ATTACHMENT E1

GEOTECHNICAL OFFICE REPORT

INTRODUCTION

The Sacramento and San Joaquin river basins have highly developed flood management systems, which rely primarily on high earthen structures, or levees, to protect adjacent floodplain lands. High levees essentially function as long dams but lack the inherent safety features that well-constructed dams possess such as spillways, outlets, and internal drains. Typically, floodwater velocities are erosive by definition and move along normally unprotected levees. These waters need only to encounter one weak spot in the system before causing a breach and potentially the loss of life or property. Extremely high hydraulic gradients can find other weak spots in the foundation materials with high hydraulic conductivity (permeability) such as loose sand and begin to migrate, or erode, material from the levee or near-surface foundation creating unstable conditions quickly followed by total or significant structural failure.

Even if not overtopped by floods, levees may fail for geotechnical reasons. Risk analysis procedures incorporate the chance of such failures through a geotechnical reliability model. This model leads to a relationship between water height and probability of geotechnical failure, which is then applied individually to each damage reach of river. This calculation assumes that damages can accrue in one of two ways – either the river stage becomes high enough to overtop the levee, or the stage rises significantly enough to cause geotechnical failure.

LEVEE FAILURE ANALYSIS METHODOLOGY

In the past, levees have often failed in unpredictable areas and at stages well below the design water surface. In other cases, water has encroached into the design freeboard (or safety level) without breaching or without significant damages. The geotechnical performance of a levee depends on local soil conditions and construction details. These details are generally not known in detail during the initial start of any planning study. Many of the levees of concern to the Sacramento and San Joaquin River Basins Comprehensive Study are neither owned nor maintained by the Corps of Engineers (Corps) or other federal agencies.

The geotechnical reliability model is generally a good first step in fulfilling the practical needs of planning studies and risk analysis. The Corps's original geotechnical reliability model began as a simple relationship between two stage heights for the levee: the probable failure point (PFP) and the probable non-failure point (PNP) (USACE, 1991). By definition, the probable failure point is the stage height associated with a high probability of failure. Numerically, this number is set at 0.85 (85% probability of failure). Likewise, the probable non-failure point is the stage height associated with a negligible probability of failure. Numerically, this number is set at 0.15. These points are assessed for local conditions only and frequently change from reach to reach. In some instances, these reaches can measure many miles in distance.

To better reflect a more sophisticated understanding of geotechnical performance this model was updated (USACE, 1999). The updated model considers multiple modes of failures including underseepage, through seepage, and strength instability as illustrated in **Figure G2-1**. These risk measures are calculated as shown in **Figure G2-2**.

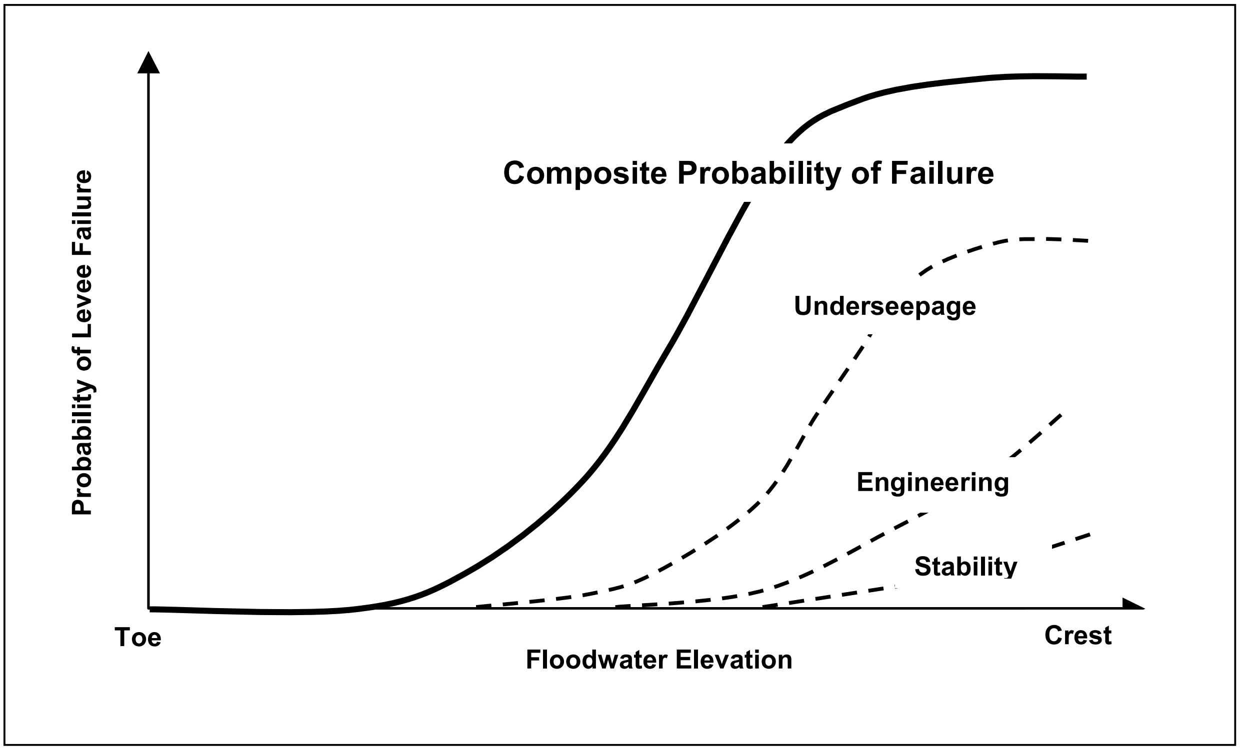

FIGURE G2-1 - CONTINUOUS MODEL OF GEOTECHNICAL LEVEE RELIABILITY

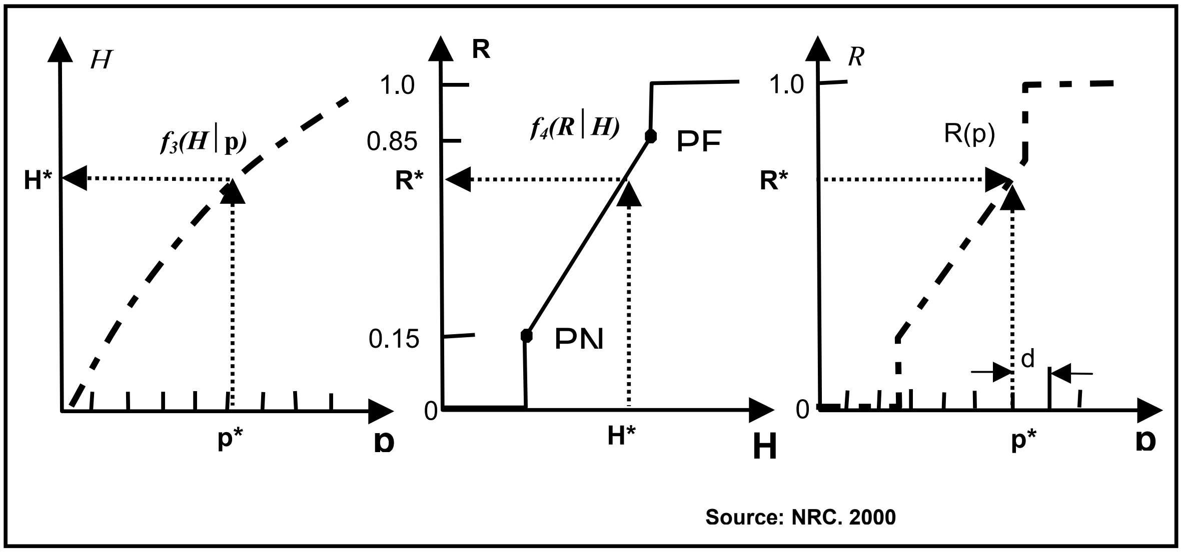

FIGURE G2-2 - COMPUTATION OF RISK MEASURES INCLUDING GEOTECHNICAL RELIABILITY

The first panel of this figure shows the stage-frequency curve, ***f_3(H|p)***, which was determined from hydrologic and hydraulic models and their uncertainties. For each frequency value (***p**** = 0.5, 0.2, 0.1, 0.4, 0.2, 0.01, 0.004, 0.002), a corresponding stage height ***H**** is determined. The middle panel of the figure is the risk of levee failure ***R*** as a function of stage, ***f_4(R|H)***, derived either from the PNP/PFP relationship, shown in **Figure G2-3,** or a composite probability of geotechnical levee reliability, shown in **Figure G2-1**.

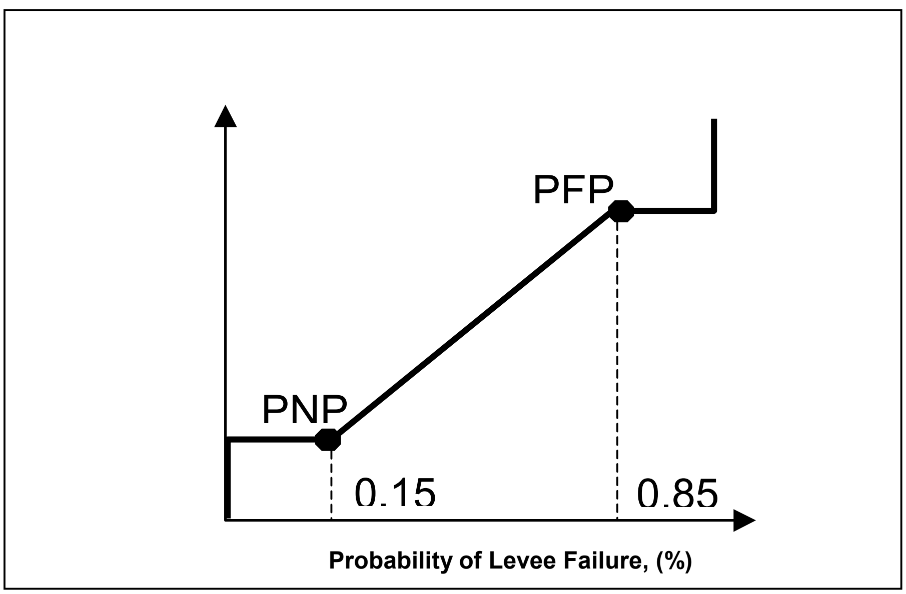

FIGURE G2-3 - TWO-POINT MODEL OF GEOTECHNICAL LEVEE RELIABILITY

For the given value of ***H****, the corresponding risk of failure ***R**** is thereby determined. The pairs of values (***R****, ***p****) are combined to form a risk-frequency curve, ***R(p)***, as shown in the last panel of **Figure G2-2**. The annual exceedence probability p_e including geotechnical uncertainty is then found in an analogous manner to the expected annual damage using the equation:

$$P_e = \int_0^1 R(p)dp$$

The conditional nonexceedence probability for any given value of ***p**** is expressed as:

1 - R* (as shown in **Figure G2-2)**

By repeating this calculation numerous times using a Monte Carlo simulation, a set of p_e and ***1 – R**** values is obtained. The p_e values are averaged to find the expected value of the annual exceedence probability. For the construction of a levee with a specified conditional probability of, for example, 90 percent or 95 percent for a 100-year flood, the procedure described in this paragraph is executed with a specific value of ***p**** = 0.01, and the levee height is adjusted upwards or downwards until the required conditional nonexceedence probability is obtained.

Levee Evaluation

Geotechnical evaluation and risk assessment is critical in flood damage reduction projects involving levees. These analyses are necessary to account for the risk of a levee to breach through soil failure even when the water surface elevation is not sufficient to over top the levee. The assessment does not generally separate the differences between *natural variability* and *knowledge uncertainty* (NRC, 2000). Natural variability arises from variations in soil conditions, or soil characteristics, and levee construction. The knowledge uncertainty arises from modeling assumptions made in calculating levee performance. These modeling assumptions are most likely to be very general. Natural variability varies independently from reach to reach and typically from sub-reach to sub-reach. The knowledge uncertainty is systematic across all reaches and is highly correlated. The important implication comes into view when calculating the probability of at least one levee failure anywhere on the river. If the reaches are truly independent, the probability generally rises according to a relation in the form,

$$Pr\{\geq 1 \text{ levee failure}\} = 1 - 1(1 - p)^n$$

Where ***p*** is the probability of failure in any one reach and ***n*** is the number of reaches. As ***n*** increases, the probability of failure quickly rises. If the reaches are highly correlated, the probability of one levee failing anywhere along the river is represented by

$$Pr\{\geq 1 \text{ levee failure}\} = p$$

Comprehensive Study Geotechnical Analysis

For the Comprehensive Study, the locations and likelihood of initial levee failure for the existing project and non-project levees in both the Sacramento and San Joaquin river basins are based on an analysis of weak points in the levee system. The weak points were identified through a reconnaissance-level geotechnical assessment of levee stability within predetermined damage impact areas. To define these weak points within any particular area, the PNP and PFP were defined for levee reaches on each impact area. The PNP and PFP were based on the results of field investigations, past levee stability calculations, and levee performance in the 1997 and 1998 flood events. To more clearly define the geotechnical conditional probability of failure for the 2,000 miles of levees evaluated in this study, probability of failure points in addition to the PNP and PFP values were defined for the 3-, 50- and 100- percent probability of failure.

For the San Joaquin River basin levees, very little information was available for inclusion into the analysis. As a result, the State of California, Department of Water Resources (DWR) conducted an in-depth reconnaissance-level field inspection detailing existing and potential problem areas through discussions with levee maintenance personnel and on-site evaluations. Field work included collecting cross sectional data, identifying remnants of sand bag rings during flood fighting efforts to control boils and seepage, discussions with levee district personnel, and engineering judgment. From this knowledge, conditional probabilities of failure curves were generated. As a result of this field study, three general levee curves highlight the state of the levees in the San Joaquin River basin. Essentially, these curves typically depict the levees as behaving similar to sand levees.

In the Sacramento River basin, geotechnical information was gathered from Corps system evaluation reports dating from the initial system evaluation reports submitted by the Mark Group in 1988 and 1989, the Flood Control System Evaluation Reports of 1992, 1993, and 1994, and supplemental evaluations reports of 1996, 2000, and 2001. In addition to these reports, on-going flood system projects in construction, nearing construction, or completed were considered as work completed, or study "without project" conditions. Engineering judgment based on past performance during the 1997 and 1998 flood events contributed a significant amount to the creation of the levee curves. Since a majority of the levees in the Sacramento River basin were constructed of a variety of levee material ranging in composition from loose sand to engineered pervious and impervious materials, levee curves were created to reflect these diverse differences in levee material. As a result, three levee curves representing the strongly constructed levees, generally of clay or a sandy clay material, were generated. For the poorer quality constructed levees and some of the non-flood control system levees, four levee curves were generated. These curves reflect both known and unknown inherent levee deficiencies.

Conditional Probability of Failure Curves

The geotechnical conditional probability of failure curves developed for the Comprehensive Study are presented in **Figures G2-4 and G2-5** for the Sacramento and San Joaquin river basins, respectively. Levee reaches were assigned a conditional probability of failure curve representing the estimated weakest point in the reach. The designations were assigned by either the Corps Soil Design Section, Geotechnical Branch for the Sacramento District, or the Levees and Canals Division of DWR. Aspects of the evaluations include levee through-seepage, foundation (or under-seepage), and static stability. Judgment reflects the uncertainty in loading, performance, severity of unknown defects, and other unseen features.

These curves represent a more qualitative approach to evaluating the major aspects of levee integrity for very large flood control systems.

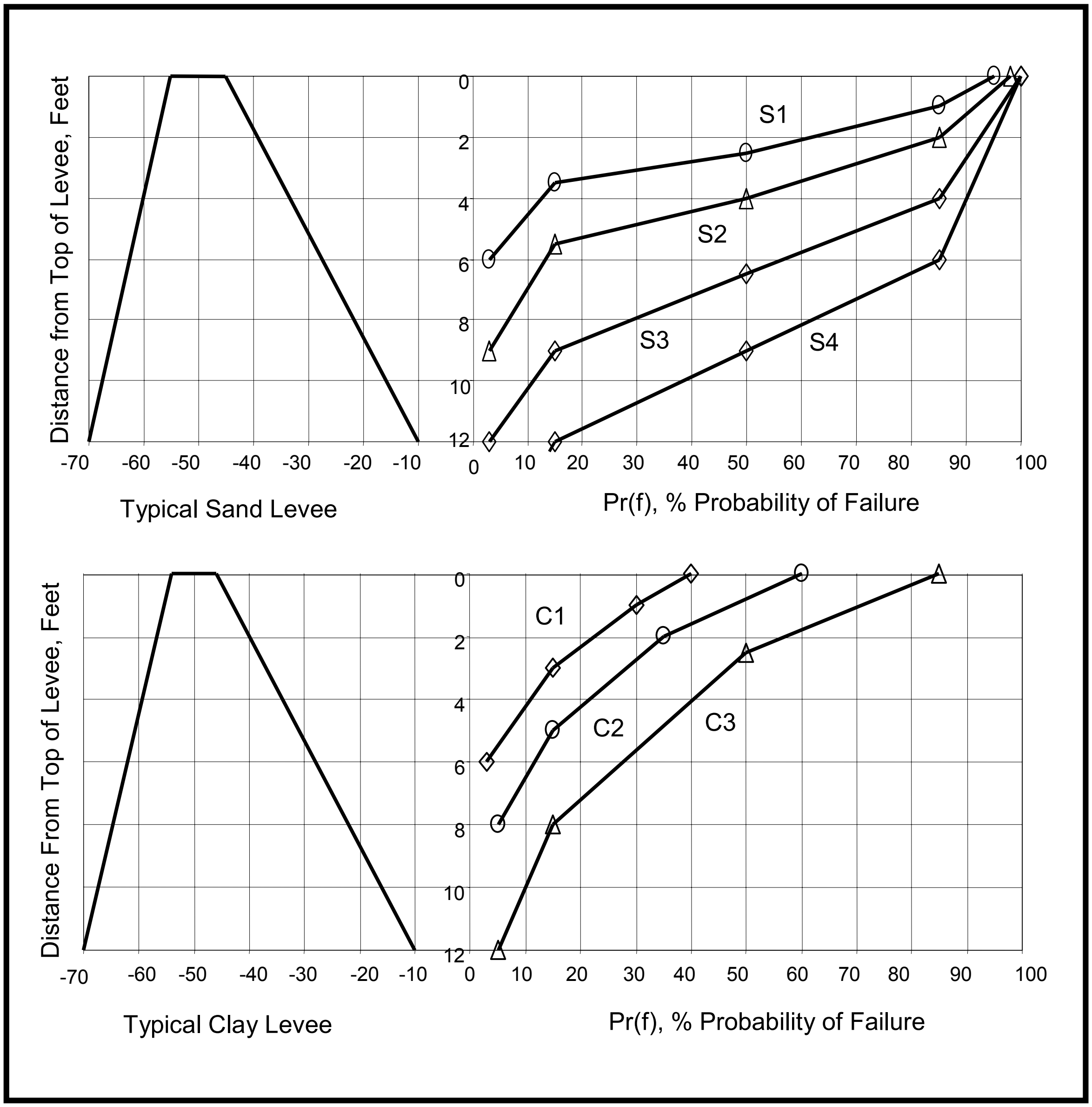

FIGURE G2-4 - CONDITIONAL PROBABILITY OF FAILURE CURVES FOR TYPICAL SACRAMENTO RIVER BASIN PROJECT LEVEES

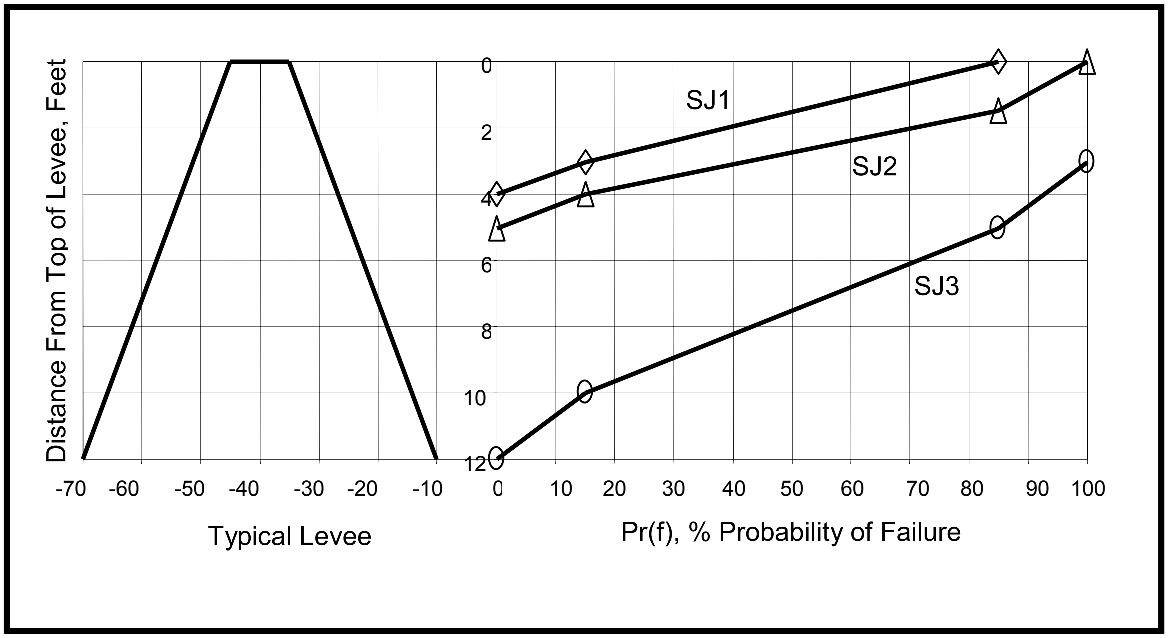

FIGURE G2-5 - CONDITIONAL PROBABILITY OF FAILURE CURVES FOR TYPICAL SAN JOAQUIN RIVER BASIN PROJECT LEVEES

Tables G2-1 and **G2-2** summarize the initial curves assigned reach by reach or area in the Sacramento and San Joaquin river basins, respectively. Both tables indicate river mile and tributary information. The curves can only be used for comparative economic analyses for the flood control systems and thus do not represent actual deterministic conditional probability of failure functions, which are only achieved through extensive evaluations of site-specific conditions, past performance, and analytical modeling in accordance with acceptable engineering manuals and regulations.

TABLE G2-1
ASSIGNMENT BY REACH OF SACRAMENTO RIVER BASIN CONDITIONAL PROBABILITY OF FAILURE CURVES

Reach No.	Reach Description	River Miles	Design Capacity[a] (cfs)	Selected P(f)[b] Model LB[c]	RB[c]
1	**Shasta Dam to Red Bluff**	**315 –245**	No Levees		
2	**Red Bluff to Chico Landing**	245 - 194			
	Sacramento River				
	Red Bluff to Elder Creek	245 - 230.5	N/A	N/A	
	Elder Creek to Deer Creek	230.5 - 220	N/A	N/A	
	Deer Creek to Chico Landing	220 - 194	N/A	N/A	
	Tributaries				
	Elder Creek		N/A	C2	C2
	Deer Creek		N/A	C2	C2
3	**Chico Landing to Colusa**	**194 - 146**			
	Sacramento River				
	Chico Landing to head of east levee	194 - 176	N/A	N/A	S3
	East Levee head to Moulton Weir	176 - 158.5	150,000	S2	S2
	Moulton Weir to Colusa Weir	158.5 - 146	110,000	S2	S2
	Tributaries				
	Mud Creek		N/A	C1	C1
	Butte Creek		3,000	C1	C1
	Cherokee Canal		12,500	S3	S3
4	**Colusa to Verona**	**146 - 80**			
	Sacramento River				
	Colusa Weir to Butte Slough	146 - 138	65,000	S3	S4
	Butte Slough to Tisdale Weir	138 - 119	66,000	S3	S4
	Tisdale Weir to Knights Landing	119 - 90	30,000	S3	S3
	Knights Landing to Verona	90 - 80	30,000	S2	S3
	Tributaries				
	Colusa Basin Drainage Canal		20,000		
	Tisdale Bypass		38,000	S3	S3
	Sutter Bypass				
	Butte Slough to Wadsworth Canal		150,000	C3	C3
	Wadsworth Canal to Tisdale Bypass		155,000	C2	C2
	Tisdale Bypass to Feather River		180,000	C2	C2
	Feather River to Verona		380,000	S3	C2
	Feather River				
	Oroville to Mouth of Yuba River		210,000	S2	S2
	Mouth of Yuba River to Bear River		300,000	S2	S2
	Bear River to Yolo Bypass		320,000	S3	S2
	Tributaries				
	Yuba River	0-5	120,000	S2	S3
	Bear River	0-3	40,000	S2	S2

TABLE G2-1 (CONT.)

Reach No.	Measure Reach Description	River Miles	Design Capacity, Q[a]	Selected P(f)[b] Model LB[a]	RB[a]
5	**Verona To Steamboat Slough**	**80 - 32.3**			
	Sacramento River				
	Verona to Sacramento Weir	80 - 63	107,000	S2	S4
	Sacramento Weir to American River	63 - 60	107,000 - 108000	S2	S2
	American River to Elk Slough	60 - 42	107,000 - 110,000	S2	S2
	Elk Slough to Sutter Slough	42 - 34	110,000	S3	S3
	Head of Sutter Sl. to Steamboat Sl.	34 - 32.3	84,500	S3	S3
	Tributaries				
	Natomas Cross Canal	0 – 5	22,000	C2	C3
	American River		115,000	S3	S2
	Yolo Bypass				
	Verona to Knight's Landing Ridge Cut		343,000	S4	S3
	Knight's Landing Ridge Cut to Cache Ck		362,000	S3	S3
	Cache Creek to Sacramento Weir		377,000	C3	C3
	Sacramento Weir to Putah Creek		480,000	C3	C3
	Putah Creek to Miner Slough		490,000	C3	C3
	Miner Slough to Cache Slough		579,000	C3	C3
	Cache Creek to Mouth Old River		N/A	C3	C3
	Tributaries				
	Knight's Landing Ridge Cut	0 - 6	20,000	S3	S3
	Cache Creek		N/A	S-3	S-3
	Willow Slough	0 - 7	6,000	C3	C3
	Putah Creek	2 - 7	62,000	C3	C3
	Miner Slough	0 - 2	10,000	S4	S4
	Cache Slough	0 - 5	N/A	S4	S4
6	**Steamboat Slough To Collinsville**	**32.3 - 0**			
	Sacramento River				
	Steamboat Sl. To head of Georgiana Sl.	26.5 – 32.3	56,500	S3	S3
	Georgiana Sl. To Cache Sl. – Junct. Pt	14 – 26.5	35,900	S3	S3
	Cache Sl. To 3-mile Sl.	9 - 14	N/A	S4	
	3-Mile Slough to Collinsville	0 - 9	N/A	S4	
	Tributaries				
	Elk Slough	0 – 9	N/A	S3	S3
	3-Mile Slough	0 - 3	65,000	S4	S4
	Steamboat Slough	0 – 6.5	43,500	S2	S3
	Sutter Slough - Steamboat to Miner	0 – 2.5	15,500	S3	S3
	Sutter Slough - Miner to Sacramento River	2.5 – 7	25,500	S4	S3
	Georgiana Slough	0 - 10	20,600	S4	S4

Notes
a) Advertised design flow capacity per DWR (May 1985)
b) P(f) = Conditional Probability of Failure
c) LB = Left Bank, RB = Right Bank

TABLE G2-2
ASSIGNMENT BY REACH OF SAN JOAQUIN RIVER BASIN CONDITIONAL PROBABILITY OF FAILURE CURVES

Reach No.	Reach Description	River Miles	Design Capacity[a] (cfs)	Selected P(f)[b] Model
A	***Mendota Dam to Friant Dam***	**205 To 286**		
	San Joaquin River		2,500 – 8,000	SJ1
	Fresno Slough & James Bypass		4,750	SJ1
B	***Sand Slough Control Structure to Mendota Dam***	**168 to 205**		
	San Joaquin River		4,500	SJ2
	Chowchilla Bypass / Eastside Bypass		5,500 – 17,000	SJ2
	Tributaries			
	Fresno River – San Joaquin to Road 18		5,000	SJ2
	Berenda Slough - San Joaquin to Route 152		2,000	SJ2
	Ash Slough - San Joaquin to Route 152		5,000	SJ2
C	***Merced River to Sand Slough Control Structure***	**118 to 168**		
	San Joaquin River			
	Merced River to Eastside Bypass		26,000	SJ2
	Eastside Bypass to Control Structure		1,500-10,000	SJ2
	Eastside Bypass		13,500 – 16,500	SJ2
	Deep Slough		18,500	SJ2
	Bear Creek		7,000	SJ2
	Mariposa Bypass		8,500	SJ2
D	***Stanislaus River to Merced River***	**75 to 118**		
	San Joaquin River		45,000 – 46,000	SJ3
	Merced River		6,000	SJ2
	Tuolumne River		15,000	SJ3
	Dry Creek		N/A	SJ3
	Stanislaus River		8,000	SJ3
E	***Deep Ship Channel to Stanislaus River***	**40 to 75**		
	San Joaquin River		37,000 – 52,000	SJ3
	Tributaries			
	Paradise Cut – Old River to San Joaquin River		15,000	SJ3
	Old River - Tracy Boulevard to San Joaquin River		-	SJ3
	Grant Line Canal - Tracy Blvd to Doughty Cut		-	SJ3
	Doughty Cut - Grant Line Canal to Old River		-	SJ3
	Middle River - Victoria Canal to Old River		-	SJ3

Notes: a) Advertised design flow capacity per DWR (May 1985)
b) P(f) = Conditional Probability of Failure (applies to left and right bank levees) .

The frequency and magnitude of physical changes and failure events affect levee integrity. Physical conditions will naturally change within the project's life. These changes may lead to unsatisfactory performance. Hence, a conditional probability of failure function for any of the levees within the systems is time-dependent and subject to change.

Additional Changes to the Levee Curves

Initial hydraulic modeling using the conditional probability of failure curves and subsequent generation of inundation areas in the Sacramento River basin indicated that the initially selected conditional probability of failure curves required adjustment. The modeling results obtained using a LFP corresponding to a 50 percent probability of failure did not reflect expected conditions for the left and right bank of the American River, and the left bank of the Sacramento River from Verona to Freeport. This issue was reviewed and the decision was made to select a more appropriate curve that would better describe the conditional probability of failure for these reaches:

1. For levees on the American River, the S3 curve (representing a LFP of 6-1/2 feet below top of levee) was replaced with the S1 Curve (representing a LFP of 2-1/2 feet below top of levee).
2. For the left bank of the Sacramento River from Verona to Freeport (a distance of about 33 miles), the S2 curve representing a LFP of 4 feet below top of levee was deemed appropriate.

References used to assist in this re-evaluation were: 1) MFR dated 23 March 1998, Review of Alternative 7 Flood Elevation of the Left Bank levee Sacramento River from I Street to Freeport; 2) MFR dated 30 April 1999, FEMA Certification for 100-year Water Surface, Sacramento River and American River Levees; and 3) MFR for PD dated 12 May 2000.

Considerations

Use of the likely failure point to trigger levee failures does not account for flood fighting and other emergency work that occurs during actual flood events. Flood fighting efforts can, and have, significantly reduced flood damages in some areas. However, these efforts often induce higher stages and pass higher flows to downstream reaches, resulting in subsequent levee failures. This is especially true for more frequent flood events. Very large flood events, on the other hand, generate flows that overwhelm the flood system to such an extent that flood fighting becomes ineffective. For plan formulation purposes, it is important to recognize that flood fighting occurs and can be effective; however, it is not considered in the Comprehensive Study geotechnical evaluation. Furthermore, geotechnical conditions are not static, and the geotechnical data used in developing projects should be re-evaluated and updated whenever information becomes available.

SUMMARY AND CONCLUSIONS

It is anticipated that the geotechnical levee performance curves and their application in the basins will change as additional technical evaluations are performed. These curves were developed for use in regional and basin-wide analyses. Therefore, additional work will be required if they are to be used for more detailed feasibility studies.

Probable failure point and probable non-failure point elevations were estimated for the existing levee system in the San Joaquin River basin. However, geotechnical explorations and evaluations were very scarce, and soil explorations and testing will be necessary to obtain geotechnical information in some reaches of the San Joaquin River during later studies. Previous geotechnical investigations performed for the Corps' Sacramento River Flood Control System Evaluation were used for an initial evaluation of Sacramento River levees. Additional information based on past performance, especially through the 1997 and 1998 flood seasons and sound engineering judgment, were also used.

For future studies, more detailed geotechnical design will be required to provide alternate remedies for levees with structural problems and to provide designs for proposed new levees. Foundation design may also be required for some proposed structural measures. Levee strengthening alternatives are likely to include the following: berms both with and without landside toe ditches; cut-off walls for pervious levees, pervious foundations, or both; and levee raising with and without landside berms. **Plates E1, E2 and E3** illustrate six typical alternatives for levee strengthening. Typical cross sections for new engineered levees are illustrated in **Plate E4**.

REFERENCES

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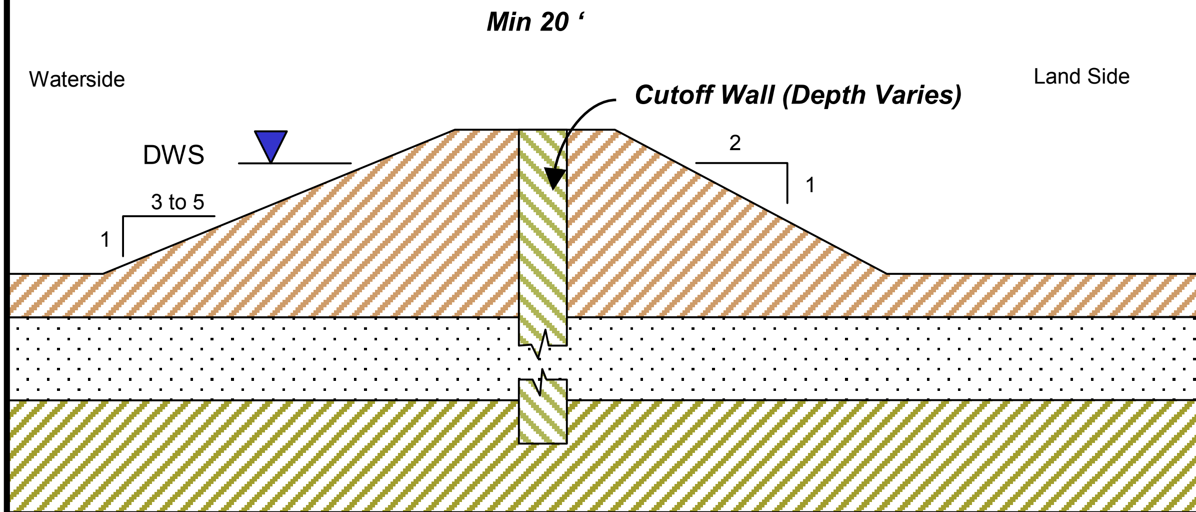
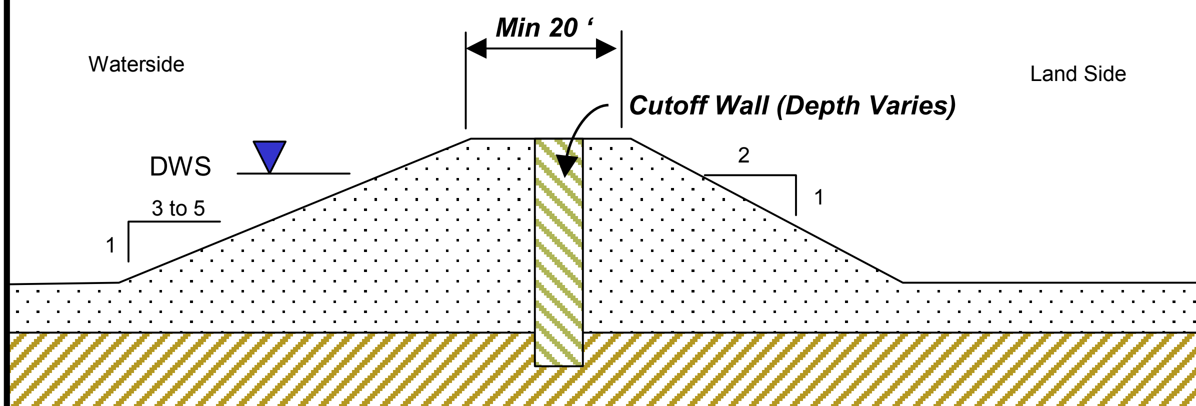


Typical Cross Section – Cutoff Wall

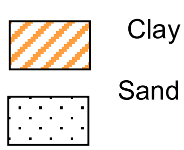
Granular Stratum Foundation



Typical Cross Section – Cutoff Wall

Clay Foundation

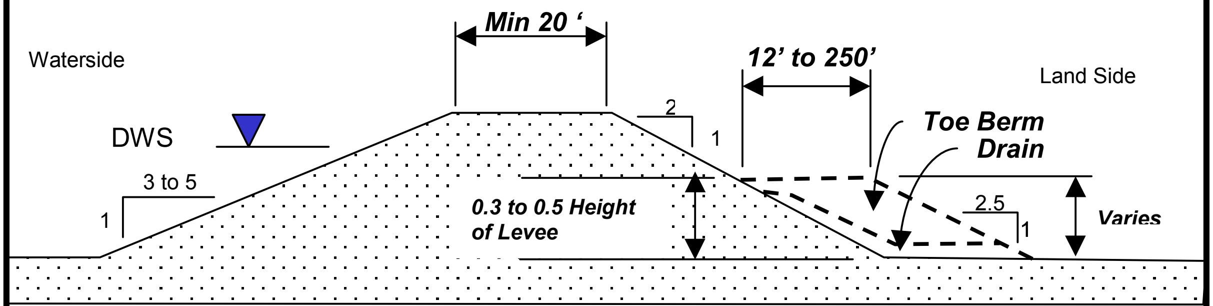
Legend



Sacramento and San Joaquin River Basins
Comprehensive Study

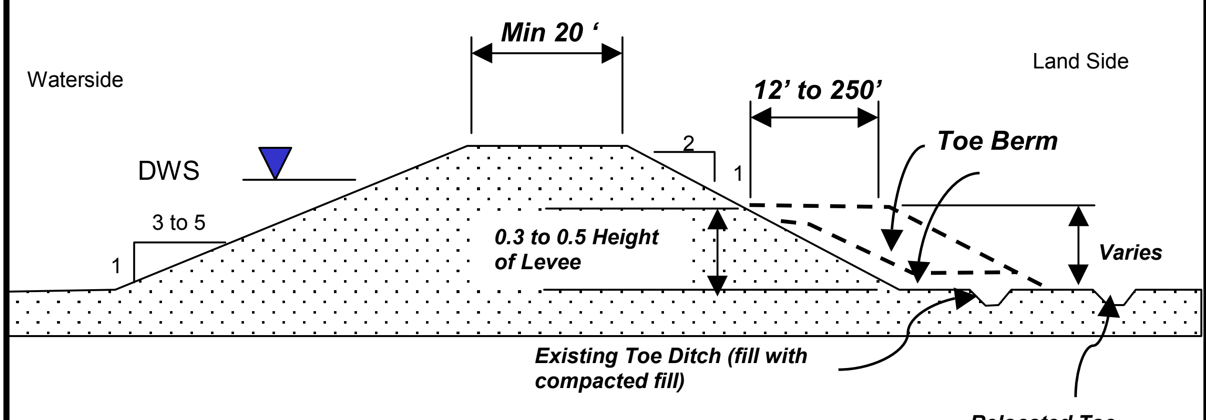
Plate E1 Levee Strengthening Cutoff Wall

Sacramento District, Corps of Engineers and
State of California, Reclamation Board



Typical Cross Section – Berm

Areas With No Existing Toe Ditch



Typical Cross Section – Berm

Areas With Existing Toe Ditch

Legend

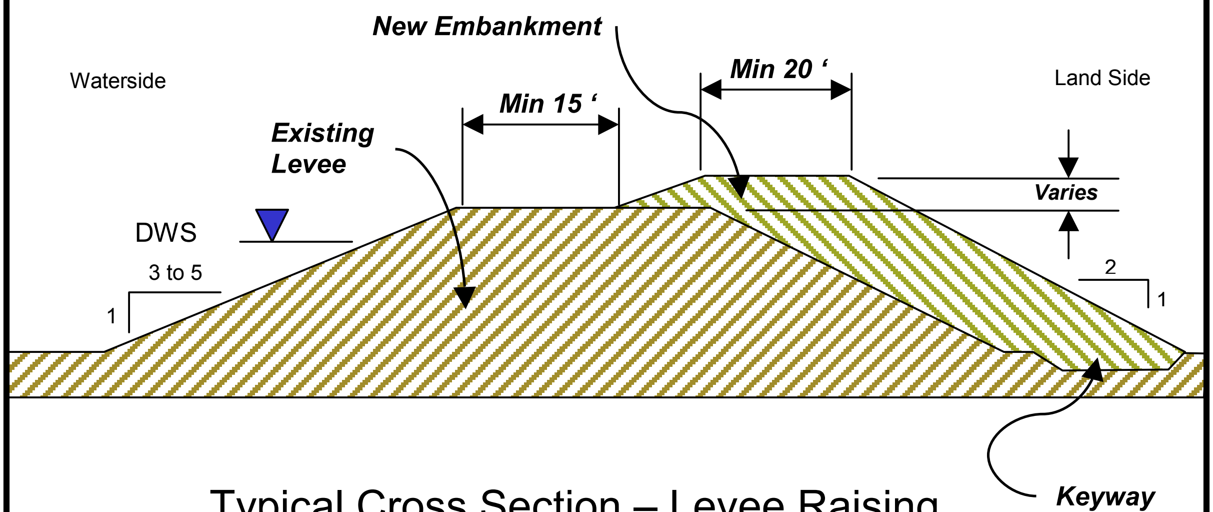
Clay

Sand

Sacramento and San Joaquin River Basins
Comprehensive Study

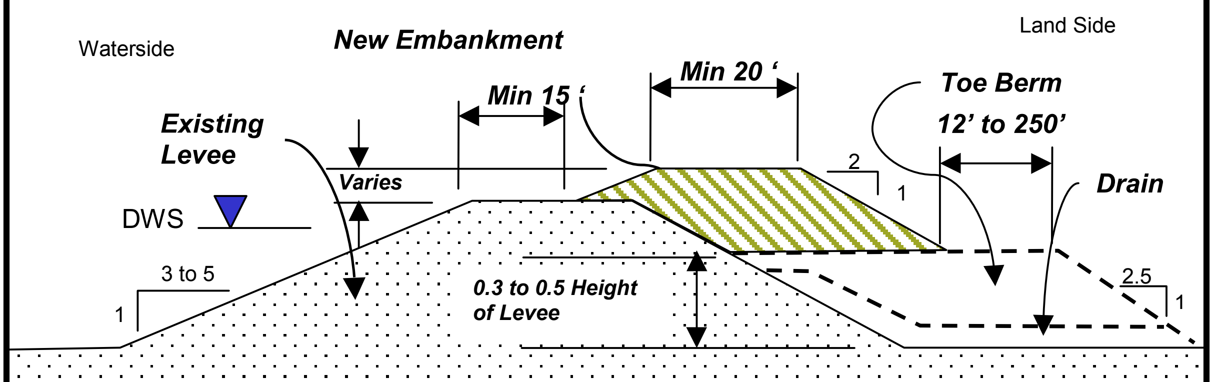
Plate E2 Levee Strengthening
Landside Toe Berm with Drain

Sacramento District, Corps of Engineers and
State of California, Reclamation Board



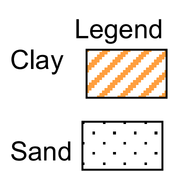
Typical Cross Section – Levee Raising

Areas Without Berm Construction



Typical Cross Section – Levee Raising

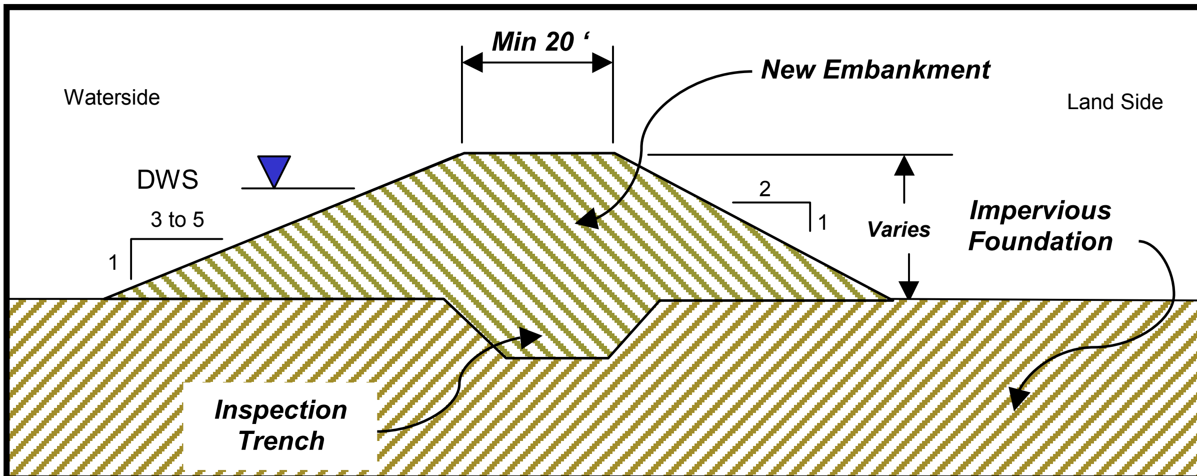
Area With Berm Construction



Sacramento and San Joaquin River Basins
Comprehensive Study

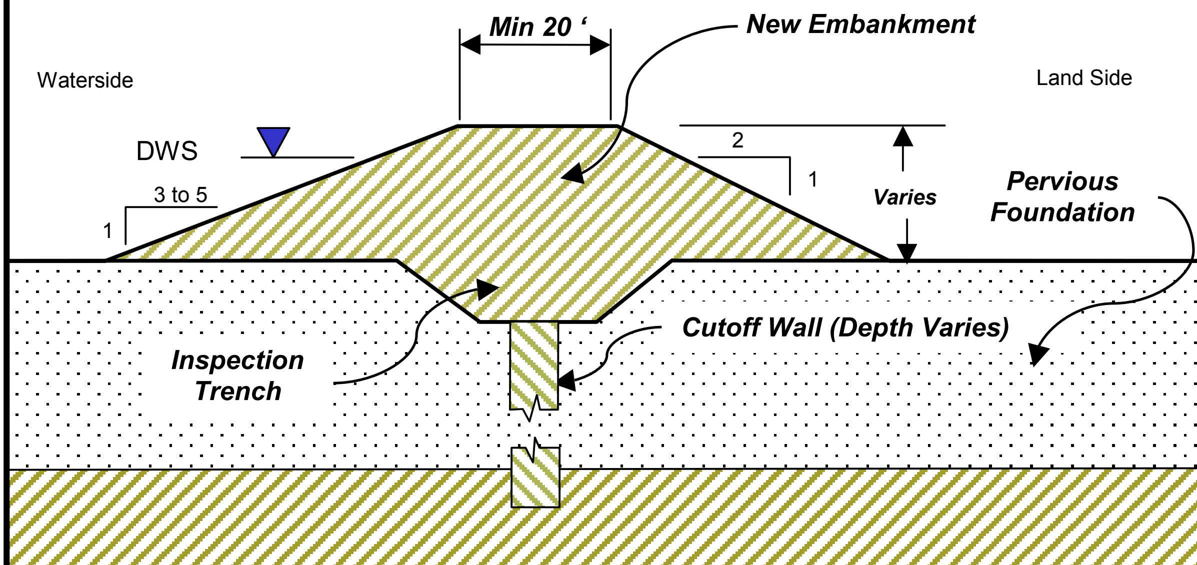
Plate E3 Levee Strengthening
Levee Raising

Sacramento District, Corps of Engineers and
State of California, Reclamation Board



Typical Cross Section – New Levee

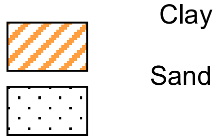
Areas With Impervious Foundation



Typical Cross Section – New Levee

Areas With Pervious Foundation

Legend



Sacramento and San Joaquin River Basins
Comprehensive Study

Plate E4 Levee Alternatives
New Levee

Sacramento District, Corps of Engineers and
State of California, Reclamation Board