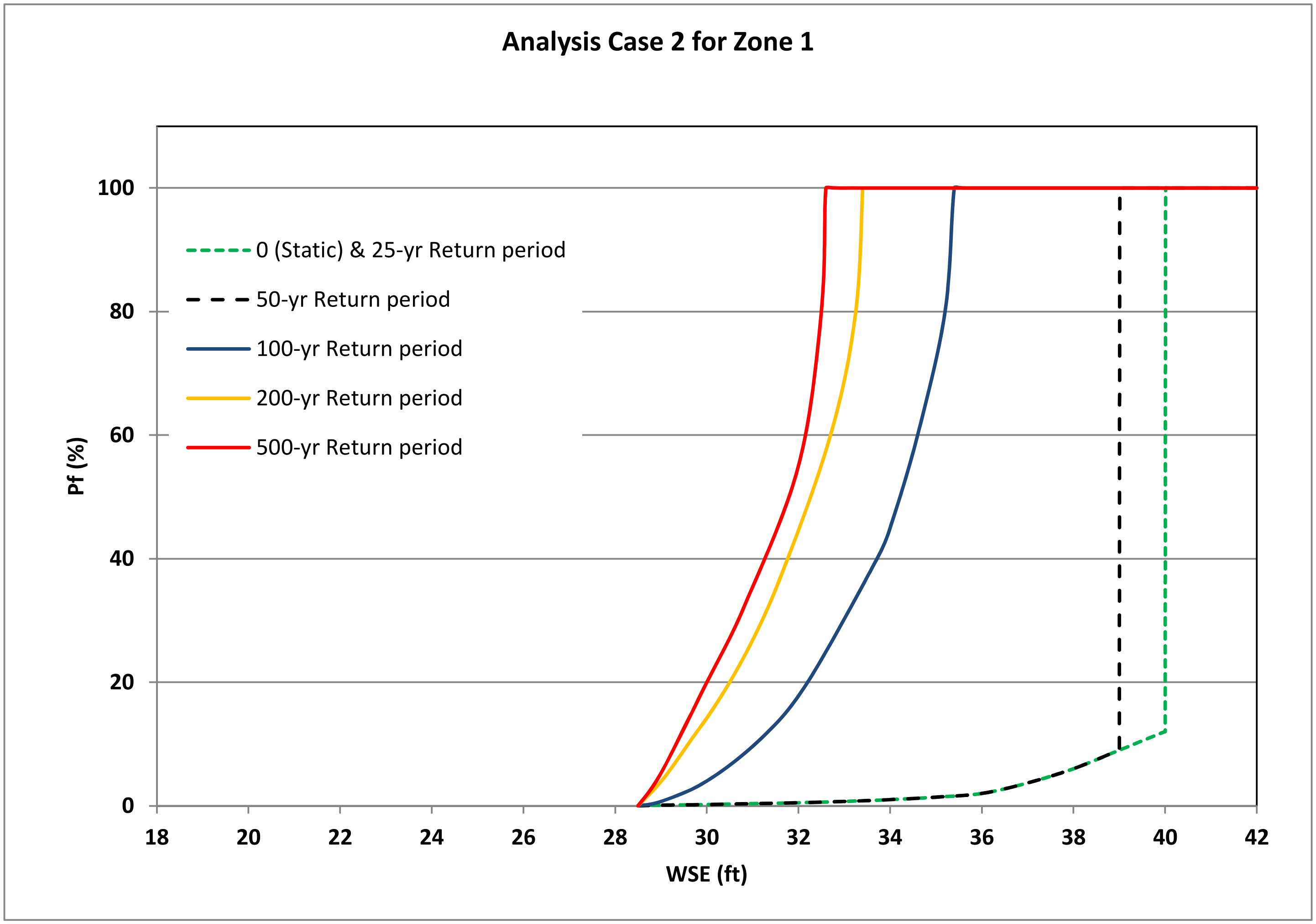
CONDITONAL PROBABILITY OF FAILURE (FLOODING) FUNCTION FOR ANALYSIS CASE 1
INDEX POINT 2, ZONE 2

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE 3-28

P:\Task Orders\TO-U13 Seismic Risk\08 Task Groups\08_2014 Updates\05_Report\post-ICB comments\Figures\Revised Originals\Figure 3-28 Zone 2 Analysis Case 1.grf



Department of Water Resources
Divison of Flood Management
Levee Evaluations Branch

URS

CONDITONAL PROBABILITY OF FAILURE (FLOODING) FUNCTION FOR ANALYSIS CASE 2
INDEX POINT 1, ZONE 1

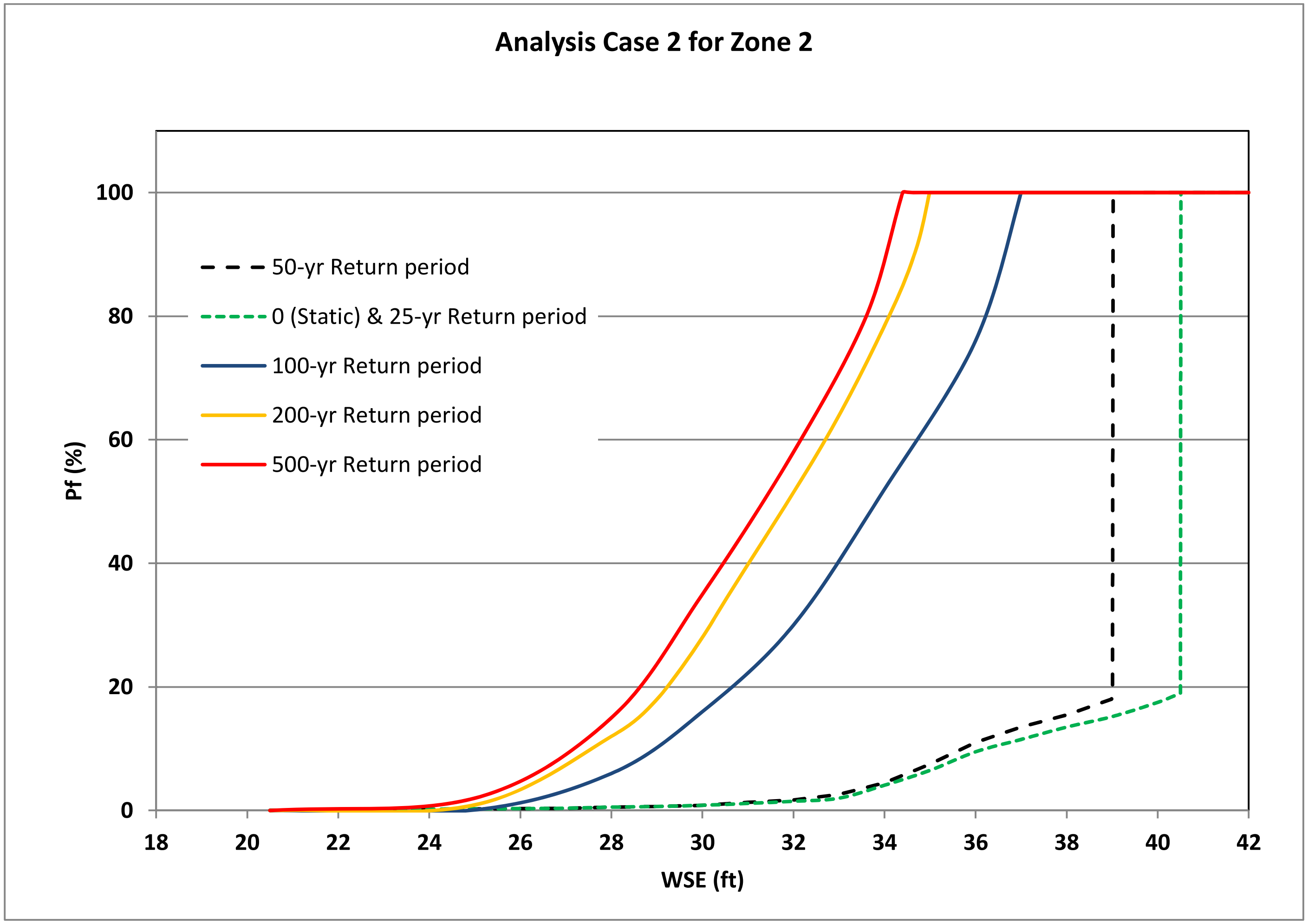
WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE

3-29

P:\Task Orders\TO-U13 Seismic Risk\08 Task Groups\08_2014 Updates\05_Report\post-ICB comments\Revisions_04102015\Figures\Revised Originals\Figure 3-29 Zone 1 Analysis Case 2_.grf



Department of Water Resources
Divison of Flood Management
Levee Evaluations Branch

URS

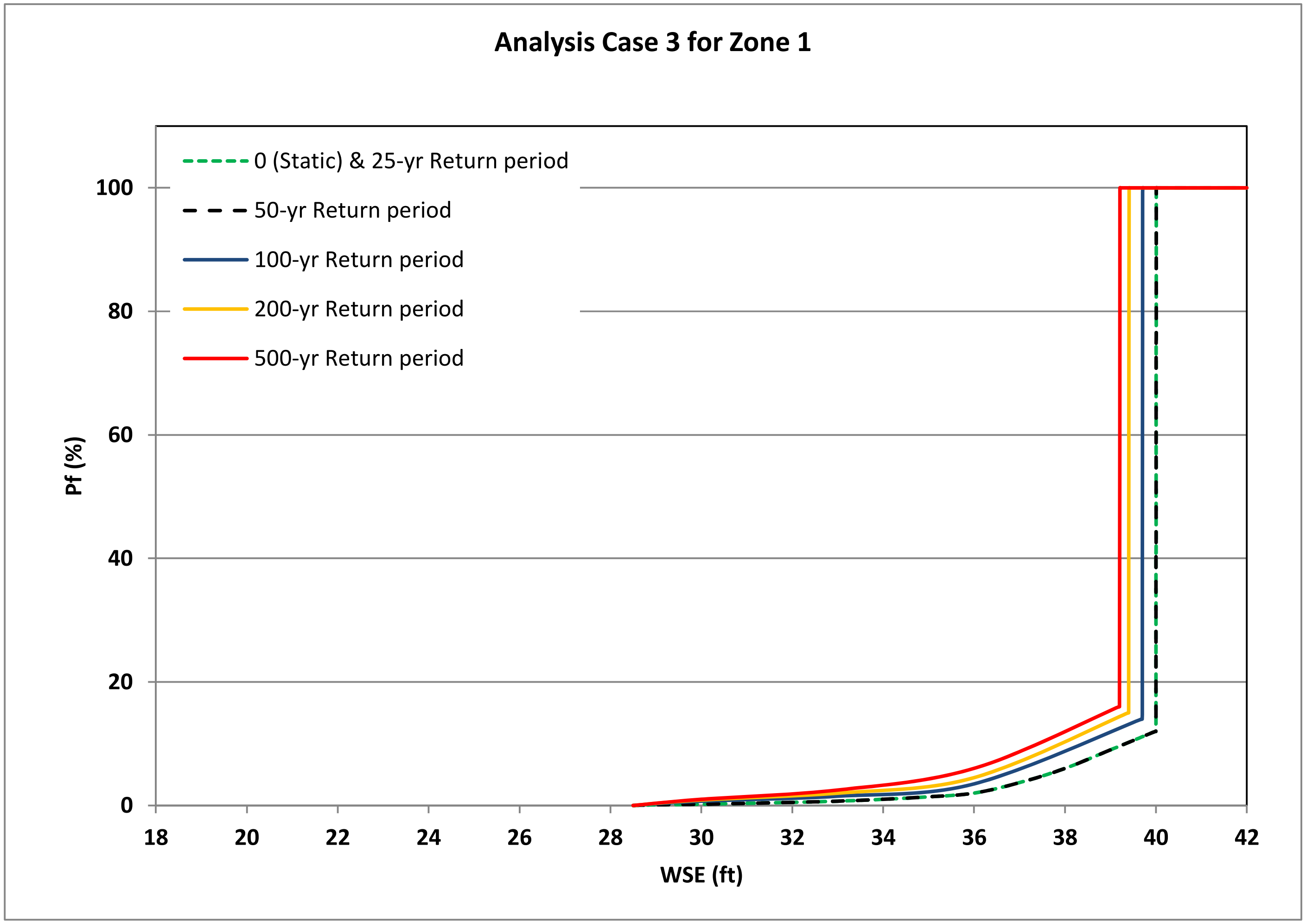
CONDITONAL PROBABILITY OF FAILURE (FLOODING) FUNCTION FOR ANALYSIS CASE 2 INDEX POINT 2, ZONE 2

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE 3-30

P:\Task Orders\TO-U13 Seismic Risk\08 Task Groups\08_2014 Updates\05_Report\post-ICB comments\Revisions_04102015\Figures\Revised Originals\Figure 3-30 Zone 2 Analysis Case 2_.grf



Department of Water Resources
Divison of Flood Management
Levee Evaluations Branch

URS

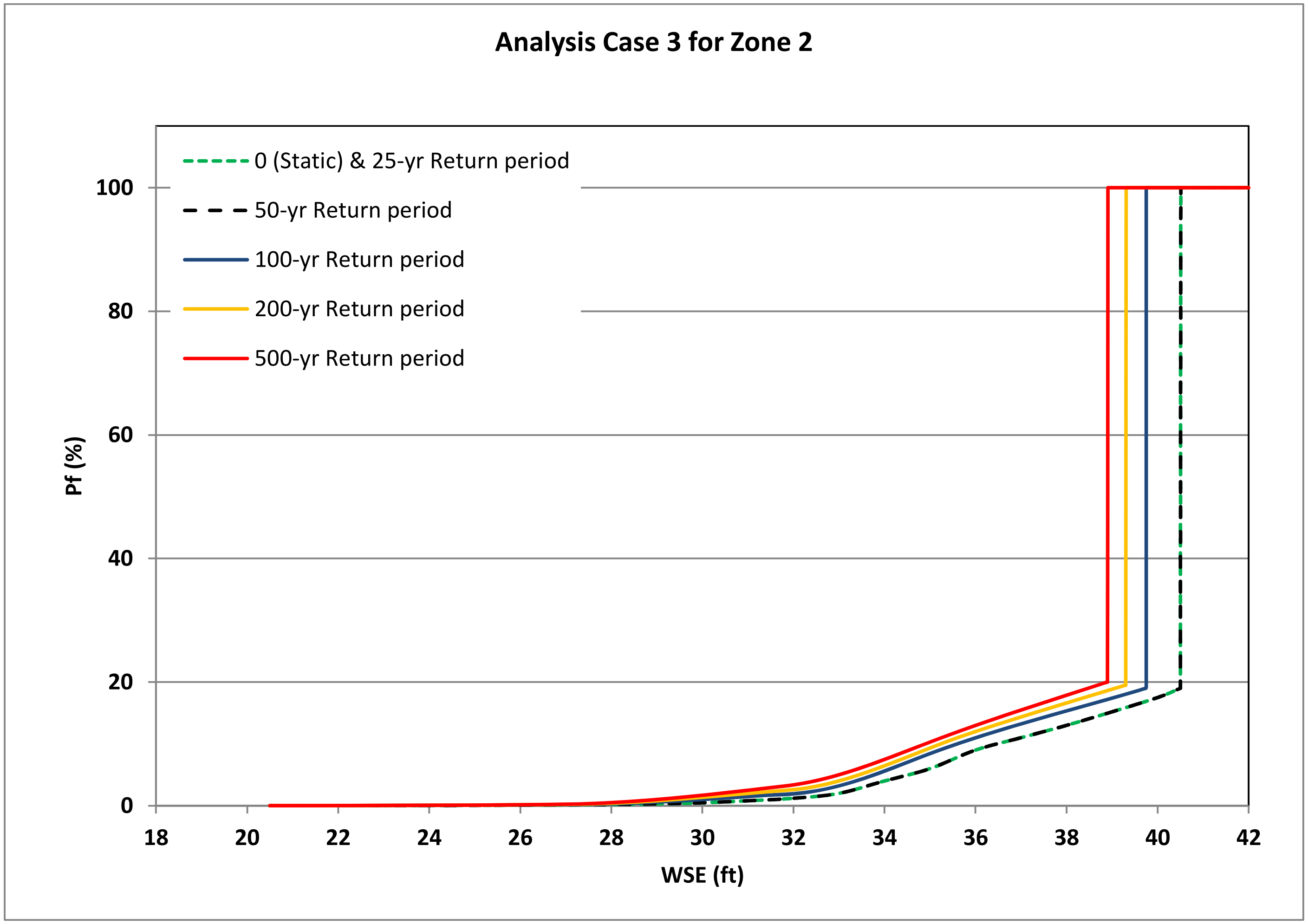
CONDITONAL PROBABILITY OF FAILURE (FLOODING) FUNCTION FOR ANALYSIS CASE 3
INDEX POINT 1, ZONE 1

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE 3-31

P:\Task Orders\TO-U13 Seismic Risk\08 Task Groups\08_2014 Updates\05_Report\post-ICB comments\Revisions_04102015\Figures\Revised Originals\Figure 3-31 Zone 1 Analysis Case 3_.grf



Department of Water Resources
Divison of Flood Management
Levee Evaluations Branch

URS

CONDITONAL PROBABILITY OF FAILURE (FLOODING) FUNCTION FOR ANALYSIS CASE 3
INDEX POINT 2, ZONE 2

WEST SACRAMENTO STUDY AREA

URBAN LEVEE EVALUATIONS

FIGURE 3-32

P:\Task Orders\TO-U13 Seismic Risk\08 Task Groups\08_2014 Updates\05_Report\post-ICB comments\Revisions_04102015\Figures\Revised Originals\Figure 3-32 Zone 2 Analysis Case 3_.grf

APPENDIX A

Meeting Notes from Seismic Expert's Meeting

URS

Cost-Benefit Study of West Sacramento

Levees under Seismic Hazards (TO U13)

Seismic Expert's Opinion on Probability of Flooding

INTRODUCTION

A meeting was held at the URS Sacramento Office on June 10, 2014 to obtain seismic expert's opinion on probability of flooding for West Sacramento levee subject to various seismic and water loadings. Prior to the meeting, a document summarizing project background, the type of analyses performed for various seismic and water loads, general framework for developing seismic fragility curves and objective of the meeting was sent out to expert panel members.

The meeting was attended by the following personnel: Loren Murray (facilitator, URS), Les Harder (voting member, HDR), Robert Green (voting member, URS), Lelio Mejia (voting member, attended a portion of the meeting, URS), Richard Millet (voting member, URS), Arul Rajendram (voting member, URS), Ariya Balakrishnan (nonvoting member, DWR), Vlad Perlea (nonvoting member, USACE), Mary Perlea (nonvoting member, USACE), Kanax Thangalingam (nonvoting member, URS), and Sujan Punyamurthula (attended only a portion of the meeting, nonvoting member, URS). The meeting agenda included the following:

- Introductions
- Presentations
    - Project overview
    - Meeting Objective
    - Seismic Fragility Development Framework
    - Analyses and Results
- Discussion
- Break
- Expert's opinion voting #1
- Working lunch: continuation of Expert's opinion voting #1
- Discussion of results from voting #1
- Closing

PROJECT BACKGROUND

DWR initiated a seismic hazard study of the West Sacramento levees to better understand seismic deficiencies of the levees. Specifically, the current study (TOU13) assesses the incremental benefit of seismically remediating “high” seismic vulnerability levee segments beyond the static remediation for the 200-year flood level. This study also assesses the cost-benefit ratios for repairing the liquefaction-induced damaged levees back to the pre-earthquake conditions**.**

For the purpose of the cost-benefit study, the West Sacramento region is divided into two impact zones as shown in Figure 1. The expected annual damage for each impact zone is calculated at a selected index point (as identified in Figure 1). The seismic fragility for the selected index point though was developed considering an analysis cross section that most representative for the impact zone. Seismic fragility curves (represented as a function of probability of flooding versus water surface elevation) were developed for three different analysis cases. The analysis cases considered are as follows:

- Analysis Case 1: without-project
- Analysis Case 2: post-earthquake repairs (without-project with post-earthquake repairs).
- Analysis Case 3: with project (seismic fixes to levee)

PROBABILITY OF FLOODING FOR DIFFERENT ANALYSIS SCENARIOS

Analysis Case 1

The seismic deformation analysis for this scenario was performed using FLAC and published correlations for lateral spreading. The seismic vertical deformation as a function of water surface elevation for three seismic levels (500-, 200-, and 100-year return periods) was presented to the panel members. The experts used the seismic deformation values and their experience to express their opinion on probability of flooding for different water surface elevations. The resulting seismic fragility curves for zones 1 and 2 are depicted in Figures 2 and 3, respectively.

Analysis Case 2

For Analysis Scenario 2, the experts used the seismic deformation values presented for Analysis Scenario 1 and their experience to express their opinion on probability of flooding for different water surface elevations. The resulting seismic fragility curves for zones 1 and 2 are depicted in Figures 4 and 5, respectively.

Analysis Case 3

The seismic deformation analysis for this scenario was performed using Newmark-type deformation analyses as presented in Guidance Document Version 14 (URS, 2014). The seismic vertical deformations were calculated for different water surface elevations and three seismic levels (500-, 200-, and 100-year return periods), and used to develop the seismic fragility curves. The resulting seismic fragility curves for zones 1 and 2 are depicted in Figures 6 and 7, respectively.

FIGURES

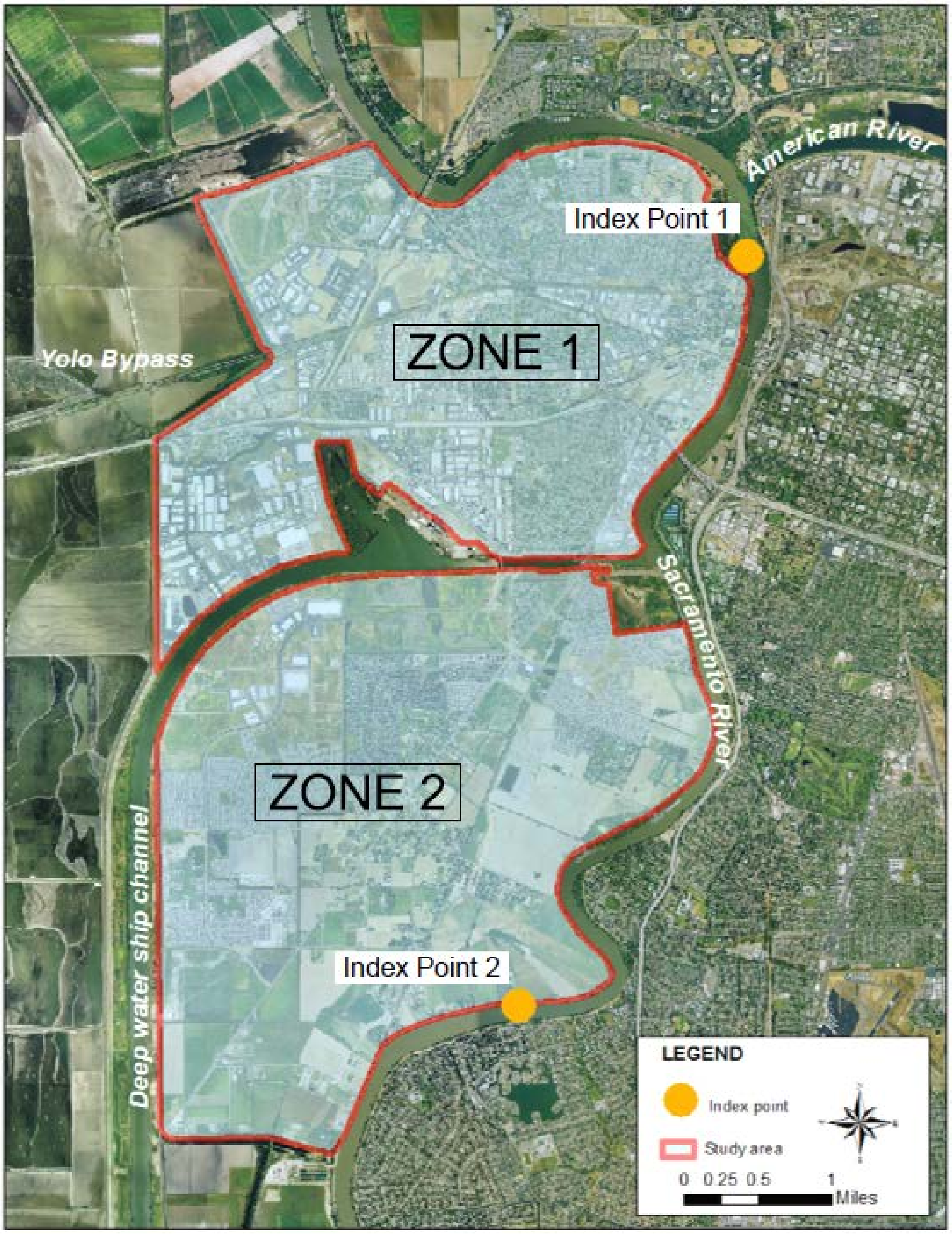


Figure 1 Impact Zones for Cost-Benefit Study

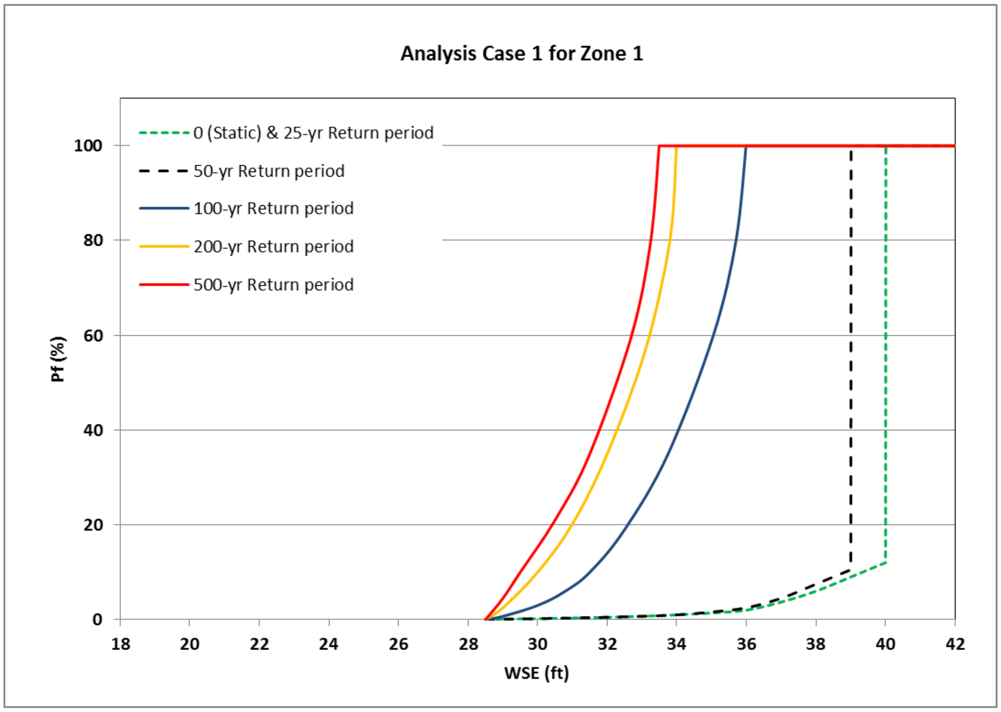


Figure 2 Seismic Fragility Curve for Case 1 – Zone 1

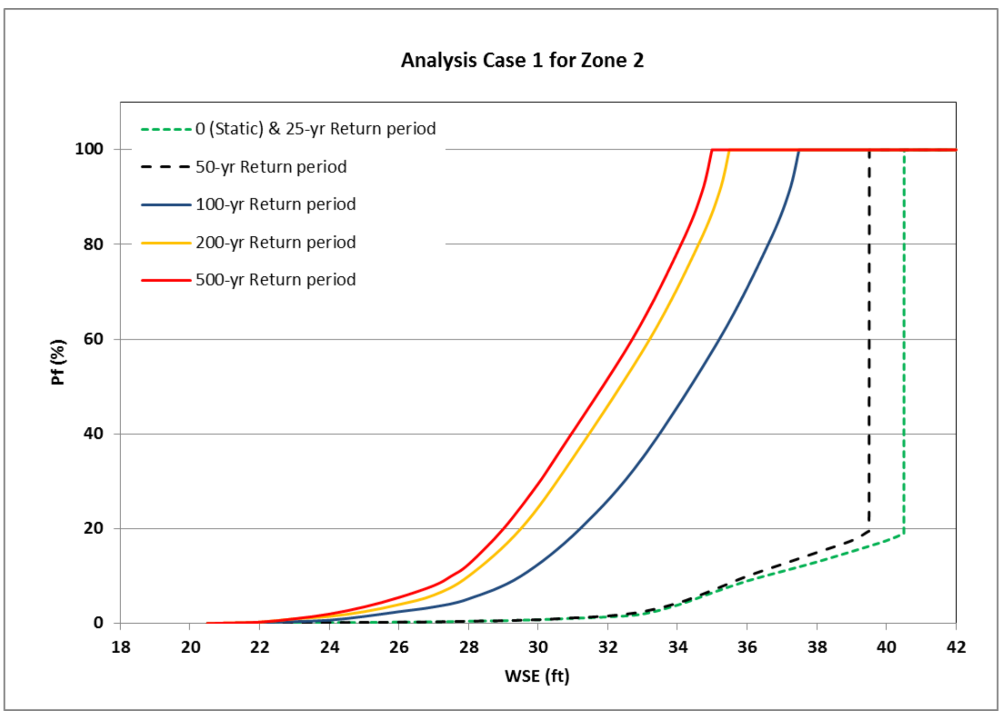


Figure 3 Seismic Fragility Curve for Case 1 – Zone 2

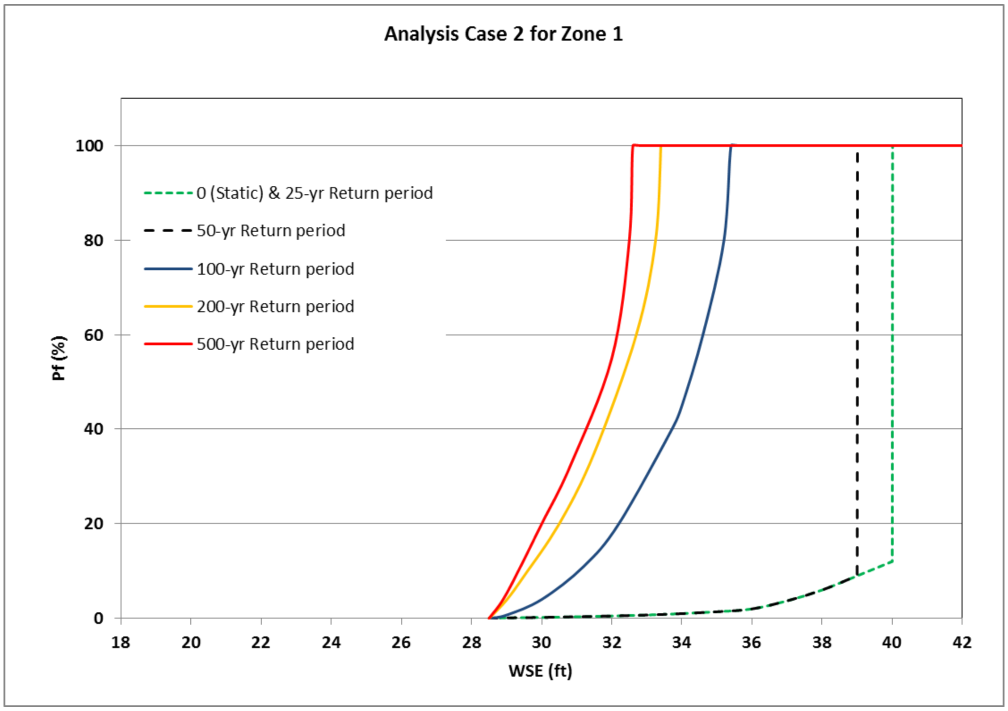


Figure 4 Seismic Fragility Curve for Case 2 – Zone 1

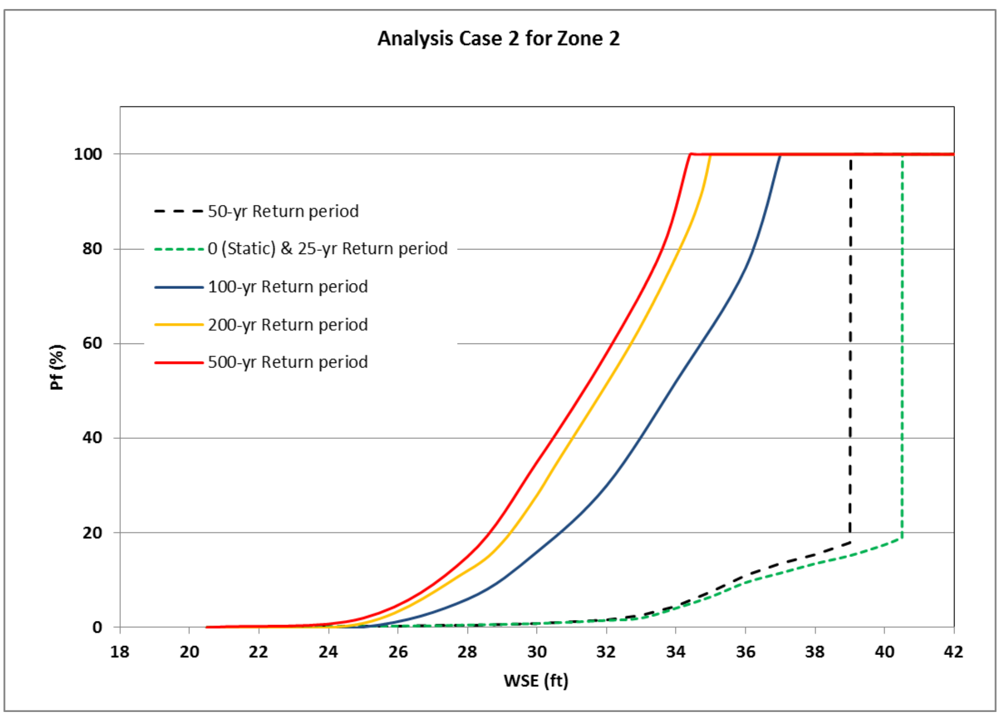


Figure 5 Seismic Fragility Curve for Case 2 – Zone 2

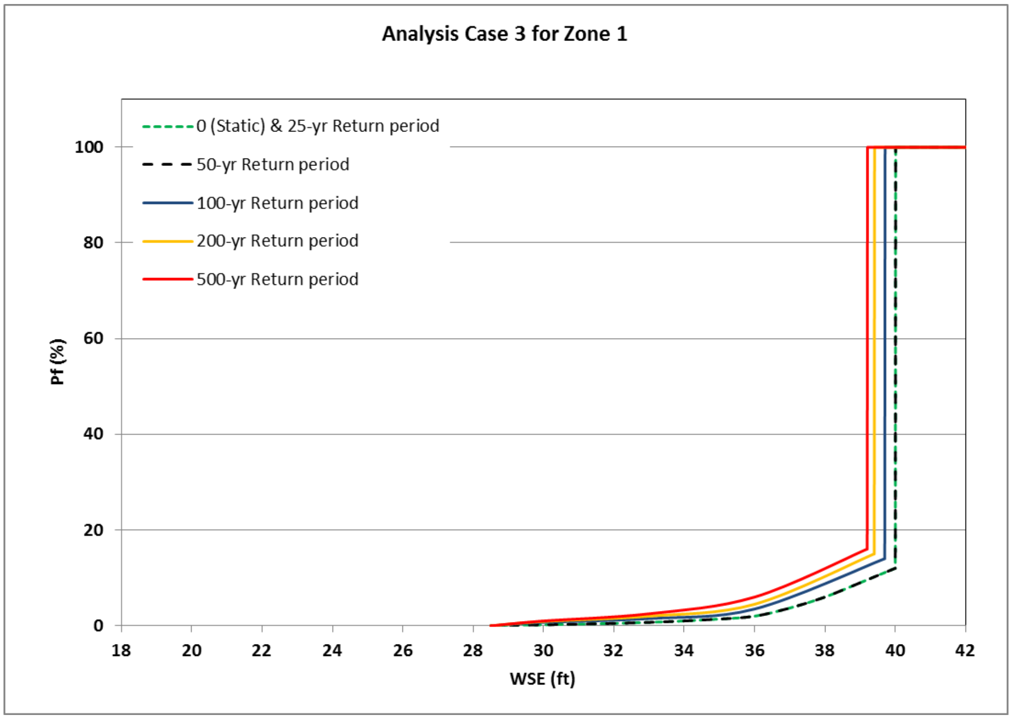


Figure 6 Seismic Fragility Curve for Case 3 – Zone 1

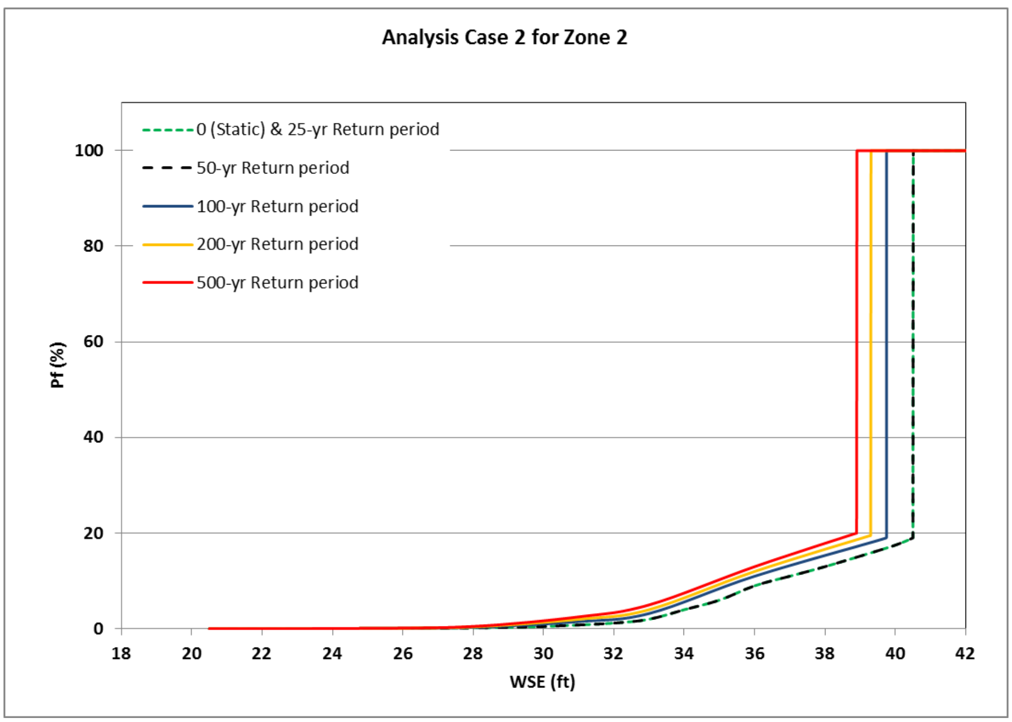


Figure 7 Seismic Fragility Curve for Case 3 – Zone 2

APPENDIX B

West Sacramento Seismic Risk Analysis, Prepared by David Ford Consulting Engineers, Inc.

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MEMORANDUM

To: (Arul) Rajendram Arulnathan, PhD, PE, GE

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Date: April 13, 2015

Subject: West Sacramento seismic risk analysis 2015 update

Summary

Situation

The City of West Sacramento (City) is protected from flooding by levees on all sides. These levees protect the area from the Sacramento River, American River, Sacramento Deep Water Ship Channel (SDWSC), and Yolo Bypass.

Recent levee investigations by the California Department of Water Resources (DWR) and US Army Corps of Engineers (Corps) have shown deficiencies in these levees. To address these deficiencies, the City has initiated the West Sacramento Levee Improvement Program (WSLIP). The goal of this program is to rehabilitate and strengthen the West Sacramento levees, thereby reducing the risk to people and property from the flood event with an annual exceedence probability of 0.005 (p=0.005, referred to as the “200-year” flood event). The City is evaluating alternatives for meeting this goal.

In 2010, we evaluated the benefits of fixing the levees to address issues such as underseepage and slope stability. These are called “static fixes.” The analysis is documented in *West Sacramento Levee Improvement Program: Economic and risk analysis* (City of West Sacramento 2010), herein referred to as the “2010 study.”

Now, DWR is considering the need to include “seismic fixes” in the levee project in addition to the static fixes. Seismic fixes are enhancements of the levees to resist damage from earthquakes. Specifically for this analysis, the seismic fixes include stone columns and deep soil mixing.

In 2013, we analyzed both static and seismic fixes and documented our analysis in a technical memorandum. Since that time, an expert elicitation panel reviewed the geotechnical analyses and assumptions.

After the panel’s review, the geotechnical analyses and assumptions were updated and used here in the West Sacramento seismic risk analysis 2015 update, herein referred to as the “2015 update.” The geotechnical analysis is described in detail in the main report, *Cost-benefit study of remediating West Sacramento levees for seismic hazard: West Sacramento study area* (DWR 2015).

The 2015 update also includes revision to the hydrologic and hydraulic analysis. As part of DWR's Central Valley Flood Protection Plan (CVFPP) development, DWR produced HEC-RAS channel hydraulic models of major Central Valley streams and FLO-2D overland flow models of their associated floodplains. Included in the CVFPP is modeling and analysis of the West Sacramento area. Updated tools and information from the CVFPP (Oct. 2014) are used here.

Task

Building on the 2010 and 2013 studies, the question we sought to answer for the 2015 update was: What is the incremental benefit of investing in a seismic fix today, as opposed to not and then repairing the levee after a seismic event occurs? Our task is described in Table 1.

Actions

To estimate the incremental benefit, we used the Corps' computer program HEC-FDA (Hydrologic Engineering Center–Flood Damage Analysis) to compute economic flood risk to the City, measured as expected annual damage (EAD), over a 50-year period (a typical period for analyzing the useful life of a project). The incremental benefit is the without-project EAD minus the with-project EAD, as described in Table 1.

Table 1. Task description

Task (1)	Evaluation scenarios[1] (2)	Description (3)	Benefit computation (4)
Compute the incremental benefit of investing in a seismic fix today versus levee repair.	Without-project	• Without-project condition levee—has static fixes only, no seismic fixes. • When a seismic event occurs, levee is deformed. • Levee remains deformed for 2 years. • Levee then repaired back to the without-project condition.	Incremental benefit is the without-project EAD minus the with-project EAD.
	With-project	• With-project condition levee—static and seismic fixes in place. • Levee conditions constant throughout analysis. Should a seismic event occur, the levee is restored back to the original condition within the same year.	

1. For both scenarios, we assumed 1 seismic event occurs during the 50-year project life. The uncertainty in when this event occurs is taken into account.

Results

In summary, Table 2 shows the results of our task as a benefit-cost (B/C) ratio—the incremental benefit of a seismic fix to the levee versus cost. For both areas where the incremental benefit was computed (shown in Figure 1, and represented by index points), the B/C ratio is less than 1. This indicates that the cost of a seismic fix outweighs the benefits.

While the B/C ratios are well below 1.0, the benefit of investing in a seismic fix today is limited in that we only reflect 1 seismic event occurring in the 50-year project life. The project would realize a further incremental benefit if additional seismic events occurred within the 50-year time frame.

Table 2. Benefit-cost ratio: Incremental benefit of a seismic fix to the levee versus cost

Index point (1)	**B/C ratio (2)**
1	0.03
2	0.10

The following sections describe our analysis and results in detail.

Risk analysis

In this section, we describe the risk analysis step by step.

1. Define measure of incremental benefit: EAD

In urban settings such as West Sacramento, flood damage analysis commonly is restricted to an accounting of damage due to the largest event that occurs in a year. The time required for recovery, repair, and reconstruction will limit the loss incurred by a second or third flood, so the total loss in that year is a function of the largest flood.

However, in some years, no flooding will occur. In those years, a flood-damage reduction project will provide little or no benefit. In other years, large floods could cause significant damage, so by protecting people and property, the project will yield great benefit.

The random nature of flooding makes it impossible to predict the damage prevented in any particular year of the project's life because we cannot predict flood flows years in advance. Consequently, for evaluation of flood-damage reduction plan performance, *Economic and environmental principles and guidelines for water and related land resources implementation studies* (US Water Resources Council 1983) and *Handbook for assessing value of state flood management investments* (DWR 2014) stipulate use of the statistical average damage value. This average is known as the expected annual damage. We compute and use EAD herein as an index of risk reduction and project benefit. We did not consider life loss in this analysis.

2. Select tool for EAD computation: HEC-FDA

The computation procedures we used are automated with the Corps' computer program Hydrologic Engineering Center–Flood Damage Analysis, HEC-FDA (USACE 2008). We used version 1.2.5a of this program. We used HEC-FDA to compute:

- Structure damage.
- Content damage.
- Automobile damage.
- Temporary housing and displacement costs.

We developed our risk analysis approach around using HEC-FDA. Therefore, certain simplifications and accommodations were necessary. Those might not be required if another application was used, but for consistency with other studies, we maintained the use of HEC-FDA.

3. Collect information that HEC-FDA requires

To compute EAD with HEC-FDA, the following are required:

- Index points and impact areas to represent the study area. These analysis locations are used for aggregating and representing system performance. Index points are selected locations that represent hydrologic, hydraulic, and geotechnical characteristics for a reach of a stream. Impact areas are regions of the floodplain with similar flooding depths that can be related to channel stage at the index point.
- Channel water surface elevation-frequency function of each index point. This describes the annual probability, or frequency, of water surface in the river (exterior) exceeding a specified elevation (stage). We enhanced this relationship in the 2015 update. Where previously we used a stage-frequency function, we now use a flow-frequency function combined with a flow-stage transform. Both functions were developed as part of DWR's CVFPP.
- Interior-exterior function for each impact area. This function relates channel stage (exterior) at the index point to the water surface elevation in the floodplain (interior) adjacent to the channel. We enhanced the interior-exterior function in the 2015 update.
- Levee fragility curve. The uncertainty in the levee performance is described with a fragility curve that specifies the probability of levee failure, given a channel water surface elevation (stage). A levee failure includes all levee behavior that allows any flooding on the interior floodplain.

The flow-frequency function, flow-stage transform, and interior-exterior function are not known with certainty. Therefore, a model of uncertainty about each function is required. HEC-FDA, consistent with guidelines in *Risk-based analysis for flood damage reduction studies*, EM 1110-2-1619 (USACE 1996), allows models of uncertainty about these functions to be described. We used those models for this analysis, providing model parameters of uncertainty about the best-estimate functions.

Index points and impact areas

The impact areas used to represent the study area are shown in Figure 1, labeled impact area 1 north of the SDWSC and impact area 2 south of the SDWSC. Each impact area is associated with an index point: a location on a stream for which a stage-frequency function (combined flow-frequency function and flow-stage transform) is considered representative of the exterior (river) stage. For damage computation, a relationship of the interior (floodplain) water surface elevation to the exterior (river) stage at the index point is developed with a hydraulic model. This relationship describes how water will flow from the channel over levees or through a breach in the levee.

We used 2 index points on the Sacramento River, as shown in Figure 1. These include:

- Index point 1: river mile (RM) 60.0, right bank.
- Index point 2: RM 53.0, right bank.

Flow-frequency functions and flow-stage transforms

The flow-frequency function at a given index point defines the probability that channel flow will equal or exceed a specified magnitude. The flow-stage transform is a relationship between a specified flow in the channel and the associated channel water surface elevation (stage). Flow-frequency and flow-stage transforms used here are consistent with DWR's CVFPP study. All flow-frequency functions and flow-stage transforms were obtained from DWR and used with their permission.

We considered using the CVFPP flow-frequency functions and flow-stage transforms directly. However, the index point locations between CVFPP and this study were not coincident, but in close proximity, as shown in Figure 2. Therefore we needed to translate some of the results from CVFPP appropriately.

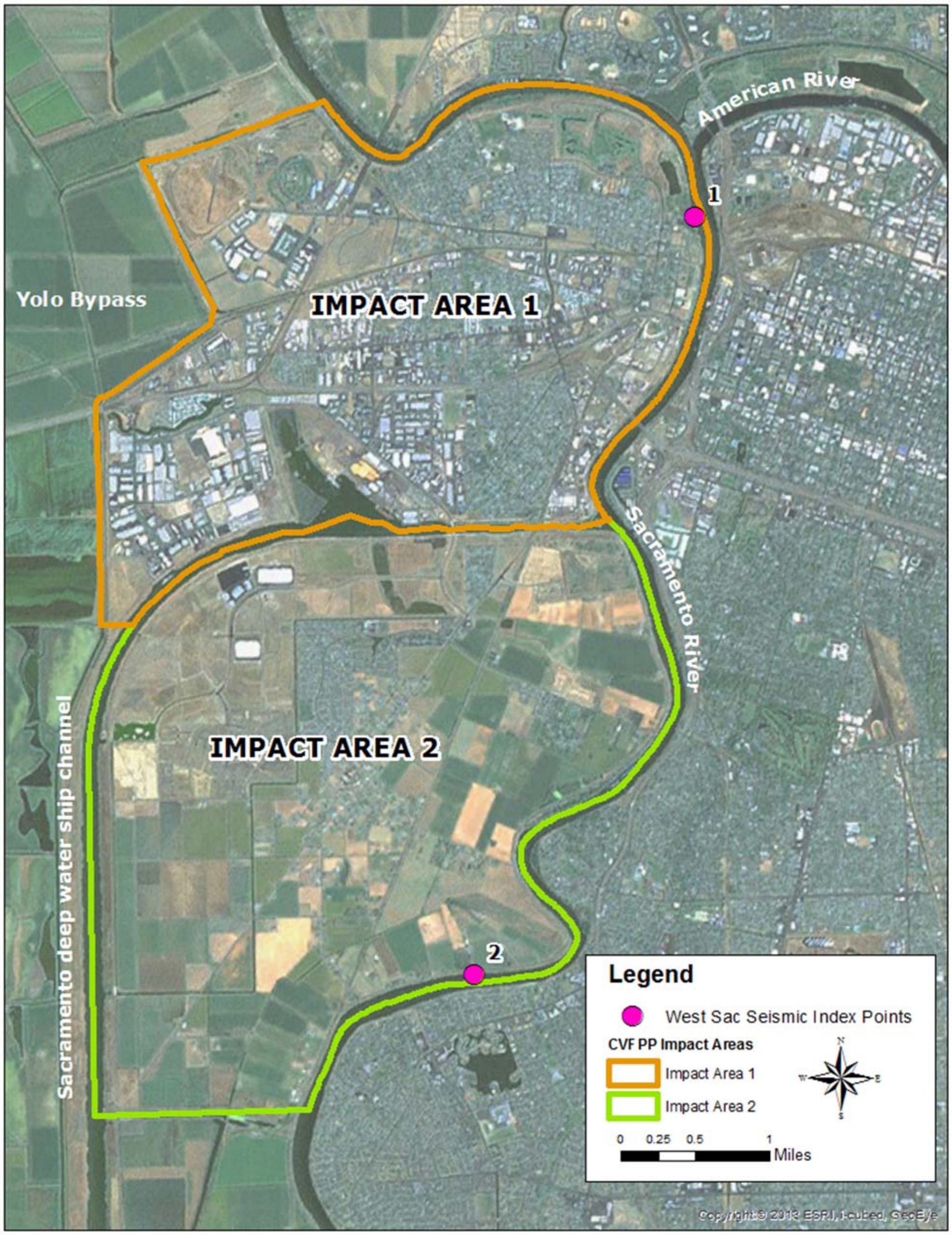

Figure 1. West Sacramento seismic analysis index points and impact areas

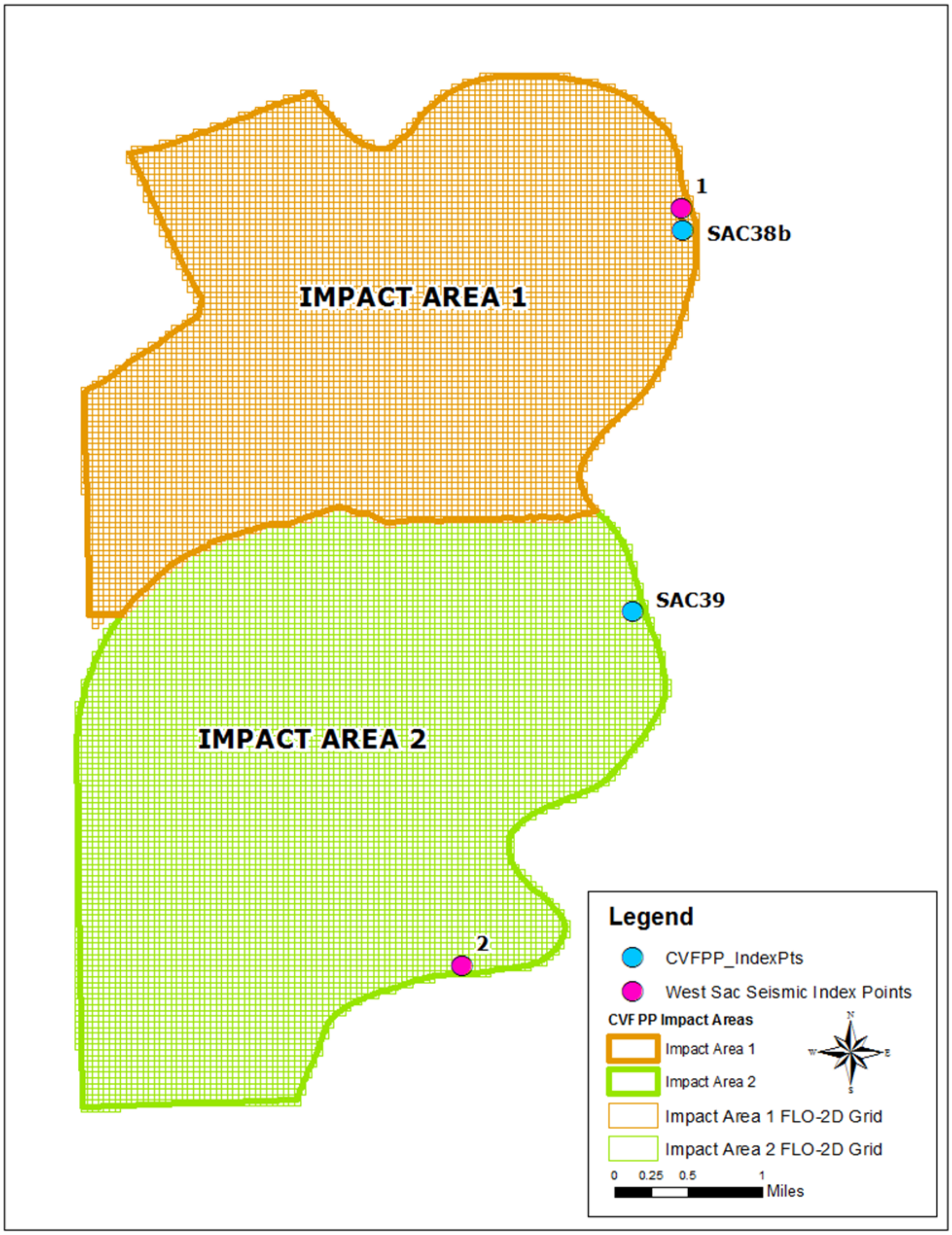

Figure 2. Comparison of CVFPP and West Sacramento seismic analysis index point locations and FLO-2D grid

Index point 1 and CVFPP index point SAC38b are approximately 800 ft apart. These 2 points are relatively close with no major changes in channel flow or geometry. Thus, we used the SAC38b CVFPP flow-frequency function and flow-stage transform as is for index point 1.

Impact area 2 index points, index point 2 and SAC39, are further apart, approximately 3.6 river miles. However, no significant inflows exist between index point 2 and SAC39, and hydraulic model simulations showed no flow rate change or attenuation between the index points. Thus, the same flow-frequency curve is valid at both locations, so we used the SAC39 CVFPP flow-frequency function for index point 2 as is.

Because of the distance between impact area 2 index points and potential difference in channel stage and slope at these locations, we used CVFPP HEC-RAS channel stages from the cross section nearest to index point 2 and paired these to the associated flows to develop a new flow-stage transform at index point 2 following CVFPP methods.

Algorithms in HEC-FDA describe the uncertainty of a flow-frequency function with a statistical model, parameters of which are related to the length of the record from which the flow-frequency function is derived. If the flow-frequency function is not derived by fitting a probability-density function with a sample of historical flow, an equivalent record length specified by the program user is employed instead. EM 1110-2-1619 provides guidance for selection of this equivalent record length. We used an equivalent record length of 104 years for modeling uncertainty about the flow-frequency function in this analysis, consistent with CVFPP. HEC-FDA also includes algorithms that describe the uncertainty of the flow-stage transform. Here we use a normal distribution with a standard deviation of error of 0.7, consistent with CVFPP.

Flow-frequency functions and flow-stage transforms used in this analysis are provided in Attachment 1.

Interior-exterior function

To compute damage in the floodplain, we must know the elevation of water in the impact area (floodplain). This can be determined with a model of the channel and floodplain hydraulics. When water overflows the channel in a small watershed, the water surface elevation in an impact area adjacent to the stream may rise to the stage in the channel if the flood causing the overflow has sufficient volume to fill the impact area. However, in systems such as the Sacramento River, with thousands of acres of floodplain, this is typically not the case. The volume is not sufficient to fill most impact areas. Near the channel, the water surface elevation in the floodplain may equal that in the channel. However, farther away, the elevation may be more or less, depending on the terrain and the conditions of the overflow into the impact area. The interior-exterior relationship represents this, defining the interior flood water surface elevation for damage computation as a function of channel stage.

Levees that protect the floodplains in West Sacramento further complicate this. If a levee protecting an impact area breaches and fails to provide the anticipated protection, water will flow through the breach and into the impact area. The water surface elevation in the floodplain may rise to that in the channel, or it may be less, depending upon the volume of water in the channel, the characteristics of the opening, and the floodplain terrain. The interior-exterior relationship describes this.

DWR provided the CVFPP interior-exterior relationships for West Sacramento at the CVFPP index points in the form of a FLO-2D grid, with interior water surface elevations specified at each grid cell. The FLO-2D model uses 200 ft by 200 ft grid cells, shown in Figure 2.

DWR developed the interior-exterior relationships by first computing a levee breach hydrograph at each index point. FLO-2D uses a breach hydrograph as input to the 2D grid. Breach hydrographs are based on levee height, levee composition, and levee toe elevation.

Because SAC39 and index point 2 are not coincident, breach hydrographs and associated FLO-2D results could differ. However, we tested whether breach hydrographs at SAC39 were similar to those computed at index point 2 by computing breach hydrographs at index point 2, using the CVFPP method. If breach hydrographs were similar, FLO-2D results would also be similar, meaning SAC39 interior-exterior relationships would be applicable for this study.

A comparison of index point 2 and SAC39 flow and volume for simulated 1986 scaled events is shown in Table 3 and Table 4, respectively. Breach hydrographs for the 1986 105% scaled event is shown in Figure 3. After comparing the index point 2 and SAC39 flow, volume, and breach hydrograph shape, we determined that differences between index point 2 and SAC39 were minimal. Differences shown in column 4 of Table 3 and column 4 of Table 4 will not yield a significant difference in floodplain depths since this flow and volume is distributed over the floodplain.

Thus, the interior-exterior relationship for SAC39 is appropriate for impact area 2. Interior-exterior functions are saved as a geographic information system (GIS) shapefile and can be provided upon request.

Table 3. Comparison of maximum breach flow between index point 2 and SAC39

Scaled event (1)	Maximum breach flow Index point 2 (cfs) (2)	Maximum breach flow SAC39 (cfs) (3)	% Difference relative to SAC39[1] (4)
1986_20%	10,940	10,063	-8.7
1986_60%	18,451	19,337	4.6
1986_80%	24,057	23,506	-2.3
1986_105%	29,237	29,262	0.1
1986_125%	35,271	35,178	-0.3
1986_155%	41,995	43,117	2.6
1986_220%	46,693	48,182	3.1

1. Percent difference = 100*(SAC39-Index point 2)/SAC39

Table 4. Comparison of total volume through breach between index point 2 and SAC39

Scaled event (1)	Total volume through the breach: Index point 2 (acre-ft) (2)	Total volume through the breach: SAC39 (acre-ft) (3)	% Difference relative to SAC39[1] (4)
1986_20%	34,596	30,637	-12.9
1986_60%	131,117	109,866	-19.3
1986_80%	227,662	192,921	-18.0
1986_105%	332,757	293,656	-13.3
1986_125%	436,339	393,821	-10.8
1986_155%	504,235	523,527	3.7
1986_220%	824,952	960,306	14.1

1. Percent difference = 100*(SAC39-Index point 2)/SAC39

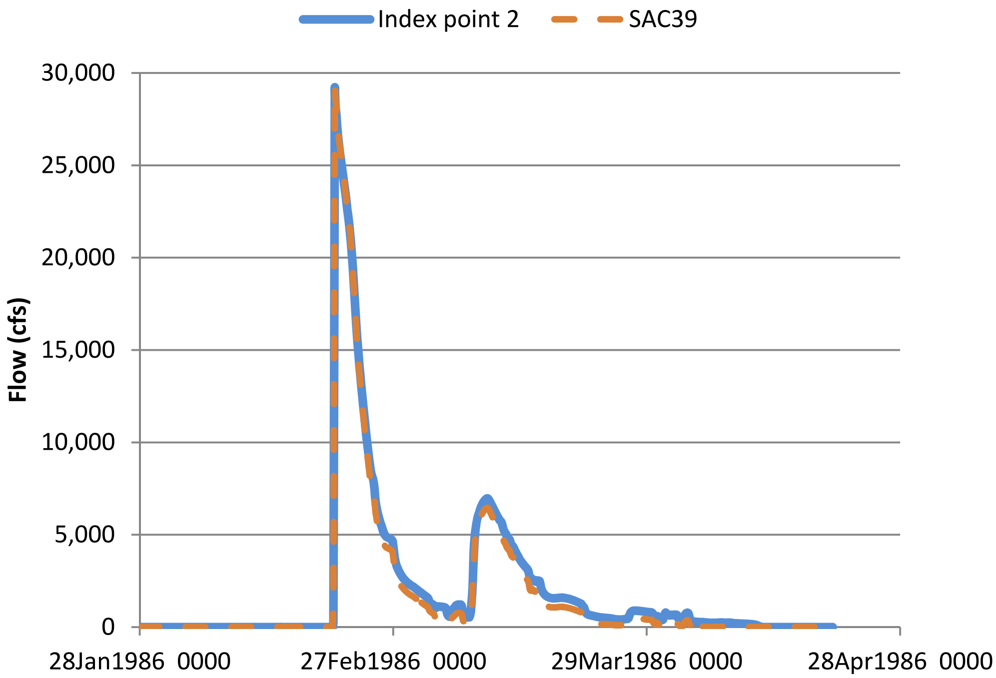

Figure 3. Comparison of breach hydrographs at index point 2 and SAC39 for the 1986 105% scaled event

Levee seismic fragility curves

A large source of uncertainty is how the levee at the index point will perform. A levee will prevent flow of water from the exterior channel into the interior area until the levee fails. A failure includes all levee behavior that allows any depth of flooding on the interior floodplain. This typically includes, but is not limited to levee through-seepage, under-seepage, instability, overtopping, breaching, etc. Here, the primary source of failure is failure due to a seismic event. HEC-FDA includes a model of levee performance uncertainty, which we used for this analysis. This relationship, referred to as the levee fragility curve, defines the probability of levee failure, given the exterior stage.

Without failure, the interior water surface elevation is zero, regardless of the exterior stage. But we must account for the probability that the levee will fail prior to overtopping. The likelihood that a levee designed for the p=0.01 ("100-yr") flood event will fail during a 100-yr flood event is small, but the analysis procedure should account for this.

For simplification, the probability of a seismic event and probability of a flood event are independent. Thus, the probability of levee failure is not conditioned on the channel reaching a particular water surface elevation.

For this analysis, where we evaluated the seismic hazard, a set of seismic fragility curves was needed for each levee condition and at each index point. Each set includes separate seismic fragility curves, 6 within each set, for each seismic event. Seismic events analyzed include the p=0, 0.04, 0.02, 0.01, 0.005, and 0.002 ("0-, 25-, 50-, 100-, 200-, and 500-yr") events. The seismic fragility curve sets are described in Table 5.

URS provided all seismic fragility curves using the North American Vertical Datum of 1988 (NAVD88). All 2015 update seismic fragility curves are included in Attachment 2.

Table 5. Seismic fragility curve set description

Seismic fragility curve set[1] (1)	**Fragility curve description (3)**
1	Static fixes to levee.
2	Levee deformed due to seismic event. The top-of-levee elevation has slumped.
3	Static and seismic fixes to levee.

1. Each seismic fragility curve set includes 6 separate seismic fragility curves, 1 for each seismic event analyzed.

Damageable property and associated flood costs

Structure inventory

We used the structure inventory from the 2010 study for this analysis. Due to slow growth, the 2010 inventory was considered still relevant for 2015. As described in the 2010 study, the structure inventory for each impact area was compiled using GIS tools to identify the relevant structures. We identified a total of 13,843 parcels with structures based on parcel coverage provided by the City in April 2009. As part of the 2015 update, we converted all structure first-floor elevations from National Geodetic Vertical Datum of 1929 (NGVD29) to NAVD88, consistent with other inputs to HEC-FDA, and converted all structure values to 2013 dollar values, consistent with the seismic fix costs (Engineering News-Record 2014). In addition, we associated each structure with a FLO-2D grid cell. HEC-FDA combines the FLO-2D grid cell water surface elevation and a structure's first-floor elevation to get the flood depth at each structure.

We categorized structures into 1 of the 7 structure types as follows:

- Single family residential, 1-story.
- Single family residential, 2-story.
- Multi-family residential, 1-story.
- Multi-family residential, 2-story.
- Commercial.
- Industrial.
- Public.

Consistent with DWR and Corps standards, we used the structure's depreciated-replacement value for the economic analysis. The depreciated-replacement value is considered the cost of replacing the structure less any depreciation, which accounts for a reduction in a structure's value due to deterioration prior to flooding. A certified appraiser estimated structure costs using Marshall and Swift procedures. After all structures and content were valued, we calculated a total damageable property value by summing the structure and content values for each category. These values are shown in Table 6 for impact area 1 and in Table 7 for impact area 2, with total damageable property at $4.95 billion for both impact areas.

Displacement and temporary housing

Displacement and temporary housing costs are a consequence of the time occupants are displaced from their homes due to flood damage. Occupants who are displaced to temporary quarters incur a range of incremental costs, including rental costs for temporary space, other monthly costs such as furniture rental or extra commuting costs, and fixed costs that are independent of length of displacement, such as moving costs. We followed Federal Emergency Management Agency (FEMA) procedures for estimating typical displacement times and temporary housing costs. The method is described in *Benefit-cost analysis tool, version 4.5.5.0* (FEMA 2009). The computations for displacement and temporary housing costs are described in Attachment 5 of the 2010 study.

Table 6. Structure, content, and total damageable property value by structure category for impact area 1

Structure category (1)	Number of structures (2)	Structure value[1] ($1,000) (3)	Content value[2] ($1,000) (4)	Total damageable property value ($1,000) (5)
Single family, 1-story	5,177	387,693	193,846	581,539
Single family, 2-story	596	99,553	49,777	149,330
Multi-family, 1-story	133	49,411	24,705	74,116
Multi-family, 2-story	21	10,268	5,134	15,401
Commercial	344	347,649	222,726	570,376
Industrial	391	702,509	448,271	1,150,780
Public	75	125,466	77,245	202,711
Total[3]	6,737	1,722,548	1,021,704	2,744,253

1. Structure, content, and total values reported in 2013 dollars.
2. Residential content is 50% of residential structure value for this table. For EAD computations, the content damage is computed as a function of the structure value.
3. Values rounded to nearest whole number.

Table 7. Structure, content, and total damageable property value by structure category for impact area 2

Structure category (1)	Number of structures (2)	Structure value[1] ($1,000) (3)	Content value[2] ($1,000) (4)	Total damageable property value ($1,000) (5)
Single family, 1-story	3,285	478,330	239,165	717,495
Single family, 2-story	3,735	806,394	403,197	1,209,591
Multi-family, 1-story	4	1,116	558	1,674
Multi-family, 2-story	0	0	0	0
Commercial	26	44,080	25,296	69,376
Industrial	33	117,367	71,020	188,387
Public	23	13,390	5,475	18,865
Total[3]	7,106	1,460,677	744,711	2,205,389

1. Structure, content, and total values reported in 2013 dollars.
2. Residential content is 50% of residential structure value for this table. For EAD computations, the content damage is computed as a function of the structure value.
3. Values rounded to nearest whole number.

Automobiles

Damage to autos was estimated as a function of average value, number of vehicles per residential structure, estimated evacuation rate, depth of flooding, and depth-damage percent loss. To develop automobile elevation-damage functions, we followed procedures consistent with the Corps' *Draft* *economic reevaluation report: American River watershed project, Folsom Dam modification and Folsom Dam raise project* (USACE 2007). Automobile damage computations are consistent with the 2010 study.

4. Compute EAD

Evaluation scenarios

To determine the incremental benefit of a seismic fix, a without- and with-project scenario must be defined and EAD computed for each using the appropriate HEC-FDA inputs. These scenarios are described in Table 8 and in sections below. For both scenarios, all HEC-FDA inputs for index point/impact area 1 and index point/impact area 2 are the same, as described in Section 3 above, except for the seismic fragility curves as shown in Table 8.

The scenarios consider a single seismic event occurring once over a 50-year analysis period. However, we do account for the uncertainty of when that event occurs.

Table 8. Evaluation scenarios

Evaluation scenario (1)	Levee description (2)	Seismic fragility curve set used (3)
Without-project	• Without-project condition—static fixes only, no seismic fixes. • Levee deformed due to a seismic event. • Levee remains deformed for 2 years. • Levee then repaired back to the without-project condition.	• Set 1 prior to seismic event. • Set 2 when levee is deformed for 2-year period. • Set 1 after levee repair.
With-project	• With-project condition—static and seismic fixes in place. • Levee conditions constant throughout analysis. Should a seismic event occur, the levee is restored back to the original condition within that same year.	• Set 3 throughout.

EAD timeline

For the without-project scenario, we must compute 2 EAD values: 1 representing the original state of the levee (without-project levee condition), and 1 representing the levee deformed by a seismic event.

For EAD prior to the seismic event (and after repair), we used seismic fragility curve set 1. Seismic fragility curve set 1 represents the original state of the levee with static fixes. We computed EAD for each seismic event, 0-, 25-, 50-, 100-, 200-, and 500-yr. With these results, we developed a probability-damage curve. To estimate project benefits, we needed a single EAD for each scenario. By integrating the probability-damage curve, we computed an average. This average EAD takes into account all seismic and flood return periods and combines damage values into a single value of EAD for the without-project condition using fragility curve set 1. This computation is further illustrated in Figure 4.

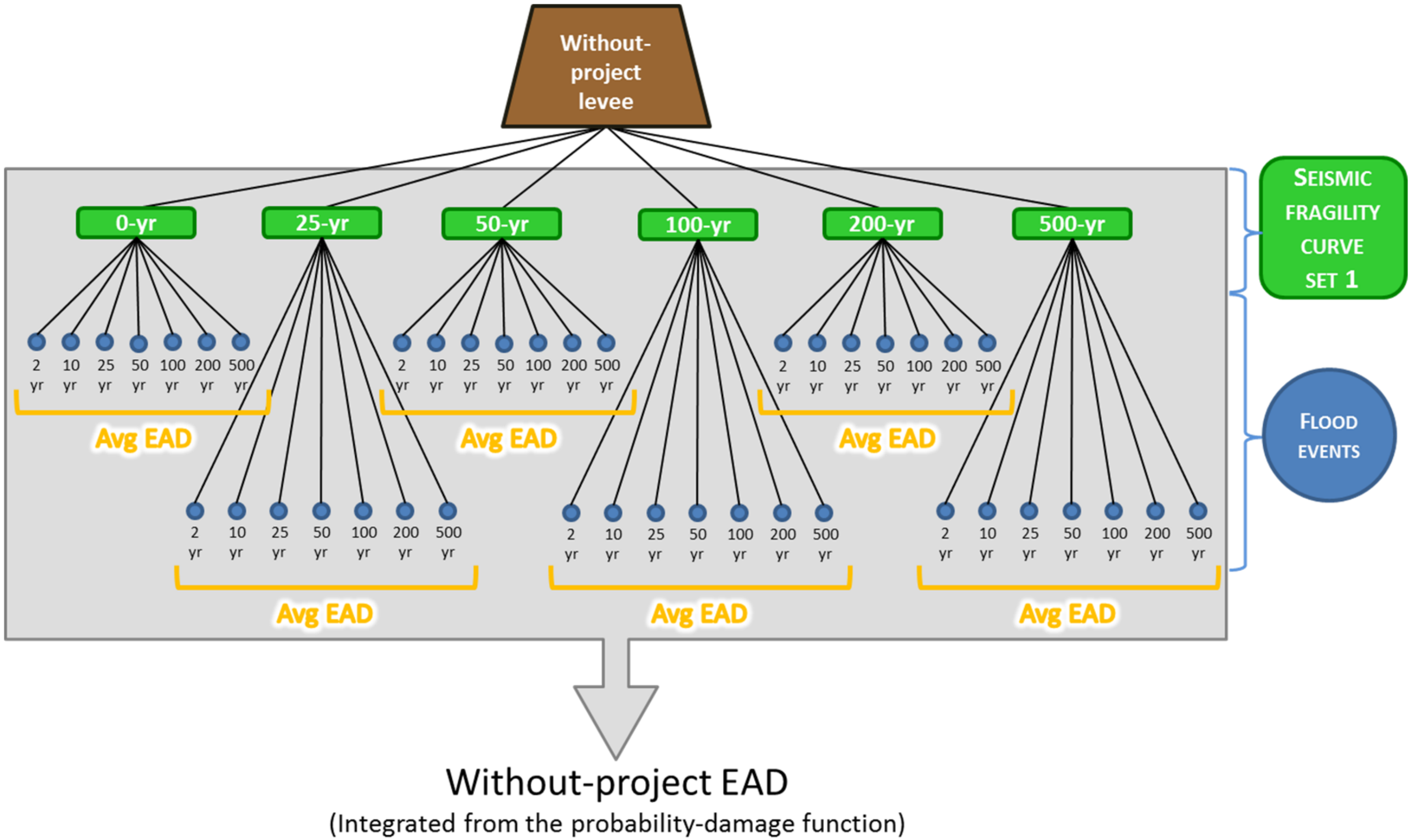

Figure 4. Without-project levee condition EAD computation

We computed an average EAD in this same way using seismic fragility curve set 2, used to represent the deformed levee.

Average EADs were computed at index point 1 and index point 2. Note that these EADs are damages that have an equal likelihood of occurring in each year of the analysis period.

With different levee conditions over the project life, thus different EAD for given years, EAD must be considered over a timeline. We computed EAD using a combination of EADs, 1 EAD using seismic fragility curve set 1 and another EAD using seismic fragility curve set 2. The without-project EAD timeline is summarized in Table 9 and illustrated in Figure 5.

Table 9. Without levee repair scenario EAD timeline

Step (1)	EAD timeline events (2)	Seismic fragility curve set used (3)
1	• Start with the without-project levee. A static fix is in place.	Set 1
2	• A seismic event occurs. • An equal chance of a seismic event occurs in each year. However, only 1 seismic event will occur in the 50-year life cycle. • The levee sustains deformation and remains deformed for 2 years.	Set 2
3	• After the levee is repaired, the without-project levee characteristics are retained.	Set 1

We consider an EAD timeline for the with-project condition as well. In this case, however, only fragility curve set 3 is used to compute an average EAD, which is applied to each year of the timeline, beginning with year 1. This presumes that the seismic fix has been constructed and paid for, and therefore is in place at the start of the analysis period. The with-project EAD timeline is illustrated in Figure 5.

Computation

For the without-project condition, we first computed EAD using seismic fragility curve set 1 and found damage values listed in column 2 of Table 10, approximately $1.9 million for index point 1 and $4.9 million for index point 2. This damage is potentially incurred when the levee has not sustained damage from a seismic event and when it is repaired to its original state.

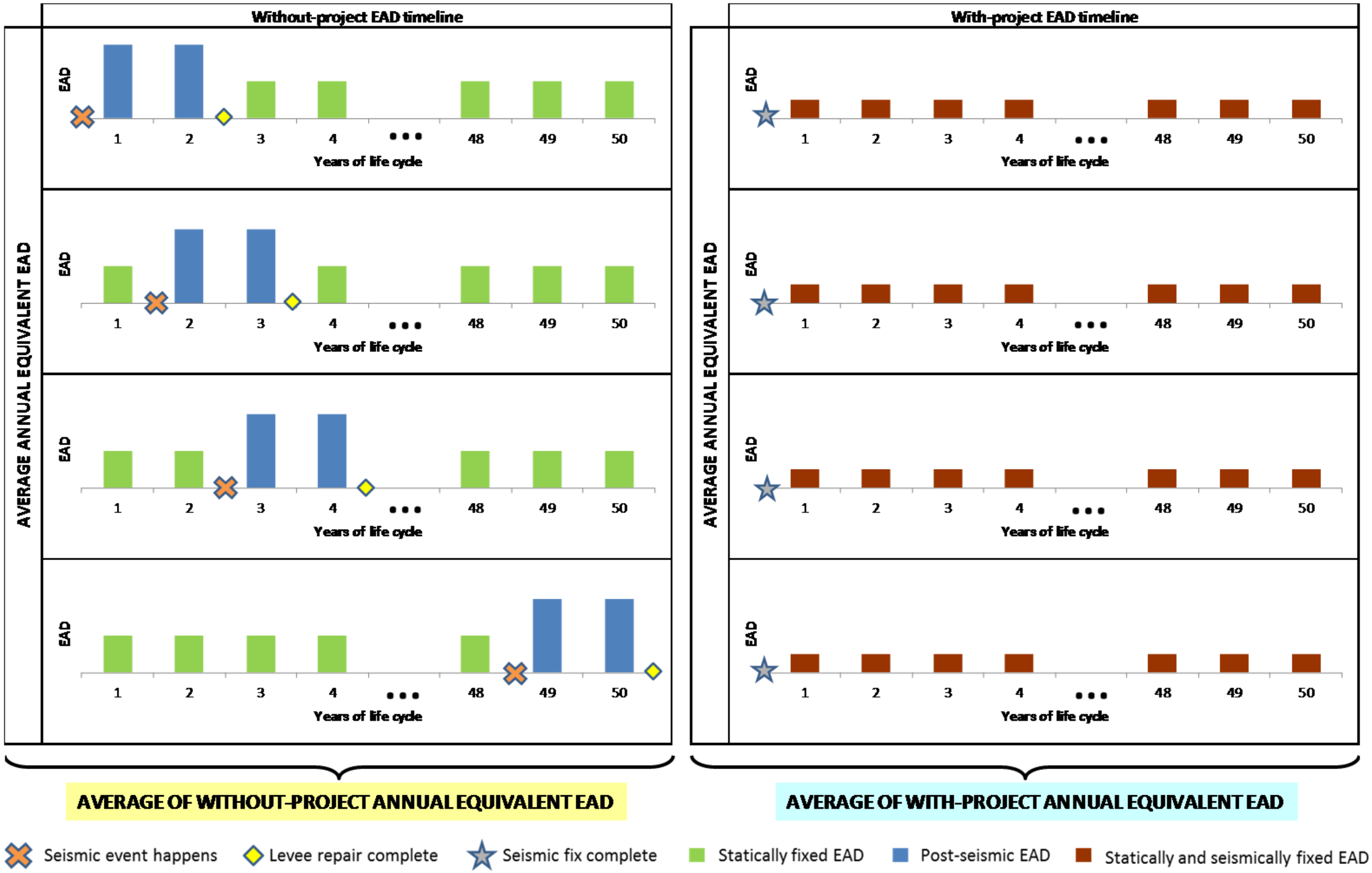

Figure 5. EAD timeline for without-project and with-project scenarios. In the with-project EAD timeline, a seismic event may occur at any time during the project life, and the with-project EAD will be applicable for each and every year in the life cycle, since the levee would be restored back to the original condition within that same year.

For years in which the levee is damaged from a seismic event, EAD using seismic fragility curve set 2 is applicable, $2.0 million for index point 1 and $5.3 million for index point 2, as shown in column 3 of Table 10. DWR's Urban Levee Design Criteria (ULDC) guidelines (DWR 2012) specify that a seismically damaged levee must be repaired within a 2-year time frame. Thus, for the without-project scenario, once the levee is damaged, the levee remains in this degraded state for 2 years. For example, if a seismic event occurs in year 1, the levee is damaged for 2 years and for these years, we computed EAD using seismic fragility curve set 2. The levee is then repaired back to the without-project condition, and EAD is computed using seismic fragility curve set 1. This combination of EAD over the project life is shown in the EAD timelines in Figure 5.

For each EAD timeline, we computed an annual equivalent EAD. In doing this we now have an annual equivalent EAD for each EAD timeline: 1 for when the seismic event occurs in year 1, 1 for when the seismic event occurs in year 2, and so on. By taking an average of all the annual equivalent EADs, we come to an adjusted EAD that takes into account the uncertainty of when the seismic event occurs. The without-project adjusted EAD is listed in column 4 of Table 10.

Table 10. Damage values associated with without-project scenario

Index point (1)	Seismic fragility curve set 1 EAD ($1,000) (2)	Seismic fragility curve set 2 EAD ($1,000) (3)	Without-project adjusted EAD ($1,000) (4)
1	1,853	2,042	1,860
2	4,857	5,289	4,873

We computed with-project EAD using seismic fragility curve set 3 and found damage values listed in column 3 of Table 11. As seen in Figure 5, the with-project EAD is the same each and every year of the analysis period. Here we do not need to adjust the EAD since average annual EAD each year is the same. Table 11 also shows the without-project adjusted EAD in column 2 for comparison.

Table 11. Damage values for without- and with-project scenarios

Index point (1)	Without-project adjusted EAD[1] ($1,000) (2)	With-project EAD ($1,000) (3)
1	1,860	1,098
2	4,873	1,710

1. EAD consistent with levee damaged from seismic event.

5. Compute costs

For the B/C ratios, we used the difference in costs between the without-project and with-project scenarios.

For the without-project scenario, we considered levee repair costs in the same 50-year timeline used for EAD computations. The cost of levee repair is different if we consider the investment is made today or 50 years from now. To compute adjusted levee repair costs, we considered levee repair occurring in the first 2 years. We divided the levee repair cost evenly over the 2-year repair period. We brought these costs to a present value using the current DWR discount rate of 6%. Next, with the seismic event occurring in year 2, the levee repair continues for years 2 and 3. These repair costs were brought to a present value. This computation continues until the repair occurs at the end of the levee life cycle. We averaged all the present value repair costs to compute an adjusted levee repair cost. Computing adjusted levee repair costs in this way considers an equal chance of levee repair occurring in any given year throughout the levee life cycle. Adjusted levee repair costs are shown in column 2 of Table 12.

For the with-project scenario, seismic fix costs were provided by URS and are shown in column 3 of Table 12. These costs are total 2013 construction costs (present value). Because the seismic fix takes place at the beginning of the analysis period and the seismic fix costs are in present value, no cost adjustments are needed here.

Table 12. Levee repair costs ($2013)

Index point (1)	Adjusted levee repair costs[1] (without-project scenario) ($1,000) (2)	Seismic fix costs (with-project scenario) ($1,000) (3)
1	9,174	398,300
2	11,009	507,000

1. Adjusted project costs brought to a present value using the current DWR discount rate of 6% and a 50-year project life. 2-year repair period has equal chance of occurring in any year throughout the levee life cycle.

Results

The incremental benefit of a seismic fix is the difference in EAD between the without-project and with-project scenarios. The without- and with-project EAD for index point 1 is shown in column 3 of Table 13. Present value costs are also shown in Table 13 (column 4). At index point 1, the incremental benefit of a seismic fix is approximately $0.8 million, as shown in column 2 of Table 14. Using the current DWR discount rate of 6% and a 50-year project life, the present value benefit of a seismic fix is approximately $12.0 million. The present value of the benefit is the accrued benefit over the life of the project. Based on the difference in costs between scenarios (column 4 of Table 14), the estimated benefit-cost ratio for a seismic fix is 0.03 at index point 1.

Table 13. EAD and costs for without-project and with-project scenarios at index point 1

Index point (1)	Scenario (2)	EAD[1] ($1,000) (3)	Present value costs[2] ($1,000) (4)
1	Without-project	1,860	9,174
	With-project	1,098	398,300

1. EAD values include damage to structures, contents, autos, and cost for displacement and temporary housing.
2. Present value computed using the current DWR discount rate of 6% and a 50-year project life.

Table 14. Benefit-cost ratio computation at index point 1

Index point (1)	Annual benefit[1] ($1,000) (2)	Present value benefit[2] ($1,000) (3)	Difference in costs ($1,000) (4)	Benefit-cost ratio[3] (5)
1	762	12,007	389,126	0.03

1. Annual benefit = difference in EAD between without-project and with-project scenarios.
2. Present value computed using the current DWR discount rate of 6% and a 50-year project life.
3. Benefit-cost ratio = present value benefit divided by difference in costs.

For index point 2, the with- and without-project EAD is shown in column 3 of Table 15. Present value costs are also shown in Table 15 (column 4). The incremental benefit of a seismic fix is approximately $3.2 million, as listed in column 2 of Table 16. Using the current DWR discount rate of 6% and a 50-year project life, the present value benefit of a seismic fix is approximately $49.9 million. Based on the difference in costs between scenarios (column 4 of Table 16), the estimated benefit-cost ratio for a seismic fix is 0.10 at index point 2.

Table 15. EAD and costs for without-project and with-project scenarios at index point 2

Index point (1)	Scenario (2)	EAD[1] ($1,000) (3)	Present value costs[2] ($1,000) (4)
2	Without-project	4,873	11,009
	With-project	1,710	507,000

1. EAD values include damage to structures, contents, autos, and cost for displacement and temporary housing.
2. Present value computed using the current DWR discount rate of 6% and a 50-year project life.

Table 16. Benefit-cost ratio computation at index point 2

Index point (1)	Annual benefit[1] ($1,000) (2)	Present value benefit[2] ($1,000) (3)	Difference in costs ($1,000) (4)	Benefit-cost ratio[2] (5)
2	3,164	49,866	495,991	0.10

1. Annual benefit = difference in EAD between without-project and with-project scenarios.
2. Present value computed using the current DWR discount rate of 6% and a 50-year project life.
3. Benefit-cost ratio = Present value benefit divided by difference in costs.

Attachment 1. Flow-frequency functions and flow-stage transforms

As noted in the body of this memorandum, we require channel stage-frequency functions at each index point. To get to a channel stage-frequency function, we now use a flow-frequency function combined with a flow-stage transform.

All flow-frequency functions and flow-stage transforms were obtained from DWR's CVFPP study. With permission from DWR, these functions are used again here for this analysis.

Flow-frequency functions

The flow-frequency function at a given index point defines the probability that channel flow will equal or exceed a specified magnitude. Table 17 shows the flow-frequency functions for index point 1 and index point 2. To describe the hydrologic and hydraulic uncertainty in the flow-frequency function, we used an equivalent record length of 104 years, consistent with DWR's CVFPP study. With the equivalent record length, the uncertainty about the flow-frequency function changes with the probability of a given flow being exceeded: the lesser the exceedence probability, the greater the uncertainty. For completeness, we report the uncertainty within 1 standard deviation about the 100-yr (p=0.01), 250-yr (p=0.004), and 500-yr (p=0.002) events in Table 18. The uncertainty represents the total uncertainty of both the hydrologic and hydraulic evaluation.

Table 17. Flow-frequency functions at index point 1 and index point 2

Probability of exceedence (1)	Flow (cfs)	
	Index point 1[1] (2)	Index point 2[2] (3)
0.999	17,156	17,156
0.5	89,719	89,597
0.1	102,525	101,901
0.04	106,963	106,877
0.02	110,223	109,956
0.01	112,245	112,055
0.004	120,182	120,630
0.002	127,097	126,966
0.001	131,873	131,310

1. Used SAC38b flow-frequency function from DWR's CVFPP study.
1. Used SAC39 flow-frequency function from DWR's CVFPP study.

Table 18. Uncertainty (1 standard deviation) about flow-frequency functions for index point 1 and index point 2

Probability of exceedence (1)	Flow uncertainty (cfs)	
	Index point 1 (2)	Index point 2 (3)
0.01	6,249	5,813
0.004	6,969	6,541
0.002	7,637	7,113

Flow-stage transforms

The flow-stage transform is a relationship between a specified flow in the channel and the associated channel water surface elevation (stage). Table 19 and Table 20 show the flow-stage transforms for index point 1 and index point 2. To describe the hydrologic and hydraulic uncertainty in the flow-stage transform, we used a normal distribution with a minimum standard deviation of 0.7, consistent with guidance on risk analysis in EM 1110-2-1619 and DWR's CVFPP study.

Table 19. Flow-stage transform at index point 1[1]

Flow (cfs) (1)	**Stage (ft NAVD88) (2)**	**Standard deviation (ft NAVD88) (3)**
62,572	23.13	0.70
95,439	29.91	0.70
96,543	30.18	0.70
97,063	30.31	0.70
98,784	30.74	0.70
103,585	31.92	0.70
103,614	31.93	0.70
108,308	32.88	0.70
109,879	33.23	0.70
111,418	33.56	0.70
112,316	33.76	0.70
112,918	33.88	0.70
113,266	33.95	0.70
115,145	34.34	0.70
116,245	34.56	0.70
116,411	34.59	0.70
116,423	34.60	0.70
126,458	36.20	0.70
126,773	36.25	0.70
146,226	37.79	0.70
153,492	38.36	0.70
162,503	39.07	0.70

1. Used SAC38b flow-stage transform from DWR's CVFPP study.

Table 20. Flow-stage transform at index point 2

Flow (cfs) (1)	**Stage (ft NAVD88) (2)**	**Standard deviation (ft NAVD88) (3)**
58,438	17.92	0.70
97,838	23.93	0.70
98,136	24.01	0.70
98,250	24.04	0.70
99,700	24.41	0.70
103,107	25.27	0.70
103,927	25.50	0.70
107,476	26.21	0.70
110,327	26.77	0.70
110,490	26.79	0.70
110,738	26.81	0.70
111,040	26.85	0.70
112,007	26.99	0.70
112,580	27.10	0.70
113,143	27.20	0.70
113,174	27.21	0.70
113,937	27.35	0.70
123,725	28.80	0.70
124,088	28.85	0.70
126,269	29.13	0.70
128,426	29.31	0.70
142,071	30.01	0.70

Attachment 2. Levee seismic fragility curves

The uncertainty in levee performance is described with a seismic fragility curve that specifies the probability of levee failure, given a channel water surface elevation (stage). A levee failure includes all levee behavior that allows any depth of flooding on the interior floodplain. This typically includes, but is not limited to levee through-seepage, under-seepage, instability, overtopping, breaching, etc.

For purposes of this analysis, where we are quantifying the seismic hazard, a set of seismic fragility curves was needed for each task at each index point. Each set includes a separate seismic fragility curve, 6 within each set, for each seismic event. Seismic events analyzed include the 0-, 25-, 50-, 100-, 200-, and 500-yr seismic events.

Seismic fragility curves used yield a probability of levee failure due to a seismic event. We did not consider other levee failure modes such as through-seepage, underseepage, instability, overtopping, breaching, etc. All seismic fragility curves were provided by URS and are listed in Table 21 through Table 26 and shown in Figure 6 through Figure 11 for index points 1 and 2.

Table 21. Index point 1 seismic fragility curve set 1

0-yr / 25-yr return period		50-yr return period		100-yr return period		200-yr return period		500-yr return period	
Water surface elevation (ft NAVD88)	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**
28.50	0.0000	28.50	0.0000	28.50	0.0000	28.50	0.0000	28.50	0.0000
29.00	0.0010	29.00	0.0010	29.00	0.0070	29.00	0.0250	29.00	0.0450
30.00	0.0020	30.00	0.0020	30.00	0.0300	30.00	0.1000	29.50	0.1000
31.00	0.0035	31.00	0.0035	30.75	0.0580	31.00	0.2020	30.50	0.2100
32.00	0.0050	32.00	0.0050	31.50	0.1000	32.00	0.3500	31.50	0.3500
33.00	0.0070	33.00	0.0070	32.50	0.1900	33.10	0.5700	32.70	0.6000
34.00	0.0100	34.00	0.0100	33.75	0.3500	33.80	0.8000	33.25	0.8000
35.00	0.0140	35.00	0.0160	35.05	0.6000	33.99	1.0000	33.49	1.0000
36.00	0.0200	36.00	0.0250	35.70	0.8000	34.00	1.0000	33.50	1.0000
37.00	0.0370	37.00	0.0450	35.99	1.0000	42.00	1.0000	42.00	1.0000
38.00	0.0600	38.00	0.0750	36.00	1.0000	--	--	--	--
39.00	0.0900	38.99	0.1050	42.00	1.0000	--	--	--	--
39.99	0.1200	39.00	0.1050	--	--	--	--	--	--
40.00	0.1200	39.01	1.0000	--	--	--	--	--	--
40.01	1.0000	39.02	1.0000	--	--	--	--	--	--
40.02	1.0000	42.00	1.0000	--	--	--	--	--	--
42.00	1.0000	--	--	--	--	--	--	--	--

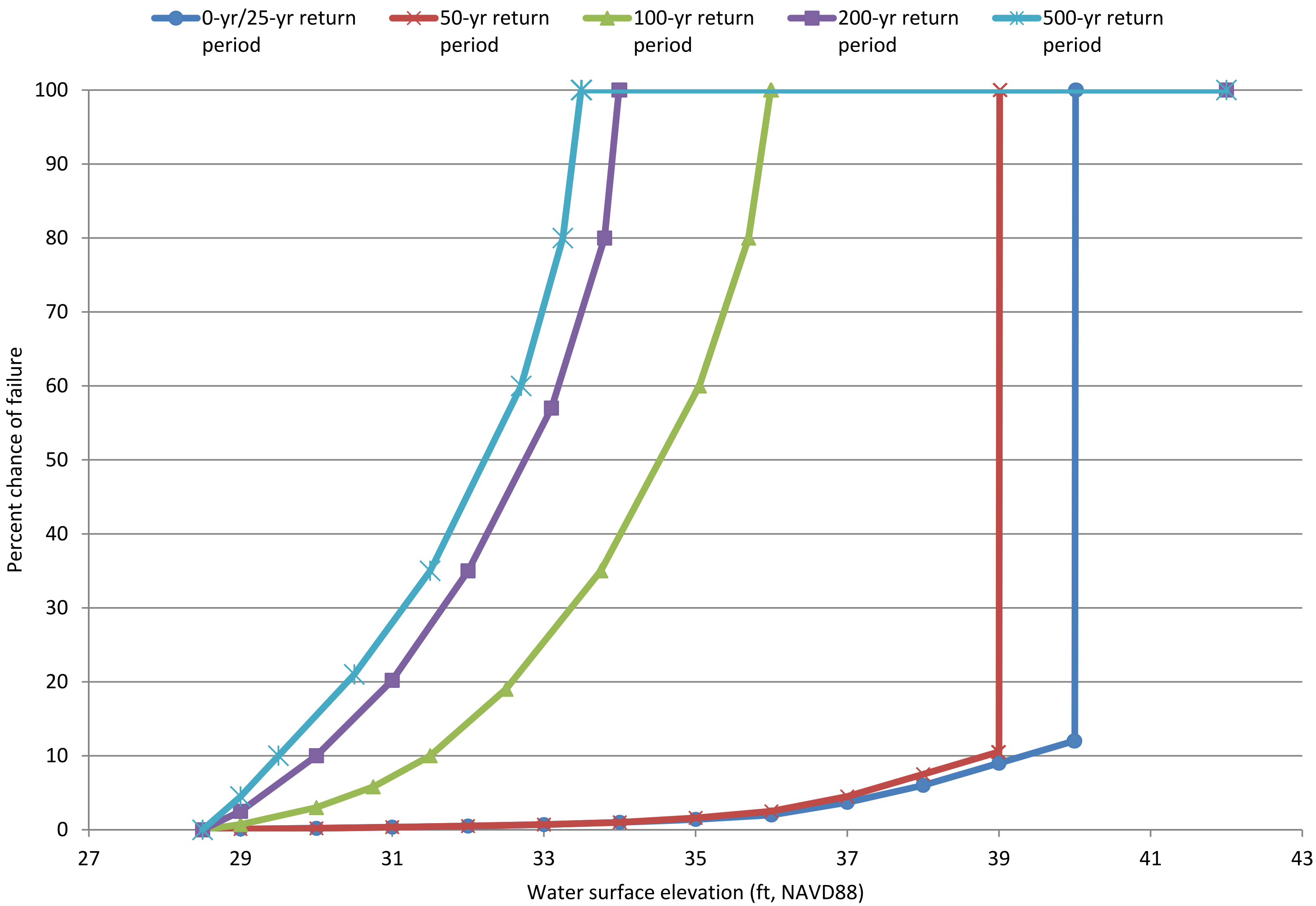

Figure 6. Index point 1 seismic fragility curve set 1

Table 22. Index point 1 seismic fragility curve set 2

0-yr / 25-yr return period		50-yr return period		100-yr return period		200-yr return period		500-yr return period	
Water surface elevation (ft NAVD88)	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**
28.50	0.0000	28.50	0.0000	28.50	0.0000	28.50	0.0000	28.50	0.0000
29.00	0.0010	29.00	0.0010	29.00	0.0070	29.00	0.0390	29.00	0.0400
30.00	0.0020	30.00	0.0020	30.00	0.0400	30.00	0.0900	30.00	0.1100
31.00	0.0035	31.00	0.0035	31.00	0.1100	31.00	0.2000	31.00	0.2000
32.00	0.0050	32.00	0.0050	34.00	0.2000	33.00	0.3500	32.00	0.3200
33.00	0.0070	33.00	0.0070	35.99	0.3980	33.99	0.6000	32.49	0.5500
34.00	0.0100	34.00	0.0100	36.00	0.4500	34.00	0.8000	32.50	0.8000
35.00	0.0140	35.00	0.0140	36.01	0.6000	34.01	1.0000	32.51	1.0000
36.00	0.0200	36.00	0.0200	36.02	0.8000	34.02	1.0000	32.52	1.0000
37.00	0.0370	37.00	0.0370	42.00	1.0000	42.00	1.0000	42.00	1.0000
38.00	0.0600	38.00	0.0600	--	--	--	--	--	--
39.00	0.0900	38.99	0.0900	--	--	--	--	--	--
39.99	0.1200	39.00	0.0900	--	--	--	--	--	--
40.00	0.1200	39.01	1.0000	--	--	--	--	--	--
40.01	1.0000	39.02	1.0000	--	--	--	--	--	--
40.02	1.0000	42.00	1.0000	--	--	--	--	--	--
42.00	1.0000	--	--	--	--	--	--	--	--

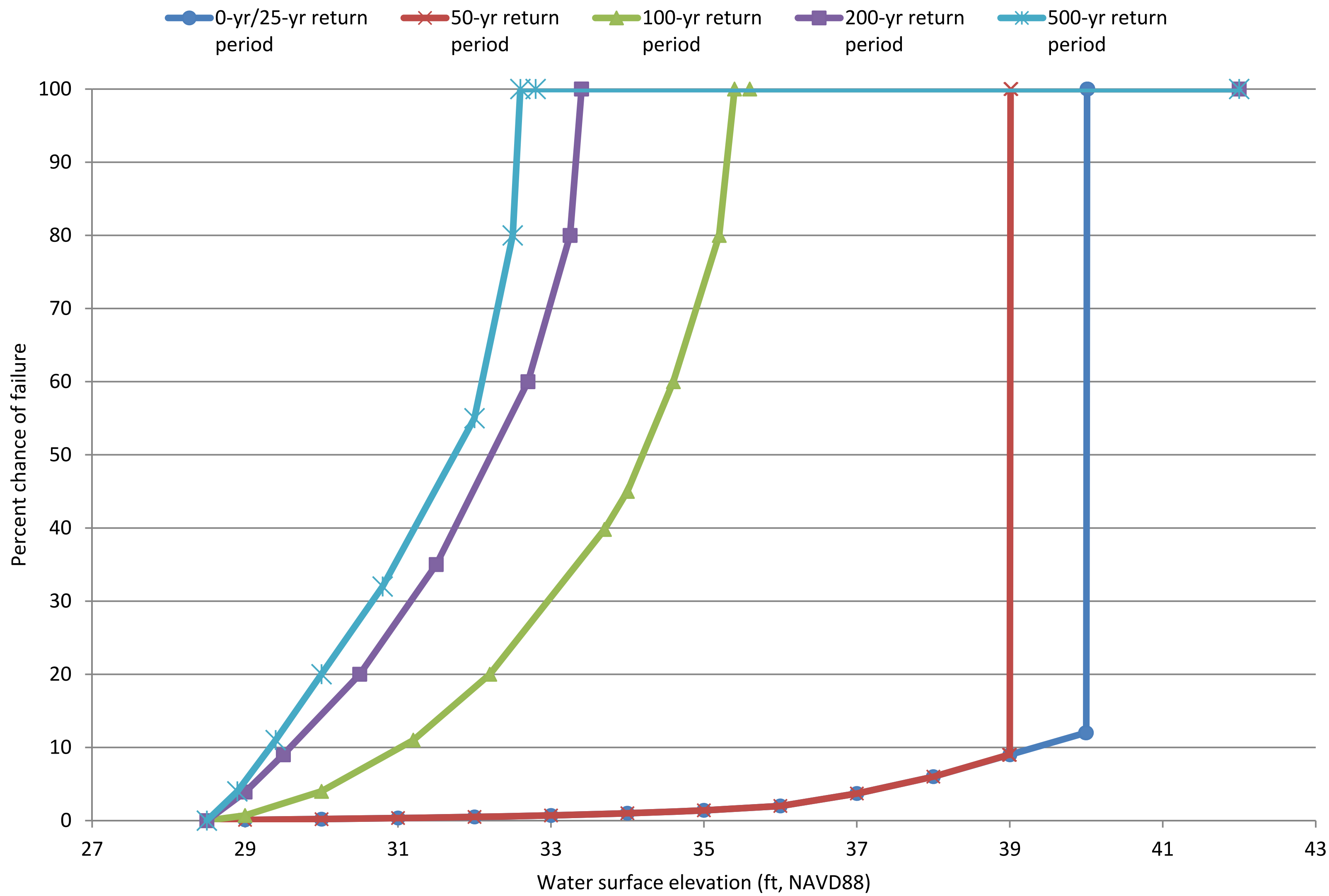

Figure 7. Index point 1 seismic fragility curve set 2

Table 23. Index point 1 seismic fragility curve set 3

0-yr / 25-yr return period		50-yr return period		100-yr return period		200-yr return period		500-yr return period	
Water surface elevation (ft NAVD88)	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**
28.50	0.0000	28.50	0.0000	28.50	0.0000	28.50	0.0000	28.50	0.0000
29.00	0.0010	29.00	0.0010	30.00	0.0070	30.00	0.0090	30.00	0.0100
30.00	0.0020	30.00	0.0020	33.00	0.0150	33.00	0.0200	33.00	0.0250
31.00	0.0035	31.00	0.0035	36.00	0.0350	36.00	0.0450	36.00	0.0600
32.00	0.0050	32.00	0.0050	39.69	0.1400	39.39	0.1500	39.19	0.1600
33.00	0.0070	33.00	0.0070	39.70	0.1400	39.40	0.1500	39.20	0.1600
34.00	0.0100	34.00	0.0100	39.71	1.0000	39.41	1.0000	39.21	1.0000
35.00	0.0140	35.00	0.0140	39.72	1.0000	39.42	1.0000	39.22	1.0000
36.00	0.0200	36.00	0.0200	42.00	1.0000	42.00	1.0000	42.00	1.0000
37.00	0.0370	37.00	0.0370	--	--	--	--	--	--
38.00	0.0600	38.00	0.0600	--	--	--	--	--	--
39.00	0.0900	39.00	0.0900	--	--	--	--	--	--
39.99	0.1200	39.99	0.1200	--	--	--	--	--	--
40.00	0.1200	40.00	0.1200	--	--	--	--	--	--
40.01	1.0000	40.01	1.0000	--	--	--	--	--	--
40.02	1.0000	40.02	1.0000	--	--	--	--	--	--
42.00	1.0000	42.00	1.0000	--	--	--	--	--	--

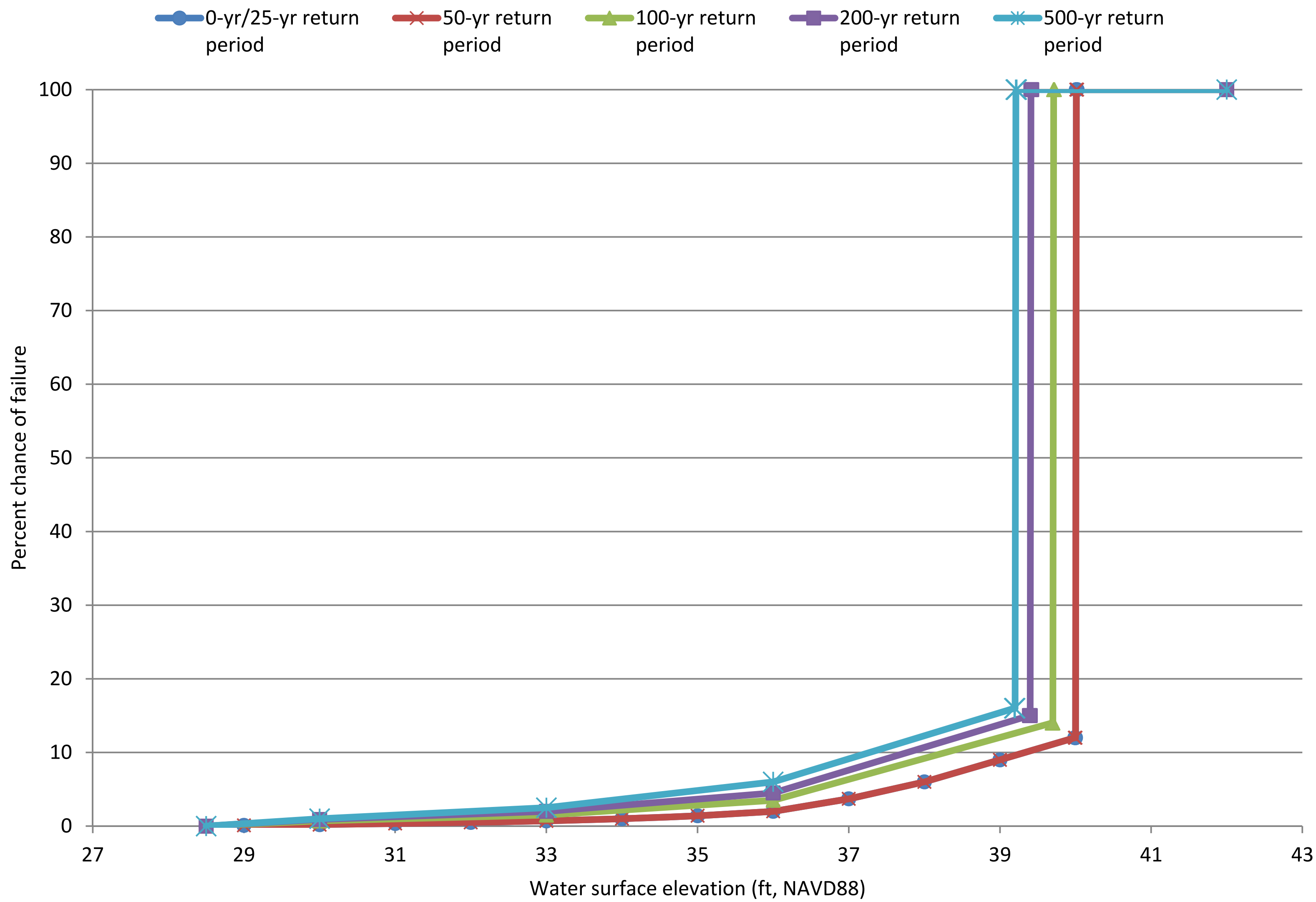

Figure 8. Index point 1 seismic fragility curve set 3

Table 24. Index point 2 seismic fragility curve set 1

0-yr / 25-yr return period		50-yr return period		100-yr return period		200-yr return period		500-yr return period	
Water surface elevation (ft NAVD88)	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**
20.50	0.0000	20.50	0.0000	20.50	0.0000	20.50	0.0000	20.50	0.0000
21.00	0.0005	21.00	0.0005	21.00	0.0005	21.00	0.0010	21.00	0.0010
22.00	0.0010	22.00	0.0010	22.00	0.0020	22.00	0.0030	22.00	0.0030
23.00	0.0015	23.00	0.0015	23.00	0.0040	23.00	0.0100	23.00	0.0100
24.00	0.0020	24.00	0.0020	24.00	0.0070	24.00	0.0150	24.00	0.0200
25.00	0.0025	25.00	0.0025	25.00	0.0150	25.00	0.0250	25.00	0.0350
26.00	0.0030	26.00	0.0030	26.00	0.0250	26.00	0.0400	26.00	0.0550
27.00	0.0035	27.00	0.0035	27.00	0.0350	27.00	0.0600	27.00	0.0800
28.00	0.0050	28.00	0.0050	28.00	0.0520	28.00	0.1000	27.50	0.1000
29.00	0.0060	29.00	0.0060	29.50	0.1000	29.50	0.2000	28.00	0.1250
30.00	0.0080	30.00	0.0080	31.20	0.2000	31.00	0.3500	29.00	0.2000
31.00	0.0110	31.00	0.0120	33.00	0.3500	33.20	0.6000	30.00	0.2950
32.00	0.0140	32.00	0.0160	35.20	0.6000	34.60	0.8000	30.50	0.3500
33.00	0.0200	33.00	0.0250	36.60	0.8000	35.20	0.9100	32.70	0.6000
34.00	0.0390	34.00	0.0430	37.20	0.9100	35.49	1.0000	34.10	0.8000
35.00	0.0650	35.00	0.0700	37.49	1.0000	35.50	1.0000	34.70	0.9100
36.00	0.0900	36.00	0.1000	37.50	1.0000	42.00	1.0000	34.99	1.0000
37.00	0.1100	37.00	0.1250	42.00	1.0000	--	--	35.00	1.0000
38.00	0.1300	38.00	0.1500	--	--	--	--	42.00	1.0000
39.00	0.1520	39.00	0.1750	--	--	--	--	--	--
40.00	0.1750	39.49	0.1950	--	--	--	--	--	--

0-yr / 25-yr return period		50-yr return period		100-yr return period		200-yr return period		500-yr return period	
Water surface elevation (ft NAVD88)	Conditional probability of levee failure	Water surface elevation (ft NAVD88)	Conditional probability of levee failure	Water surface elevation (ft NAVD88)	Conditional probability of levee failure	Water surface elevation (ft NAVD88)	Conditional probability of levee failure	Water surface elevation (ft NAVD88)	Conditional probability of levee failure
40.50	0.1900	39.50	0.1950	--	--	--	--	--	--
40.50	0.1900	39.51	1.0000	--	--	--	--	--	--
40.51	1.0000	39.52	1.0000	--	--	--	--	--	--
40.52	1.0000	42.00	1.0000	--	--	--	--	--	--
42.00	1.0000	--	--	--	--	--	--	--	--

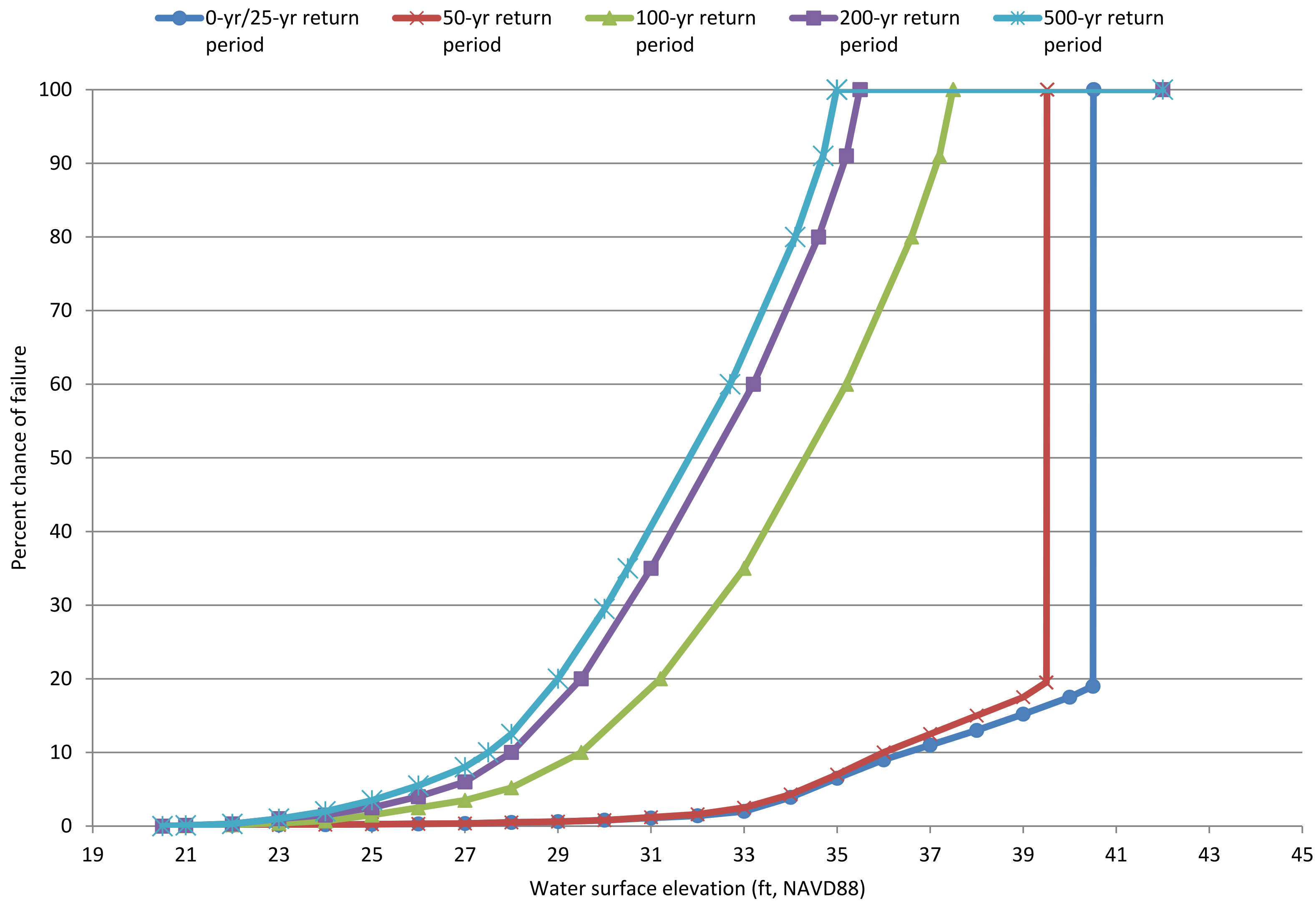

Figure 9. Index point 2 seismic fragility curve set 1

Table 25. Index point 2 seismic fragility curve set 2

0-yr / 25-yr return period		50-yr return period		100-yr return period		200-yr return period		500-yr return period	
Water surface elevation (ft NAVD88)	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**
20.50	0.0001	20.50	0.0001	20.50	0.0001	20.50	0.0000	20.50	0.0001
21.00	0.0005	21.00	0.0006	25.00	0.0010	25.00	0.0090	25.00	0.0200
22.00	0.0011	22.00	0.0015	28.00	0.0600	28.00	0.1200	28.00	0.1500
23.00	0.0017	23.00	0.0018	30.00	0.1600	29.00	0.1800	30.00	0.3500
24.00	0.0022	24.00	0.0023	32.00	0.3000	30.00	0.2800	32.00	0.5800
25.00	0.0027	25.00	0.0028	34.00	0.5200	30.50	0.3400	33.60	0.8000
26.00	0.0032	26.00	0.0033	36.00	0.7600	32.70	0.6000	34.40	1.0000
27.00	0.0037	27.00	0.0037	37.00	1.0000	34.10	0.8000	34.60	1.0000
28.00	0.0055	28.00	0.0055	37.00	1.0000	34.70	0.9100	42.00	1.0000
29.00	0.0065	29.00	0.0065	42.00	1.0000	34.99	1.0000	--	--
30.00	0.0085	30.00	0.0085	--	--	35.00	1.0000	--	--
31.00	0.0115	31.00	0.0130	--	--	42.00	1.0000	--	--
32.00	0.0150	32.00	0.0170	--	--	--	--	--	--
33.00	0.0200	33.00	0.0260	--	--	--	--	--	--
34.00	0.0410	34.00	0.0450	--	--	--	--	--	--
35.00	0.0650	35.00	0.0750	--	--	--	--	--	--
36.00	0.0950	36.00	0.1100	--	--	--	--	--	--
37.00	0.1150	37.00	0.1350	--	--	--	--	--	--
38.00	0.1350	38.00	0.1550	--	--	--	--	--	--
39.00	0.1520	38.99	0.1800	--	--	--	--	--	--
40.00	0.1750	39.00	0.1980	--	--	--	--	--	--

0-yr / 25-yr return period		50-yr return period		100-yr return period		200-yr return period		500-yr return period	
Water surface elevation (ft NAVD88)	Conditional probability of levee failure	Water surface elevation (ft NAVD88)	Conditional probability of levee failure	Water surface elevation (ft NAVD88)	Conditional probability of levee failure	Water surface elevation (ft NAVD88)	Conditional probability of levee failure	Water surface elevation (ft NAVD88)	Conditional probability of levee failure
40.50	0.1900	39.01	0.1980	--	--	--	--	--	--
40.50	0.1900	39.02	1.0000	--	--	--	--	--	--
40.51	1.0000	42.00	1.0000	--	--	--	--	--	--
40.52	1.0000	--	--	--	--	--	--	--	--
42.00	1.0000	--	--	--	--	--	--	--	--

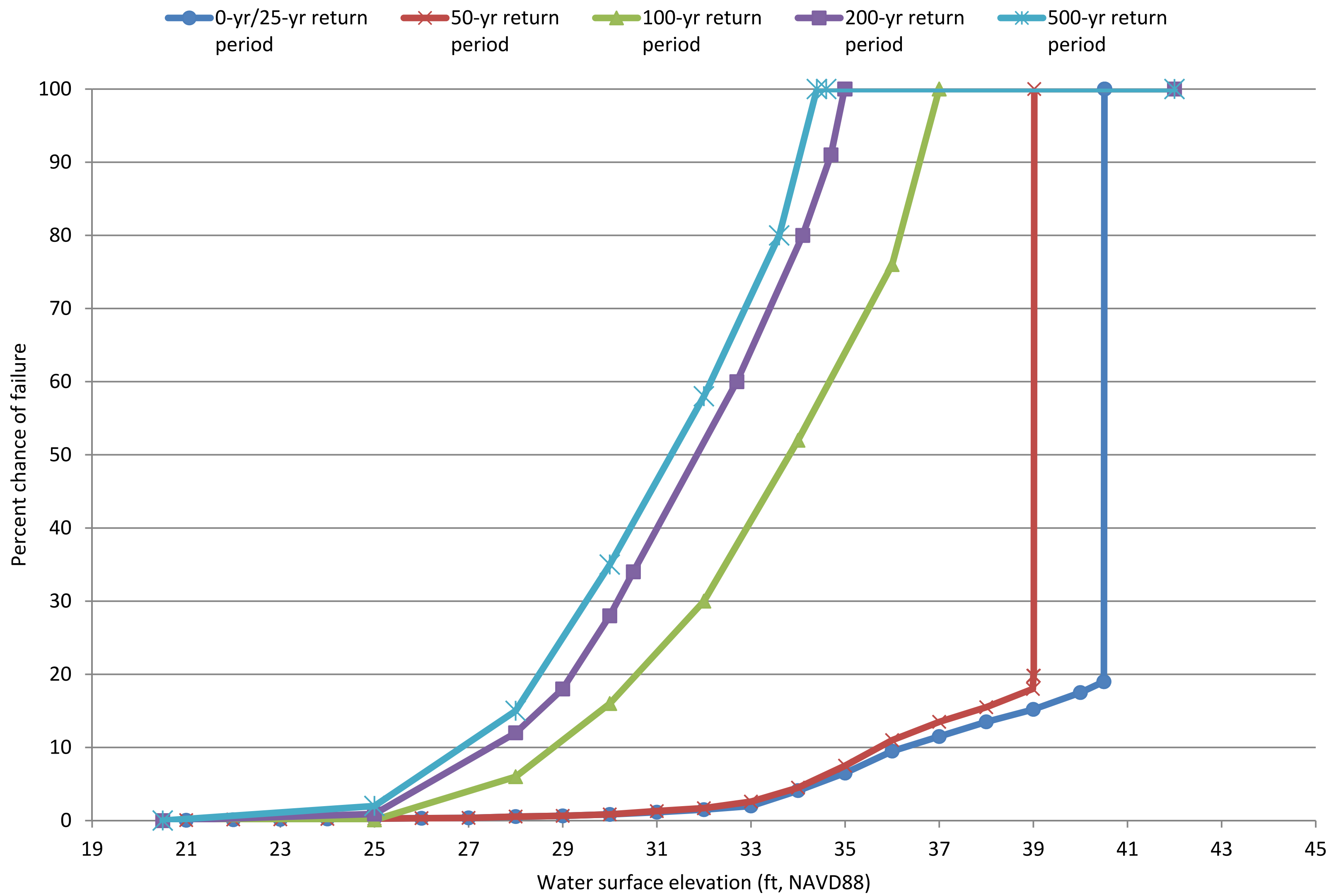

Figure 10. Index point 2 seismic fragility curve set 2

Table 26. Index point 2 seismic fragility curve set 3

0-yr / 25-yr return period		50-yr return period		100-yr return period		200-yr return period		500-yr return period	
Water surface elevation (ft NAVD88)	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**	**Water surface elevation (ft NAVD88)**	**Conditional probability of levee failure**
20.50	0.0001	20.50	0.0001	20.50	0.0000	20.50	0.0000	20.50	0.0000
21.00	0.0001	21.00	0.0001	25.00	0.0010	25.00	0.0010	25.00	0.0010
22.00	0.0002	22.00	0.0002	28.00	0.0030	28.00	0.0040	28.00	0.0050
23.00	0.0002	23.00	0.0002	31.00	0.0150	31.00	0.0200	31.00	0.0250
24.00	0.0003	24.00	0.0003	33.00	0.0320	33.00	0.0400	33.00	0.0500
25.00	0.0005	25.00	0.0005	36.00	0.1100	36.00	0.1200	36.00	0.1300
26.00	0.0008	26.00	0.0008	39.74	0.1900	39.29	0.1950	38.89	0.2000
27.00	0.0012	27.00	0.0012	39.75	0.1950	39.30	0.1950	38.90	0.2000
28.00	0.0020	28.00	0.0020	39.75	1.0000	39.31	1.0000	38.91	1.0000
29.00	0.0030	29.00	0.0030	39.75	1.0000	39.32	1.0000	38.92	1.0000
30.00	0.0048	30.00	0.0048	42.00	1.0000	42.00	1.0000	42.00	1.0000
31.00	0.0080	31.00	0.0080	--	--	--	--	--	--
32.00	0.0120	32.00	0.0120	--	--	--	--	--	--
33.00	0.0200	33.00	0.0200	--	--	--	--	--	--
34.00	0.0400	34.00	0.0400	--	--	--	--	--	--
35.00	0.0600	35.00	0.0600	--	--	--	--	--	--
36.00	0.0900	36.00	0.0900	--	--	--	--	--	--
37.00	0.1100	37.00	0.1100	--	--	--	--	--	--
38.00	0.1300	38.00	0.1300	--	--	--	--	--	--
39.00	0.1520	39.00	0.1520	--	--	--	--	--	--
40.00	0.1750	40.00	0.1750	--	--	--	--	--	--

0-yr / 25-yr return period		50-yr return period		100-yr return period		200-yr return period		500-yr return period	
Water surface elevation (ft NAVD88)	Conditional probability of levee failure	Water surface elevation (ft NAVD88)	Conditional probability of levee failure	Water surface elevation (ft NAVD88)	Conditional probability of levee failure	Water surface elevation (ft NAVD88)	Conditional probability of levee failure	Water surface elevation (ft NAVD88)	Conditional probability of levee failure
40.50	0.1900	40.50	0.1900	--	--	--	--	--	--
40.50	0.1900	40.50	0.1900	--	--	--	--	--	--
40.51	1.0000	40.51	1.0000	--	--	--	--	--	--
40.52	1.0000	40.52	1.0000	--	--	--	--	--	--
42.00	1.0000	42.00	1.0000	--	--	--	--	--	--

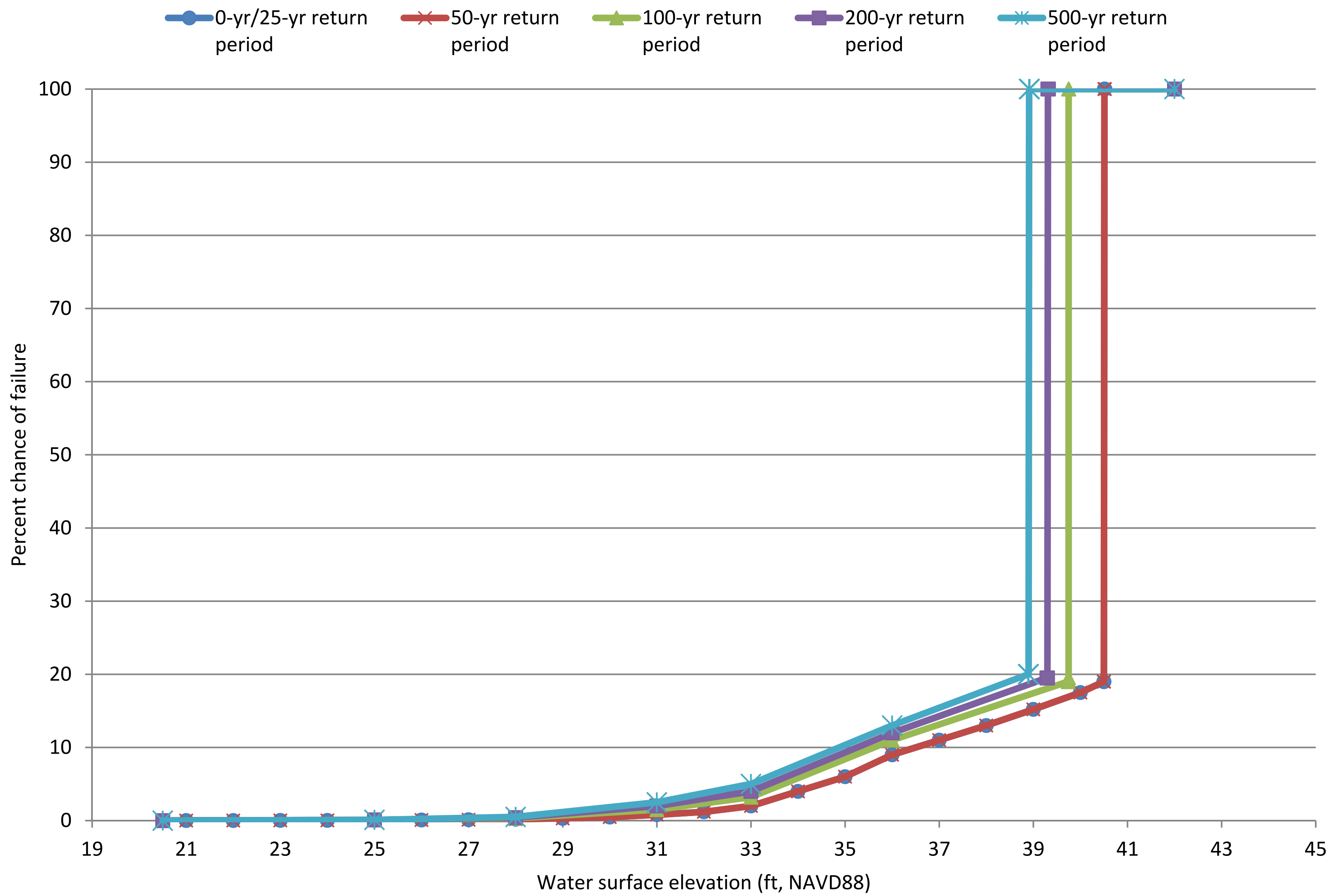

Figure 11. Index point 2 seismic fragility curve set 3

Attachment 3. References

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APPENDIX C

Responses to Comments on Draft Report

AGENCY COMMENTS

Client	DWR	Contract Number:	4600008101
Program Name	DWR Urban Levee Geotechnical Evaluations Program		
Document in Review/Rev No.	Cost-Benefit Study of Remediating West Sacramento Levees for Seismic Hazard	Document Date:	November-14
Reviewers:	DWR, Vlad Perlea, USACE, ICB	Review Date:	December 10, 2014
Responder:	URS	Response Date:	January 2, 2015
Verified by:		Verification Date:	

[1]Status: A = Will Incorporate; B = Needs further Discussions; C = Comment Acknowledged/No Action Needed

No.	Reference	Comment	Status[1]	Response to Comments	Response Verified	Included In Report
Ariya Balakrishnan and Steve Mahnke						
1	General	Please include a brief write up at the end of executive summary (as we discussed in the Dec. 3rd meeting) about the general conclusion of this study and how it supports the profession's thinking in regards to seismic remediation of intermittently loaded levees. Also include key assumptions used in the cost benefit study that might change the benefit-cost ratio.	A	The executive summary now includes a conclusion section as we discussed in the December 3 meeting.		
2	General	Fragility functions/Scenarios: As discussed in the Dec. 3rd meeting, please provide additional explanations and assumptions used to develop fragility curves for each scenario. Especially for Scenario 3 to properly model the damage due to a second earthquake in the two year window, one should consider the probability of occurring two earthquakes within two years in the same region. In addition, different damaged conditions should be used when developing fragility curves based on intensity of the first earthquake. Please indicate that this level of detail was not incorporated in the study and list the assumptions used to develop fragility curves in each scenario	A	Concur. As discussed in December 2014 meeting assumptions are included in appropriate sections of the report.		
3	Section 3	Throughout the report it is called conditional failure probability function. We understand that the fragility function is based on many assumptions. It would be good to list some of those conditions, e.g. the failures are mainly due to overtopping not initiated by seepage.	A	Concur. Key assumptions are included in appropriate subsections.		
4	Section 3	Results of the Seismic analysis, Section 3.4.4.2: the last paragraph on page 3-8 says that the vertical displacements were assumed to be ½ of the estimated lateral displacements using the correlations. However, in Table 3-1 indicates that the vertical crest displacement can be 0.7 times the deviator deformation. Please acknowledge the differences and mention that the factor ½ was considered for this study based on the limited FLAC analysis results.	A	Concur. Text has been revised per the comment.		

AGENCY COMMENTS

[1]Status: A = Will Incorporate; B = Needs further Discussions; C = Comment Acknowledged/No Action Needed

No.	Reference	Comment	Status[1]	Response to Comments	Response Verified	Included In Report
5	Section 3	Results of the Seismic Analysis, Section 3.4.4.2: Figures 3-11 and 3-12 shows average vertical deformation in one reach increases with increasing WSE while the other reach shows the opposite. Please provide explanation for this kind of behavior in the report.	A	Concur. A brief explanation is added per comment.		
6	Appendix B (Section 5)	Please include more details about how the earthquake and flood loads were applied in combinations with fragility curves in Task 1 and Task 2. As discussed, please clearly state the assumptions including that the levees will be brought back to original condition within a year for scenarios 1 and 2 in Task 1 and 2; however it will be 2 years for scenario 3 in Task 2.	A	Concur. Text has been revised per the comment.		
7	Table 3-3	Table 3-3: Please provide the 10-year flood water surface elevation in the table.	A	Concur. 10-year flood elevations are included now.		
8	Table 4-1	The average cost per 1000 feet of levee is same as the total remediation cost. Please make necessary changes.	A	Concur. The format of this table has been revised based on internal comments.		
Vlad Perlea, USACE						
9	Tables 3-4, 3-5, and 3-7	I understand that, at the present stage, review of all previous steps is not appropriate; however the assumptions considered in the evaluation of stabilized zone strength should be stated, at least as a note under the tables. Minimum details should be provided for someone to understand why the estimated Φ′ for SC w/ARR of 25% was 33°, 35° or 36°.	A	Concur, a footnote is added to the respective tables.		
10	Table 3-6	I understand that, at the present stage, review of all previous steps is not appropriate; however the assumptions considered in the evaluation of stabilized zone strength should be stated, at least as a note under the table. Minimum justification should be provided for consideration of static strength of the stabilized material, although under seismic loading the rigid material is expected to crack and only the frictional component of the strength may remain mobilized.	A	concur, a footnote is added to the table.		
11	Figures 3-20, 3-22, 3-24, and 3-26	I agree that with the current preliminary design it is not necessary to optimize the remediated zone for a minimum FS close to 1.3. However, a required range for minimum FS should be stated and considered. The current range 1.3 – 2.4 is too large. A range 1.3 - 1.4 seems to me more appropriate. For example, the extent of the landside stabilized zone can be reduced in all four cases.	C	It is a good comment. For this screening level study, we try to target a post-seismic slope stability FS of 1.3-1.5 for the critical slip surfaces.		