

2870 Gateway Oaks Drive, Suite 150
Sacramento, CA 95833
Tel: 916.679.2000 Fax: 916.679.2900

Prepared For Department of Water Resources (DWR) Division of Flood Management
Project Non-Urban Levee Evaluations Project
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Subject Fragility Curve Development
Prepared By Derek Morley and Richard Millet (URS), Rick Stauber (Kleinfelder)
Reviewed By Sujan Punyamurthula and Loren Murray (URS)

INTRODUCTION

This technical memorandum summarizes the approach used in developing a suite of fragility curves provided to the Central Valley Flood Management Planning Program (CVFMP) team for use in damage modeling and for preparing the 2012 Central Valley Flood Protection Plan (CVFPP). A previous version of this technical memorandum was submitted to DWR in December 2010 with the original submittal of fragility curves. Subsequently, refinement of some fragility curves and development of additional fragility curves was performed. This version of the technical memorandum includes updated information.

The Scope of Work for this Task Order U108 consisted of developing fragility curves for Non-Urban Levee Evaluation (NULE) and Urban Levee Evaluation (ULE) levee segments in the Sacramento (North) and San Joaquin (South) river basins. This technical memorandum and the subject fragility curves and fragility curve tool have been produced by URS Corporation and Kleinfelder consulting teams together. The fragility curves are based on available existing (November 2010) geotechnical data; no new data were collected for this task.

The Levee Evaluations Program includes the ULE Project, covering Project and appurtenant non-Project levees in highly populated areas, and the NULE Project covering the remaining Project and appurtenant non-Project levees. The ULE Project includes approximately 400 miles of State-Federal Project (Project) levees and non-State-Federal Project (non-Project) levees protecting populations of 10,000 people or more and the NULE Project includes the remaining Project levees protecting populations of fewer than 10,000 people. Non-Project levees are considered appurtenant and are included in the NULE project when these levees protect part of a basin partially protected by Project levees or may impact the performance of Project levees.

In Phase 1 of the NULE project, existing data were assessed to categorize levees by hazard level and results were provided in the Geotechnical Assessment Reports (GAR) (URS, 2011; Kleinfelder, 2011) as follows:

- **Hazard Level A.** When water reaches the assessment water surface elevation, there is a low likelihood of either levee failure or the need to flood-fight to prevent levee failure.
- **Hazard Level B.** When water reaches the assessment water surface elevation, there is a moderate likelihood of either levee failure or the need to flood-fight to prevent levee failure.

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- **Hazard Level C.** When water reaches the assessment water surface elevation, there is a high likelihood of either levee failure or the need to flood-fight to prevent levee failure.
- **Lacking Sufficient Data (LD):** Currently lacking sufficient data regarding past performance or hazard indicators.

Flood-fight refers to actions associated with geotechnical failure modes, not flood-fighting to prevent overtopping.

The category *lacking sufficient data* indicates that the available data do not resolve potential discrepancies between the expected performance of the levee and the actual past performance or that the existing data are contradictory or ambiguous. The category does not necessarily indicate that insufficient data were available to assess the levee segment. Where assessment data were not available, the levee segment was not assessed.

The NULE program has assessed individual levee *segments*, which were generally 2 to 5 miles long, but were as long as 25 miles at some locations. In the ULE program, based upon an initial phase of geotechnical evaluation, field exploration, and laboratory testing, levees in each Urban study area were subdivided into *reaches*, typically 1000 feet to 3000 feet long.

To begin the task of developing fragility curves, the North and South NULE teams reviewed the data collected and conclusions drawn during preparation of the NULE Draft GARs (prepared 2010). For the ULE study areas, the ULE teams reviewed data and analysis results from the ULE Technical Review Memoranda, Phase 1 Geotechnical Data Reports, Phase 1 Geotechnical Evaluation Reports, and where already prepared, Supplemental Geotechnical Data Reports. Each team compiled and summarized key performance events relevant to preparation of fragility curves, such as information related to historical levee failures and estimates of the water surface elevation during these events, using readily available records.

Based upon review and compilation of this information, a standard set of fragility curves was developed for application to ULE reaches and NULE levee segments. An Expert Panel was formed to provide expertise, advice and review (Table 1). The comments and suggestions of the levee Expert Panel have been incorporated in the development of two separate fragility curve tools (Excel workbooks), one for NULE levees and one for ULE levees. These tools incorporate and make use of data generated during earlier ULE and NULE work, and provide the user options for generating fragility curves.

Table 1. Expert Panel

Name	Organization
David Ford (facilitator)	David Ford Consulting
Ray Costa	Consultant to DWR
Mike Inamine	DWR
Steve Verigen	GEI
Les Harder	HDR
Scott Anderson	Kleinfelder
Pat Dell	Neil O. Anderson and Associates
Ram Kulkarni	URS Corporation
Michael Ramsbotham	USACE
Ed Ketchum	USACE

Initially, a pilot study was planned to evaluate the applicability of the fragility curve tool by testing about five fragility curves in the current CVFMP hydraulic model and the damage model used by DWR and its consultants to assess future damages. However, after working with DWR and its consultants, it was decided that a pilot study with so few new curves would not be as valuable as initially assumed. The limited number of new fragility curves compared to the total number of fragility curves in the CVFMP model would be inadequate to provide a sufficient basis for evaluating the model outputs. Instead, a sensitivity study was performed to evaluate both the viability and the effect of varying parameters in the fragility curve tool on estimated damages. Additionally, preliminary hydraulic modeling was conducted by DWR’s consultants using a complete set of preliminary fragility curves to evaluate (1) how these draft fragility curves fit in the existing hydraulic model¹, and (2) the number of levee failures predicted using the model and the preliminary fragility curves. Refinement of the preliminary NULE and ULE fragility curve tools followed the sensitivity analysis and the preliminary hydraulic modeling.

Fragility curves for anomalous hazards have also been provided. Anomalous hazards are short sections of levees (few to hundreds of feet long) for which:

- (a) the conditions are known to be different from the rest of the segment or reach;
- (b) the current scope of levee assessment approaches used in ULE and NULE Phase 1 do not lend themselves to further detailed analyses of the hazard at these sites (e.g. analyses of structures, penetrations, encroachments);
- (c) in many cases, the anomalous conditions are associated with observations of past poor performance, and/or
- (d) available information in the area with anomalous conditions suggests that it may be susceptible to failing in one of the four failure modes assessed in NULE Phase 1 (underseepage, stability, through seepage or erosion).

¹ The hydraulic model and the ULE/NULE fragility curves were based on different topographic models. Where discrepancies were encountered, elevations from the newer ULE/NULE topographic model were used.

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Anomalous hazards are not related to the potential for overtopping (e.g. low spots in a levee crown at a bridge or ramp) as overtopping is not included as a failure mode.

Deliverables for this Task Order include this memo, the ULE and NULE fragility curve Excel tools, and files with NULE and ULE fragility curves for subsequent hydraulic and damage modeling. The fragility curves and the NULE and ULE Excel tools (workbooks) have been provided to DWR separately. The NULE Excel workbook includes fragility curves for each NULE segment, many more than the number of segments included in the original Scope of Work. Additionally, the CVFMP hydraulic and damage modeling was found to include some levee segments that were not included within either the ULE or NULE scope of study. For these segments, fragility curves were prepared using the NULE fragility curve tool and approach (described below), although the data upon which these curves were based were much more limited than the data used as a basis for segments included in the NULE scope of study.

TECHNICAL APPROACH

Fragility curves developed for this task provide relationships between river water surface elevation (or stage) and the probability that the levee segment will fail when exposed to that water surface elevation. In this application “failure” is defined as a levee breach in which water from the flood side of the levee is allowed to flow in an uncontrolled manner to the landside of the levee, potentially inundating the assets protected by the levee. The approach used to develop fragility curves in this task generally follows a process similar to that described in the U.S. Army Corps of Engineers Manual ETL 1102-2-556 (USACE, May, 1999).

Figure 1 provides three example fragility curves. The probability of failure is plotted on the vertical axis and water surface elevation is plotted on the horizontal axis; some previous studies (e.g. Comprehensive Study, USACE, 2001) have shown probability of failure on the horizontal axis. We have chosen to show probability of failure here and in the tools developed for generating the fragility curves on the vertical axis. The range of water surface elevations of interest begin at the toe of the levee, below which the probability of failure is assumed to be zero, to the levee crest, where the probability of failure is assumed to be 100% because of overtopping. The three example fragility curves shown include a poor levee, a good levee and a generic fragility curve. The good levee has a low probability of failure until higher water levels are reached and is concave upward, while the poor levee has high probability of failure even at low water surface elevations, and is concave downward. The generic fragility curve includes elements of both the poor and the good levee and follows a characteristic fragility curve “s” shape. An assessment water surface elevation is shown in Figure 1.

For NULE levees, the earlier Phase 1 assessments consider the likely performance only at a single design or assessment water surface elevation. Figure 1 shows “PNP” and “PFP”, the probable non-failure point and the probable failure point, respectively. Previous studies developing fragility curves for Central Valley levees (e.g. Comprehensive Study, USACE, 2001) have made use of these terms; in this study, however, we have not used these terms.

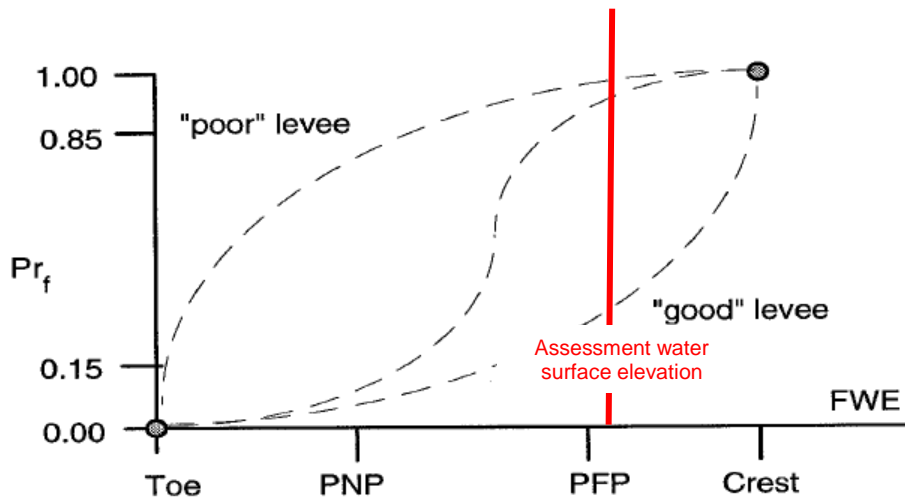


Figure 1. Conceptual fragility curves examples

Development of fragility curves for NULE segments

In Phase 1 of the NULE program, existing data were collected and used to characterize the levees. As described above, each levee segment was categorized A, B, C or LD. The categorization was done for each of four failure modes: underseepage, stability, through seepage and erosion, and was also done cumulatively for the levee as a whole. It is important to note that the categorization was performed for only one water level, the assessment water surface elevation, which, where available, was the 1955/57 water surface (for further information regarding water surface elevations used, refer to the *Recommended Water Surface Elevations Approach for Geotechnical Assessment* Technical Memorandum dated April 26, 2011, included in Appendix B in the NULE Geotechnical Assessment Report). All NULE characterizations and results are, therefore, for the single assessment water surface elevation. To produce fragility curves for each NULE segment, fragility curves for each failure mode were developed. These independent failure mode fragility curves are then mathematically combined to produce the cumulative or overall fragility curve for the segment. Thus, two levees with similar failure mode categorizations and similar topographic profiles will have very similar fragility curves.

Topographic information necessary for fragility curve development includes the levee crest elevation, the levee toe elevation, and the assessment water surface elevation. Topographic data used in this study for development of fragility curves were based on two sources: levee center line survey data obtained from the California Levee Database and project specific LiDAR surveys.

Little additional data were used to generate the NULE fragility curves; however, abundant data on past performance and past flood water levels collected during Phase 1 was used to calibrate and review the parameters selected in developing the fragility curves.

To make use of the failure mode categorizations assigned in NULE to each segment, it was

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necessary to assign a probability of failure at the assessment water surface elevation for A, B and C categories. Such probability of failure values were not explicitly included in the NULE GAR, and part of the efforts expended in this task involved discussions and sensitivity analyses to constrain the values used for each category. Based on review of the sensitivity analysis and input from the Expert Panel, the values for each category, at the assessment water surface elevation, are: A -0.5%, B – 2%, and C -16%. These points, which define the fragility curve at the assessment water surface elevation, are called the “pin points”. Figure 2 shows an example of three schematic fragility curves for a single failure mode, categories A (green), B (yellow) and C (red) curves. The stars represent the pin points, or probability of failure at the assessment water surface elevation for each category. It is important to note that the values used here for the pin point probabilities are for the purposes of this fragility curve effort; they should not retroactively be imposed on the NULE GAR.

For NULE fragility curves there are thus three water surface elevations used to define the fragility curves: (1) the levee toe elevation at which the probability of failure is assumed to be zero, (2) the levee crest elevation at which overtopping will occur and the probability of failure is set to 100 percent, and (3) the pin point at the assessment water surface elevation (Figure 2). The NULE fragility curve Excel tool simply fits a curve through these three points for each failure mode using the assigned probability of failure at the assessment water surface elevation. Below the assessment water surface elevation the curve is fit using a “concavity factor” that ranges between 0 and 1, with 0 yielding a curve of constant slope of no concavity, and 1 yielding a curve that is concave upward and very steep at the assessment water surface elevation. At this time, a concavity factor of 0.5 was used for all fragility curves based on the results of the sensitivity analyses. The fragility curves are extended above the assessment water surface elevation based on their slope as they approach the assessment water level. A and B curves extend at constant slope (although the schematic example in Figure 2 shows a curving line), and C curves roughly mirror the shape of the curve below the assessment water surface elevation. The same probability values are used for every A, B or C pin point – e.g., all B fragility curves have been assigned a probability of failure of 2% at the assessment water surface elevation, independent of the failure mode, the size of the levee, or other differences in levees. For levee segments categorized LD, pin point values between those of A and B or B and C are used, depending on the nature of the LD categorization (e.g. LD [A or B] vs LD [B or C]).

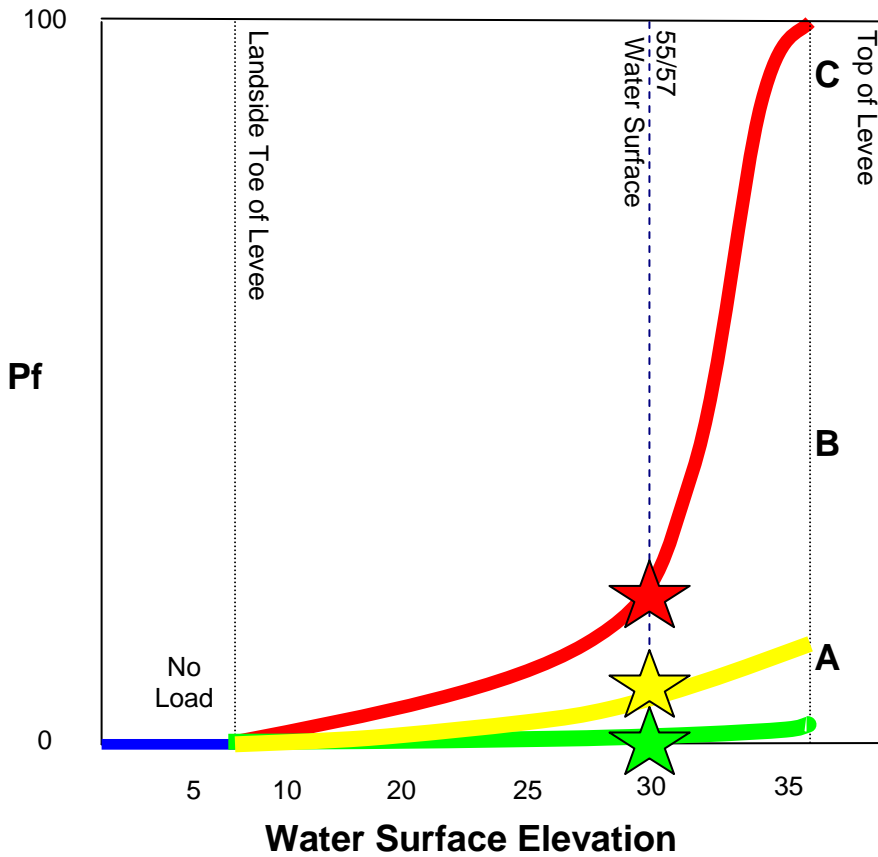


Figure 2. Conceptual NULE fragility curves, categories A, B and C.

Past flood information (the water surface elevation and the record of performance) can be used to calibrate or validate fragility curves for individual segments. We have used basin-wide compilations of past performance to guide us in constraining the chosen pin point probability values.

The four individual failure mode fragility curves are mathematically combined using the conventional probabilistic summing expression:

$$\text{Cumulative probability of failure} = 1 - (1-P(f)\text{underseepage}) (1-P(f)\text{stability}) (1-P(f)\text{through seepage}) (1-P(f)\text{erosion})$$

Figure 3 shows an example of output generated by the NULE fragility curve Excel tool developed for this project. For this example segment, the individual failure modes were categorized in the GAR as: underseepage – B; stability – A; through seepage – LD (B or C); and erosion -C. The levee landside toe is at elevation 13, the crest is at elevation 33, and the assessment water surface elevation was 29 ft, or 4 ft below the levee crest. The yellow line shows the fragility curve for stability, the dark blue line with circles is for underseepage, the light blue line with squares is for through seepage, and the

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green line is for erosion. The black line shows the combined or cumulative fragility curve when the failure mode fragility curves are summed using the expression above. Also shown are vertical lines depicting the assessment water surface elevation and water surface elevations for a number of historical high-water events. The magenta lines show the fragility curves used for this area in the Comprehensive study (USACE, 2001). The solid line shows the Comprehensive study curve at the levee crest elevation used in the NULE program, which was estimated based on LiDAR and California Levee Database (CLD) information. The dashed magenta curve shows the Comprehensive study curve tied to the elevation used in the Comprehensive study.

During our interactions with DWR's modeling consultant, we identified many locations where the elevations used in the Comprehensive study are different from the top-of-levee elevations used in the NULE and ULE studies, which are based on more recent and better constrained topographic data. The team decided to modify the hydraulic model to be consistent with new top-of-levee elevations.

Note that the fragility curves for the failure modes categorized A (stability) and B (underseepage) extend above the assessment water surface to the elevation of the levee crest at nearly a constant slope. This means that this example levee is expected not to fail due to either of these failure modes, even when the water surface reaches the levee crest. The failure mode fragility curves for through seepage and erosion have the more classic "s" shaped fragility curves, as does the combined or cumulative fragility curve. This example fragility curve shows that there is little probability of the levee failing at low water levels, and that the cumulative probability of failure at the assessment water surface elevation is about 25 percent.

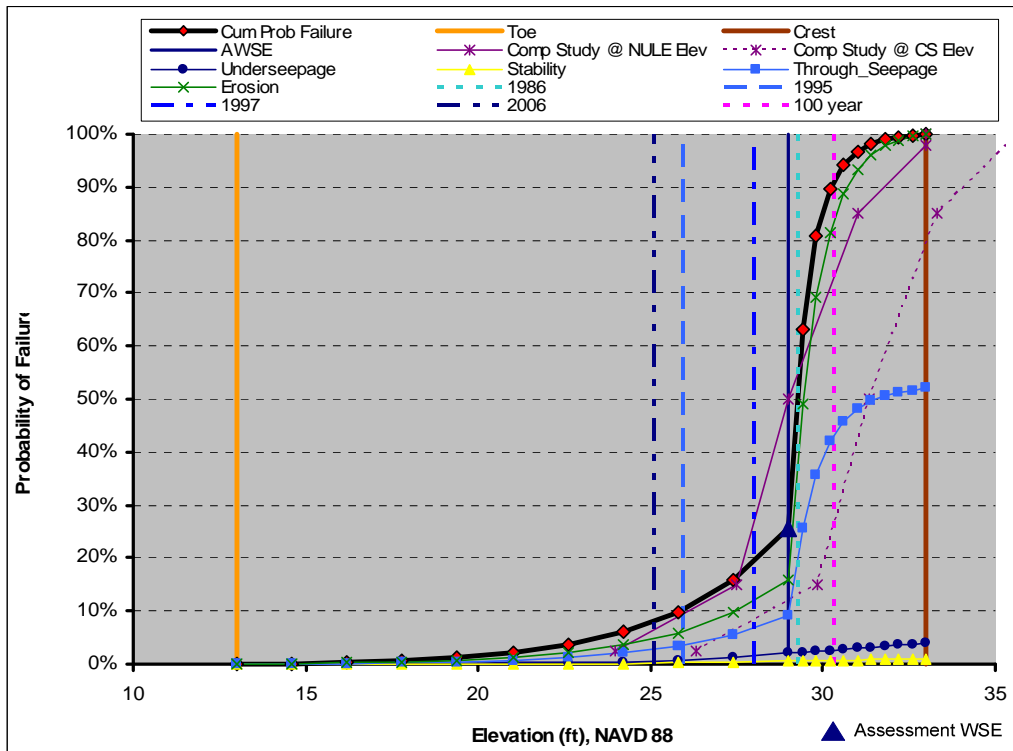


Figure 3. Example NULE fragility curve (with failure mode categories from the GAR of B for underseepage, A for stability, LD (B or C) for through seepage, and C for erosion)

Development of fragility curves for ULE segments

To support the overall basin modeling study, representative reaches and corresponding cross-sections within individual Urban Study Areas were selected for development of fragility curves. A cumulative ULE fragility curve for each of these selected cross sections was prepared based on the individual curves for the same four failure modes assessed in the NULE program (underseepage, stability, through seepage, and erosion).

For steady state underseepage and steady state stability, historical data and field and laboratory geotechnical data collected in the initial phase of the ULE Project were used as input to calculate average vertical exit gradients (*i*) and stability factors of safety (FS) for various flood elevations for each respective cross-section location.

To establish the relationships between (*i*) and probability of failure (Pf) and between stability Factor of Safety (FS) and Pf, input from the Expert Panel and program-specific information were used to generate classic “s” shaped curves (see Figure 4); note that Figure 4 is a generic example. For this study, the following control points were used to develop the applicable “s” curves:

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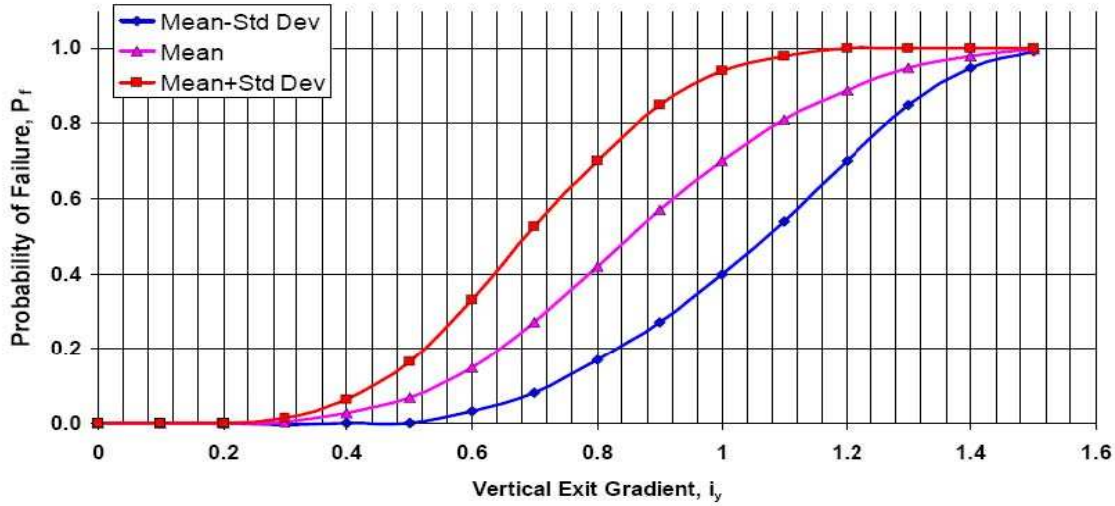


Figure 4. Relationship between vertical exit gradient and probability of failure (from Delta Risk Management Strategy report [2008])

Underseepage $i=0.5$, $P_f = 1\%$ and $i=0.9$, $P_f = 50\%$;

Stability $FS=1.4$, $P_f = 1\%$ and $FS=1.0$, $P_f = 50\%$.

Using these relationships for underseepage and stability, and correlating them to specific results at various river water surface elevations, fragility curves for underseepage and stability were then developed using the same concavity factor (0.5) used in the development of NULE curves. Figures 5 and 6 show examples of ULE fragility curves for the underseepage and stability failure modes.

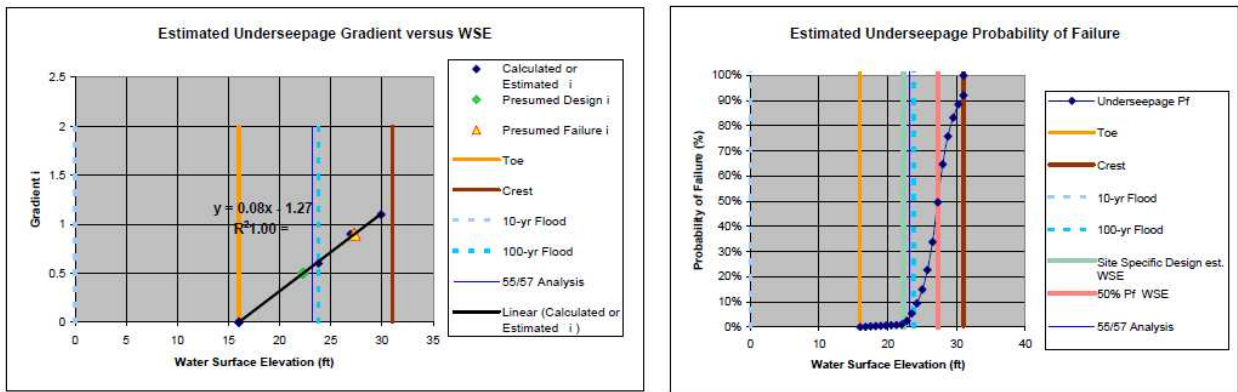


Figure 5. Example ULE underseepage fragility curves

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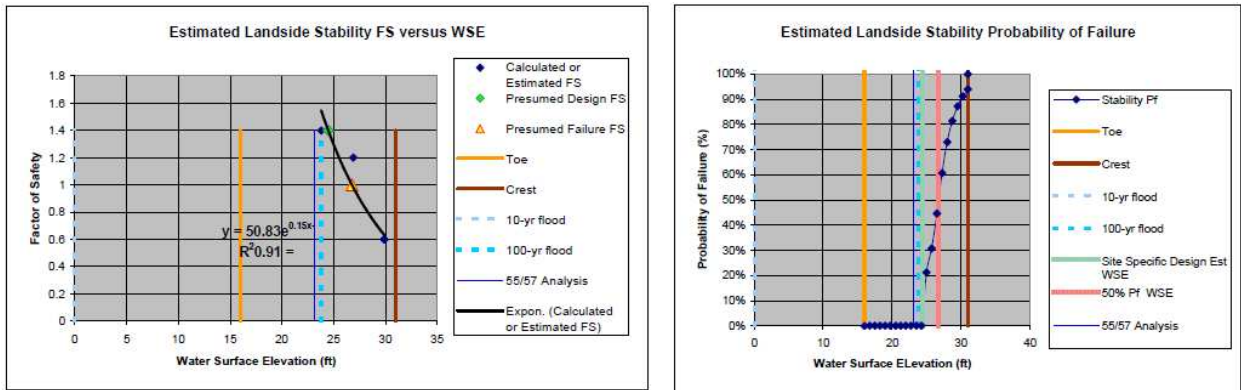


Figure 6. Example ULE stability fragility curves

To develop ULE fragility curves for through seepage, a failure model was developed for landside levee slopes that are composed of erodible materials, typically silts and sands. If these soils are present, then a failure assessment based on the height of seepage “breakout” above the landside toe of the levee was used. The height of seepage breakout above the landside toe was identified from the seepage analyses, which therefore relates the height of seepage breakout to the water surface elevation (flood elevation). The fragility curve model relates the probability of failure to the height of seepage breakout where erodible materials are present – the higher the breakout, the higher the probability of failure. Figure 7 shows the relationship used relating breakout probability of failure versus flood elevation.

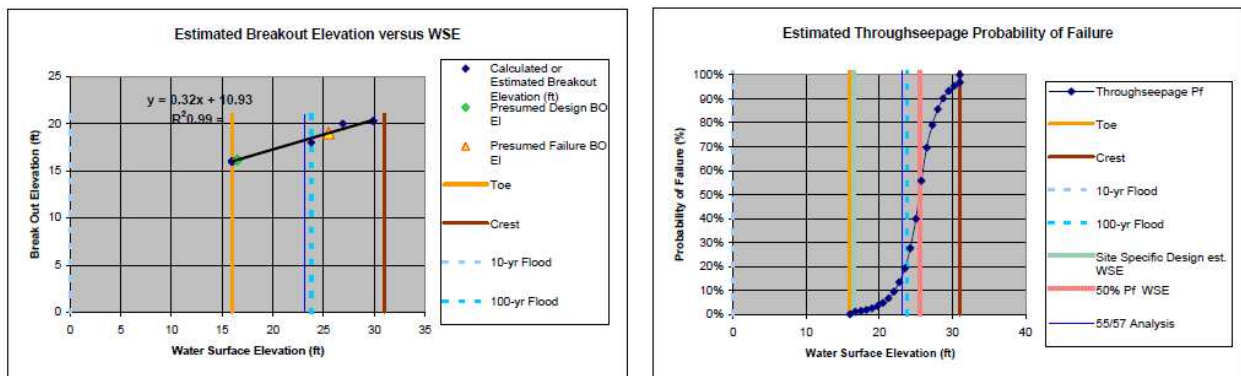


Figure 7. Example ULE through seepage fragility curve

To develop ULE erosion fragility curves, because a formal erosion analyses is not yet available (this work is planned for the final ULE Geotechnical Evaluation Reports), a more qualitative assessment was performed resulting in an erosion A, B, or C classification for each ULE reach for which a fragility curve was developed. The erosion fragility curve developed in NULE described above was then used in the ULE assessment.

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 Sacramento, CA 95833
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The final step was to mathematically combine the four failure modes into one cumulative fragility curve for each selected cross section. Figure 8 provides an example cumulative ULE fragility curve.

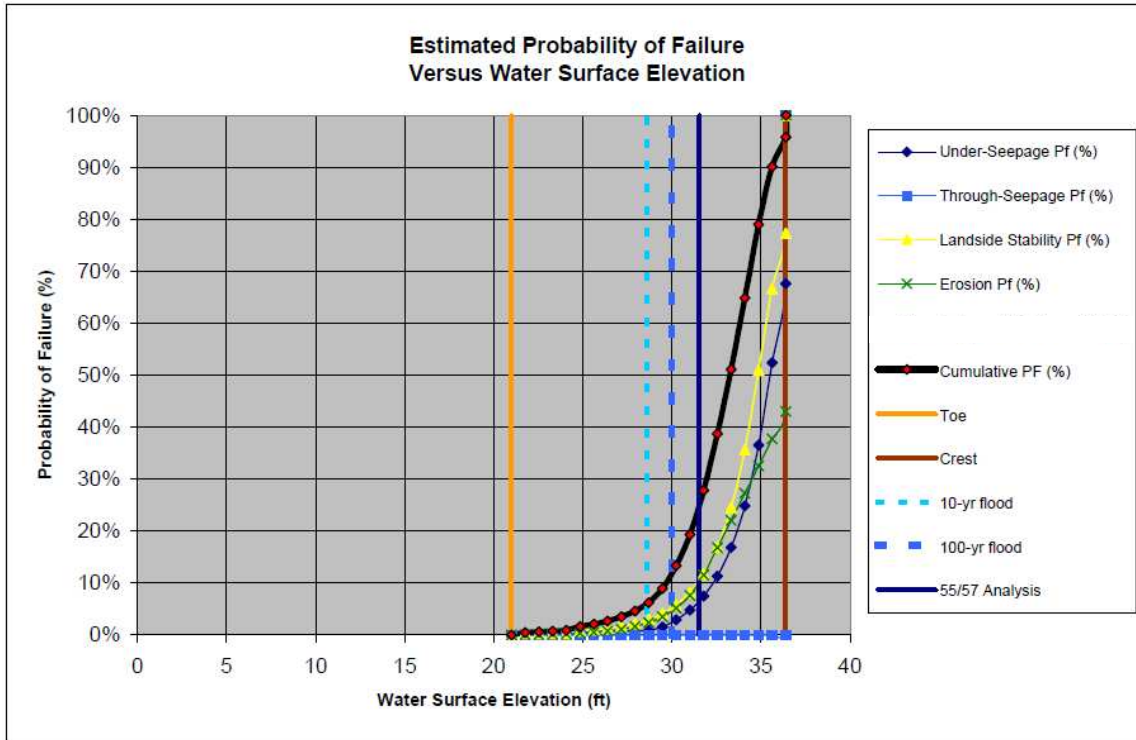


Figure 8. Example ULE fragility curve (with failure mode and combined curves)

An informal review of ULE fragility curves was provided by some URS team Task Managers who are responsible for the ULE study area in question where each cross section is located.

Anomalous hazards

Anomalous hazards were identified in the NULE GAR as isolated locations distinct from the overall segment. Additional fragility curves were developed for anomalous hazard locations identified in the NULE GAR and by ULE teams. Groups of anomalous hazards and suggested modifications to parent segment category ratings are listed below:

- Erosion coincident with man-made features -increase erosion rating to C
- Poor past performance coincident with a penetration (usually through seepage) - increase through seepage rating to C
- Large siphon -increase underseepage rating to C
- Site of past breach which has been repaired with either (1) poor performance since repair, or (2) an adjacent landside hole (e.g. scour pool, which shortens flow path) -increase underseepage and through seepage ratings to C
- Soft foundations resulting from buried sloughs or the like, with associated indicators of stability

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- problems -increase stability rating to C
- Landside holes (adjacent or near to levee) associated with boils or other poor performance - increase underseepage rating to C
- Permanent unrepaired breach -use new topography and assign all failure modes a category of C
- Significant encroachment/transition in levee geometry -increase impacted failure mode to C
- Other failure mode ratings were increased based on documented conditions at specific anomalous hazard locations

In some cases the anomalous hazard rating and parent segment rating are identical. If used in the hydraulic and damage models, the anomalous hazard will still impact the hydraulic and damage models by adding an additional potential break location within the segment.

Caveats

The current version of the NULE fragility curve tool produces curves for more than 200 NULE levee segments using cross section-specific geometry, LAT/GAR categories, and a few curve-fitting parameters. Because geometries of levees vary widely some curves may look distorted when compared to the expected curve shapes presented in Figure 1. This distortion is present to greater or lesser degrees for levees with only one or two C or LD(B or C) ratings and is further exacerbated for levees that are either very short (particularly if they have more than three feet of freeboard) or very tall (particularly if they have less than three feet of freeboard.) The implementation team believes the tool provides a set of curves with consistent properties relative to each other appropriate for the intended use in system-wide models and that the curves are sufficient for initial hydraulic and damage modeling. The impact of these distortions (if any) can be addressed once results of initial damage model runs become available.

Fragility curves developed in this task are intended for use with hydraulic and damage modeling performed by DWR and its consultants. Together with other DWR consultants, we are working to produce fragility curves that work well (provide reasonable results) in the modeling. However, the hydraulic and damage modeling results depend on a number of factors beyond the geotechnical fragility curves (such as hydrologic and hydraulic uncertainty), and though the fragility curves may seem reasonable, they may, when combined with other factors and used in the modeling produce unexpected results. The fragility curves and tools that have been delivered for this study represent our best effort based on limited feedback; with time and additional modeling, revisions to the delivered fragility curves may be needed to improve the model.

In this project, the individual failure mode fragility curves are combined to yield a cumulative or combined fragility curve. This approach assumes that the failure modes are independent, and that the different failure processes operate independently. This assumption is likely not true in all cases and has been offset to some extent by reducing the probability of failure for individual failure modes.

In developing NULE fragility curves, for simplicity, we have used the geometry and location of the underseepage cross section that was assessed in the Draft GARs (2010). For some NULE segments, the GAR used different cross sections for different failure modes. In developing fragility

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curves, the geometry from the GAR underseepage cross section has been used, and its location has been provided to the hydraulic and damage modelers.

It was noted earlier in this report that levee crest elevations used in the Comprehensive study (USACE, 2002) are different from those identified in the NULE and ULE studies. The NULE and ULE Projects relied on recent LiDAR and California Levee Database topographic data to estimate topographic parameters. The Comprehensive study relied on older, since-superseded, topographic information. It will be up to DWR's modelers to discern the most appropriate way to resolve these differences in levee crest elevations and to make their models work most defensibly.

In developing NULE fragility curves, we have used results from the Draft GARs (2010) without modification. In the final version of the GARs (URS, 2011; Kleinfelder, 2011), some of the data used in development of the fragility curves changed. Similarly, we used ULE data that were current through the FCSSR, and some data used to develop the fragility curves may change as the ULE Project proceeds.

The fragility curves and the Excel tools that were submitted and are the subject of this technical memorandum should be considered draft or interim. Given the schedule under which this effort was performed, there was little opportunity for interaction with DWR's modeling team during initial development of the curves. Subsequently, as DWR's modeling team performed initial modeling runs using the fragility curves, the modeling team identified some curves for further discussion and review. Following these discussions and reviews, some curves were refined and resubmitted for use in the modeling. We understand that as the modeling results are produced there will be the opportunity for additional interactions and further calibration of the provided fragility curves.

SUMMARY

This technical memorandum summarizes the approach used in developing a suite of fragility curves provided to the Central Valley Flood Management Planning Program (CVFMP) team for use in damage modeling and for preparing the 2012 Central Valley Flood Protection Plan (CVFPP).

The subject of this technical memorandum is a set of files with fragility curves for NULE segments and ULE reaches necessary to perform the modeling. We also have provided the Excel tools used to develop these fragility curves. The NULE tool allows the user to modify certain parameters and rapidly generate a set of fragility curves for all NULE segments. The ULE tool should be used on a reach by reach basis.

These fragility curves are intended to be used in hydraulic and damage modeling performed by DWR and its consultants; they should not be taken out of this context in forecasting local levee issues.

Limitations

This assessment has been 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 geographic area performing the same services under similar circumstances during the same time period.



Technical Memorandum

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Tel: 916.679.2000 Fax: 916.679.2900

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URS does not attest to the accuracy, completeness, or reliability of maps, data sources, geotechnical borings and other subsurface data produced by others that are included in, or referenced by, this technical memorandum. URS has not performed independent validation or verification of data reported by others.

Data presented in this technical memorandum are time-sensitive in that they apply only to locations and conditions that were identified at the time of preparation of this report. Data should not be applied to any other projects in or near the area of this study nor should they be applied at a future time without appropriate verification, at which point the one verifying the data takes on the responsibility for it and any liability for its use.

This technical memorandum is for the use and benefit of DWR. Use by any other party is at their own discretion and risk.

This technical memorandum should not to be used as a basis for design, construction, remedial action or major capital spending decisions.

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