Skagit River Levee General Investigation (GI)
Levee Risk and Reliability Analysis
Skagit County, Washington

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1.0 INTRODUCTION

The Skagit River Levee General Investigation study is part of an effort by the Seattle District U.S. Army Corps of Engineers (USACE) to identify available levee information and to investigate measures to reduce flood impacts along the Skagit River. This report summarizes an analysis of levee risk and reliability at eight locations along the Skagit River.

Shannon & Wilson's (S&W's) services for this analysis were authorized by the USACE under Task Order No. 0013 of Contract No. W912DW-09-D-1005. Our services were performed in general accordance with the Statement of Work for the task order.

The scope of the project was to

- Review available data
- Develop ground surface and subsurface profiles for eight levee cross sections
- Identify potential levee failure modes at each cross section
- Identify an appropriate analysis method for each failure mode
- Identify the critical input variables for each failure mode and develop estimates of the most likely value and standard deviation for each variable
- Estimate the river stage at which the conditional probability of failure (P_f) is zero for calibration of the reliability analysis for each cross section
- Determine an appropriate range of river stages for the reliability analyses for each cross section and failure mode
- Perform the appropriate reliability analysis for each cross section and failure mode
- Calibrate the reliability analyses based on the estimated $P_f = 0$ river stage
- Prepare tables and graphs of levee fragility for each cross section

This report presents the data, assumptions, methods, and results of our levee risk and reliability analysis. Electronic copies of the analysis input files and levee fragility spreadsheets are enclosed with this report.

2.0 DATA AND DATA SOURCES

The data generally required for a levee risk and reliability analysis include levee geometry and material properties, subsurface conditions and material properties, river hydraulic and hydrologic conditions, levee design and construction records, and levee maintenance and performance history. The reliability of the analytical results will depend on the accuracy and completeness of the available data.

The data used to perform the analyses described in this report were drawn from the following sources:

- Report of field explorations and results of field tests performed at the eight levee cross section locations selected for this study
- Results laboratory tests performed on samples obtained from the field investigation of the eight levee locations
- Previous investigations at other locations in the Skagit River levee system
- USACE reports, drawings, and historical data
- Skagit County records
- Supplemental data from the levee analysis and design literature
- Engineering judgment

Additional background information was provided in discussions with personnel from USACE, Skagit County, and Northwest Hydraulic Consultants, Inc. (NHC).

3.0 LEVEE CROSS SECTIONS

The eight levee cross sections used for our risk and reliability analysis are at the locations chosen for exploration and evaluation of subsurface conditions. The locations were selected to coincide with known seepage areas along the levee. The specific boring locations were selected based on the information obtained from our review of existing project data and conversations with the USACE, Skagit County, and Dike Districts 1, 3, 17, and 22. The naming convention used for analyses follows the naming convention of the borings presented in S&W's geotechnical report (Shannon & Wilson, 2010). The analysis section names and river mile locations are shown in Table 1.

The analysis locations are shown in plan view in Figure 1 and the cross section profiles for each location are presented in Figures 2 through 9. Cross section profiles of the levee embankments, river bathymetry, and foundation soils were developed from information obtained from design and construction drawings (USACE, various), bathymetry data (USACE, 2010, see Figures 10 to 13), subsurface exploration data (Shannon & Wilson, 2010, see Appendix A), and LIDAR and survey data (PSLC, 2003, USACE 2010).

3.1 Ground Surface Profile

Design and construction drawings of the levee embankments were typically for sites other than the specific locations selected for analysis. However, the drawings generally show a levee embankment 10 to 20 feet in height, crest widths of 12 to 16 feet, riverside slopes ranging from 1.5 to 2 horizontal to 1 vertical (1.5 to 2 H:1V), and landside slopes ranging from 2 to 3 H:1V. In some cases, the design and construction drawings also showed riverside or landside berms extending beyond the toe of the levee slopes. Ground surface profiles at the analysis locations were generated from 3-meter LIDAR data and crest survey data provided by the USACE to obtain location-specific profiles. The generated profiles were generally in good agreement with the typical profiles found in the design and construction drawings and were used to develop the analysis section ground surface profiles.

3.2 Subsurface Profile

Subsurface soil contacts in the levee foundation and adjacent soils were developed primarily from boring logs (Appendix A) prepared for the geotechnical report of explorations at the eight analysis locations (Shannon & Wilson, 2010). Boring logs from previous field explorations (USACE various, Golder, 2009) were used to corroborate the conclusions drawn from the site-specific subsurface explorations.

In general, the boring logs indicate that levee foundation soils at the eight locations consist of overbank deposits underlain by channel deposits. Overbank deposits range from 5 to 17 feet thick and generally consist of sands and silts with some clay. The channel deposits range from 4 to 40 feet thick and vary from slightly silty sand and gravel to sandy gravel. Borings that were advanced through the channel deposits indicate that the channel deposits are underlain by soils similar in composition and characteristics to the overbank deposits. Estuary deposits were found in the borings at analysis section DD22-1L near Skagit Bay and consist of silt and fine sand with shell fragments.

Based on our interpretation of the boring log and laboratory data, we generalized the levee foundation soils to a three-layer system consisting of overbank deposits (overbank), channel deposits (pervious layer), and an underlying soil similar to the overbank deposits (sub-layer).

The thicknesses of the overbank and pervious layer at each analysis section were derived from the boring logs at each section. Because only two borings were completed at each location, we assumed a horizontal projection of the subsurface conditions beyond the limits of the boring locations.

Based on visual observation and laboratory test results, the levee embankment materials appear to be predominantly locally obtained from the overbank deposits, although four of the eight borings in the levees encountered clayey soils in the upper 5 to 7 feet of the levee embankment that may be imported from other sources. For purposes of the risk and reliability analyses, the levee embankment materials at all analysis sections were assumed to be constructed of overbank deposit soils.

3.3 Bathymetry

River bathymetric profiles at the analysis locations were developed from bathymetry measurements (USACE, 2010). The locations of the bathymetry measurements relative to the locations of the analysis sections are shown in Figure 10 and the bathymetry measurements nearest to the analysis locations are shown in Figures 11 through 13.

The location of bathymetry measurements coincided with two of the analysis locations; however, the location of bathymetry measurements ranged from approximately 500 to 2,600 feet upstream or downstream for the other six analysis locations. The bathymetric profiles used at each location and the rationale for the selections are summarized in Table 2.

4.0 POTENTIAL FAILURE MODES

Levee failure is generally defined as a failure of the levee to provide the intended protection to the people and property on the landside of the levee. The intended protection is typically defined in terms of a specific return period water level (e.g., protection from a 100-year return period event). Levee fragility curves are a description of the likelihood of levee failure for a range of water levels. Fragility curves can be used to compare different levee designs or locations and provide input to an analysis of levee failure consequences.

An analysis of levee failure consequences typically begins from a fragility curve, but must also consider potential breach characteristics. A breach is generally defined as the opening created after failure of the levee embankment. The depth and width of the breach generally depends on the water level, duration, and levee material properties. Many of the potential levee failure modes can lead to a levee breach; however, the failure modes most frequently associated with breaches are slope failure and overtopping.

The potential failure modes used for the Skagit River levees risk analysis were identified from a review of historical levee failures, river hydraulic and hydrologic characteristics, levee structural characteristics, and geotechnical characteristics of the levee embankment and foundation soils. Some of the identified failure modes can be analyzed by conventional, quantitative methods to estimate conditional probabilities of failure; and others require qualitative or semi-quantitative approaches to estimate conditional probability of failure. Not all levee failures are equally catastrophic. For example, underseepage failure in the absence of slope failure may not immediately lead to significant flooding. The analysis that is generally performed, however, treats each failure mode equally and may lead to a conservative estimate of the likelihood of levee failure.

The Skagit River levees have experienced a number of failures but evidence of the failure mode for each case is often unavailable. As with most levees, first-hand observation of the Skagit River levee failures is rare and post-failure investigation and analysis are limited by the need for immediate repair and the cost of investigation and analysis. The historical evidence suggests that underseepage and slope failure due to scour and overtopping are the most common levee failure modes on the Skagit River (Shannon & Wilson, 2010).

The hydraulic characteristics of the river that are relevant to a risk analysis of a levee are the geometry of the channel and flow velocity. Channel bathymetry and levee profile form the riverside slope that is to be analyzed. Flow velocity and channel impingements are determinants of scour potential. For the risk analyses presented in this report, channel shapes were developed from bathymetry measurements (USACE, 2010) and estimated flow velocities (NHC, 2010a).

For purposes of a levee risk analysis, the hydrologic characteristics of the river are only indirectly relevant. A risk analysis is based on conditional probabilities of failure where the assumed condition is one or more river stages. The analysis does not depend on knowledge of the likelihood of occurrence of a given river stage; however, the assumed maximum river stages must be consistent with the river's hydrologic regime and hydraulic characteristics. For the risk analyses presented in this report, the maximum river stage was assumed to be equal to the elevation of the levee crest based on historical evidence of overtopping (Shannon & Wilson, 2010).

The levee structural characteristics that are relevant to a risk analysis include the geometry of the levee, including height, slope angles, crest width, set back and armoring (e.g., riprap); and the location and type of non-levee structural features such as bridge piers or utility under-crossings. Levee geometry for the risk analyses presented in this report were derived from a review of design and construction drawings and LIDAR data. The only non-levee structural features on the lower Skagit River (River Mile [RM] 7.1 to RM 17.4) appear to be roadway and railway bridges.

The levee and foundation geotechnical characteristics that are important to a risk analysis include the soil physical strength and hydraulic conductivity properties; subsurface layering; and other natural forces, such as earthquakes, that could affect a levee's reliability. The geotechnical characteristics for the risk analyses presented in this report were developed from site-specific subsurface exploration data and field and laboratory test results (Shannon & Wilson, 2010) and previous subsurface exploration data (USACE, various; Golder, 2009).

4.1 Quantifiable Failure Modes

Quantifiable failure modes are those for which conventional, quantitative methods are available to estimate conditional probabilities of failure. The quantifiable failure modes identified for the Skagit River levees include:

- Underseepage
- Riverside and landside static slope failure
- Riverside and landside seismic slope failure
- Riverside slope failure due to rapid drawdown

4.1.1 Underseepage

Underseepage can occur in situations in which one or more highly permeable soil layers extend beneath a levee from the river to the landside of the levee. A high river stage of sufficient duration creates a hydraulic gradient from the river to the landside surface that may result in landside heave and sand boils. Underseepage that occurs in these conditions, even in the absence of levee slope failure, is considered to be a levee failure.

4.1.2 Riverside and Landside Static Slope Failure

Static slope failure occurs when the steepness of a slope and the mass of the soil on the slope exceed the strength of the slope soils. The static stability of a levee is also affected by the river stage. Of special concern with respect to levees are riverside or landside static slope failures that intersect the levee crest.

4.1.3 Riverside and Landside Seismic Slope Failure

Seismic slope failure is similar to static slope failure but with an added, potentially destabilizing, seismic inertial force. Seismic slope failure is distinguished from seismic liquefaction failure (discussed in Section 4.2) in that seismic slope failure can occur without the reduction of soil shear strength that typically occurs during seismic liquefaction failure.

Seismic slope failure occurs when the steepness of a slope and the mass of the soil on the slope plus the seismic inertial force exceed the strength of the slope soils. The seismic stability of a levee is also affected by the river stage. Although the likelihood of an earthquake occurring simultaneously with high river stage may be low, a seismic slope failure that occurs without sufficient time to repair the failure before the next high river stage would have the same effect as a simultaneous earthquake and high river stage event.

4.1.4 Riverside Slope Failure Due to Rapid Drawdown

Slope failure due to rapid drawdown can occur when the river stage drops quickly from a relatively static level. During the higher static river stage, the groundwater level in the levee embankment would be at or near the river stage level. When the river stage drops more quickly than the groundwater level in the embankment can respond, a potentially unstable condition is created by the groundwater level in the embankment remaining above the river level.

4.2 Other Failure Modes

Other failure modes are those that require qualitative or semi-quantitative approaches to estimating a conditional probability of failure. The other failure modes identified for the Skagit River levees include:

- Liquefaction
- Throughseepage
- Scour
- Sequential failure

4.2.1 Liquefaction

Liquefaction or partial liquefaction is the loss of shear strength in a saturated, granular soil during an earthquake. Liquefaction in the soils in or beneath the Skagit River levees could result in lateral displacement and settlement of the levee or levee foundation soils. Although the likelihood of an earthquake occurring simultaneously with high river stage may be low, liquefaction may occur at any river stage. The damage may occur without sufficient time to repair before the next high river stage or the damages may not be clearly evident but still sufficiently severe to reduce the design level of protection provided by the levee.

4.2.2 Throughseepage

Throughseepage is flow of water through a levee embankment, as distinguished from underseepage, which is flow of water in a permeable soil layer beneath a levee embankment. Throughseepage occurs when a high river stage of sufficient duration creates a hydraulic gradient from the river to the landside surface of the levee. Water flowing through a levee tends to follow the most permeable path which may be more permeable levee materials, animal burrows, vegetation roots, or other openings in the embankment. Throughseepage can result in piping or excess porewater pressures that can lead to levee slope failure.

4.2.3 Scour

Scour is the removal of river bank or levee embankment soils by the water in the river. The potential for scour depends on the river bank or levee soil type, the velocity and impingement angle of the flowing water, and the roughness of the river bank or levee surface. River bank and levee scour tends to remove soil from the toe or slope of an embankment, resulting in a less stable embankment or embankment failure.

4.2.4 Sequential Failure

Sequential failure of a levee is a series of smaller embankment failures that can lead to failure of the entire embankment. In a sequential failure, each successive failure leaves behind an unstable slope that also fails. Sequential failures can be initiated by changes in the embankment's structure or properties due to factors such as scour, earthquake, or seepage.

4.3 Other Failure Mode Factors and Uncertainties

Other factors that have been identified for the Skagit River levees that can affect the estimates of the conditional probability of failure are listed below. Some of these factors are partially considered in the quantitative methods used to estimate conditional probabilities of failure and others must be considered qualitatively. In general, qualitative methods will have more uncertainty that quantitative methods.

- River stage duration
- Length effect
- Channel configuration
- Non-levee structural features
- Surface elevation uncertainty
- Soil unit contact uncertainty
- Method uncertainty

4.3.1 River Stage Duration

The duration of a river stage can affect quantitative estimates of the conditional probability of levee failure due to underseepage, static slope failure, and rapid drawdown. In general, quantitative estimates of the conditional probability of levee failure are made under the assumption that the river stage duration is sufficient to develop a static hydraulic gradient from the river to the levee's landside surface elevation. A river stage of shorter duration may result in a less severe hydraulic gradient and a lower estimate of the conditional probability of levee failure. The river stage duration can also affect qualitative estimates of scour probability and likelihood of sequential failure. The effect of river stage duration on the conditional probabilities of levee failure can be evaluated by considering transient hydraulic conditions in the quantitative analyses.

4.3.2 Length Effect

Length effect refers to the applicable length of an estimate of conditional probability of levee failure and the impact of levee length on the estimated probability. The estimated conditional probabilities of failure are generally based on a representative section of levee within a longer stretch of levee with similar characteristics and similar response to changes in river stage. If the entire levee reach is viewed as a system, with each section being an independent link, then the conditional probability of failure of the entire length will be greater than the conditional probability of failure of an individual section. The effect of levee length on the conditional probabilities of levee failure is generally evaluated using a semi-quantitative approach.

4.3.3 Channel Configuration

Conventional, quantitative methods of estimating conditional probability of levee failure are generally based on the assumption that the river channel at the analysis location is straight and flow is parallel to the levee. The effect that river bends, bars, and other natural features have on flow direction and velocity can alter the estimated conditional probabilities of levee failure.

The effect of channel configuration on the conditional probabilities of levee failure is generally evaluated using semi-quantitative or qualitative approaches.

4.3.4 Non-Levee Structures

The presence of non-levee structural features such as bridge piers can also alter the estimated conditional probability of levee failure. Conventional, quantitative methods of estimating conditional probability of levee failure do not consider the presence of non-levee structural features. The effect of non-levee structural features on the conditional probabilities of levee failure is generally evaluated qualitatively.

4.3.5 Surface Elevation Uncertainty

River channel, levee, and ground surface profiles for the eight Skagit River levee analysis locations were developed from bathymetry measurements, design and construction drawings, and LIDAR and survey data. The data used to develop the profiles have inherent uncertainties that can alter the estimated conditional probabilities of levee failure. River channel, levee, and ground surface profiles between the analysis sections will likely vary as well, which adds another source of uncertainty to the application of the probabilities of levee failure to those locations. The effect of surface profile elevation uncertainty on the conditional probabilities of levee failure can be evaluated by varying the elevations in the quantitative analyses.

4.3.6 Subsurface Contact Elevation Uncertainty

The contact elevations between the levee embankment and foundation soil layers at the eight analysis sections were developed primarily from data from the two geotechnical borings at each location. For the quantitative analyses, the contact elevations were extended horizontally beyond the boring locations. The data used to develop the contact elevations have inherent uncertainties and the contact elevations between the analysis sections will likely vary as well. These uncertainties can alter the estimated conditional probabilities of levee failure and will add another source of uncertainty to the application of the probabilities to locations between the analysis sections. The effect of contact elevation uncertainty on the conditional probabilities of levee failure can be evaluated by varying the elevations in the quantitative analyses.

4.3.7 Method Uncertainty

The analytical methods used to estimate conditional probabilities of levee failure are approximations of the behavior of a levee embankment and foundation at a given river stage. These approximations introduce uncertainty into the estimated conditional probabilities of levee failure. The relative degree of uncertainty introduced by the choice of analytical methods can be evaluated by calculating conditional probabilities of levee failure by alternative methods.

5.0 ANALYTICAL METHODS

The quantitative and semi-quantitative analytical methods used to calculate factors of safety (FSs) and conditional probabilities of failure are described in the following sections.

5.1 Underseepage

An FS for underseepage is defined as:

$$F_S = i_c / i$$

where:

i = calculated steady state gradient at the landside toe of the levee
i_c = critical gradient

and the critical gradient is defined as:

$$i_c = \gamma'_s / \gamma_w$$

where:

γ'_s = buoyant unit weight of the overbank soil at the landside toe of the levee
γ_w = unit weight of water

A seepage gradient greater than or equal to the critical gradient is assumed to cause sand boils or heave (flotation) of the relatively less permeable soils overlying the more pervious underseepage soil layer.

Underseepage gradients (i) were calculated for each river stage at each analysis location using SEEP/W 2007 (Geo-Slope, 2010a). Underseepage gradients at selected river stages and locations were also calculated using a method described in EM 1110-2-1913, Appendix B (USACE 2000).

5.1.1 Underseepage Calculation with SEEP/W

SEEP/W is a software program that uses a two-dimensional finite element method to simulate fluid flow and pressure distribution in saturated and unsaturated porous materials such as soil and rock. Fluid flow and pressure distribution can be analyzed under steady state or transient conditions.

The software is based on the assumption that fluid flow through the material obeys Darcy's Law:

$$q = -K\,i$$

where:

q = specific discharge
K = hydraulic conductivity
i = hydraulic gradient

The governing equation used in SEEP/W is:

$$K_x \frac{\partial^2 H}{\partial x^2} + K_y \frac{\partial^2 H}{\partial y^2} + Q = 0$$

where:

K_x = hydraulic conductivity in the x-direction
K_y = hydraulic conductivity in the y-direction
H = total head
Q = applied boundary flux

The general steps required for an analysis with SEEP/W are to:

(1) Define the cross section geometry (river bathymetry, levee and ground surface profile, and subsurface soil layer contacts)
(2) Create the finite element mesh
(3) Define the material properties for each soil type
(4) Define the flow boundary conditions

The geometry of a model is defined in its entirety before creating a mesh. A mesh is generally created using an automatic mesh generator and modified by the user as required.

Boundary conditions are specified according to the physical conditions and the type of analysis (steady state or transient). For steady state analysis, boundary conditions are either fixed-head (or pressure) or fixed-flux values. For transient analysis, one or more boundary conditions can be set as a function of time or a response to flow exiting or entering the flow regime. An example is presented in Appendix B showing the geometry, mesh, and boundary conditions for a seepage analysis at analysis section DD17-1L.

The material properties used in the SEEP/W analyses are presented in Section 6.0.

5.1.2 Underseepage Calculation by USACE EM 1110-2-1913 Method

The underseepage calculation method presented in EM 1110-2-1913 is a closed-form solution based on the following simplifying assumptions:

(1) Seepage may enter the pervious layer at any point on the riverside of the levee
(2) Flow through the soil layer(s) overlying the seepage layer is vertical
(3) Flow through the pervious layer is horizontal
(4) Flow is laminar
(5) The levee and soil layer(s) overlying the seepage layer are impervious.

This method provided a basic check of the SEEP/W analysis and provided data for an evaluation of the uncertainty associated with the selected approach to calculating underseepage gradients.

The geometric relationships of river, levee, and foundation soils and material properties used in the closed-form calculation of underseepage were the same as used in the equivalent SEEP/W analyses. The material properties used for seepage analysis are presented in Section 6.0.

5.2 Slope Stability

Slope stability analyses were completed to provide input to calculations of probability of failure (see Section 5.3). These analyses were completed in general accordance with EM 1110-2-1913 (USACE, 2000) and EM 1110-2-1902 (USACE, 2003). Analyses were performed using the software program SLOPE/W 2007 (GEO-SLOPE, 2010b).

5.2.1 Slope Stability Calculation with SLOPE/W

SLOPE/W is a software program that uses two-dimensional limit equilibrium methods to calculate an FS against sliding along a continuous surface in a soil or rock mass. The calculation can include the effects of groundwater and seismic forces on the FS. FSs were computed for circular failure surfaces using the Morgenstern-Price limit equilibrium procedure which satisfies moment and force equilibrium equations and accounts for interslice shear and normal forces.

The general steps required for the calculation of an FS with SLOPE /W are to:

(1) Define the cross section geometry (ground surface profile and subsurface soil layer contacts)

(2) Define the material failure criteria and properties for each soil type

(3) Define the groundwater regime, if any

(4) Define the analysis type and limits

The geometry developed for the SEEP/W models and porewater pressure distributions calculated by SEEP/W were used for the Skagit River levee stability analyses. The Mohr-Coulomb failure criterion was used for all of the soil types in the SLOPE/W analyses. Material properties for the soils are presented and discussed in Section 6.0.

In conventional deterministic slope stability analysis it is typical practice to seek a slip surface with the lowest FS, as the consequences of slope failure can only be evaluated after the location of the potential failure surface is determined. For levee risk analysis, however, the primary interest is in slope failures that compromise the ability of the levee to provide the intended protection.

To consider slip surfaces that would compromise the levee, we restricted the slip surface search to entry points at the levee crest and exit points near the levee toe (riverside or landside toe). The SLOPE/W slip surface search routine was used to find the critical slip surface within the entry and exit point limits. Slip surfaces with lower FSs may exist in the riverside or landside levee embankment, but embankment failure along those surfaces would not immediately compromise the levee and we assume that surface failures would be repaired during routine maintenance.

An example is presented in Appendix B showing the geometry and search criteria for a slope stability calculation at analysis section DD17-1L.

5.2.2 Static Factor of Safety (FS) Calculations

Static FSs were calculated for riverside and landside slip surfaces for four to six river stages at each of the eight analysis locations.

An FS was first calculated for the most-likely-value case at each location (riverside and landside). The most-likely-value case was based on our determination of the most likely values of the SLOPE/W input parameters of unit weight, friction angle, and steady state porewater pressure for the two soil types used in the analysis. An additional 12 FSs were then calculated by sequentially varying one of the input parameters by plus or minus one standard deviation from its most likely value. Most-likely-value and plus or minus one standard deviation values of steady state porewater pressures were imported from the SEEP/W analysis completed for each river stage at each location.

Slip surface entry and exit point limits were defined separately for the riverside and landside static FS calculations, but the same limits were used for the most-likely-value case and the associated parameter variation cases. The critical slip surface for each case was allowed to vary subject to the entry and exit point limits.

5.2.3 Seismic Factor of Safety (FS) Calculations

Seismic FSs were calculated for riverside and landside slip surfaces in the same manner as static FSs except with an additional horizontal force applied to represent the inertial forces of an earthquake. The horizontal force is determined from the mass of the soil slices used in the calculation of FS and from an input acceleration coefficient. The acceleration coefficient is generally assumed to be one-half of the peak ground acceleration of the earthquake (Hynes-Griffin, Franklin, 1984). The force is applied to the slices in the downslope direction. Seismic FSs were calculated assuming that there is no reduction of shear strength of the levee and foundation soils as would be considered in an analysis of liquefaction.

A peak ground acceleration coefficient of 0.2 was used to calculate seismic FSs for the Skagit River levees. The acceleration coefficient was obtained from our analysis of the Operating Basis Earthquake with a return period of 144 years and a 50 percent probability of exceedance for a service life of 100 years (Shannon & Wilson, 2010).

Seismic FSs were first calculated for the most-likely-value case at each location (riverside and landside). An additional twelve FSs were then calculated by sequentially varying one of the input parameters by plus or minus one standard deviation from its most likely value. Most-likely-value and plus or minus one standard deviation values of steady state porewater pressures were imported from the SEEP/W analysis completed for each river stage at each location.

5.2.4 Rapid Drawdown Factor of Safety (FS) Calculations

Static FSs for the riverside levee under rapid drawdown conditions were calculated at each analysis location for a scenario of a 13-foot drop in river stage over a period of 3.6 days beginning from a river stage equal to the levee crest.

The rapid drawdown scenario was developed from a discharge rating curve for the U.S. Geological Survey river gage at Mt. Vernon (USGS, 2010) and hydrographs from the gage at Mt. Vernon from November-December 1995, October 2003, and November 2006 (USGS, 1995, 2003, 2006). In each of these periods there was a high discharge event that peaked at or near 140,000 cubic feet per second (cfs). The discharge following these events fell at an average rate of about 25,000 cfs per day over a period of three to five days. The rating curve and hydrographs are shown in Figure 14. These data were used to calculate the average drop in river stage and average drawdown period used as the rapid drawdown scenario. Because this scenario was developed from three apparently extreme cases and the calculated probability of failure was near zero, no further rapid drawdown scenarios were considered.

An FS for rapid drawdown was first calculated for the most-likely-value case at each location (riverside only). An additional twelve FSs were then calculated by sequentially varying one of the input parameters by plus or minus one standard deviation from its most likely value. Most-likely-value and plus or minus one standard deviation values of transient porewater pressures were imported from the SEEP/W analysis completed for the rapid drawdown scenario at each location.

The slip surface entry and exit point limits that were established for the calculation of static FSs were used in the rapid drawdown factor of safety calculations.

5.3 Probability of Failure by Taylor Series Method

River stage versus probability-of-failure functions were developed for each of the analysis sections using the Taylor Series method (USACE, 1992, 1995; Wolff and Wang, 1992; Shannon & Wilson and Wolff, 1994; Wolff and others, 1996). The Taylor Series method is one of several first-order second-moment methods used to assess reliability. These methods are based on the concept that uncertainty in a given performance function (e.g., an FS) can be estimated from the uncertainty in the model parameters (e.g., soil strength parameters or porewater pressures).

The general procedure of the Taylor Series method used to determine a probability of failure is as follows: the expected value of the performance function is obtained by first evaluating the performance function using the expected values of the input parameters, x_N, to obtain the most likely value of the function, F_{MLV}. The standard deviation of the performance function, σ_F, is then determined using the following equation:

$$\sigma_F = \sqrt{\left(\frac{\partial F_1}{\partial x_1}\right)^2 \sigma_{x,1}^2 + \left(\frac{\partial F_2}{\partial x_2}\right)^2 \sigma_{x,2}^2 + \cdots + \left(\frac{\partial F_N}{\partial x_N}\right)^2 \sigma_{x,N}^2}$$

where $\partial F_N / \partial_{xN}$ is the partial derivative of the performance function with respect to the Nth input parameter and σ_{xN} is the standard deviation of the Nth input parameter. The partial derivatives are approximated numerically over an interval centered on the expected value. To evaluate partial derivatives we used an interval of plus one to minus one standard deviation as is generally recommended in the literature (USACE, 1999; Shannon & Wilson and Wolff, 1994).

When an interval of plus one to minus one standard deviation is used to evaluate the partial derivatives, the equation for σ_F simplifies to:

$$\sigma_F = \sqrt{\left(\frac{\Delta F_1}{2}\right)^2 + \left(\frac{\Delta F_2}{2}\right)^2 + \cdots + \left(\frac{\Delta F_N}{2}\right)^2}$$

where $\Delta F_N = (F_N^+ - F_N^-)$. F_N^+ is the performance function evaluated with the Nth parameter value increased one standard deviation from its expected value, and F_N^- is the performance function evaluated with the Nth parameter variable decreased one standard deviation from its expected value. In calculating F_N^+ and F_N^- for the Nth parameter, the values of the other parameters are kept at their expected values. Once the expected value and standard deviation of the performance function are determined, the coefficient of variability of the performance function V_F and log normal reliability index, β_{LN}, are calculated as follows:

$$V_F = \frac{\sigma_N}{F_{MLV}} \qquad \text{and} \qquad \beta_{LN} = \frac{ln\left(\frac{F_{MLV}}{\sqrt{V_F}}\right)}{ln(V_F)}$$

Because the reliability index is assumed to be from a standard normal distribution (mean = 0.0 and standard deviation = 1.0), the probability of non-failure, P_{nf}, can be determined from a table of the standard normal distribution and the probability of failure from $P_f = 1 - P_{nf}$.

5.4 Probability of Failure by Monte Carlo Method

The Monte Carlo method is an alternative to the Taylor Series method for estimating the conditional probability of slope failure. Whereas the Taylor Series method assumes that the FS for a slope is log-normally distributed, the Monte Carlo method uses the individual distributions of the input parameters (e.g., unit weight, friction angle) to determine the distribution of the FS. The distribution is determined by making repeated calculations of FS, each time randomly drawing a complete set of input parameters from the individual parameter distributions.

The Monte Carlo method implemented in SLOPE/W was used to estimate a conditional probability of failure for three Skagit River levee cases. The results of these three cases were used to evaluate the uncertainty in the estimated conditional probability of failure associated with the choice of analytical method (Taylor Series or Monte Carlo).

The general, the steps required for the calculation of a probability of failure with SLOPE/W are similar to the steps for a deterministic analysis as described in Section 5.2 with the exception that the material parameters are defined as probability distributions rather than discrete values.

The input parameters that can be entered as distributions are the unit weight of the soils and failure criteria parameters. For the Mohr-Coulomb failure criterion used in these analyses, the input parameters that can be entered as distributions are cohesion and friction angle. The input parameter distributions for the three Skagit River levee cases were assumed to be Gaussian (normal) distributions with mean values equal to the most likely values used in the Taylor Series analyses and standard deviation values equal to the standard deviation values used in the Taylor Series analyses. Material property distributions for the soils are presented and discussed in Section 6.0.

To calculate a probability of failure, the SLOPE/W software first determines a critical slip surface for the given slope geometry and analysis type using the average values of the input parameters. The FS for the critical slip surface is then repeatedly calculated with each calculation using a different set of input parameters drawn from the specified distributions. The software counts the frequency of occurrence of FSs in intervals to develop a histogram representing the probability distribution of the FS for the critical slip surface. We specified that 2,000 calculations of FS be performed to develop the histogram for each of the three Skagit River levee cases.

5.5 Scour Probability

The contribution of scour to the conditional probability of failure of the Skagit River levees was evaluated semi-quantitatively using a probabilistic procedure described in ETL 1110-2-556 (USACE, 1999). This procedure, which is based on the evaluation of a performance function similar to a Taylor Series analysis (see Section 5.3), was used to develop graphs of the conditional probability of scour versus water height. The quantitative estimate of probability of scour was used to make a qualitative estimate based on engineering judgment of the impact of scour on the combined conditional probability of levee failure.

The probabilistic procedure described in ETL 1110-2-556 is based on a comparison between a probable flow velocity, V, and a critical flow velocity, V_{crit}, that would result in scour. Flow velocity is assumed to be a function of water depth, the slope of the energy line (approximately equal to the average slope of the river channel), and surface roughness. Water depth is assumed to range from the deepest point in the river to levee crest and the mean and coefficient of variation of slope and roughness can be estimated or measured.

The procedure uses an adaptation of Manning's formula to calculate flow velocity, V, as:

$$V = \frac{1.486y^{2/3}S^{1/2}}{n}$$

where:

y = depth of flow
S = slope of the energy line
n = Manning's roughness coefficient

The coefficient of variation of velocity, CV_{vel}, is calculated from the coefficients of variation of S and n as:

$$CV_{vel} = \sqrt{CV_n^2 + \frac{CV_S^2}{4}}$$

where:

CV_n = coefficient of variation of Manning's n
CV_s = coefficient of variation of the slope of the energy line

If the performance function, V_{crit}/V is assumed to be log-normally distributed, a reliability index, β, can be calculated as:

$$\beta = \frac{ln\left(\frac{V_{crit}}{V}\right)}{\sqrt{CV_{vel\ crit}^{2}+CV_{vel}^{2}}}$$

where:

V_{crit} = critical velocity
V = velocity
$CV_{vel\ crit}$ = coefficient of variation of the critical velocity
CV_{vel} = coefficient of variation of probable velocity

Scour probability, i.e., the probability of the limit state of the performance function, V_{crit}/V being equal to or greater than 1, can then be determined by comparing β to tables of the cumulative normal distribution.

5.6 Liquefaction

Liquefaction or partial liquefaction is the loss of shear strength in a saturated, granular soil during an earthquake and can result in settlement or lateral spreading of a levee and its foundation. The settlement or lateral spreading can result in a lowering of the levee crest or an embankment failure which would compromise the ability of the levee to provide its intended protection. Although the likelihood of an earthquake occurring simultaneously with a high river stage may be low, liquefaction may occur at any river stage.

Previous analysis of liquefaction potential at the analyses locations (Shannon & Wilson, 2010) concluded that the FS against liquefaction during an Operating Basis Earthquake (OBE) was less than one for thicknesses of up to 15 feet. The OBE has a return period of 144 years and a 50 percent probability of exceedance for a service life of 100 years.

The semi-quantitative approach taken to evaluate the contribution of liquefaction to the conditional probability of failure of the Skagit River levees was to estimate a threshold return period that could cause liquefaction. Earthquakes with a return period less or equal to than the threshold would be assumed to have an FS against liquefaction greater than one. Earthquakes with a return period greater than the threshold would be assumed to have an FS against liquefaction less than one at some locations and depths, potentially resulting in liquefaction or partial liquefaction.

The underlying assumption of this approach is that earthquakes that are less severe than OBE, but with a greater frequency of occurrence, can cause liquefaction damage to the levees. The quantitative estimate of liquefaction potential was used to make a qualitative estimate based on engineering judgment of the impact of liquefaction on the combined conditional probability of levee failure.

The threshold return period was determined using the same analytical procedures that were used in the previous analysis of the OBE. The input peak soft rock acceleration and amplification factor were incrementally reduced to find a level at which the FS against liquefaction was greater than one for every analysis location and depth.

5.7 Throughseepage

Numerical and closed form calculations of seepage failure in the Skagit River levees are controlled by underseepage through a highly permeable soil layer beneath the levees and overbank soils. Consequently, the contribution of throughseepage to the combined conditional probability of failure of the Skagit River levees was evaluated qualitatively.

Erosion or piping resulting from high hydraulic gradients may occur within a levee embankment due to the presence of preferential seepage paths resulting from conditions such as cracking, animal burrowing, or decay of roots. High exit gradients on the landside face of the levee or internal erosion from high hydraulic gradients within the levee may initiate piping beginning at the landside face of the levee where the hydraulic gradient is highest and progressing into the levee.

The Skagit River levees are vegetated in many areas and may be susceptible to animal burrowing, but, in our opinion, the likelihood of through-going seepage paths being initiated in these levees by decaying roots or animal burrows is small in comparison to the other factors affecting levee reliability and, therefore, a more detailed quantitative analysis was not justified. However, the potential for throughseepage failure was incorporated in our estimate of probability of failure based on engineering judgment.

5.8 Sequential Failure

The contribution of sequential failure to the combined conditional probability of failure of the Skagit River levees was evaluated semi-quantitatively by calculating the conditional probability of a scenario of sequential riverside slope failures. The quantitative estimate of probability of sequential failure was used to make a qualitative estimate based on engineering judgment of the impact of sequential failure on the combined conditional probability of levee failure.

A sequential failure scenario was developed by assuming that during a rapid drawdown condition an initial riverside slope failure would occur that did not intersect the levee crest and that the soil mass that failed would be washed away by the river, leaving a new slope. The new slope in turn would fail and the second soil mass would be washed away. The third and final slope failure was assumed to intersect the levee crest, thereby compromising the ability of the levee to provide the intended protection.

The conditional probability of the first failure can be expressed as $Pf_1 = P(f_1 \mid H)$. The notation is read as '*the probability of the first failure* ***given*** *a river stage of H'*. The conditional probability of the second failure is $Pf_2 = P(f_2 \mid H \cup f_1)$ which is read as '*the probability of the second failure* ***given*** *a river stage of H* ***and*** *the first failure has occurred*'. Finally, the conditional probability of the third failure is $Pf_3 = P(f_3 \mid H \cup f_1 \cup f_2)$ which is read as '*the probability of the third failure* ***given*** *a river stage of H* ***and*** *the first failure has occurred* ***and*** *the second failure has occurred.*' If $P(H)$ is the probability of river stage H occurring, the probability of all four events (river stage H and three failures) is $P(H \cup f_1 \cup f_2 \cup f3) = P(H) \cdot Pf_1 \cdot Pf_2 \cdot Pf_3$.

Rearranging terms yields $P(H \cup f_1 \cup f_2 \cup f3) / P(H) = Pf_1 \cdot Pf_2 \cdot Pf_3$, which is a conditional probability of failure that is directly comparable to the other conditional probabilities of failure calculated for the levee risk analysis.

Conditional probabilities of failure Pf_1, Pf_2, and Pf_3 were calculated for the sequential failure scenario using SLOPE/W by specifying a fixed river stage and performing the following steps:

(1) Calculate the first probability of failure, Pf_1
(2) Remove the soil mass above the first failure surface from the model
(3) Calculate the second probability of failure, Pf_2
(4) Remove the soil mass above the second failure surface from the model
(5) Calculate the third probability of failure, Pf_3

6.0 INPUT VARIABLES AND DISTRIBUTIONS

The limit state calculations performed for the Skagit River levee risk analysis included seepage, slope stability, scour probability, and liquefaction potential. The input variables for these calculations and our estimates of most likely values and variability of the parameters are presented in the following sections.

6.1 Seepage Variables

The input parameters used for the Skagit River levee seepage analyses performed with the SEEP/W software were horizontal hydraulic conductivity, a ratio of vertical to horizontal hydraulic conductivity, and a volumetric water content function.

Horizontal hydraulic conductivity is a measure of the rate of the horizontal flow of water through a volume of soil. Field test data (Shannon & Wilson, 2010) were used to develop horizontal hydraulic conductivity values for the pervious layer underlying the levee and overbank soils. The average (most likely value) and standard deviation of the horizontal hydraulic conductivity of the pervious soil layer and the values used in our analyses are presented in Table 3. The average and standard deviation were calculated from the results of eight slug tests performed in the landside borings at the Skagit River analysis locations (Shannon & Wilson, 2010). A range of horizontal hydraulic conductivity values for the levee, overbank, and sub-layer soils was estimated from typical values reported in the literature for these material types (Freeze and Cherry, 1979). The most likely value and estimated standard deviation of horizontal hydraulic conductivity for these soils are also shown in Table 3.

As a further check of these estimates, hydraulic conductivity was also calculated from grain size distribution tests performed on 87 sand and gravel samples from the pervious layer (Shannon & Wilson, 2010). Hydraulic conductivity was computed using the relationship (USAWES, 1956):

$$k = C \bullet (D_{10})^2$$

where:

k = hydraulic conductivity, centimeters per second (cm/sec)
C = a constant
D_{10} = effective grain size, millimeter (mm)

The effective grain size is the particle diameter at which 10 percent of the soil particles are smaller. The constant was assumed to be equal to one. The average hydraulic conductivity calculated from this relationship was 3.6×10^{-2} cm/sec with a coefficient of variation of about 85 percent as compared to an average of 1.2×10^{-2} cm/sec and a coefficient of variation of about 33 percent for the slug tests. The relatively close agreement between the two methods of estimating hydraulic conductivity provided further evidence that the most likely value estimated from the slug tests was reasonable.

The ratio of vertical to horizontal hydraulic conductivity describes the relative rate of vertical to horizontal flow of water through a soil mass. The range of this ratio was estimated from typical values reported in the literature for these material types (Freeze and Cherry, 1979). A fixed value for the ratio was used in the seepage FS calculations, but a sensitivity analysis was performed to estimate the impact of the ratio on the combined conditional probability of failure of the levees. The most likely values and estimated standard deviations of hydraulic conductivity ratio are shown in Table 4.

A volumetric water content function describes the volume of water stored in voids in a soil mass as function of porewater pressure. In the absence of site-specific test data for this function we used a function for sand provided in the SEEP/W documentation (Geo-Slope, 2010a). We performed a parametric analysis of the function control values and concluded that the model results were not sensitive to the assumed range of function control values for the soils present in the Skagit River levees and foundations.

Boundary conditions are a critical component of a numerical seepage analysis. In the SEEP/W analyses, the riverside boundary of the model was defined as a constant head boundary equal to the head of the river stage being analyzed. The landside face of the levee from crest to toe was defined as a seepage face and the horizontal ground surface from the toe and beyond was defined as a zero pressure boundary. Vertical boundaries of the model were defined as constant head boundaries equal to the head at those locations. An example is presented in Appendix B showing the geometry, mesh, and boundary conditions for a seepage analysis at analysis section DD17-1L.

Secondary seepage calculations performed by the method presented in EM 1110-2-1913 (USACE, 2000) require input variables of horizontal hydraulic conductivity and hydraulic conductivity ratio. The values of these variables that were used in the SEEP/W analyses were also used in the secondary seepage calculations.

6.2 Slope Stability Variables

The calculation of FS for a Mohr-Coulomb soil by limit equilibrium methods using the SLOPE/W software requires input of soil total unit weight, cohesion, and friction angle.

Total unit weight describes the weight of a unit volume of soil and water. Total unit weight values for the overbanks and sub-layer soils were determined from the results of laboratory tests performed on those soils. Total unit weight values for the pervious layer were estimated from typical values reported in the literature (Peck and others, 1974). The most likely values and standard deviations for total unit weight are shown in Table 5. The coefficient of variability (CoV) for the unit weight of the soils is generally less than CoV's reported in the literature. In our opinion, the lower CoV values used in our analyses are reasonable based on laboratory measurements and our experience with similar soils and geologic environments.

Cohesion and friction angle describe the shear strength of a Mohr-Coulomb soil. Because the Skagit River levee and foundation soils are predominantly granular soils, cohesion was assumed to be zero and an effective stress analysis was performed. Friction angle values for the levee, overbank, and sub-layer soils were estimated from the results of laboratory tests performed on those soils. Friction angle values for the pervious layer were estimated from SPT blow counts and typical values reported in the literature (Peck and others, 1974). The most likely values and standard deviations for friction angle are shown in Table 6.

6.3 Scour Probability Variables

Scour probability is the likelihood that scour would occur under a given set of river and levee conditions. The input variables required for the scour probability calculations include the critical velocity, slope of the energy line, Manning's roughness coefficient, and water depth.

The critical velocity is the water velocity at which scour is initiated. Scour probability versus water depth was determined for critical velocities of 3, 4, and 5 feet per second (fps). This range of critical velocities was selected from a table of allowable velocities for soil type ranging from silty sands to coarse gravels (Simons and Senturk, 1992). Although modeling performed by NHC indicated that cross sectional channel velocities range from 5.5 to 9.5 fps (NHC, 2010a), the water velocity at the river bank and levee slope will generally be less than the average channel velocity, hence the choice of critical velocities.

The slope of the energy line was approximated by the river bed slope. River bed slope values were obtained from a numerical model developed by NHC (NHC, 2010b) and from LIDAR data.

Manning's roughness coefficient values were estimated from typical values reported in the literature (ASCE, 1996). The most likely values and standard deviations for the scour probability input variables are shown in Table 7.

6.4 Liquefaction Potential Variables

An analysis of the liquefaction potential for a given earthquake depends on Standard Penetration Test (SPT) blow counts, percent fines of a granular soil, and the Atterberg Limits plasticity index for a cohesive soil. SPT blow counts are a measure of the relative density/consistency of a soil. Percent fines is the percentage by weight of particles in a soil mass that are less than 0.075 mm in diameter. Atterberg Limits plasticity index is a range of water contents where a soil is considered plastic.

The SPT blow counts, percent fines, and Atterberg Limits plasticity indices used in our analysis of liquefaction potential were obtained from our previous geotechnical report (Shannon & Wilson, 2010). Rather than determining the distribution (most likely value and standard deviation) of the input variables, the measured values of the input variables were used to estimate liquefaction threshold return periods at each analysis location and a most likely value and standard deviation of threshold return period was calculated from those results.

7.0 RELIABILITY ANALYSIS RESULTS

7.1 Quantifiable Failure Modes

7.1.1 Overview

The results of the quantitatively analyzed failure modes are discussed in the following sections. We prepared depth-normalized graphs of the results for several of the failure modes (see Figures 15 to 18). The depth-normalization consisted of converting river stage (elevation) to water-depth-below-crest. Although the analyses were performed using river stage and elevation data and the fragility curves are presented in terms of river stage (elevation), we found it useful to compare the conditional probabilities of individual failure modes in terms of water-depth-below-crest rather than river stage. This comparison aided us in identifying the similarities and differences among the eight analysis locations.

7.1.2 Underseepage

The conditional probability of underseepage failure (exit gradient greater than critical gradient) is plotted versus depth below levee crest in Figure 15 for direct comparison of the analysis sections. This figure shows that our analysis of underseepage with SEEP/W indicates that the conditional probability of underseepage failure is near zero at all analysis sections except DD1-1R, DD1-2R, and DD17-1L. In general, the analysis sections exhibiting underseepage failure have the greatest difference in elevation between the levee crest and landside toe (seepage exit point) which would lead to larger water head differences between the river and seepage exit point.

As shown in Figure 15, a non-zero conditional probability of underseepage failure begins at river stages 4 to 6 feet below the levee crest for analysis sections DD1-1R and DD17-1L. However, at analysis section DD1-2R, the non-zero conditional probability of underseepage failure begins at a river stage 10 feet below the levee crest. The earlier onset of seepage failure at DD1-2R is attributed to the relatively shorter seepage path to the levee landside toe (approximately 120 feet) and the relatively thinner (approximately 8-foot-thick) overbank layer at the landside toe at this location as compared to conditions at sections DD1-1R and DD17-1L. The other five analysis locations have relatively longer seepage paths and relatively thicker landside toe overbank layers.

A sensitivity analysis for the hydraulic conductivity ratio was performed using section DD1-1R at a river stage of 35.2 feet. The sensitivity analysis was run using minimum and maximum credible values for the ratio. The conditional probability of underseepage failure for the most likely value was 0.29, and for the minimum and maximum credible values, 0.22 and 0.38, respectively. The effect on the fragility curve for this range of conditional probabilities (~±25%) would be similar at this analysis section as underseepage appears to be the controlling mode of failure at this location. The fragility curve at analysis section DD17-1L also appears to be controlled by underseepage and may have similar sensitivity to the assumed hydraulic conductivity ratio. The uncertainty of the hydraulic conductivity ratio was considered in the development of the fragility curves for DD1-1R and DD17-1L. The other six analysis sections have near-zero conditional probabilities of underseepage failure and, hence, would be less affected by the uncertainty of the hydraulic conductivity ratio.

7.1.3 Landside Static Failure

The conditional probability of landside static slope failure is plotted versus depth below levee crest in Figure 16. In general, landside static slope stability appears to be controlled by the high porewater pressures that develop in the levee during steady state seepage.

A non-zero conditional probability of landside static failure was found at every analysis section except DD1-1R and DD22-1R. The absence of landside static slope failures at DD1-1R is attributed to the thickness of the landside toe overbank layer (more than 20 feet thick, limiting seepage) and the buttressing effect of soil at the landside toe that has the shape of a seepage control blanket. The absence of landside static slope failures at DD22-1R is attributed to the thickness of the landside toe overbank layer (about 18 feet thick) and to the relatively smaller difference in elevation between the levee crest and landside toe.

For analysis sections DD3-1L, DD17-1L, DD17-2L, DD17-3L, and DD22-2L, the onset of landside static failures was at river stages from 2 to 5 feet below the levee crest. At DD1-2R, the onset of landside static failures began at a river stage 10 feet below the levee crest. The earlier onset at DD3-1L, DD17-1L, DD17-2L, DD17-3L, and DD22-2L is attributed to the relatively thinner (approximately 8- to 10-foot-thick) overbank layer at the landside toe at this location which resulted in earlier development of high porewater pressure in the levee and earlier onset of underseepage.

7.1.4 Riverside Static Failure

The calculated conditional probabilities of riverside static failure were essentially equal to zero for all analysis sections and river stages analyzed. Although pore water pressures in the riverside levee slopes would be as great, or greater, than in the landside levee slopes, the buttressing effect of the water helps to maintain an FS greater than one in the riverside slopes.

7.1.5 Landside Seismic Failure

The calculated conditional probabilities of landside seismic failure are presented in Figure 17. The calculated probabilities in this figure have two conditions, a given river stage has occurred and an OBE has occurred.

The doubly conditioned probability is expressed as $P(f_S \mid H \cup E)$ which is read as '*the probability of the failure* ***given*** *a river stage of H* ***and*** *an earthquake E*'. By definition, the conditional probability is $P(f_S \mid H \cup E) = P(f_S \cup H \cup E) / P(H \cup E)$, which is read as '*the probability of failure* ***and*** *river stage* ***and*** *earthquake* ***divided by*** *the probability of the river stage* ***and*** *the earthquake.*'

Assuming that the river stage and earthquake are independent events, $P(H \cup E)$ can be rewritten as $P(H) \bullet P(E)$. Rearranging terms yields $P(f_S \mid H \cup E) \bullet P(E) = P(f_S \cup H \cup E) / P(H)$, which is a conditional probability of failure that is directly comparable to the other conditional probabilities of failure calculated for the levee risk analysis. Thus, in calculating the combined probability of failure for a given river stage, the probabilities shown in Figure 17 were multiplied by probability of an OBE to obtain a probability that is only conditioned on the given river stage.

The variability in the conditional probabilities of landside seismic failure curves appear to be partially due to the variable conditions described for landside static failures and partially due to the steepness and angle of the landside slopes.

7.1.6 Riverside Seismic Failure

The calculated conditional probabilities of riverside seismic failure are presented in Figure 18. The calculated probabilities in this figure have two conditions, a given river stage has occurred and an OBE has occurred. In calculating the combined conditional probability of failure for a given river stage, the probabilities shown in Figure 18 were multiplied by probability of an OBE to obtain a probability that is only conditioned on the given river stage as described in Section 7.1.5.

The conditional probabilities of riverside seismic failure appear to fall in three groups. One group, represented by analysis sections DD1-1R and DD17-1L, has a conditional probability of failure at or near one at all river stages. The second group, represented by analysis sections DD1-2R, DD17-2L, DD17-3L and DD22-2L, has a conditional probability of failure of about 0.5 beginning at the lowest river stage analyzed, rising to a probability of near one at a river stage 7 to 8 feet below the levee crest. The third group, represented by analysis sections DD3-1L and DD22-1R, has a non-zero conditional probability of failure beginning at river stages 18 to 19 feet below the levee crest, rising to a probability of near 0.5 at a river stage 6 feet below the levee crest. The increase and subsequent decrease in the conditional probabilities of riverside seismic failure versus river stage is attributed to the buttressing effect of the water relative to the seismic inertial force. At lower river stages the buttressing effect has a smaller influence on riverside slope stability; but, at some critical river stage, the buttressing effect becomes sufficient to reduce the probability of seismic failure.

7.2 Other Failure Modes

7.2.1 Liquefaction Potential

The results of our analysis of liquefaction potential are presented in Table 8. This table shows the estimated threshold return period for the initiation of liquefaction for each of the Skagit River analysis sections.

The results of the liquefaction potential analysis indicate that the range of threshold return periods is 20 to 219 years with an average of about 61 years and a standard deviation of about 48 years. These results imply that partial liquefaction and subsequent lateral spreading or settlement could occur more frequently than would be indicated by consideration of an OBE alone.

Based on our analysis and engineering judgment, we have incorporated the effects of liquefaction potential in our estimate of the combined conditional probability of failure, recognizing that liquefaction may not result in complete failure of a levee.

7.2.2 Throughseepage

Erosion or piping resulting from high hydraulic gradients may occur within a levee embankment due to the presence of preferential seepage paths resulting from conditions such as cracking, animal burrowing, or decay of roots. High exit gradients on the landside face of the levee or internal erosion from high hydraulic gradients within the levee may initiate piping beginning at the landside face of the levee where the hydraulic gradient is highest and progressing into the levee.

The Skagit River levees are vegetated in many areas and may be susceptible to animal burrowing, but, in our opinion, the likelihood of through-going seepage paths being initiated in these levees by decaying roots or animal burrows is small in comparison to the other factors affecting levee reliability. However, the potential for throughseepage failure was incorporated in our estimate of probability of failure based on engineering judgment.

7.2.3 Scour Probability

The results of the scour probability analysis are presented in Figures 19 and 20 for the Skagit River main stem and the North and South Forks, respectively. The graphs show the probability of scour for a range of water depths, channel slopes (slope of the energy line), roughness coefficients, and critical velocities. The upper graph in each of these figures shows the relative effect of varying the channel slope for a fixed roughness coefficient and critical velocity, the middle graphs show the relative effect of varying the roughness coefficient for a fixed channel slope and critical velocity, and the lower graphs show the relative effect of varying the critical velocity for a fixed channel slope and roughness coefficient.

For the range of channel slopes, roughness coefficients, and critical velocities considered, the graphs in Figures 19 and 20 indicate that the greatest uncertainty in the estimates of scour probability is due to uncertainty in the critical velocity. The critical velocity primarily depends on the levee or river bank soil type and vegetation cover, and may have considerable variation along the length of the study area. Although there are no revetments at the eight analysis sections, the protection provided by a revetment would reduce the likelihood of scour.

At seven of the eight analysis sections, the riverside slope of the levee extends 50 to 70 feet toward the river at a relatively flat angle. Consequently, the water depths near the levee crest would generally be less than about 15 feet even at the highest river stage. The scouring probability would be lower in these areas than in the river channel where the water may be 30 to 50 feet deep when the river stage is at the levee crest. At analysis section DD22-1R, however, the riverside slope of the levee extends toward the river at a steeper angle, which would result in greater water depths nearer to the levee crest and, hence, a greater probability of scour near the levee crest. In general, the presence of a sloping bench between the levee and the river would appear to limit the probability of scour that could directly impact the levee crest. Based on our analysis of scour probability and engineering judgment, we have incorporated the effects of scour in our estimate of the combined conditional probability of failure.

7.2.4 Sequential Failure

The results of an analysis of a sequential failure scenario are presented in Figure 21. The conditional probabilities of failure for the sequence of three scour and sliding events given an initial river stage of 31.4 feet drawn down to 18.4 feet are 0.59, 0.71, and 0.88. The combined conditional probability of failure for the three events is then 059 • 0.71 • 0.88 = 0.37. The combined conditional probability of failure should also be reduced by an estimate of the probability of scour occurring at each step in this scenario. The river level at the conclusion of the sequential failure is below the landside surface elevation and, therefore no immediate flooding would occur in this scenario. However, in the absence of repairs, the levee would no longer provide its intended level of protection and would be susceptible to further damage and potential flooding during subsequent high river stages.

Based on our analysis and interpretation of this scenario, it appears that the probability of sequential failure would only be significant in the case of a repeated high river stage and significant scour of the riverside slopes. Sequential failure can also occur on the landside slope of a levee due to seepage related erosion and piping. However, a landside sequential failure may be a relatively slower process and may require more than one high river stage to progress to failure. The possibility of riverside and landside sequential failures has been incorporated in our estimate of probability of failure based on engineering judgment.

7.2.5 Contribution to Combined Conditional Probability of Failure

Based on our semi-quantitative analysis of other failure modes and engineering judgment, we have concluded that these modes could make a substantial contribution to the combined probability of levee failure. We estimate that the conditional probability of failure for the aggregate of these modes could range from 0.1 to 0.3 for a river stage 1 foot below the levee crest. This range of probabilities was estimated by considering the number of potential failure modes evaluated by semi-quantitative and qualitative methods. Each potential failure mode will have a small conditional probability of failure that, in the aggregate, can constitute a probability of this magnitude. Considering the number of potential failure modes that cannot be analyzed by quantitative methods and the uncertainty in the input parameters and methods used for the quantitative methods, it is our opinion that this range of judgmental conditional probabilities is realistic.

We have included a conditional probability of failure of 0.2 for a river stage 1 foot below the levee crest in the fragility curves presented in Section 9. These failure modes may also contribute a small amount to the conditional probability of failure at lower river stages, but, in our opinion, the uncertainty of estimating small probabilities does not justify their inclusion in the combined conditional probability of failure.

7.3 Other Failure Mode Factors

7.3.1 River Stage Duration

The stability analyses used to develop the combined conditional probabilities of levee failure presented in this report were based on a conservative assumption of steady state seepage conditions. Our transient seepage analysis for each of the eight locations indicate that steady stage seepage conditions are reached in three to four days for a constant river stage.

To evaluate the effect of the steady state assumption, we considered a scenario at analysis section DD17-1L in which the river stage was assumed to rise and fall approximately 20 feet to elevation 38.9 feet within two days. In this scenario, the seepage conditions are transient and porewater pressures do not fully develop in the levee embankment. The most likely static FS for the landside slope under steady state conditions was 1.2 with conditional probability of failure of 0.013. For the transient condition, the most likely static FS was 2.5 with a conditional probability of failure of 0.0.

The effects of transient seepage conditions scenarios were not included in our estimates of the combined conditional probabilities of levee failure. However, in our opinion, the probability of levee failure would generally be lower for short duration river stages.

7.3.2 Length Effect

The length effect was evaluated by estimating a conditional probability of failure of a chain of levee sections using a generic conditional probability of failure curve for a single section in the system as the basis of the calculation. The system of levee sections and the single section are assumed to have similar conditions and response to changes in river stage. In this evaluation, we assumed that the conditional probability of failure of the single section applied to a length of levee L, and estimated a conditional probability of failure for 2L, 3L, 5L, 10L, and 20L levee lengths. The length L could be taken as a breach width or other characteristic length of levee. The system of levees was assumed to have failed if any one of the levee sections failed.

The results of the length effect evaluation are shown in Figure 22. The figure shows that as the length of the system of levees increase, the conditional probability of failure of the chain increases at every river stage.

The length effect was not included in our estimates of the combined conditional probabilities of levee failure because there is insufficient information to define a characteristic length L. However, in our opinion, the length effect should be included in subsequent risk-based analyses that address the levees as a system.

7.3.3 Channel Configuration

The effect of river bends, bars, and other natural features on flow direction and velocity were not explicitly considered in the development of the combined conditional probabilities of levee failure presented in this report. These effects should be considered if the probabilities are used in the analysis of levees in other than straight reaches.

7.3.4 Non-Levee Structures

The effect of river non-levee structures on flow direction and velocity were not explicitly considered in the development of the combined conditional probabilities of levee failure presented in this report. These effects should be considered if the probabilities are used in the analysis of levees at or adjacent to non-levee structures.

7.3.5 Measurement Uncertainty

The influence of measurement uncertainty on the combined conditional probabilities of levee failure was evaluated by varying the elevation of the top of the pervious layer at one analysis section. Based on measurement uncertainties and uncertainties introduced by projecting this elevation over the width of our model, we assumed that the elevation of the top of the pervious layer could vary by plus or minus 1 foot and calculated a conditional probability of underseepage failure and landside static slope failure. These calculations were performed using the DD17-1L model and a river stage of 38.9 feet.

The conditional probability of underseepage failure at this analysis section and river stage using the most likely value of the elevation of the top of the pervious layer was 0.28. If the elevation of this subsurface contact is lowered one foot, the conditional probability of underseepage failure becomes 0.0012. If the elevation is raised 1 foot, the conditional probability of underseepage failure is 0.9998. The top stratum in this case is the only barrier to underseepage, hence the conditional probability of underseepage failure is sensitive to changes in the thickness of the top stratum. For this analysis section, the most likely value of the top stratum thickness is approximately 8 feet at the landside toe of the levee.

The conditional probability of landside static slope failure at this analysis section and river stage using the most likely value of the elevation of the top of the pervious layer was 0.013. If the elevation of this subsurface contact is lowered 1 foot, the conditional probability of static slope failure becomes 0.004. If the elevation is raised 1 foot, the conditional probability of static slope failure is 0.295.

These analyses demonstrate the potential effect of measurement uncertainty on the conditional probabilities of failure. The assumption of a uniform, 1-foot error in one direction or the other may be conservative because measurement errors are more likely to be randomly distributed. However, the uncertainty introduced by projecting measured elevations over the width of the model may not be conservative. The consequence of this uncertainty would be reflected in uncertainty in the fragility curves presented in Section 9.

7.3.6 Method Uncertainty

The influence of method uncertainty on the combined conditional probabilities of levee failure was evaluated by comparing probabilities calculated by the Taylor Series and Monte Carlo methods.

Monte Carlo analyses were performed for three static stability cases: DD17-1L landside at river stage 42.0 feet, DD1-2R landside at river stage 15.0 feet, and DD17-1L riverside at river stage 19.4 feet. These cases were selected because they represented a wide range of most likely FSs and probabilities of failure. The input parameter distributions were assumed to be Gaussian (normal) distributions with mean values equal to the most likely values used in the Taylor Series analyses and standard deviation values equal to the standard deviation values used in the Taylor Series analyses.

The results of the Taylor Series and Monte Carlo analyses for these three cases are summarized in Table 9. Because of the similarity of input parameters and assumed distributions for both methods, the probabilities of failure are also similar. The differences between the two methods are seen in the range of FSs considered and in the reliability index. If non-normal distributions were assumed for the input parameters for the Monte Carlo method, the differences in probabilities could be greater.

Based on the results of our limited Monte Carlo analysis, we did not include a component of method uncertainty in the calculation of conditional probabilities of levee failure presented in this report.

8.0 $P_f = 0$ CALIBRATION

8.1 Estimate of $P_f = 0$ River Stage

Based on the historical evidence of seepage failure generally being the first sign of levee failure on the Skagit River, we assumed that the $P_f = 0$ river stage could be estimated using Casagrande's seepage theory to determine the river stage that would result in the onset of seepage at the landside levee toe. Based on the average dimensions of the Skagit River levees, we estimated that seepage would begin at a river stage 5 to 6 feet below the levee crest. We selected a river stage of 5 feet below the levee crest as the $P_f = 0$ river stage for seepage-only failure for all analysis sections. Also, based on the historical records, it appears that flooding due to other failure modes such as embankment failure are relatively rare events. This would imply that a $P_f = 0$ river stage with respect to other failure modes is closer to the levee crest. We estimated that the $P_f = 0$ river stage for failure modes other than seepage is approximately 2 feet below the levee crest for all analysis sections.

8.2 $P_f = 0$ Calibration

Our analyses indicated that for analysis sections controlled by underseepage failure, the onset of a non-zero conditional probability would begin at river stages from 3 to 10 feet below the levee crest with an average of about 6 feet. For analysis sections controlled by other modes of failure, the onset of a non-zero conditional probability would begin at river stages from 2 to 4 feet below the levee crest with an average of about 3 feet. Based on these results, additional calibration of the levee reliability was, in our opinion, not required.

9.0 FRAGILITY CURVES

9.1 Fragility Curve Development

The fragility curves (conditional probability of levee failure versus river stage) for the eight Skagit River levee analysis sections are presented in Figure 23 through 30. The fragility curves for each failure mode and the combined fragility curve for all failure modes are shown in these figures. The combined conditional probability of failure was calculated under an assumption of independence of the individual failure modes. Based on this assumption, we calculated the combined conditional probability of failure (P_{fc}) as

$$P_{fc} = 1 - (1 - P_{f1})*(1 - P_{f2})* \dots (1 - P_{fn})$$

where P_{f1} through P_{fn} are the conditional probabilities of failure for failure modes 1 through n.

The fragility curves for each analysis section are accompanied by a table showing the conditional probability of failure and the conditional probability of non-failure for each failure mode and river stage. In the accompanying tables, the probabilities with a yellow background were calculated by one of the quantitative methods described in this report. The probabilities with a blue background were calculated by linear interpolation between adjoining river stages where it was determined to be necessary and reasonable. The probabilities with a gray background were determined using engineering judgment and were included in the calculation of the combined conditional probability of failure.

9.2 Fragility Curve Discussion

The following is a summary of the primary conclusions we have drawn from the fragility curves. For this summary, we have selected a conditional probability of failure of $P_f <= 0.01$ as being approximately equivalent to the $P_f = 0$ discussed in Section 8. Almost all river stages have some conditional probability of failure greater than 0, but the probabilities at lower river stages are often very small.

Section DD1-1R:
Fragility controlled by underseepage, estimated P_f >= 0.01 river stage is about 36 feet (approximately 3 feet below crest).

Section DD1-2R:
Fragility controlled by underseepage, estimated P_f >= 0.01 river stage is about 15 feet (approximately 10 feet below crest).

Section DD3-1L:
Fragility controlled by landside static stability, estimated P_f >= 0.01 river stage is about 27 feet (approximately 2 feet below crest).

Section DD17-1L:
Fragility controlled by underseepage, estimated P_f >= 0.01 river stage is about 39 feet (approximately 4 feet below crest).

Section DD17-2L:
Fragility controlled by landside static stability, estimated P_f >= 0.01 river stage is about 37 feet (approximately 2 feet below crest).

Section DD17-3L:
Fragility controlled by landside static stability, estimated P_f >= 0.01 river stage is about 34 feet (approximately 5 feet below crest).

Section DD22-1R:
Fragility controlled by judgment, estimated P_f >= 0.01 river stage is about 22 feet (approximately 2 feet below crest).

Section DD22-2L:
Fragility controlled by landside static stability, estimated P_f >= 0.01 river stage is about 17 feet (approximately 4 feet below crest).

As noted in Section 4, a fragility curve analysis treats each failure mode equally and may lead to a conservative estimate of the likelihood of levee failure.

10.0 LIMITATIONS

This report was prepared for the exclusive use of the USACE. Within the limitations of the scope, schedule and budget, the recommendations presented in this report were prepared in accordance with generally accepted professional geotechnical engineering principles and practice in this area at the time this report was prepared. The analyses and conclusions contained in this report are based on site conditions as they existed at the time of our studies. Rivers are complex and dynamic systems that are continually changing due to erosion, deposition, and other natural processes and human activities. The uncertainty associated with complex and dynamic systems must be recognized in these types of studies. We make no other warranty, either express or implied.

Shannon & Wilson, Inc. has prepared Appendix C, "Important Information About Your Geotechnical/Environmental Report," to assist you and others in understanding the use and limitations of our report.

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TABLE 1
ANALYSIS SECTION NAMES AND RIVER MILE

Analysis Section Name	River	Bank	River Mile
DD17-1L	Skagit River	Left	17.40
DD17-2L	Skagit River	Left	16.10
DD1-1R	Skagit River	Right	14.00
DD17-3L	Skagit River	Left	13.55
DD3-1L	South Fork	Left	8.75
DD1-2R	North Fork	Right	8.60
DD22-1R	South Fork	Right	8.30
DD22-2L	North Fork	Left	7.10

TABLE 2
ANALYSIS SECTION BATHYMETRIC MEASUREMENTS

Analysis Section	River	River Mile	Bathymetry Location	Rationale
DD17-1L	Skagit River	17.40	17.51	Bathymetric measurement at River Mile (RM) 17.51 shows right bank bar similar to bar visible in air photo at analysis location; next nearest bathymetric measurement does not show a bar
DD17-2L	Skagit River	16.10	16.25	Bathymetric measurement at RM 16.25 in straight reach of river similar to analysis location; next nearest bathymetric measurement in start of bend
DD1-1R	Skagit River	14.00	14.00	Bathymetric measurement location matches analysis location
DD17-3L	Skagit River	13.55	13.88	Bathymetric measurement at RM 13.88 in straight reach of river; next nearest bathymetric measurement in start of bend with bar
DD3-1L	South Fork	8.75	8.75	Bathymetric measurement location matches analysis location
DD1-2R	North Fork	8.60	8.85	Bathymetric measurement at RM 8.85 in straight reach of river similar to analysis location; next nearest bathymetric measurement in start of bend with bar
DD22-1R	South Fork	8.30	7.80	Nearest bathymetric measurement used; next nearest bathymetric measurement may in an area with a bar
DD22-2L	North Fork	7.10	7.20	No other adjacent bathymetric measurement

TABLE 3
SUMMARY OF INPUT VARIABLES, HYDRAULIC CONDUCTIVITY

Pervious Layer Soils Data Source: Slug Tests				
	Measured Values		Analysis Values	
	ft/sec	cm/sec	ft/sec	cm/sec
Average	3.8E-04	1.2E-02	4.0E-04	1.2E-02
St Deviation	1.3E-04	3.9E-03	1.3E-04	4.0E-03
CoV	33%	33%	33%	33%
Avg + 1 St Dev	5.1E-04	1.5E-02	5.3E-04	1.6E-02
Avg - 1 St Dev	2.5E-04	7.7E-03	2.7E-04	8.2E-03

Levee, Overbank, and Sublayer Soils Data Source: Credible Values				
	Estimated Values		Analysis Values	
	ft/sec	cm/sec	ft/sec	cm/sec
MLV(1)	1.8E-06	5.5E-05	1.8E-06	5.5E-05
MaxCV(2)	3.3E-06	1.0E-04		
MinCV(3)	3.3E-07	1.0E-05		
3 Sigma St Dev	4.9E-07	1.5E-05	5.0E-07	1.5E-05
3 Sigma CoV(4)	27%	27%	28%	28%
Avg + 1 St Dev	2.3E-06	7.0E-05	2.3E-06	7.0E-05
Avg - 1 St Dev	1.3E-06	4.0E-05	1.3E-06	4.0E-05

Notes:
(1) MLV = most likely value
(2) MaxCV = maximum credible value
(3) MinCV = minimum credible value
(4) CoV = coefficient of variability
ft/sec = feet per second

TABLE 4
SUMMARY OF INPUT VARIABLES, HYDRAULIC CONDUCTIVITY RATIO(*)

Pervious Layer Soils Data Source: Credible Values		
	Estimated Values	**Analysis Values**
MLV(1)	0.35	0.35
MaxCV(2)	0.50	
MinCV(3)	0.20	
3 Sigma St Dev	0.05	
3 Sigma CoV(4)	14%	
Avg + 1 St Dev	0.40	
Avg - 1 St Dev	0.30	
Levee, Overbank, and Sublayer Soils Data Source: Credible Values		
	Estimated Values	**Analysis Values**
MLV(1)	0.20	0.20
MaxCV(2)	0.30	
MinCV(3)	0.10	
3 Sigma St Dev	0.03	
3 Sigma CoV(4)	17%	
Avg + 1 St Dev	0.23	
Avg - 1 St Dev	0.17	

Notes:
(*) Hydraulic conductivity ratio = ratio of vertical hydraulic conductivity to horizontal hydraulic conductivity
(1) MLV = most likely value
(2) MaxCV = maximum credible value
(3) MinCV = minimum credible value
(4) CoV = coefficient of variability

TABLE 5
SUMMARY OF INPUT VARIABLES, TOTAL UNIT WEIGHT

Pervious Layer
Data Source: Credible Values

	Effective Stress	
	Estimated Values	**Analysis Values**
	lb/cu. ft.	
MLV(1)	120	120
MaxCV(2)	125	
MinCV(3)	115	
3 Sigma St Dev	2	2
3 Sigma CoV(4)	1%	2%
Avg + 1 St Dev	122	122
Avg - 1 St Dev	118	118

Levee, Overbank, and Sublayer Soils
Data Source: Laboratory Tests

	Measured Values	Analysis Values
	lb/cu. ft.	
Consol-1(5)	107	
Consol-2	108	
CU-1(6)	108	
CU-2	107	
CU-3	110	
Average	108	108
CoV	1%	1%
Std Deviation	1	1
Avg + 1 St Dev	109	109
Avg - 1 St Dev	107	107
3 Sigma CoV	1%	
3 Sigma Std Dev	1	
Avg + 1 St Dev	108	
Avg - 1 St Dev	107	

Notes:
(1) MLV = most likely value
(2) MaxCV = maximum credible value
(3) MinCV = minimum credible value
(4) CoV = coefficient of variability
(5) Consol-X = consolidation test
(6) CU-X = consolidated, undrained triaxial test
lb/cu. ft. = pounds per cubic foot

TABLE 6
SUMMARY OF INPUT VARIABLES, FRICTION ANGLE

Pervious Layer **Data Source: Credible Values**		
	Effective Stress	
	Estimated Values	**Analysis Values**
	degrees	
MLV[1]	31	31
MaxCV[2]	38	
MinCV[3]	24	
3 Sigma St Dev	2	2
3 Sigma CoV[4]	8%	6%
Avg + 1 St Dev	33	33
Avg - 1 St Dev	29	29
Levee, Overbank, and Sublayer Soils **Data Source: Laboratory Tests**		
	Effective Stress	
	Measured Values	**Analysis Values**
	Degrees	
CU-1[5]	33	
CU-2	36	
CU-3	37	
Average	35	35
CoV	6%	6%
Std Deviation	2	2
Avg + 1 St Dev	37	37
Avg - 1 St Dev	33	33
3 Sigma CoV	2%	6%
3 Sigma Std Dev	1	2
Avg + 1 St Dev	36	37
Avg - 1 St Dev	35	33

Notes:

(1) MLV = most likely value
(2) MaxCV = maximum credible value
(3) MinCV = minimum credible value
(4) CoV = coefficient of variability
(5) CU-X = consolidated, undrained triaxial test
% = percent

TABLE 7
SUMMARY OF INPUT VARIABLES, SCOUR PROBABILITY

Slope of the Energy Line
Data Source: Credible Values

	Skagit River	North and South Fork
MLV(1)	0.00048	0.00040
CoV(2)	15%	15%
Std Dev	0.00007	0.00006
Avg + 1 St Dev	0.00055	0.00046
Avg - 1 St Dev	0.00041	0.00034

Manning's Roughness Coefficient
Data Source: Credible Values

	Estimated Values
MLV(1)	0.035
CoV(2)	10%
Std Dev	0.004
Avg + 1 St Dev	0.039
Avg - 1 St Dev	0.032

Critical Velocity
Data Source: Credible Values

	Estimated Values feet/second
MLV(1)	4
CoV(2)	20%
Std Dev	0.8
Avg + 1 St Dev	5
Avg - 1 St Dev	3

Notes:
(1) MLV = Most likely value
(2) CoV = Coefficient of variability
% = percent

TABLE 8
LIQUEFACTION THRESHOLD RETURN PERIOD

Analysis Section	Threshold Soil Acceleration (g)	Threshold Recurrence Interval (years)
DD1-1 Landward	0.14	43
DD1-1 Levee	0.18	100
DD1-2 Landward	0.11	23
DD1-2 Levee	0.16	69
DD3-1 Landward	0.13	38
DD3-1 Levee	0.23	219
DD17-1 Landward	0.14	47
DD17-1 Levee	0.16	63
DD17-2 Landward	0.18	100
DD17-2 Levee	0.16	63
DD17-3 Landward	0.14	42
DD17-3 Levee	0.13	38
DD22-1 Landward	0.13	38
DD22-1 Levee	0.12	32
DD22-2 Landward	0.10	20
DD22-2 Levee	0.14	47
	Average	61
	Std Dev	48
	Coefficient of Variation	78%

Note:
% = percent

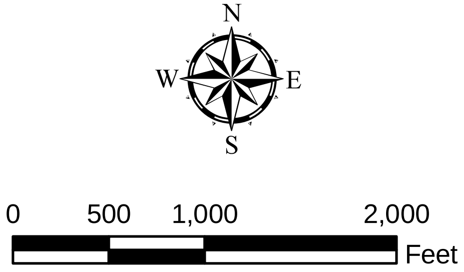
TABLE 9
SUMMARY OF MONTE CARLO ANALYSES

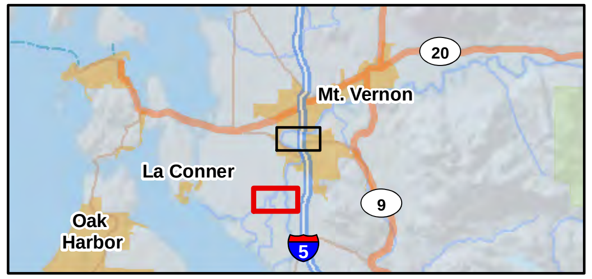
Location	**DD17-1L**		**DD1-2R**		**DD17-1L**	
Slope	**Landside**		**Landside**		**Riverside**	
River Stage (feet)	**43.2**		**15.8**		**20.6**	
Analysis	MC(1)	TS(2)	MC	TS	MC	TS
Mean FS(3)	0.60	0.56	1.07	1.07	1.58	1.58
Standard Deviation of FS	0.06	0.13	0.08	0.08	0.10	0.10
Minimum(4) FS	0.38	0.53	0.73	0.99	1.22	1.48
Maximum(4) FS	0.79	0.63	1.51	1.15	1.88	1.67
Reliability Index	-6.39	-4.52	0.90	0.84	5.90	7.21
Conditional Probability of Failure	1.00	1.00	0.21	0.20	0.00	0.00

Notes:
(1) MC = Monte Carlo method
(2) TS = Taylor Series method
(3) FS = factor of safety
(4) Minimum and maximum factor safety considered in the analysis.

LEGEND

Approximate Boring Location	◐
Profiles	🟥
City Boundary	🟧
Levees	🟨





Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

ANALYSIS CROSS SECTION LOCATIONS

January 2011

21-1-21199-003

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FIG. 1
Sheet 1 of 2

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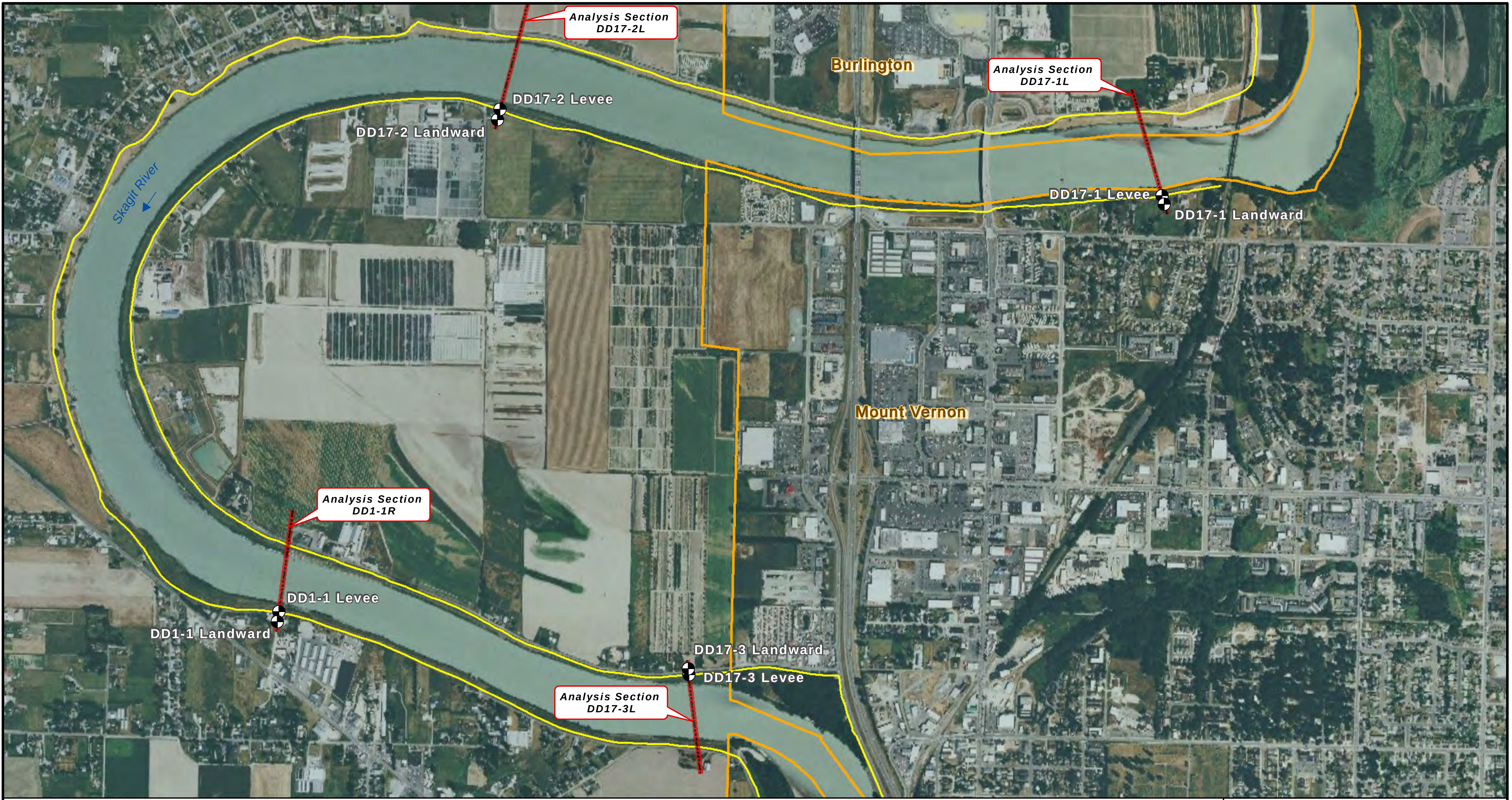


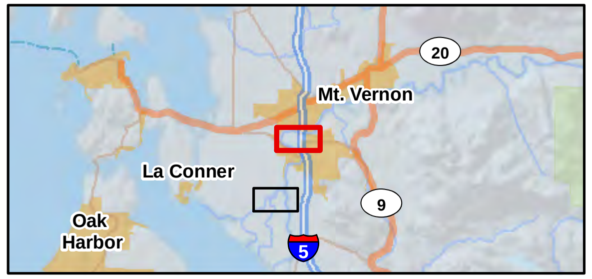
LEGEND

Approximate Boring Location ◑

Profiles

City Boundary

Levees



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

ANALYSIS CROSS SECTION LOCATIONS

January 2011

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FIG. 1

Sheet 2 of 2

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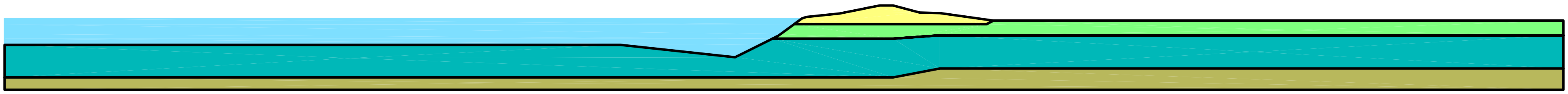
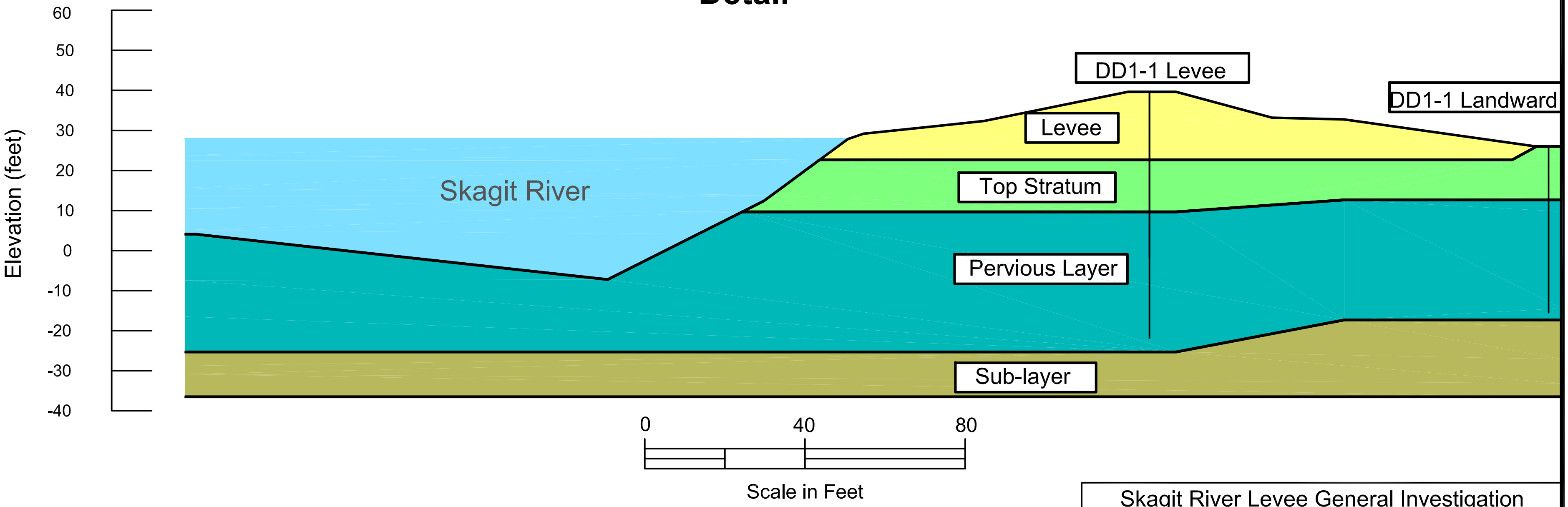
Filename: I:\WIP\21-1\21199 Skagit River\Phase -003\SEEPW-SLOPEW\SEEPW-SLOPEW Sections\cross section FIGURES (AutoCAD)\Skagit SEEPW-SLOPEW Sections (FIGURES)-rev2.dwg Date: 01-24-2011 Login: mmy

Complete Model



Detail



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DD1-1R CROSS SECTION

January 2011
21-1-21199-003

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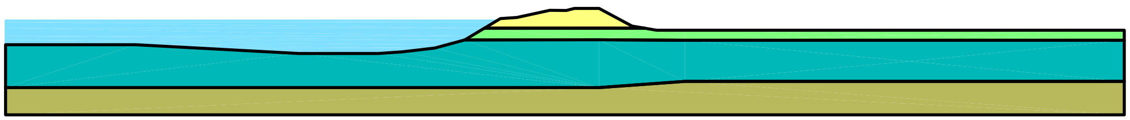
FIG. 2

FIG. 2

Complete Model



Detail

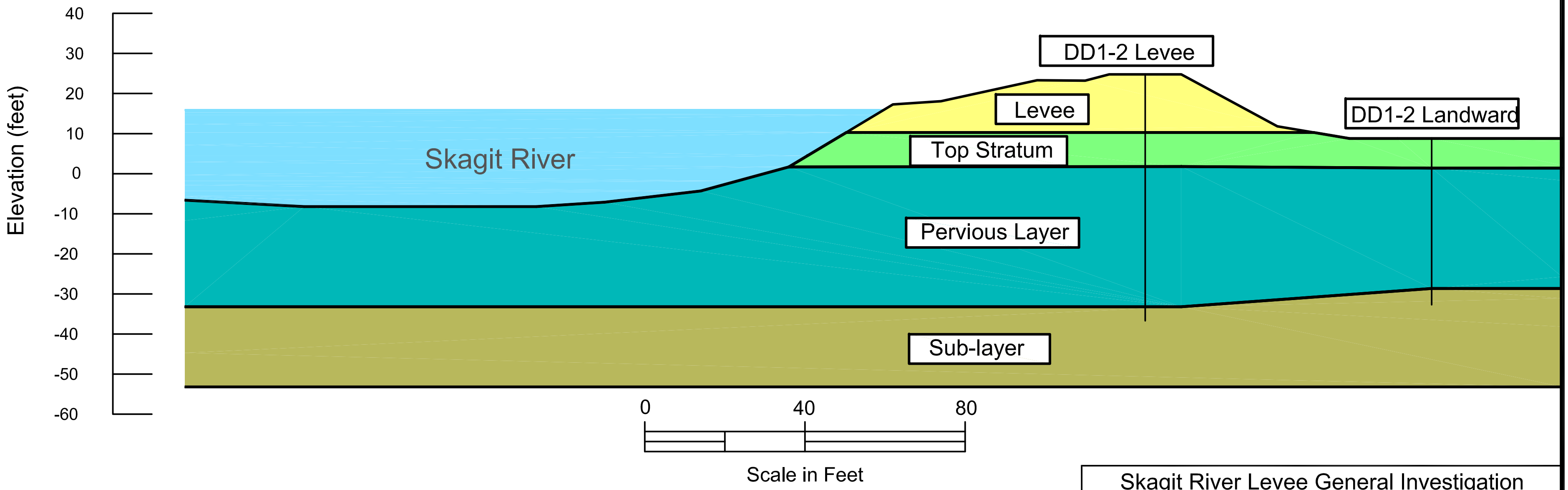


FIG. 3

Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DD1-2R CROSS SECTION

January 2011 21-1-21199-003

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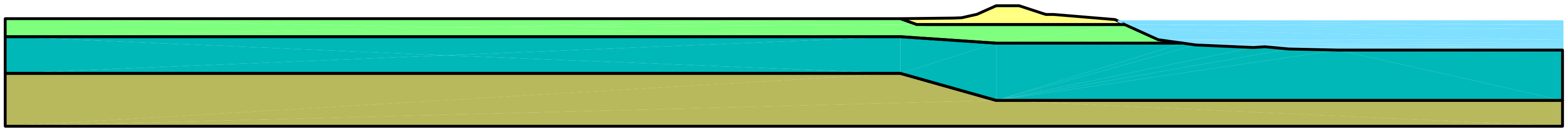
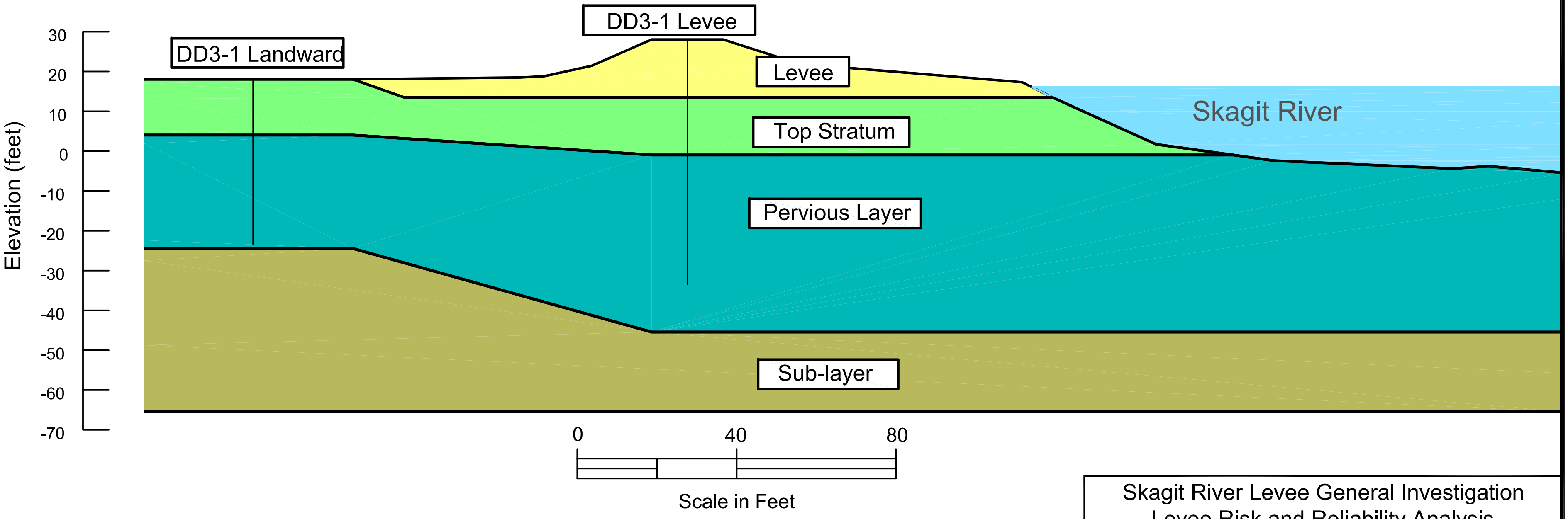
FIG. 3

Filename: I:\WIP\21-1\21199 Skagit River\Phase -003\SEEPW-SLOPEW\SEEPW-SLOPEW Sections\cross section FIGURES (AutoCAD)\Skagit SEEPW-SLOPEW Sections (FIGURES)-rev2.dwg Date: 01-24-2011 Login: mmy

Complete Model



Detail



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DD3-1L CROSS SECTION

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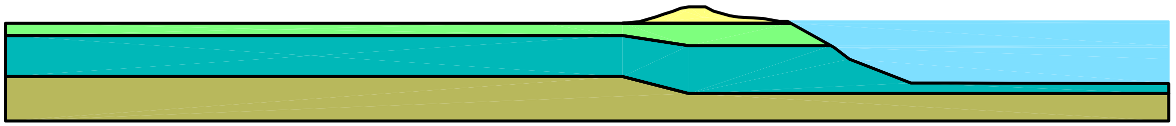
FIG. 4

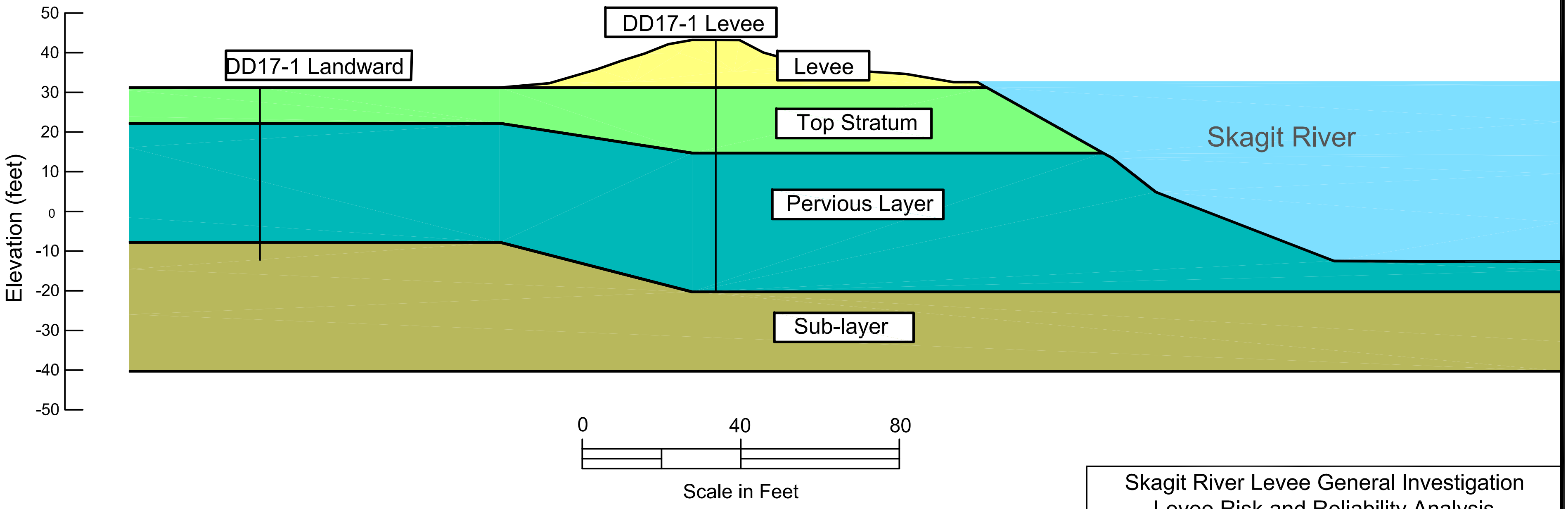
FIG. 4

Filename: I:\WIP\21-1\21199 Skagit River\Phase -003\SEEPW-SLOPEW\SEEPW-SLOPEW Sections\cross section FIGURES (AutoCAD)\Skagit SEEPW-SLOPEW Sections (FIGURES)-rev2.dwg Date: 01-24-2011 Login: mmy

Complete Model



Detail



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DD17-1L CROSS SECTION

January 2011 21-1-21199-003

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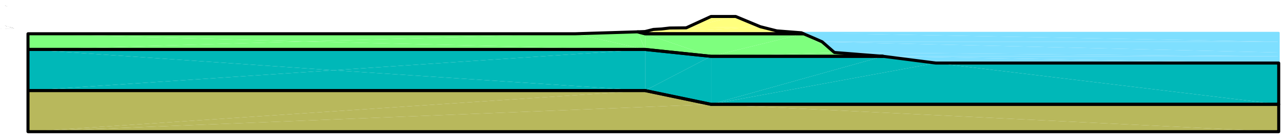
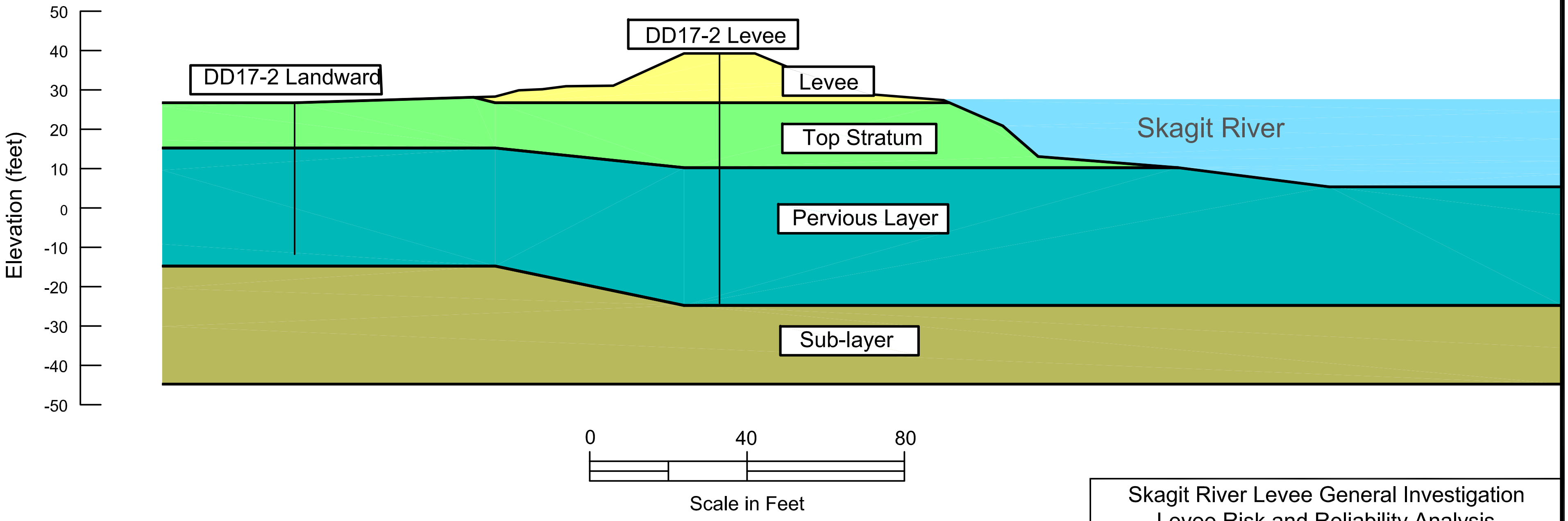
FIG. 5

FIG. 5

Complete Model



Detail



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DD17-2L CROSS SECTION

January 2011 21-1-21199-003

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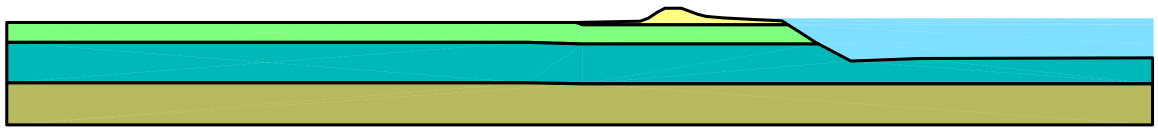
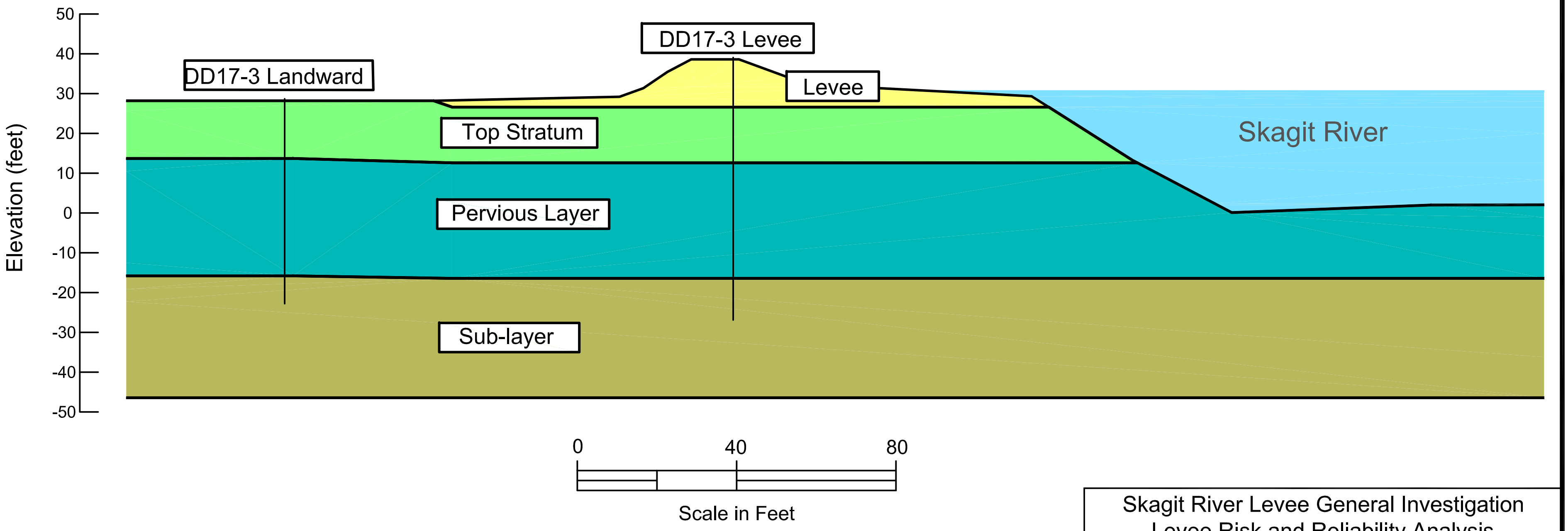
FIG. 6

Complete Model



Detail



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DD17-3L CROSS SECTION

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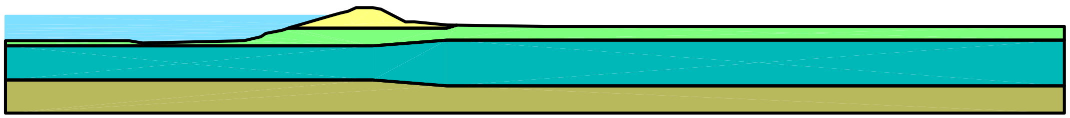
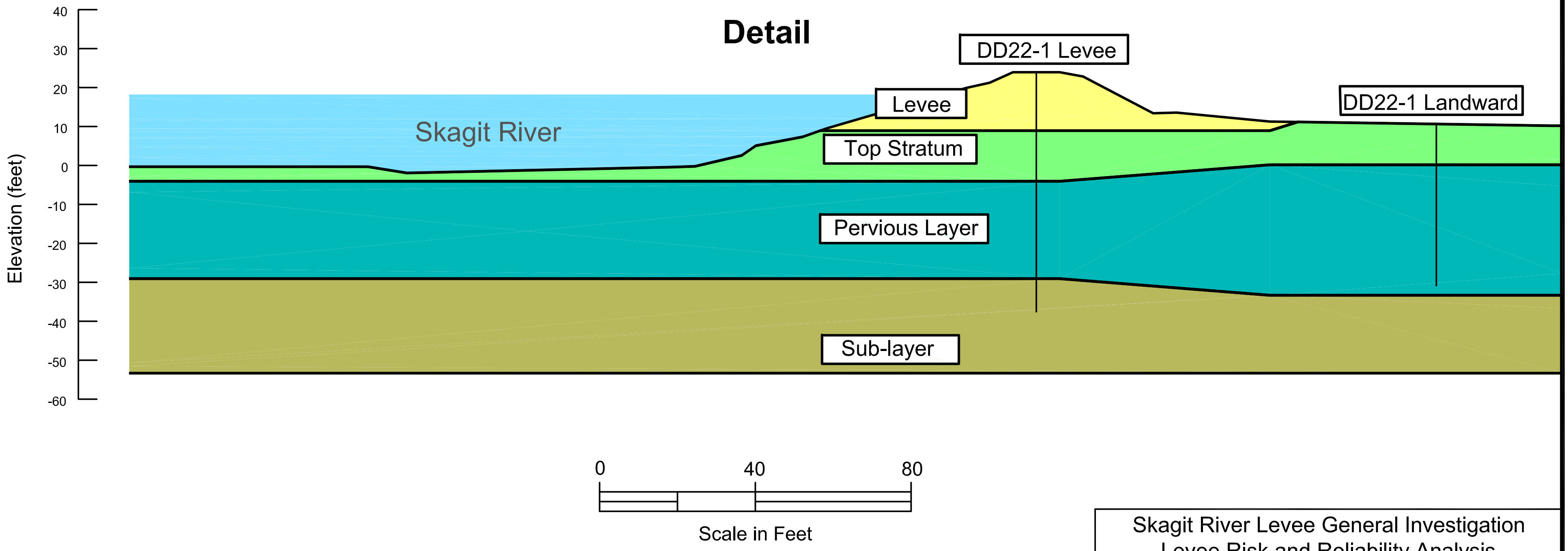
FIG. 7

Complete Model



Detail



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DD22-1R CROSS SECTION

January 2011 21-1-21199-003

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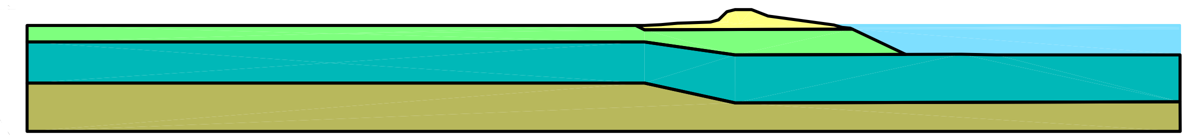
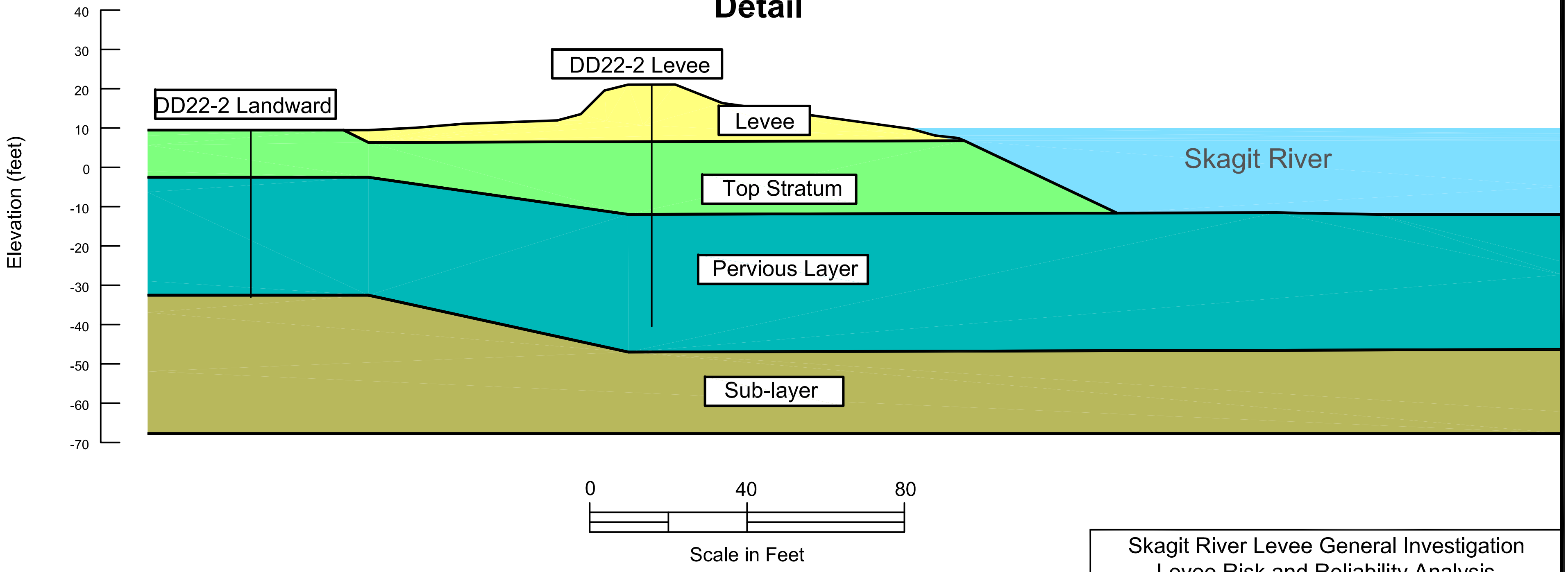
FIG. 8

Complete Model



Detail



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DD22-2L CROSS SECTION

January 2011 21-1-21199-003

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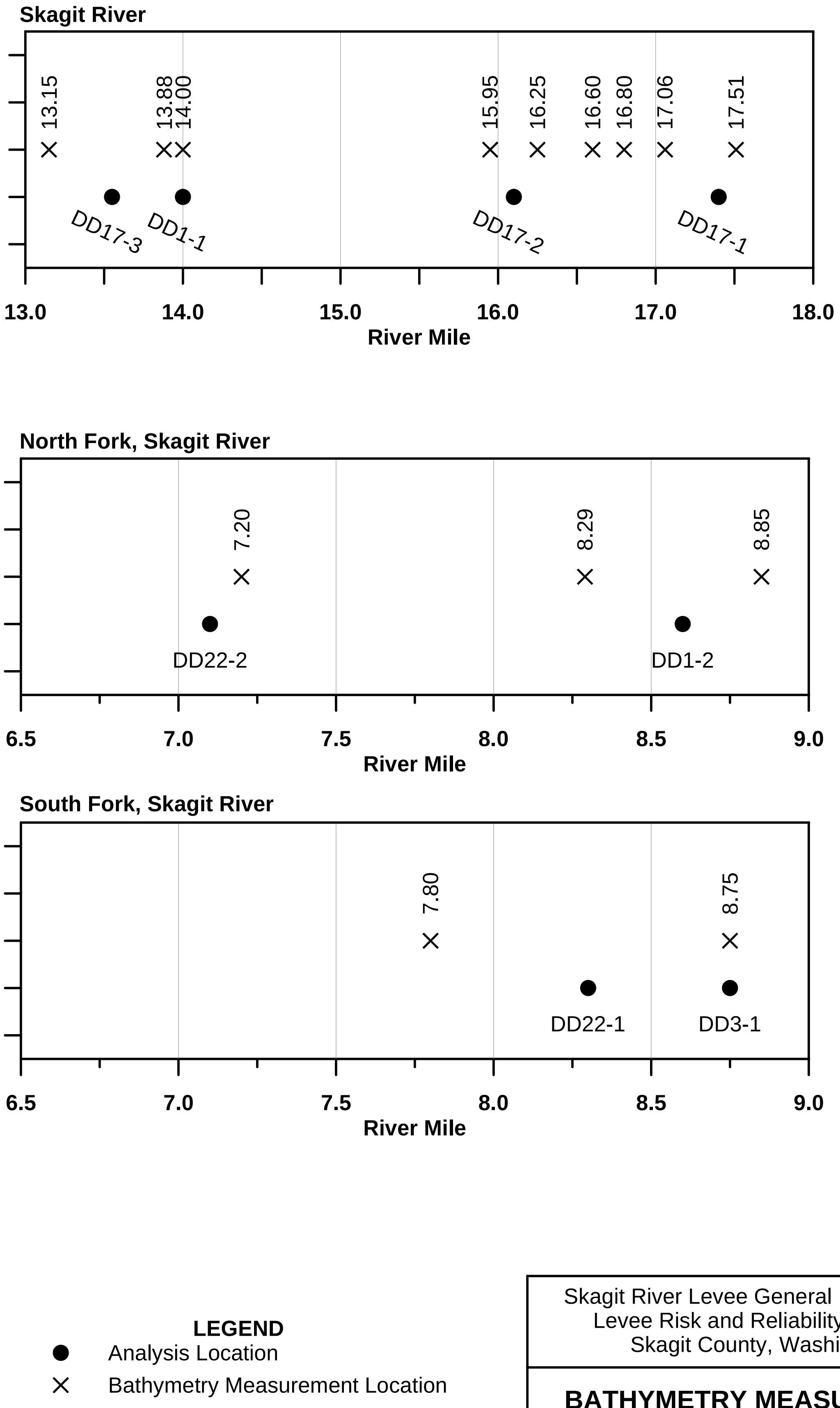
FIG. 9



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

BATHYMETRY MEASUREMENT AND ANALYSIS LOCATIONS

January 2011
21-1-21199-003

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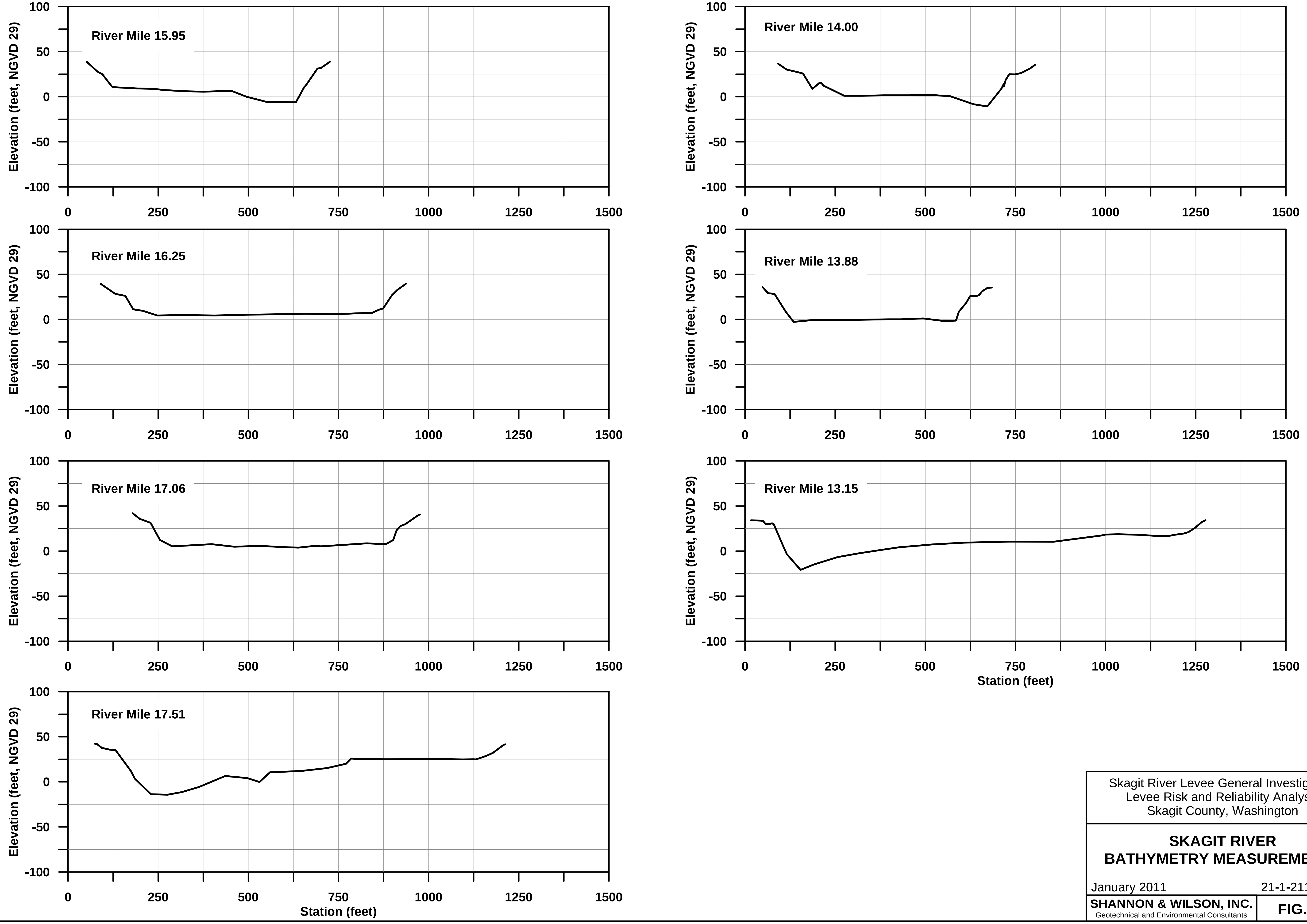
FIG. 10



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

SKAGIT RIVER
BATHYMETRY MEASUREMENTS

January 2011
21-1-21199-003

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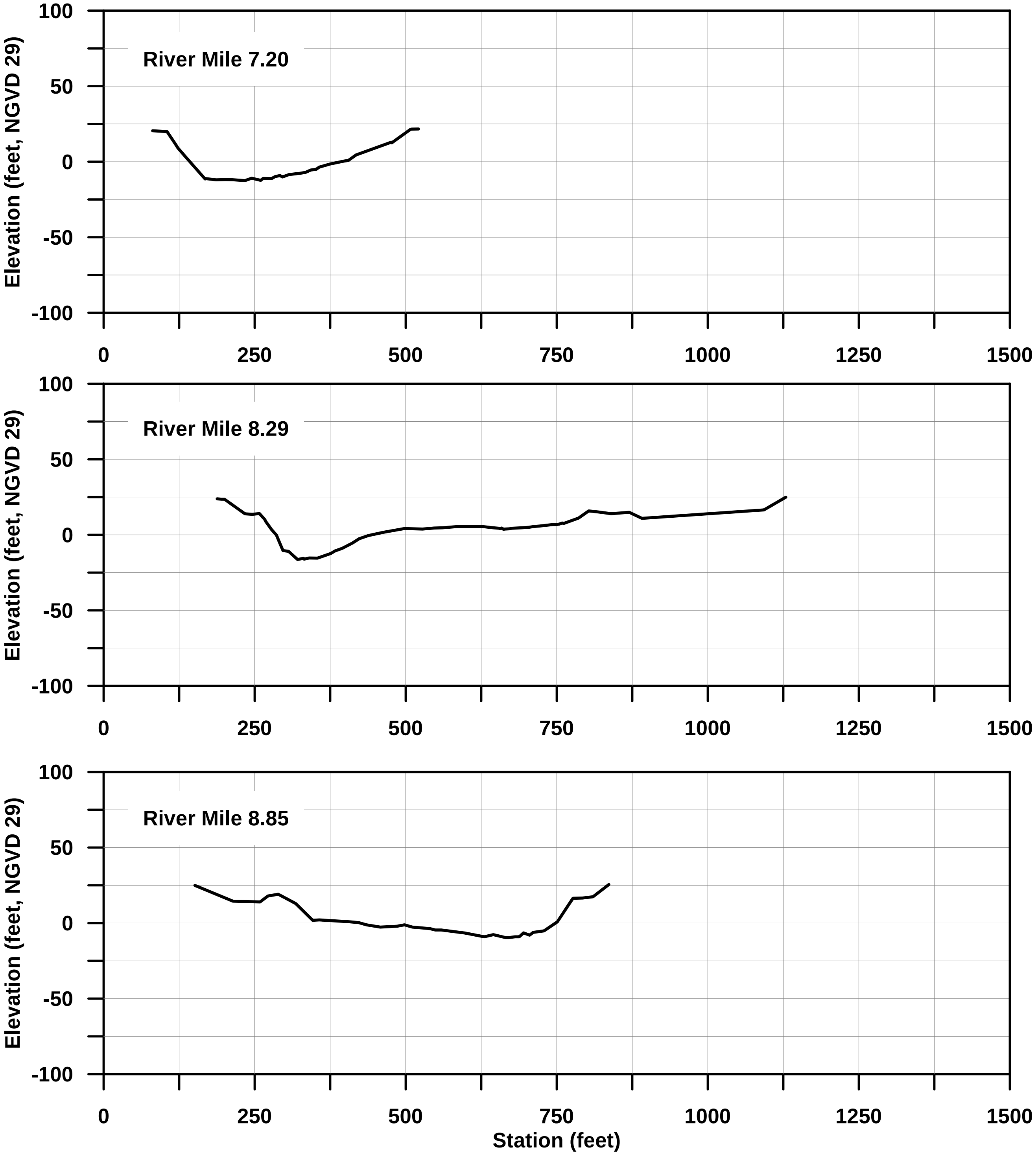
FIG. 11



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

NORTH FORK SKAGIT RIVER BATHYMETRY MEASUREMENTS

January 2011 21-1-21199-003

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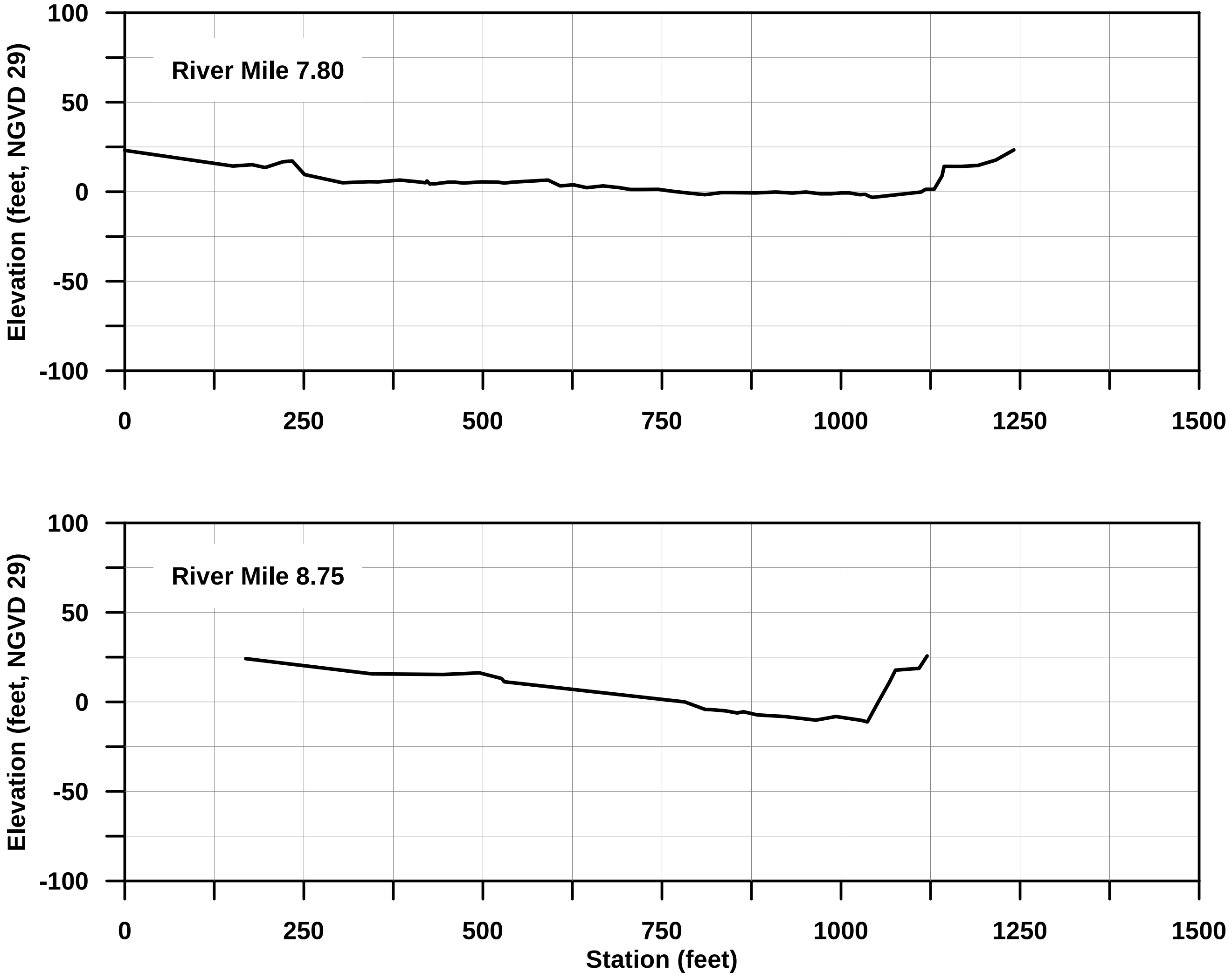
FIG. 12



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

SOUTH FORK SKAGIT RIVER BATHYMETRY MEASUREMENTS

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21-1-21199-003

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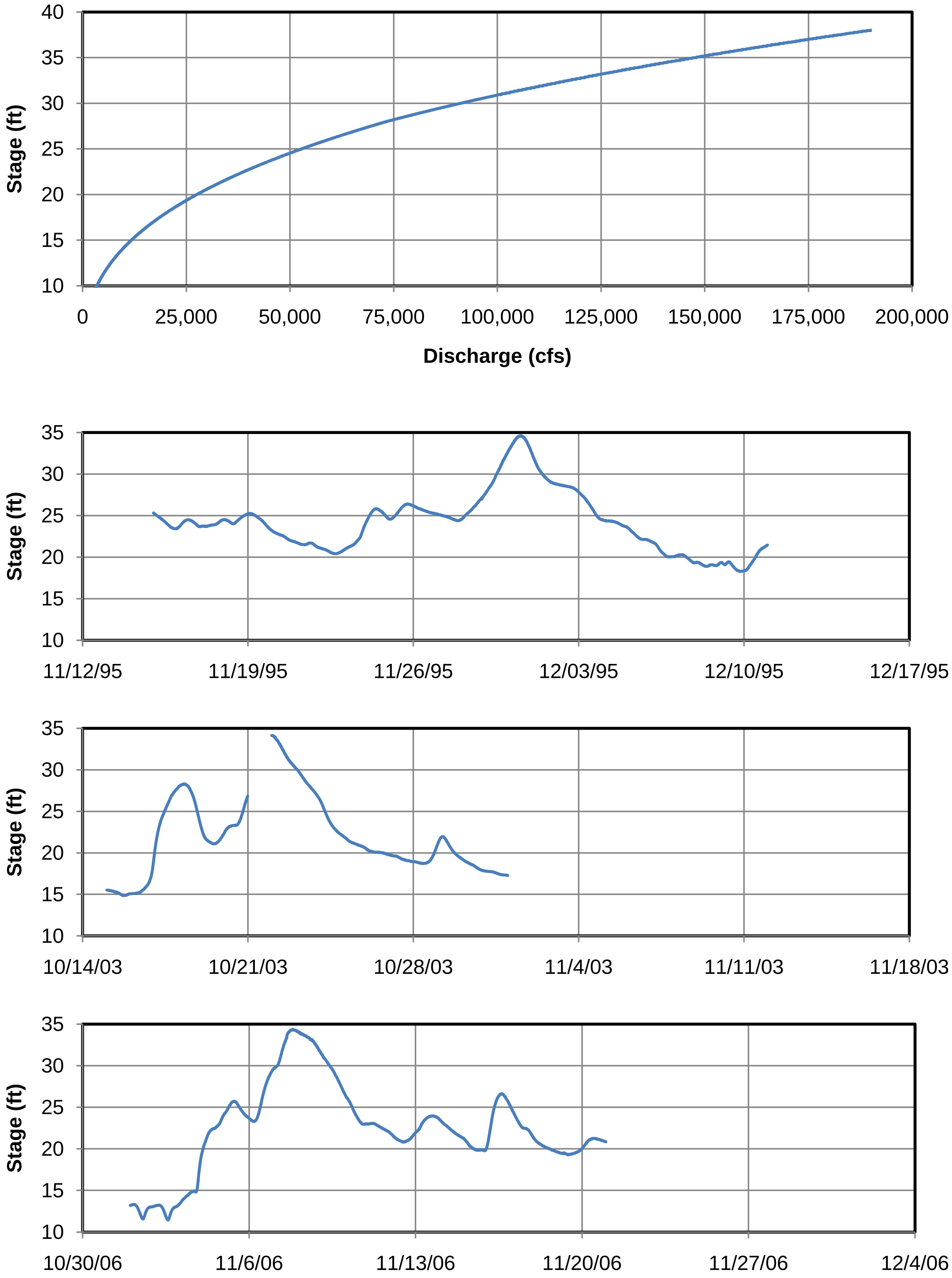
FIG. 13



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

SKAGIT RIVER RATING CURVE AND HYDROGRAPHS

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21-1-21199-003

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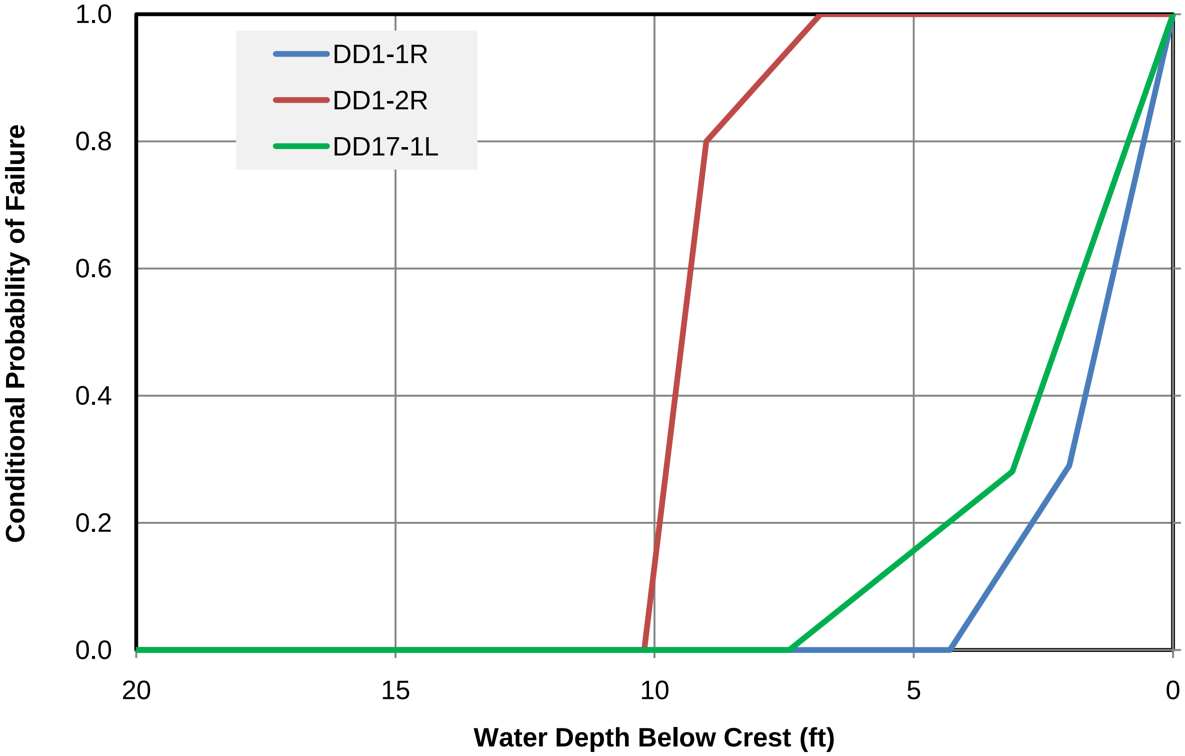
FIG. 14



NOTE:

The conditional probabilities of underseepage failure at analysis sections DD3-1L, DD17-2L, DD17-3L, DD22-1R, and DD22-2L were near zero for all river stages and are not included in this graph.

Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DEPTH-NORMALIZED UNDERSEEPAGE FAILURE PROBABILITIES

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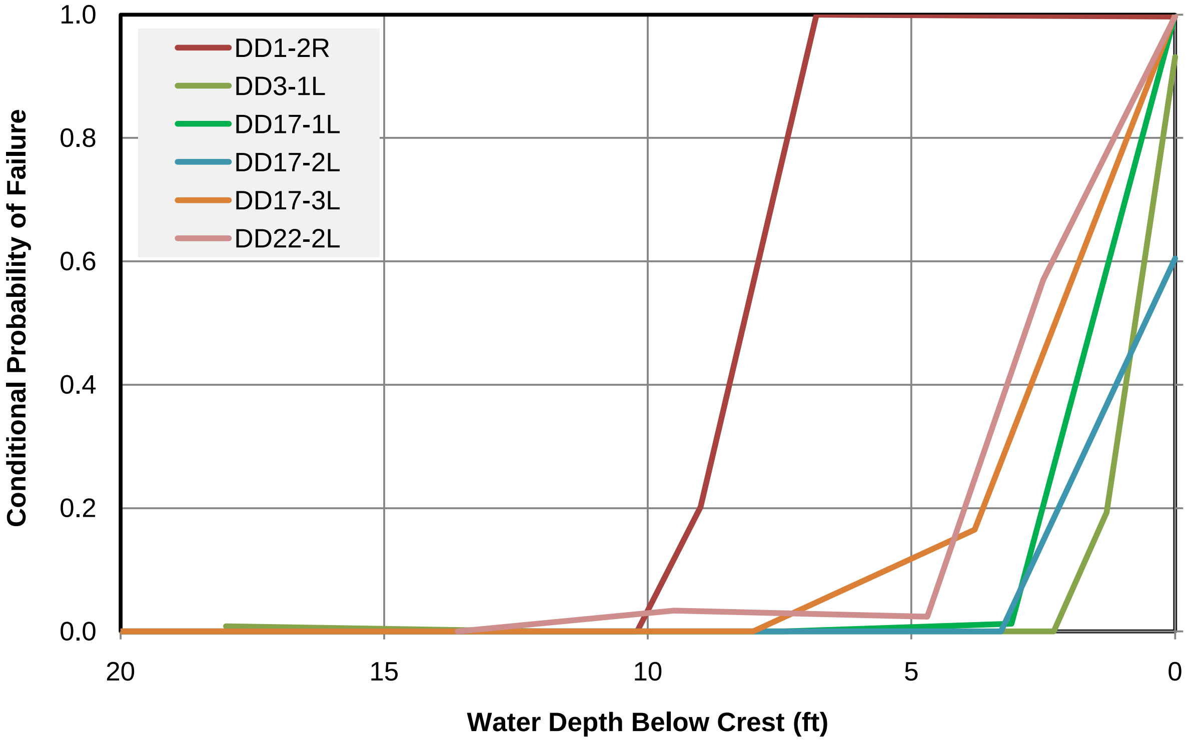
FIG. 15



NOTE:

The conditional probabilities of static landside failure at analysis sections DD1-1R and DD22-1R were near zero for all river stages and are not included in this graph.

Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DEPTH-NORMALIZED LANDSIDE STATIC FAILURE PROBABILITIES

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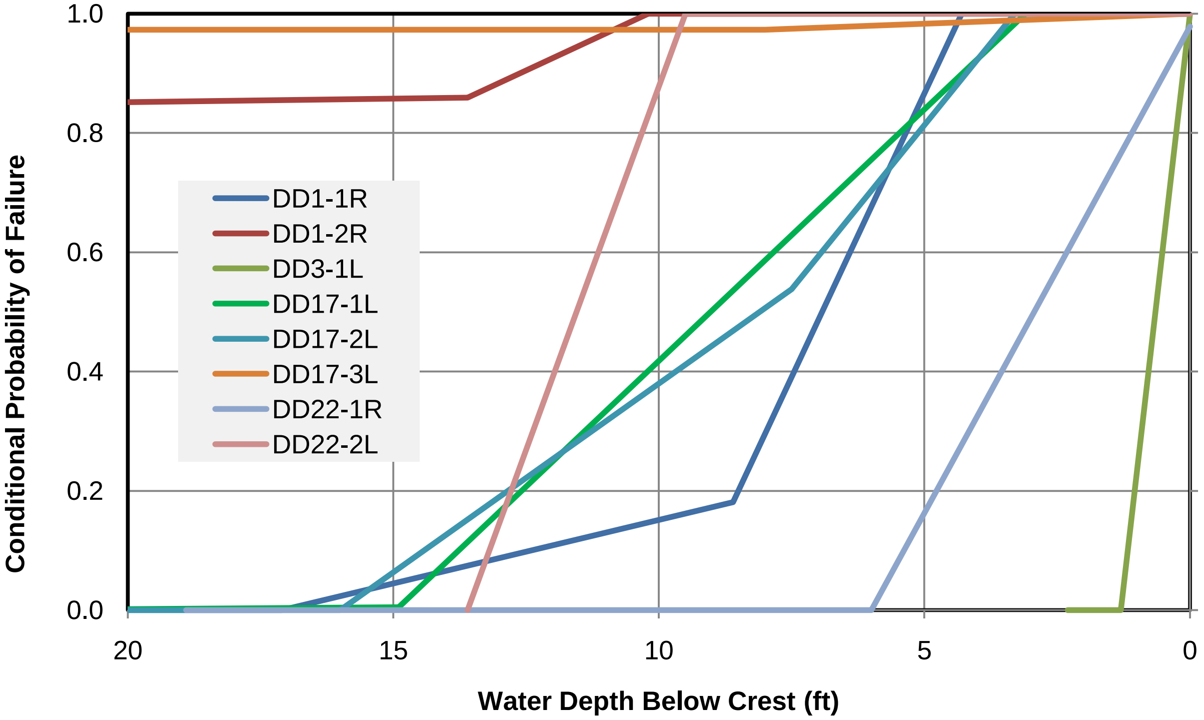
FIG. 16



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DEPTH-NORMALIZED LANDSIDE SEISMIC FAILURE PROBABILITIES

Janauary 2011 21-1-21199-003

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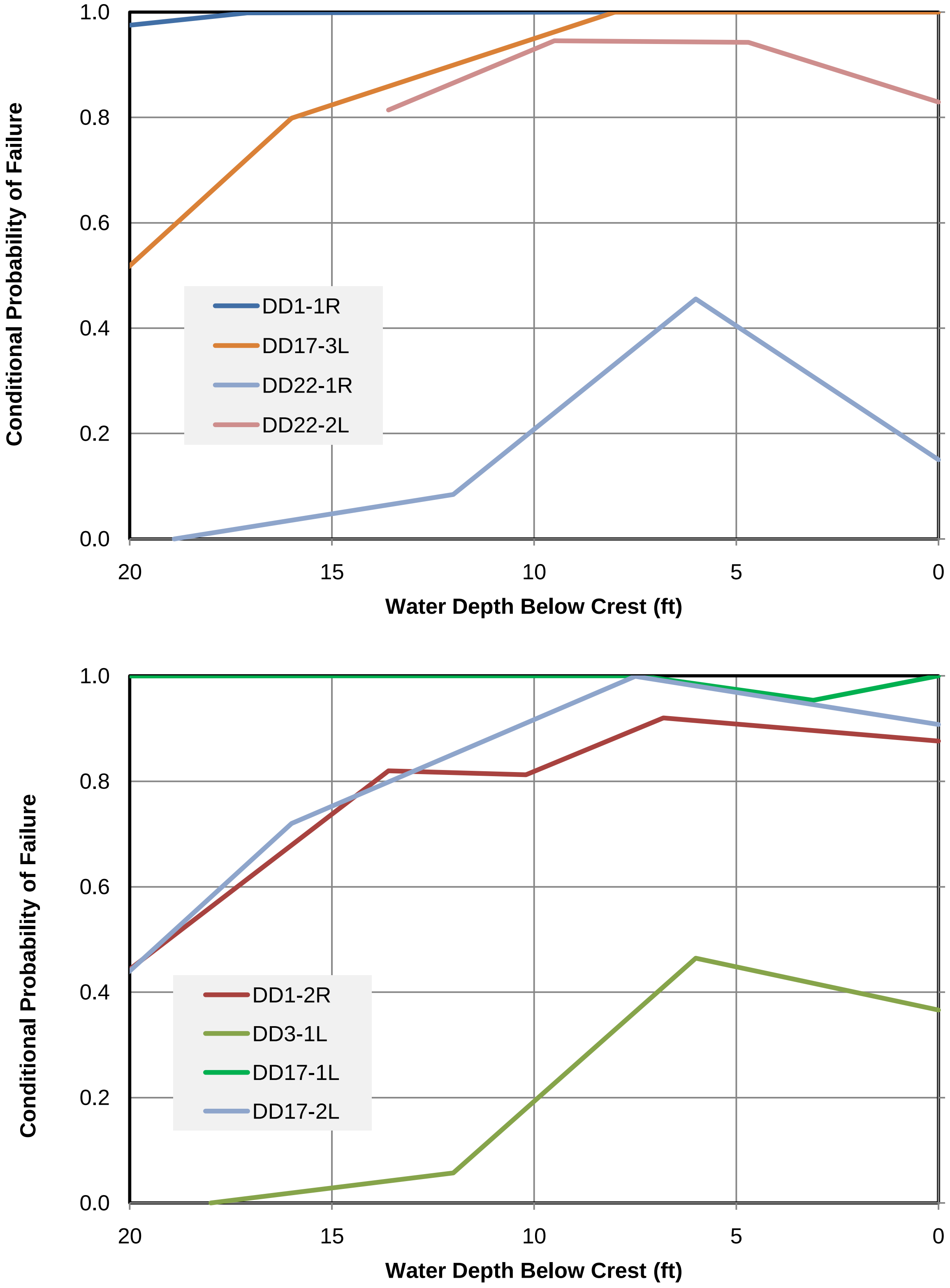
FIG. 17



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DEPTH-NORMALIZED RIVERSIDE SEISMIC FAILURE PROBABILITIES

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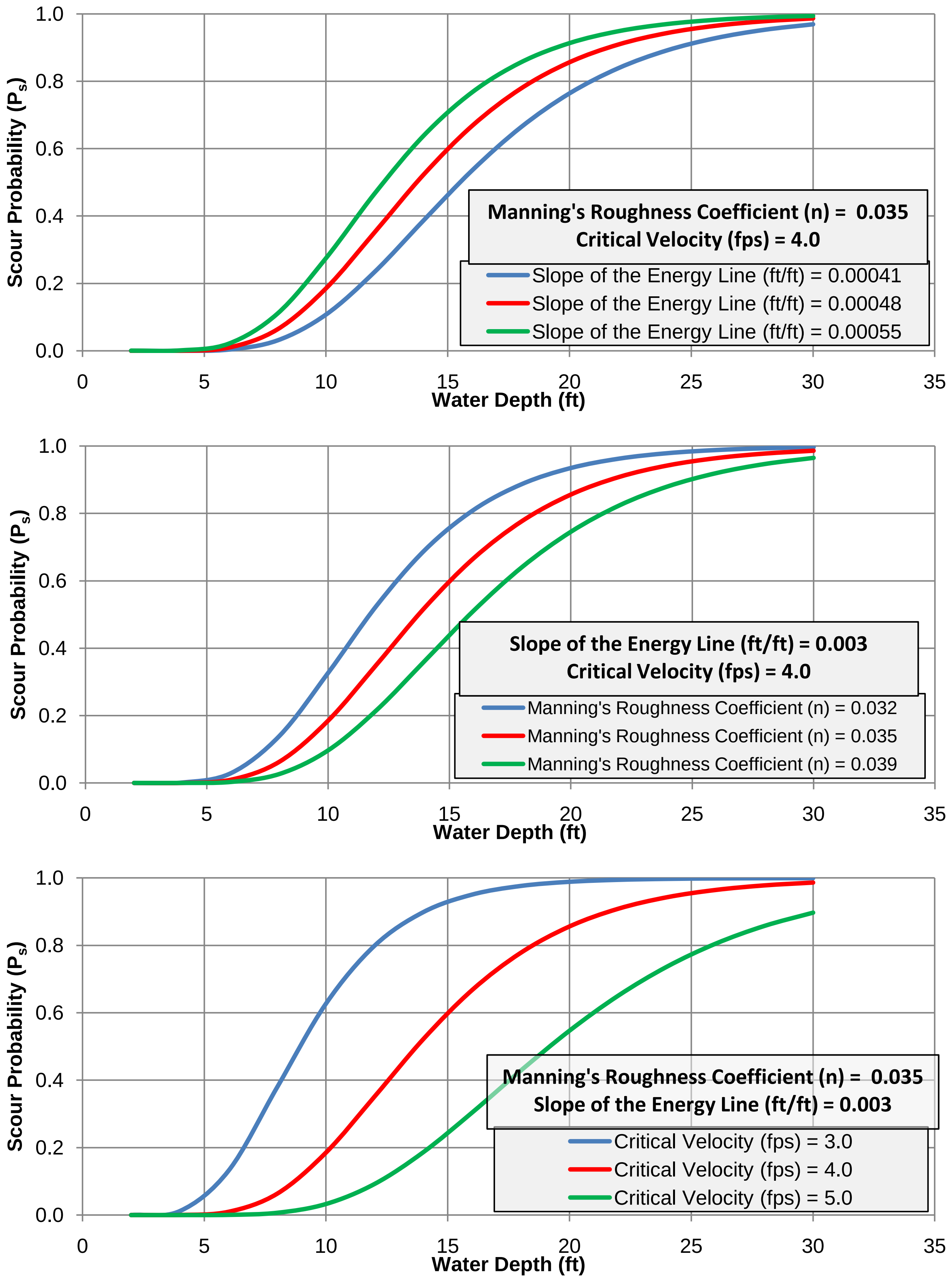
FIG. 18



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

SCOUR PROBABILITY
VS WATER DEPTH
SKAGIT RIVER

January 2011 21-1-21199-

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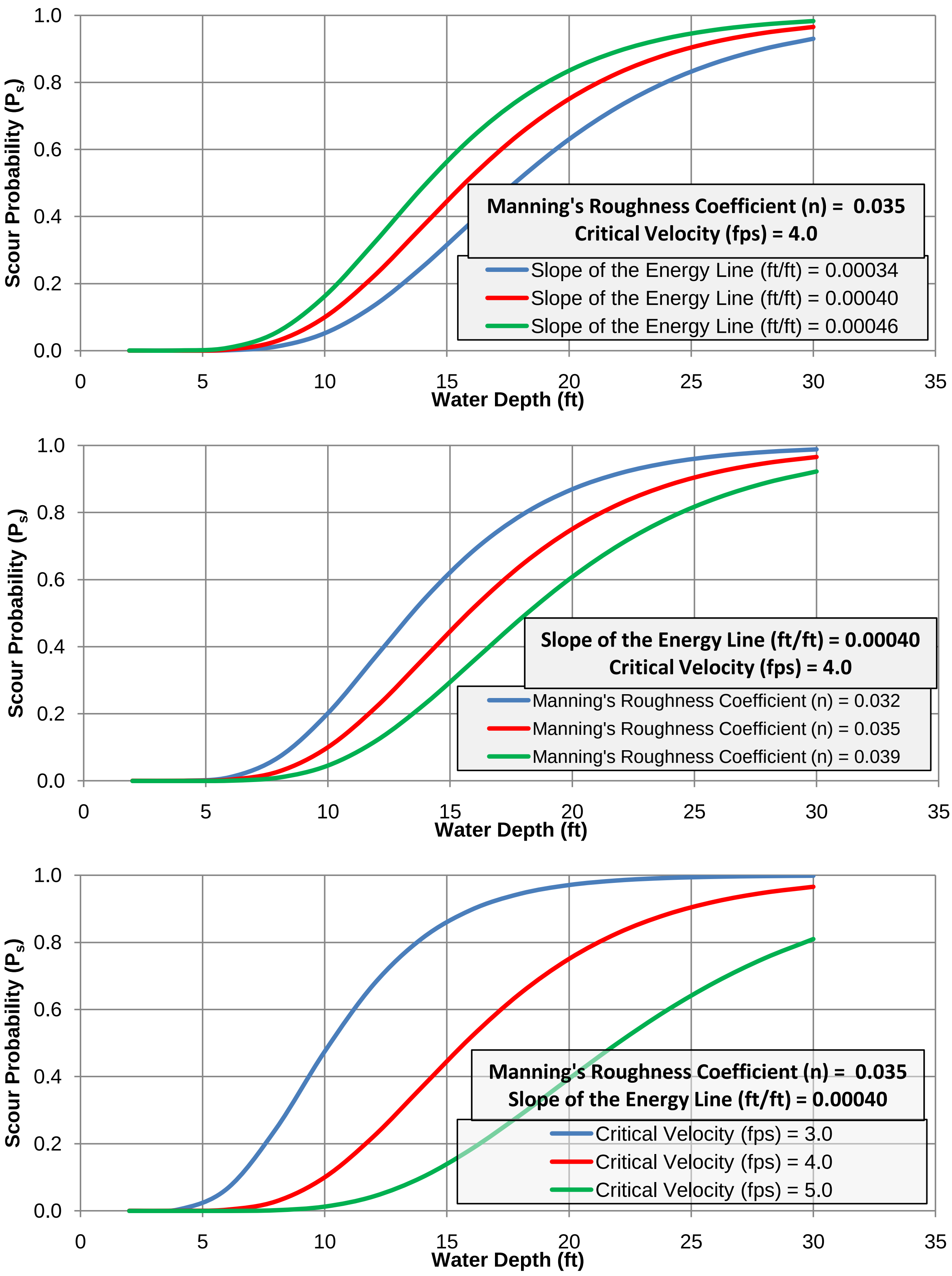
FIG. 19



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

SCOUR PROBABILITY VS WATER DEPTH NORTH ANDSOUTH FORK

January 2011 21-1-21199-

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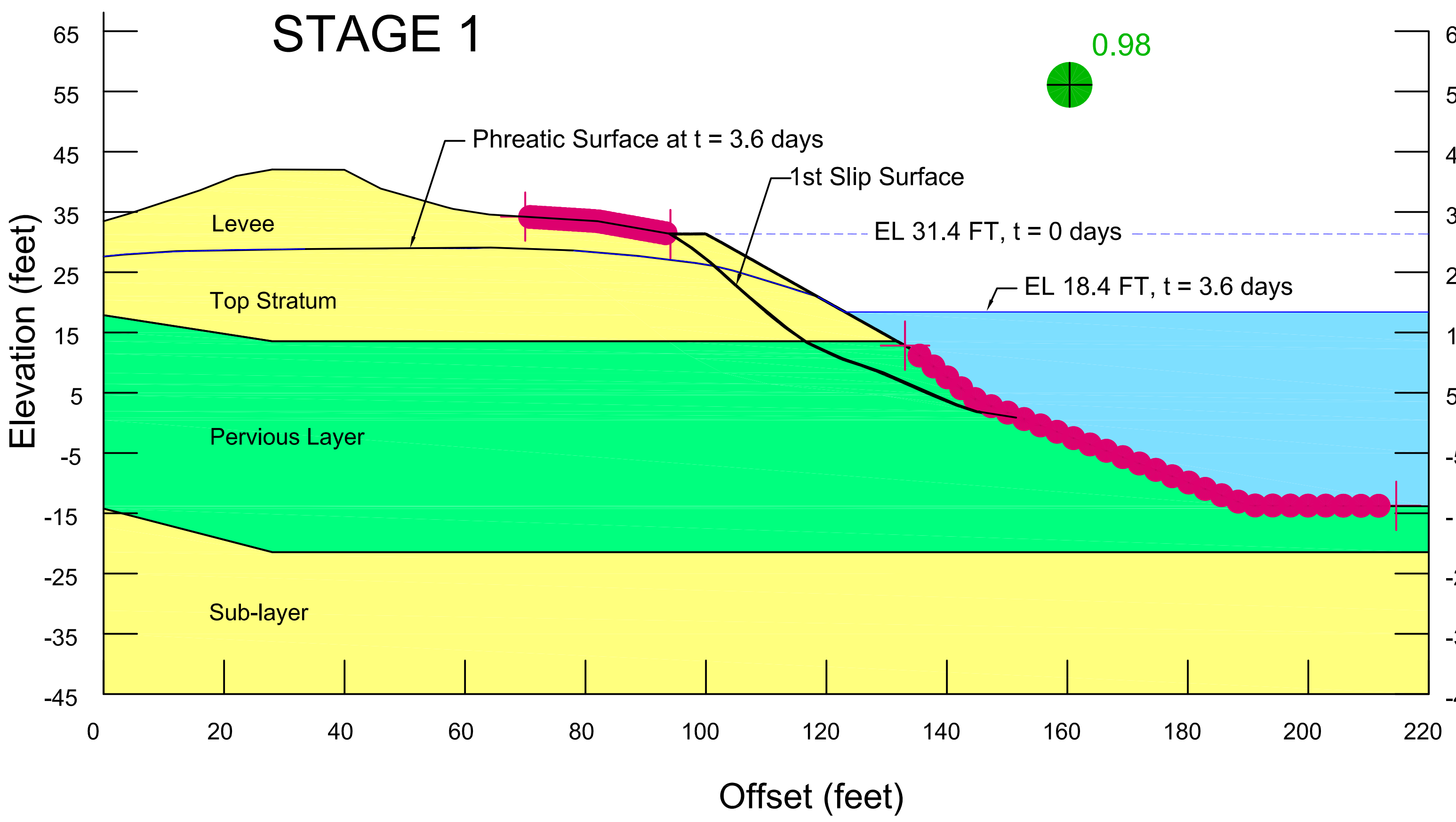
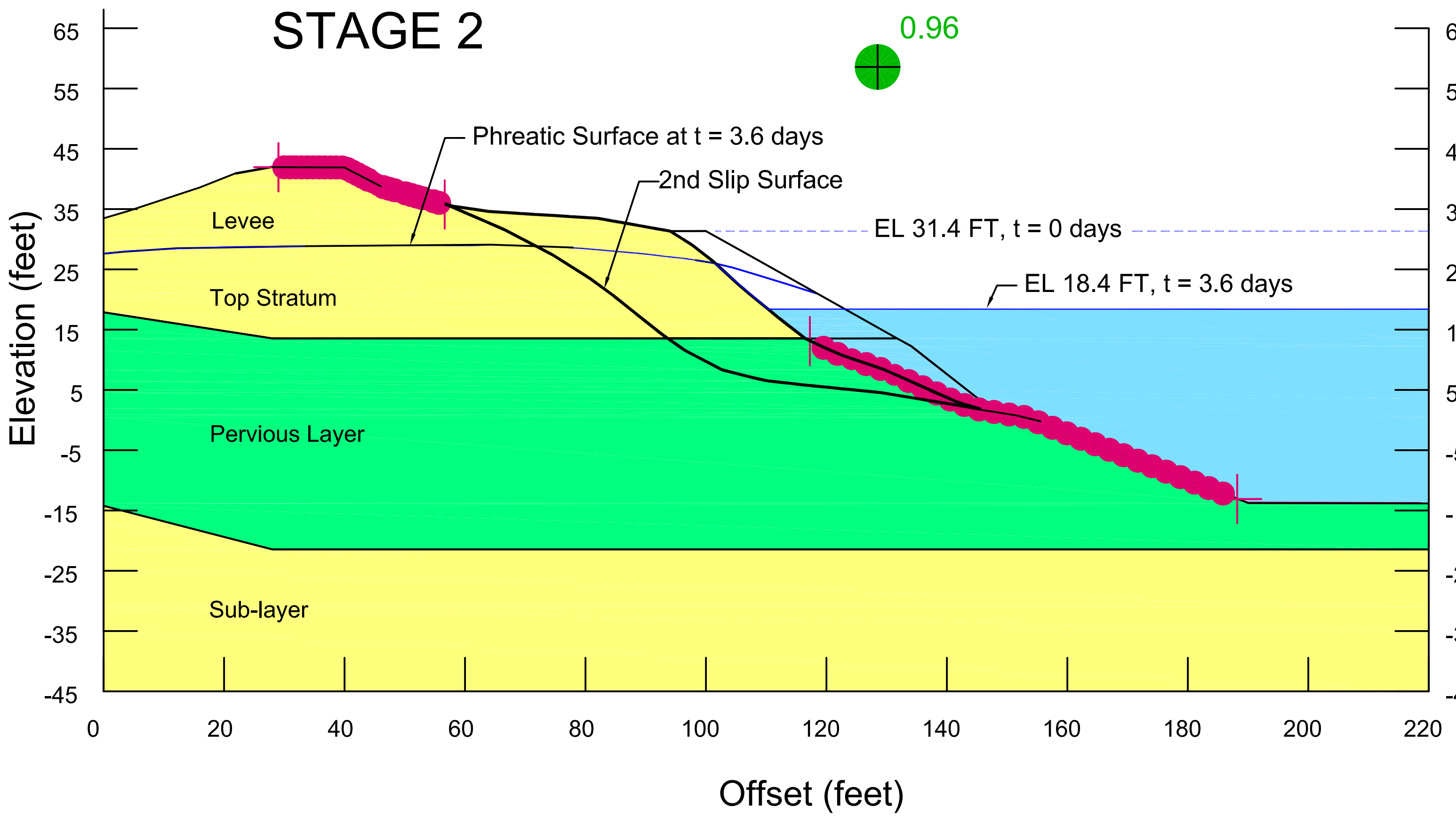
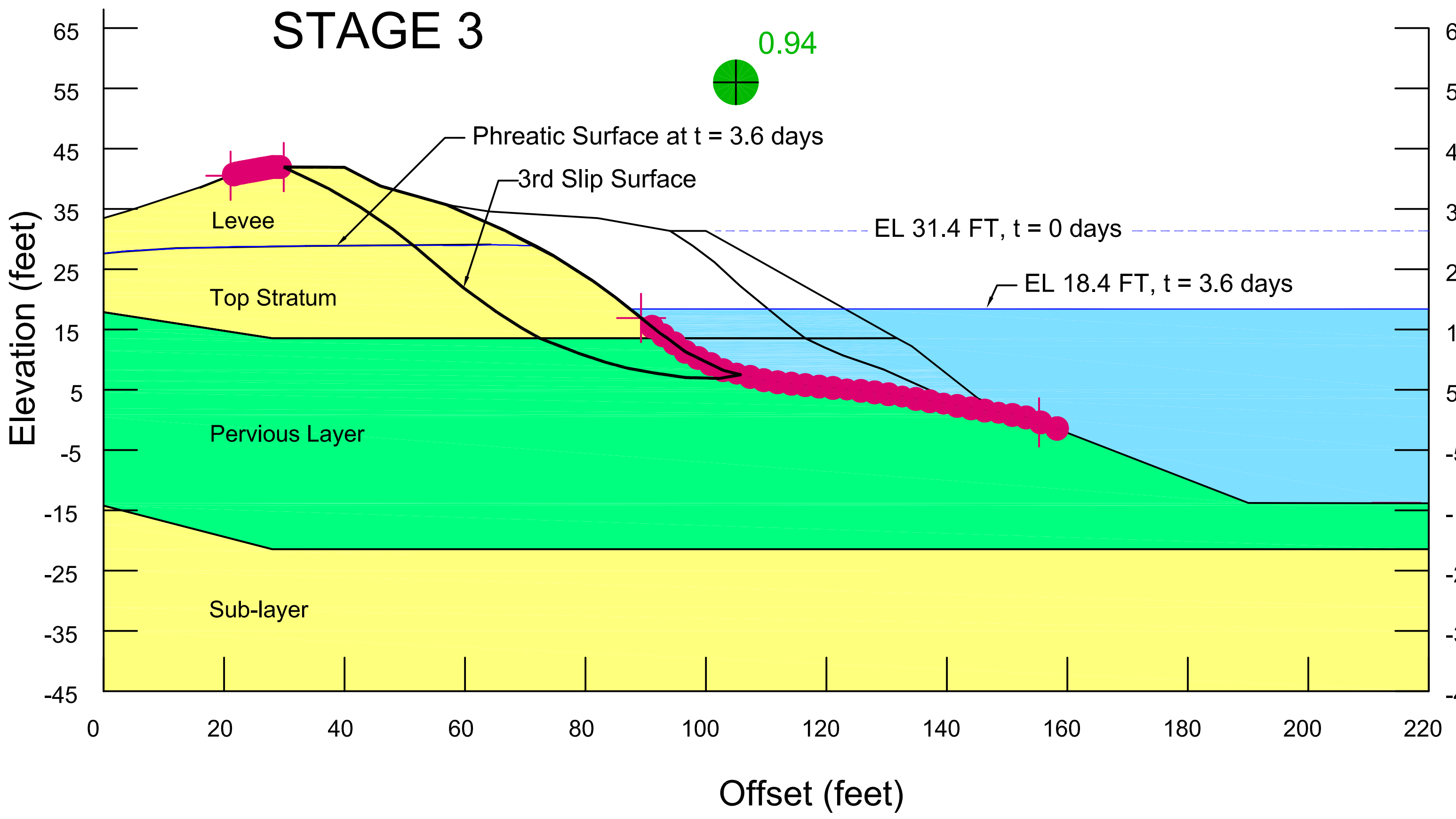
FIG. 20

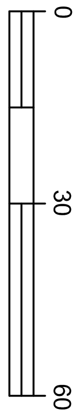






SOIL PARAMETERS

LV-OB-SUB-Base	Multiple Trial: 108 pcf	0 psf	Multiple Trial: 35 °	
Pervious-base	Multiple Trial: 120 pcf	0 psf	Multiple Trial: 31 °	



Scale in Feet

Skagit County Levee General Investigation
Skagit County, Washington

SEQUENTIAL FAILURE SCENARIO
RIVER SECTION DD17-1L

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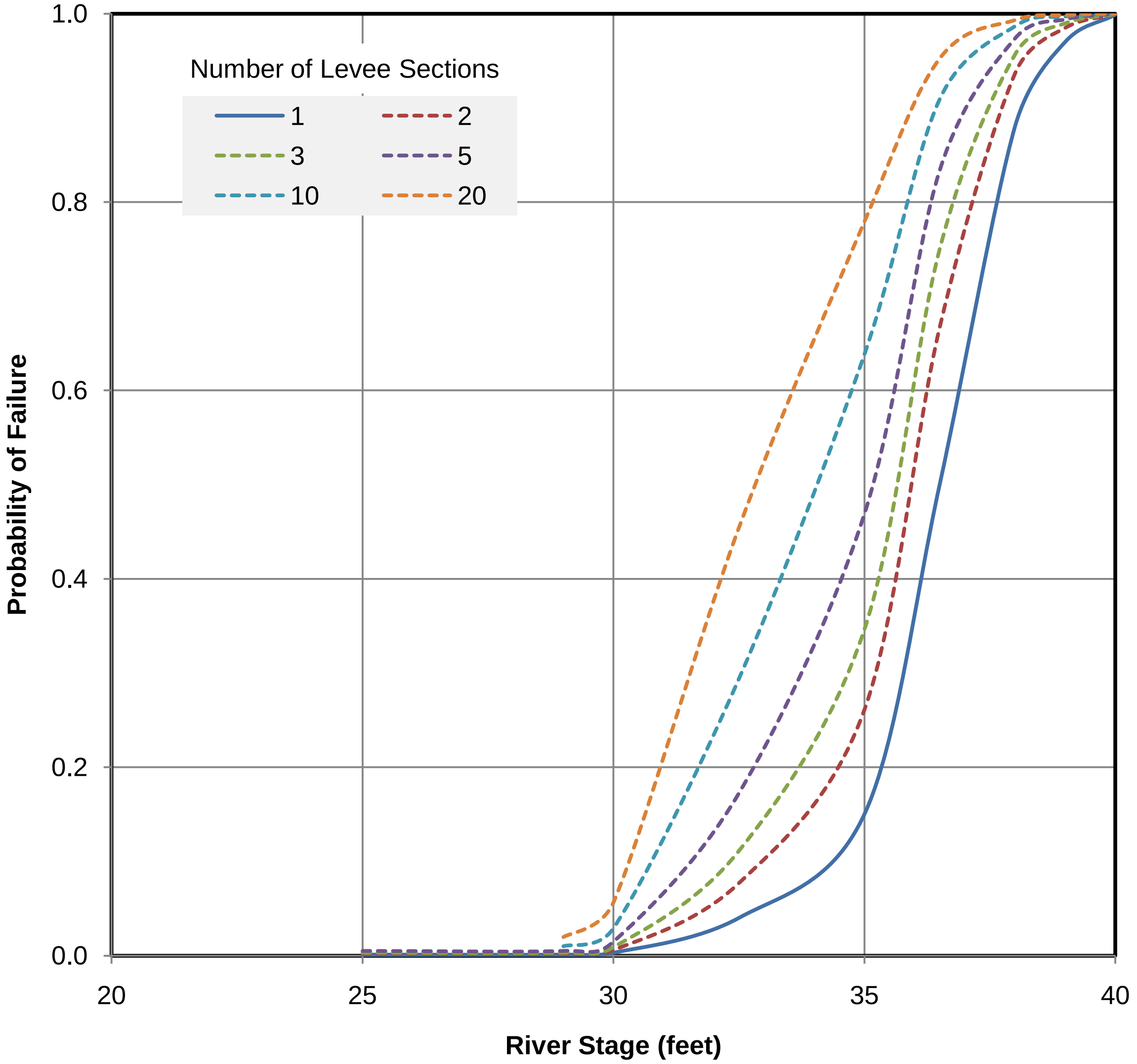
FIG. 21



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

LENGTH EFFECT ON CONDITIONAL PROBABILITY OF LEVEE FAILURE

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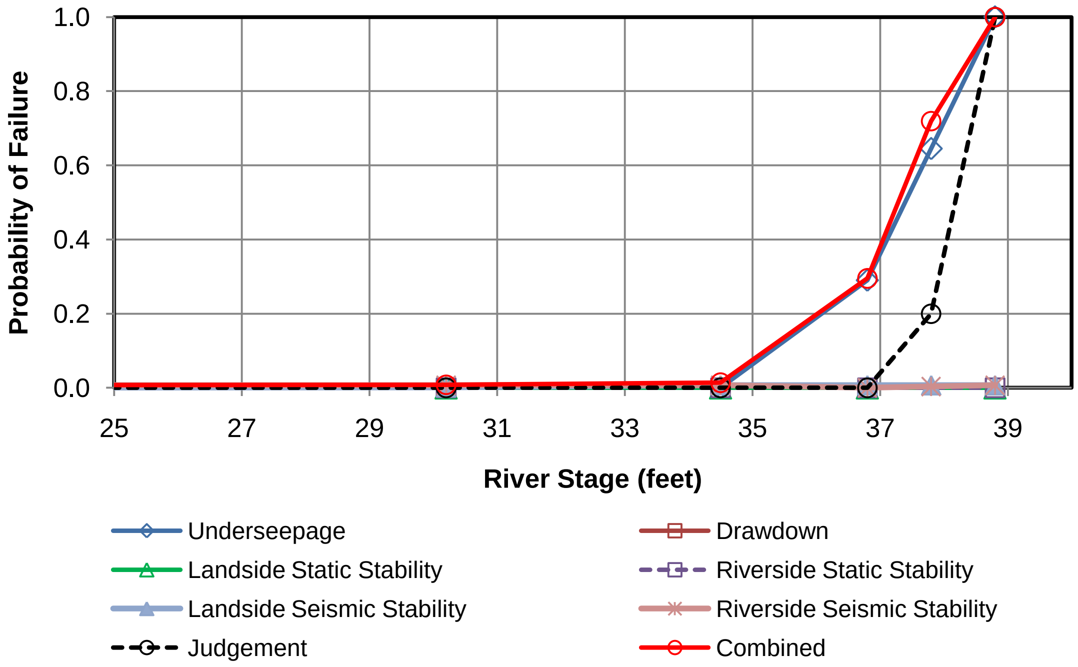
FIG. 22

Conditional Probability of Failure Analysis DD1-1R

Project	NWS Skagit River GI
Feature	Analysis Section DD1-1R
Date	5/6/2010
Computed by	MMY/OTH/HLE

River Stage (feet)		**13.1**	**21.7**	**30.2**	**34.5**	**36.8**	**37.8**	**38.8**
Underseepage	p_f	0.00	0.00	0.00	0.00	0.29	0.65	1.00
	p_{nf}	1.00	1.00	1.00	1.00	0.71	0.35	0.00
Drawdown	p_f				0.00			0.00
	p_{nf}				1.00			1.00
Landside Static Stability	p_f		0.00	0.00	0.00	0.00		0.00
	p_{nf}		1.00	1.00	1.00	1.00		1.00
Riverside Static Stability	p_f	0.00	0.00	0.00	0.00	0.00		0.00
	p_{nf}	1.00	1.00	1.00	1.00	1.00		1.00
Landside Seismic Stability	p_f	0.00	0.00	0.00	0.01	0.01	0.01	0.01
	p_{nf}	1.00	1.00	1.00	0.99	0.99	0.99	0.99
Riverside Seismic Stability	p_f	0.01	0.01	0.01	0.01	0.00	0.00	0.01
	p_{nf}	0.99	0.99	0.99	0.99	1.00	1.00	0.99
Judgement	p_f	0.00	0.00	0.00	0.00	0.00	0.20	1.00
	p_{nf}	1.00	1.00	1.00	1.00	1.00	0.80	0.00
Combined	p_f	0.01	0.01	0.01	0.01	0.30	0.72	1.00
	p_{nf}	0.99	0.99	0.99	0.99	0.70	0.28	0.00



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

FRAGILITY CURVE AND TABLE
SECTION DD1-1R

January 2011 21-1-21199-003

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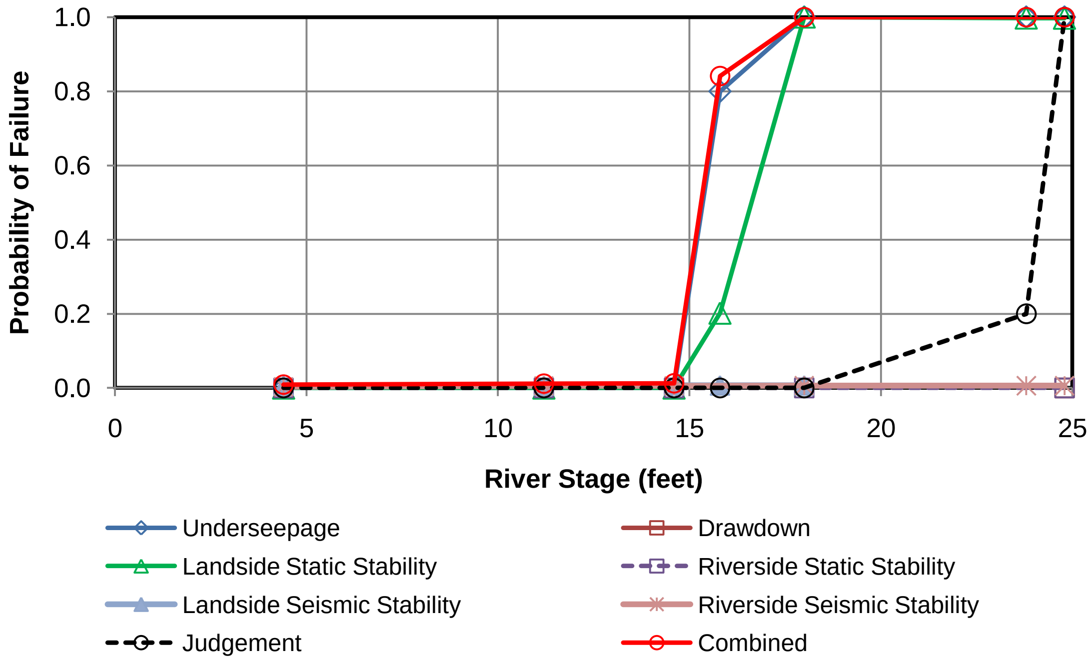
FIG. 23

Conditional Probability of Failure Analysis

Project	NWS Skagit River GI
Feature	Analysis Section DD1-2R
Date	5/10/2010
Computed by	MMY

River Stage (feet)		4.4	11.2	14.6	15.8	18.0	23.8	24.8
Underseepage	p_f	0.000	0.000	0.000	0.800	1.000	1.000	1.000
	p_{nf}	1.000	1.000	1.000	0.200	0.000	0.000	0.000
Drawdown	p_f							0.000
	p_{nf}							1.000
Landside Static Stability	p_f	0.000	0.000	0.000	0.202	1.000	0.997	0.997
	p_{nf}	1.000	1.000	1.000	0.798	0.000	0.003	0.003
Riverside Static Stability	p_f	0.000	0.000	0.000		0.000		0.000
	p_{nf}	1.000	1.000	1.000		1.000		1.000
Landside Seismic Stability	p_f	0.006	0.006	0.007	0.007	0.007	0.007	0.007
	p_{nf}	0.994	0.994	0.993	0.993	0.993	0.993	0.993
Riverside Seismic Stability	p_f	0.003	0.006	0.006		0.006	0.006	0.006
	p_{nf}	0.997	0.994	0.994		0.994	0.994	0.994
Judgement	p_f	0.000	0.000	0.000	0.000	0.000	0.200	1.000
	p_{nf}	1.000	1.000	1.000	1.000	0.200	0.800	0.000
Combined	p_f	0.009	0.012	0.013	0.841	1.000	1.000	1.000
	p_{nf}	0.991	0.988	0.987	0.159	0.000	0.000	0.000



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

FRAGILITY CURVE AND TABLE
SECTION DD1-2R

January 2011 21-1-21199-003

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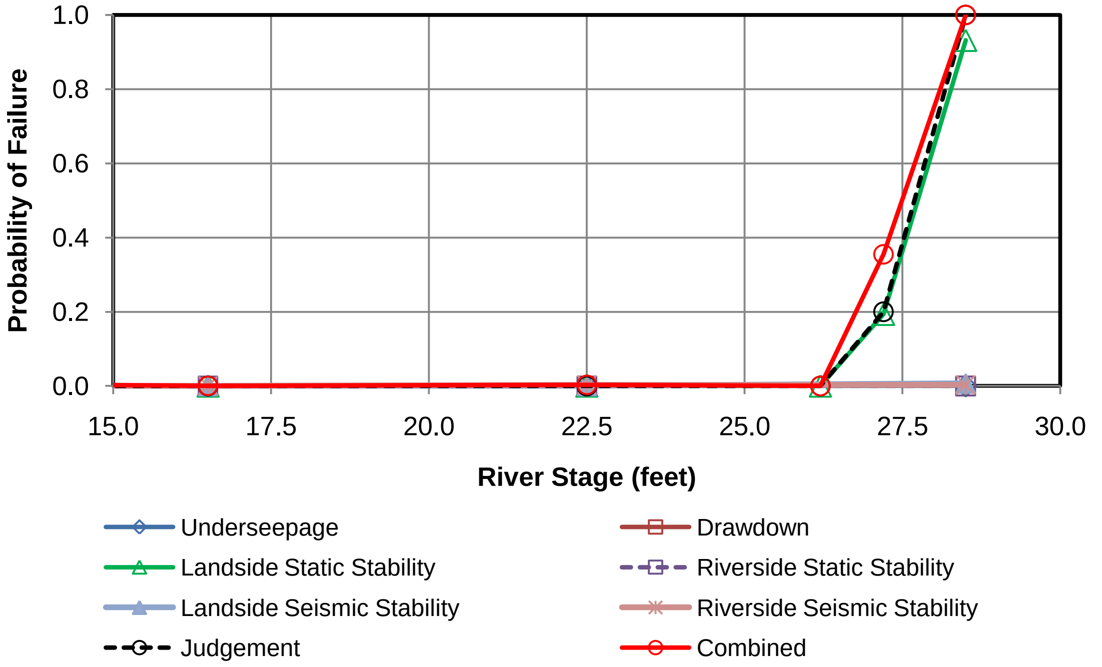
FIG. 24

Conditional Probability of Failure Analysis

Project	NWS Skagit River GI
Feature	Analysis Section DD3-1L
Date	5/10/2010
Computed by	MMY

River Stage (feet)		10.5	16.5	22.5	26.2	27.2	28.5
Underseepage	p_f			0.00			0.00
	p_{nf}			1.00			1.00
Drawdown	p_f						0.00
	p_{nf}						1.00
Landside Static Stability	p_f	0.01	0.00	0.00	0.00	0.19	0.93
	p_{nf}	0.99	1.00	1.00	1.00	0.81	0.07
Riverside Static Stability	p_f	0.00	0.00	0.00			0.00
	p_{nf}	1.00	1.00	1.00			1.00
Landside Seismic Stability	p_f	0.00	0.00	0.00			0.01
	p_{nf}	1.00	1.00	1.00			0.99
Riverside Seismic Stability	p_f	0.00	0.00	0.00			0.00
	p_{nf}	1.00	1.00	1.00			1.00
Judgement	p_f	0.00	0.00	0.00	0.00	0.20	1.00
	p_{nf}	1.00	1.00	1.00	1.00	0.80	0.00
Combined	p_f	0.01	0.00	0.00	0.00	0.35	1.00
	p_{nf}	0.99	1.00	1.00	1.00	0.65	0.00



Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

FRAGILITY CURVE AND TABLE
SECTION DD3-1L

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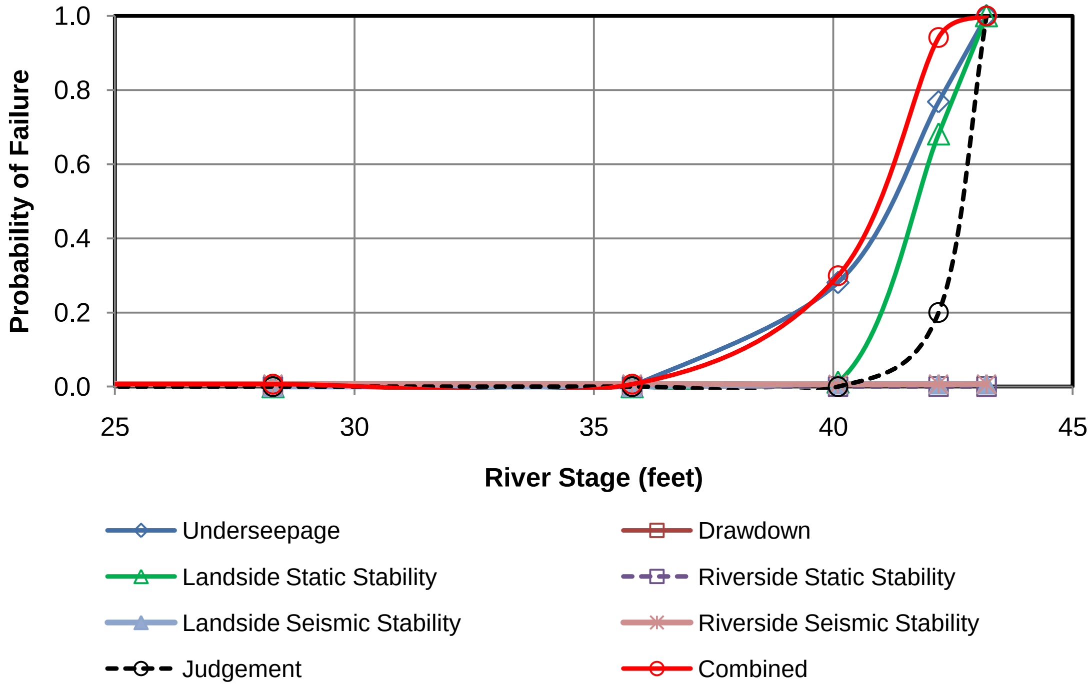
FIG. 25

Conditional Probability of Failure Analysis

Project	NWS Skagit River GI
Feature	Analysis Section D17-1L
Date	5/10/2010
Computed by	MMY

River Stage (feet)		**20.6**	**28.3**	**35.8**	**40.1**	**42.2**	**43.2**
Underseepage	p_f			0.000	0.281	0.768	1.000
	p_{nf}			1.000	0.719	0.232	0.000
Drawdown	p_f						0.000
	p_{nf}						1.000
Landside Static Stability	p_f		0.000	0.000	0.013	0.681	1.000
	p_{nf}		1.000	1.000	0.987	0.319	0.000
Riverside Static Stability	p_f	0.000	0.000	0.000	0.000	0.000	0.000
	p_{nf}	1.000	1.000	1.000	1.000	1.000	1.000
Landside Seismic Stability	p_f		0.000	0.000	0.007	0.007	0.007
	p_{nf}		1.000	1.000	0.993	0.993	0.993
Riverside Seismic Stability	p_f	0.007	0.007	0.007	0.007	0.007	0.007
	p_{nf}	0.993	0.993	0.993	0.993	0.993	0.993
Judgement	p_f	0.000	0.000	0.000	0.000	0.200	1.000
	p_{nf}	1.000	1.000	1.000	1.000	0.800	0.000
Combined	p_f	0.007	0.007	0.007	0.299	0.942	1.000
	p_{nf}	0.993	0.993	0.993	0.701	0.058	0.000



Skagit River Levee General Investigation
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FRAGILITY CURVE AND TABLE
SECTION DD17-1L

January 2011 21-1-21199-003

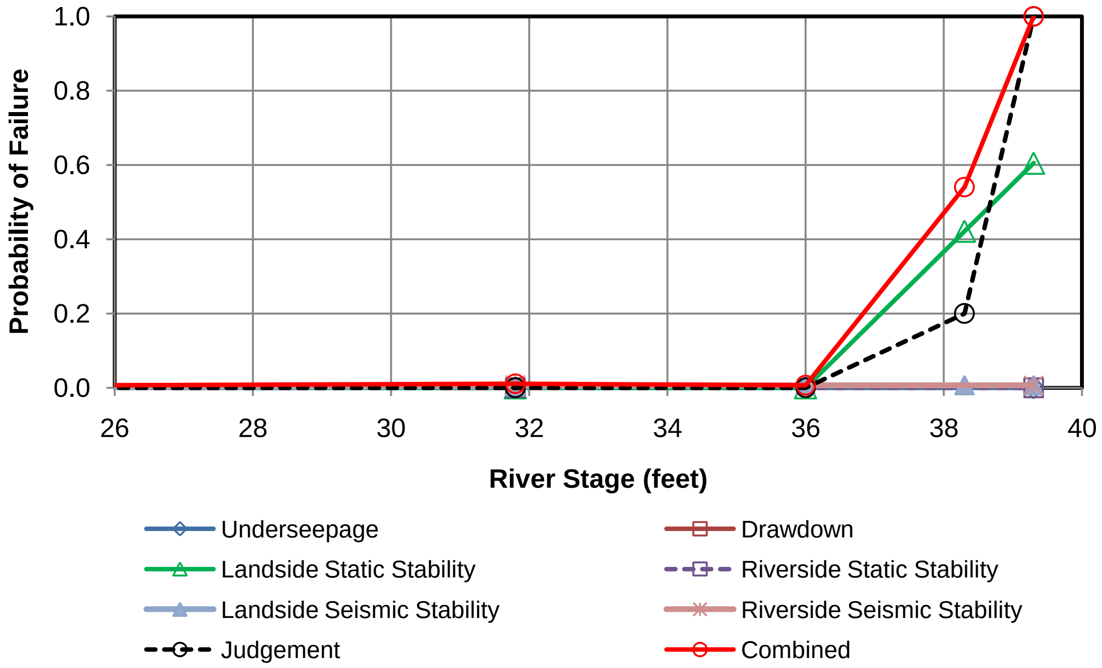
SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. 26

Conditional Probability of Failure Analysis

Project	NWS Skagit River GI
Feature	Analysis Section DD17-2L
Date	5/10/10
Computed by	MMY

River Stage (feet)		**13.1**	**23.3**	**31.8**	**36.0**	**38.3**	**39.3**
Underseepage	p_f	0.00	0.00	0.00	0.00		0.00
	p_{nf}	1.00	1.00	1.00	1.00		1.00
Drawdown	p_f						0.00
	p_{nf}						1.00
Landside Static Stability	p_f		0.00	0.00	0.00	0.42	0.60
	p_{nf}		1.00	1.00	1.00	0.58	0.40
Riverside Static Stability	p_f	0.00	0.00	0.00			0.00
	p_{nf}	1.00	1.00	1.00			1.00
Landside Seismic Stability	p_f		0.00	0.00	0.01	0.01	0.01
	p_{nf}		1.00	1.00	0.99	0.99	0.99
Riverside Seismic Stability	p_f	0.00	0.01	0.01			0.01
	p_{nf}	1.00	0.99	0.99			0.99
Judgement	p_f	0.00	0.00	0.00	0.00	0.20	1.00
	p_{nf}	1.00	1.00	1.00	1.00	0.80	0.00
Combined	p_f	0.00	0.01	0.01	0.01	0.54	1.00
	p_{nf}	1.00	0.99	0.99	0.99	0.46	0.00



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FRAGILITY CURVE AND TABLE
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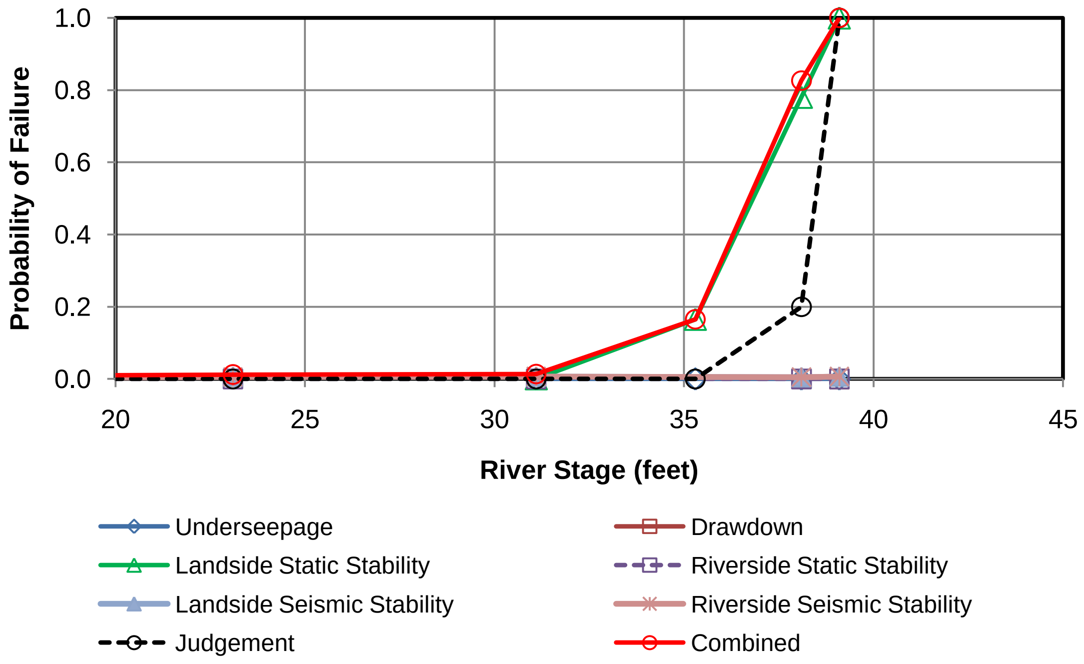
FIG. 27

Conditional Probability of Failure Analysis

Project	NWS Skagit River GI
Feature	Analysis Section DD17-3L
Date	5/10/2010
Computed by	MMY

River Stage (feet)		13.8	23.1	31.1	35.3	38.1	39.1
Underseepage	p_f			0.00	0.00	0.00	0.00
	p_{nf}			1.00	1.00	1.00	1.00
Drawdown	p_f						0.00
	p_{nf}						1.00
Landside Static Stability	p_f			0.00	0.16	0.78	1.00
	p_{nf}			1.00	0.84	0.22	0.00
Riverside Static Stability	p_f	0.00	0.00	0.00		0.00	0.00
	p_{nf}	1.00	1.00	1.00		1.00	1.00
Landside Seismic Stability	p_f	0.01	0.01	0.01		0.01	0.01
	p_{nf}	0.99	0.99	0.99		0.99	0.99
Riverside Seismic Stability	p_f	0.00	0.01	0.01		0.01	0.01
	p_{nf}	1.00	0.99	0.99		0.99	0.99
Judgement	p_f	0.00	0.00	0.00	0.00	0.20	1.00
	p_{nf}	1.00	1.00	1.00	1.00	0.80	0.00
Combined	p_f	0.01	0.01	0.01	0.16	0.83	1.00
	p_{nf}	0.99	0.99	0.99	0.84	0.17	0.00



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FRAGILITY CURVE AND TABLE
SECTION DD17-3L

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FIG. 28

Conditional Probability of Failure Analysis

Project	NWS Skagit River GI
Feature	Analysis Sectin DD22-1R
Date	5/10/2010
Computed by	MMY

River Stage (feet)		**5.1**	**12.0**	**18.0**	**23.0**	**24.0**
Underseepage	p_f	0.00	0.00	0.00	0.00	0.00
	p_{nf}	1.00	1.00	1.00	1.00	1.00
Drawdown	p_f					0.00
	p_{nf}					1.00
Landside Static Stability	p_f		0.00	0.00	0.00	0.00
	p_{nf}		1.00	1.00	1.00	1.00
Riverside Static Stability	p_f	0.00	0.00	0.00	0.00	0.00
	p_{nf}	1.00	1.00	1.00	1.00	1.00
Landside Seismic Stability	p_f		0.00	0.00	0.01	0.01
	p_{nf}		1.00	1.00	0.99	0.99
Riverside Seismic Stability	p_f	0.00	0.00	0.00	0.00	0.00
	p_{nf}	1.00	1.00	1.00	1.00	1.00
Judgement	p_f	0.00	0.00	0.00	0.20	1.00
	p_{nf}	1.00	1.00	1.00	0.80	0.00
Combined	p_f	0.00	0.00	0.00	0.21	1.00
	p_{nf}	1.00	1.00	1.00	0.79	0.00

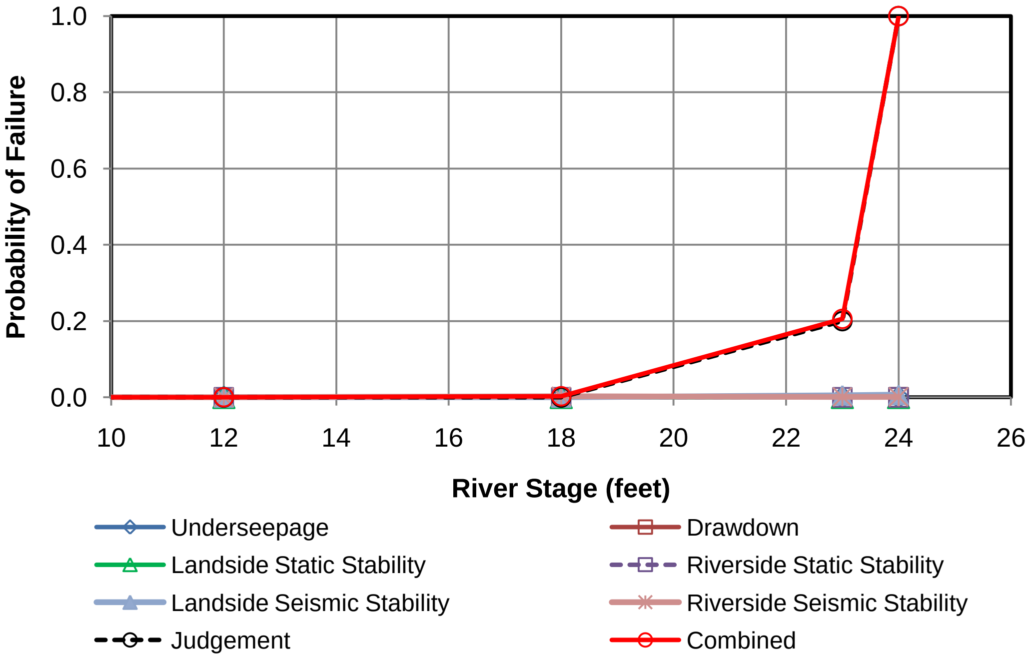

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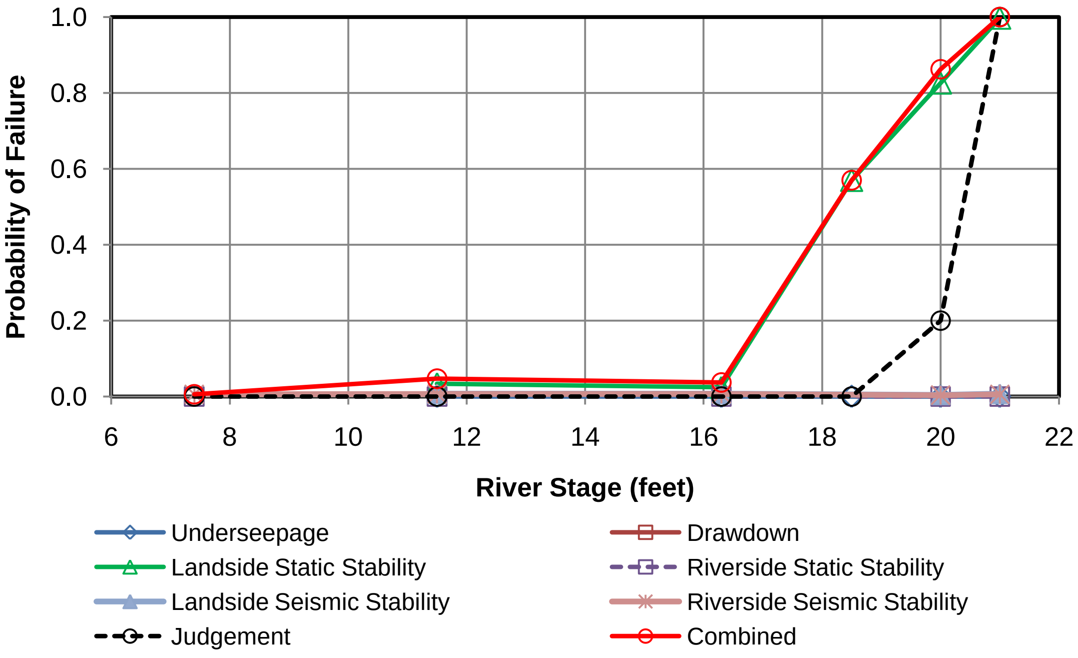
FIG. 29

Conditional Probability of Failure Analysis

Project	NWS Skagit River GI
Feature	Analysis Section DD22-2L
Date	5/10/2010
Computed by	MMY

River Stage (feet)		7.4	11.5	16.3	18.5	20.0	21.0
Underseepage	p_f		0.00	0.00	0.00	0.00	0.00
	p_{nf}		1.00	1.00	1.00	1.00	1.00
Drawdown	p_f						0.00
	p_{nf}						1.00
Landside Static Stability	p_f		0.03	0.02	0.57	0.83	1.00
	p_{nf}		0.97	0.98	0.43	0.17	0.00
Riverside Static Stability	p_f	0.00	0.00	0.00		0.00	0.00
	p_{nf}	1.00	1.00	1.00		1.00	1.00
Landside Seismic Stability	p_f		0.01	0.01		0.00	0.01
	p_{nf}		0.99	0.99		1.00	0.99
Riverside Seismic Stability	p_f	0.01	0.01	0.01		0.00	0.01
	p_{nf}	0.99	0.99	0.99		1.00	0.99
Judgement	p_f	0.00	0.00	0.00	0.00	0.20	1.00
	p_{nf}	1.00	1.00	1.00	1.00	0.80	0.00
Combined	p_f	0.01	0.05	0.04	0.57	0.86	1.00
	p_{nf}	0.99	0.95	0.96	0.43	0.14	0.00



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FRAGILITY CURVE AND TABLE
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FIG. 30

APPENDIX A

BORING LOGS

Shannon & Wilson, Inc. (S&W), uses a soil classification system modified from the Unified Soil Classification System (USCS). Elements of the USCS and other definitions are provided on this and the following page. Soil descriptions are based on visual-manual procedures (ASTM D 2488-93) unless otherwise noted.

S&W CLASSIFICATION OF SOIL CONSTITUENTS

- MAJOR constituents compose more than 50 percent, by weight, of the soil. Major consituents are capitalized (i.e., SAND).
- Minor constituents compose 12 to 50 percent of the soil and precede the major constituents (i.e., silty SAND). Minor constituents preceded by "slightly" compose 5 to 12 percent of the soil (i.e., slightly silty SAND).
- Trace constituents compose 0 to 5 percent of the soil (i.e., slightly silty SAND, trace of gravel).

MOISTURE CONTENT DEFINITIONS

Dry	Absence of moisture, dusty, dry to the touch
Moist	Damp but no visible water
Wet	Visible free water, from below water table

ABBREVIATIONS

ATD	At Time of Drilling
Elev.	Elevation
ft	feet
FeO	Iron Oxide
MgO	Magnesium Oxide
HSA	Hollow Stem Auger
ID	Inside Diameter
in	inches
lbs	pounds
Mon.	Monument cover
N	Blows for last two 6-inch increments
NA	Not applicable or not available
NP	Non plastic
OD	Outside diameter
OVA	Organic vapor analyzer
PID	Photo-ionization detector
ppm	parts per million
PVC	Polyvinyl Chloride
SS	Split spoon sampler
SPT	Standard penetration test
USC	Unified soil classification
WOH	Weight of hammer
WOR	Weight of drill rods
WLI	Water level indicator

GRAIN SIZE DEFINITION

DESCRIPTION	SIEVE NUMBER AND/OR SIZE
FINES	< #200 (0.08 mm)
SAND*	
- Fine	#200 to #40 (0.08 to 0.4 mm)
- Medium	#40 to #10 (0.4 to 2 mm)
- Coarse	#10 to #4 (2 to 5 mm)
GRAVEL*	
- Fine	#4 to 3/4 inch (5 to 19 mm)
- Coarse	3/4 to 3 inches (19 to 76 mm)
COBBLES	3 to 12 inches (76 to 305 mm)
BOULDERS	> 12 inches (305 mm)

* Unless otherwise noted, sand and gravel, when present, range from fine to coarse in grain size.

RELATIVE DENSITY / CONSISTENCY

COARSE-GRAINED SOILS		FINE-GRAINED SOILS	
N, SPT, BLOWS/FT.	RELATIVE DENSITY	N, SPT, BLOWS/FT.	RELATIVE CONSISTENCY
0 - 4	Very loose	Under 2	Very soft
4 - 10	Loose	2 - 4	Soft
10 - 30	Medium dense	4 - 8	Medium stiff
30 - 50	Dense	8 - 15	Stiff
Over 50	Very dense	15 - 30	Very stiff
		Over 30	Hard

WELL AND OTHER SYMBOLS

▧	Bent. Cement Grout	▒	Surface Cement Seal
▨	Bentonite Grout	■	Asphalt or Cap
▩	Bentonite Chips	▒	Slough
☐	Silica Sand	▩	Bedrock
▤	PVC Screen		
◨	Vibrating Wire		

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SOIL CLASSIFICATION AND LOG KEY

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SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-1
Sheet 1 of 2

BORING CLASS1 21-21199.GPJ SWNEW.GDT 6/1/10

UNIFIED SOIL CLASSIFICATION SYSTEM (USCS)
(From USACE Tech Memo 3-357)

MAJOR DIVISIONS			GROUP/GRAPHIC SYMBOL		TYPICAL DESCRIPTION
COARSE-GRAINED SOILS *(more than 50% retained on No. 200 sieve)*	Gravels *(more than 50% of coarse fraction retained on No. 4 sieve)*	Clean Gravels *(less than 5% fines)*	GW	●	Well-graded gravels, gravels, gravel/sand mixtures, little or no fines.
			GP	○	Poorly graded gravels, gravel-sand mixtures, little or no fines
		Gravels with Fines *(more than 12% fines)*	GM	●	Silty gravels, gravel-sand-silt mixtures
			GC	▨	Clayey gravels, gravel-sand-clay mixtures
	Sands *(50% or more of coarse fraction passes the No. 4 sieve)*	Clean Sands *(less than 5% fines)*	SW	⁘	Well-graded sands, gravelly sands, little or no fines
			SP	⁘	Poorly graded sand, gravelly sands, little or no fines
		Sands with Fines *(more than 12% fines)*	SM	▥	Silty sands, sand-silt mixtures
			SC	▨	Clayey sands, sand-clay mixtures
FINE-GRAINED SOILS *(50% or more passes the No. 200 sieve)*	Silts and Clays *(liquid limit less than 50)*	Inorganic	ML	▥	Inorganic silts of low to medium plasticity, rock flour, sandy silts, gravelly silts, or clayey silts with slight plasticity
			CL	▨	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
		Organic	OL	☰	Organic silts and organic silty clays of low plasticity
	Silts and Clays *(liquid limit 50 or more)*	Inorganic	MH	▥	Inorganic silts, micaceous or diatomaceous fine sands or silty soils, elastic silt
			CH	▨	Inorganic clays of medium to high plasticity, sandy fat clay, or gravelly fat clay
		Organic	OH	▨	Organic clays of medium to high plasticity, organic silts
HIGHLY-ORGANIC SOILS	Primarily organic matter, dark in color, and organic odor		PT	≋	Peat, humus, swamp soils with high organic content (see ASTM D 4427)

NOTE: No. 4 size = 5 mm; No. 200 size = 0.075 mm

NOTES

1. Dual symbols *(symbols separated by a hyphen, i.e., SP-SM, slightly silty fine SAND)* are used for soils with between 5% and 12% fines or when the liquid limit and plasticity index values plot in the CL-ML area of the plasticity chart.
2. Borderline symbols *(symbols separated by a slash, i.e., CL/ML, silty CLAY/clayey SILT; GW/SW, sandy GRAVEL/gravelly SAND)* indicate that the soil may fall into one of two possible basic groups.

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SOIL CLASSIFICATION AND LOG KEY

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FIG. A-1
Sheet 2 of 2

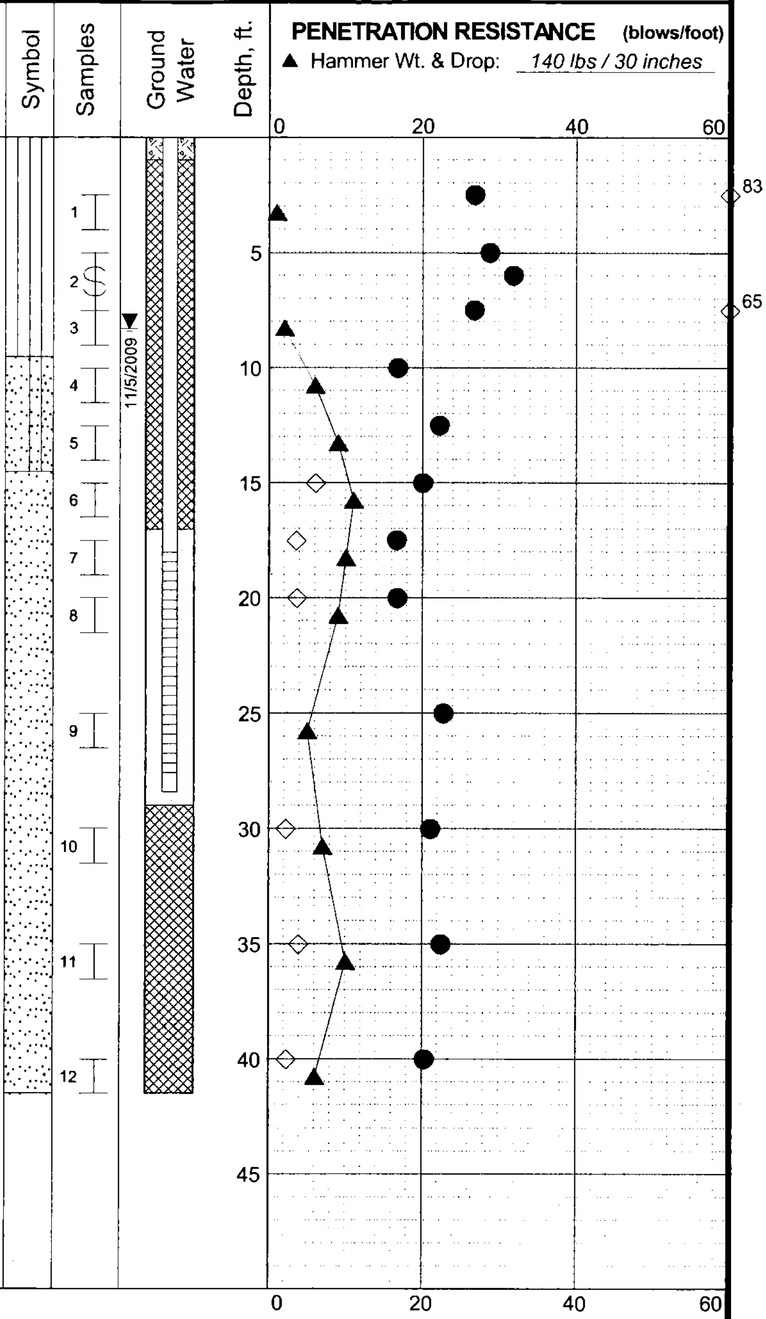
Total Depth:	41.5 ft.	Northing:	~ 525,847 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,268,352 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	B-61 Mobile Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

SOIL DESCRIPTION	Depth, ft.
Very loose, brown, fine sandy SILT to silty, fine SAND; moist; trace of fine roots, laminated; (Ha[ob]) ML/SM.	9.5
Interbedded, loose, brown and gray, slightly silty, fine to medium SAND and silty, fine SAND; moist to wet; (Ha[cd]) SP-SM/SM.	14.5
Loose to medium dense, gray, trace of silt to slightly silty, slightly fine gravelly to fine gravelly, fine to medium SAND; wet; (Ha[cd]) SP/SP-SM.	41.5

BOTTOM OF BORING
COMPLETED 10/16/2009



LEGEND

*	Sample Not Recovered
Ⅰ	Standard Penetration Test
$	3" O.D. Thin-Walled Tube
▯	Piezometer Screen and Sand Filter
▧	Bentonite-Cement Grout
▩	Bentonite Chips/Pellets
▨	Bentonite Grout
▼	Ground Water Level in Well

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

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LOG OF BORING DD1-1 Landward

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FIG. A-2

MASTER LOG E 21-21199.GPJ SHAN WIL.GDT 6/1/10

Log: EVP Rev: JKN Typ: CLP

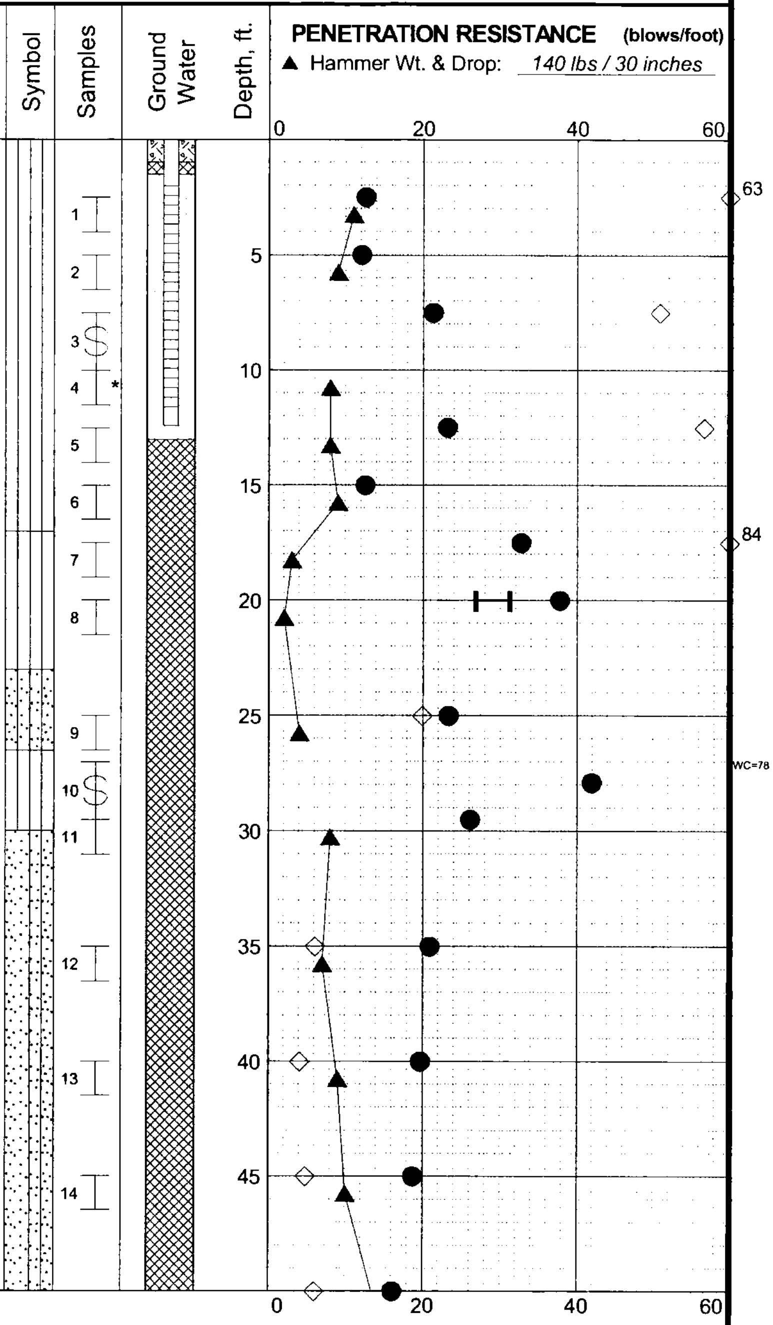
Total Depth:	*61.5 ft.*	Northing:	*~ 525,954 ft.*	Drilling Method:	*Mud Rotary*	Hole Diam.:	*5 in.*
Top Elevation:	*~*	Easting:	*~ 1,268,368 ft.*	Drilling Company:	*Holocene Drilling*	Rod Diam.:	*NWJ*
Vert. Datum:		Station:	*~*	Drill Rig Equipment:	*B-61 Mobile Truck*	Hammer Type:	*Automatic*
Horiz. Datum:	*NAD83*	Offset:	*~*	Other Comments:			

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

SOIL DESCRIPTION	Depth, ft.
Loose to medium dense, brown, fine sandy SILT; moist; trace of organics; (Hf) ML.	
Soft, brown, trace to slightly clayey, trace of fine sand to slightly fine sandy SILT; moist to wet; scattered roots; (Ha[ob]) ML.	17.0
Loose, gray, silty, fine to medium SAND; wet; scattered silty, fine sand seams, iron-oxide staining; (Ha[ob]) SM.	23.0
Interbedded, loose, gray-brown, slightly fine sandy to fine sandy SILT, silty, fine SAND, and medium stiff, organic SILT; wet; 1/2-inch silty clay seam and 7-inch-thick wood fragment; (Ha[ob]) ML/SM/OL.	26.5
Loose to medium dense, gray, trace to slightly fine gravelly, trace to slightly silty SAND; wet; (Ha[cd]) SP-SM/SP.	30.0

CONTINUED NEXT SHEET



LEGEND

- * Sample Not Recovered
- Ⅰ Standard Penetration Test
- $ 3" O.D. Thin-Walled Tube
- ▥ Piezometer Screen and Sand Filter
- ▧ Bentonite-Cement Grout
- ▩ Bentonite Chips/Pellets
- ▨ Bentonite Grout

◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├─●─┤ Liquid Limit
Natural Water Content

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

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LOG OF BORING DD1-1 Levee

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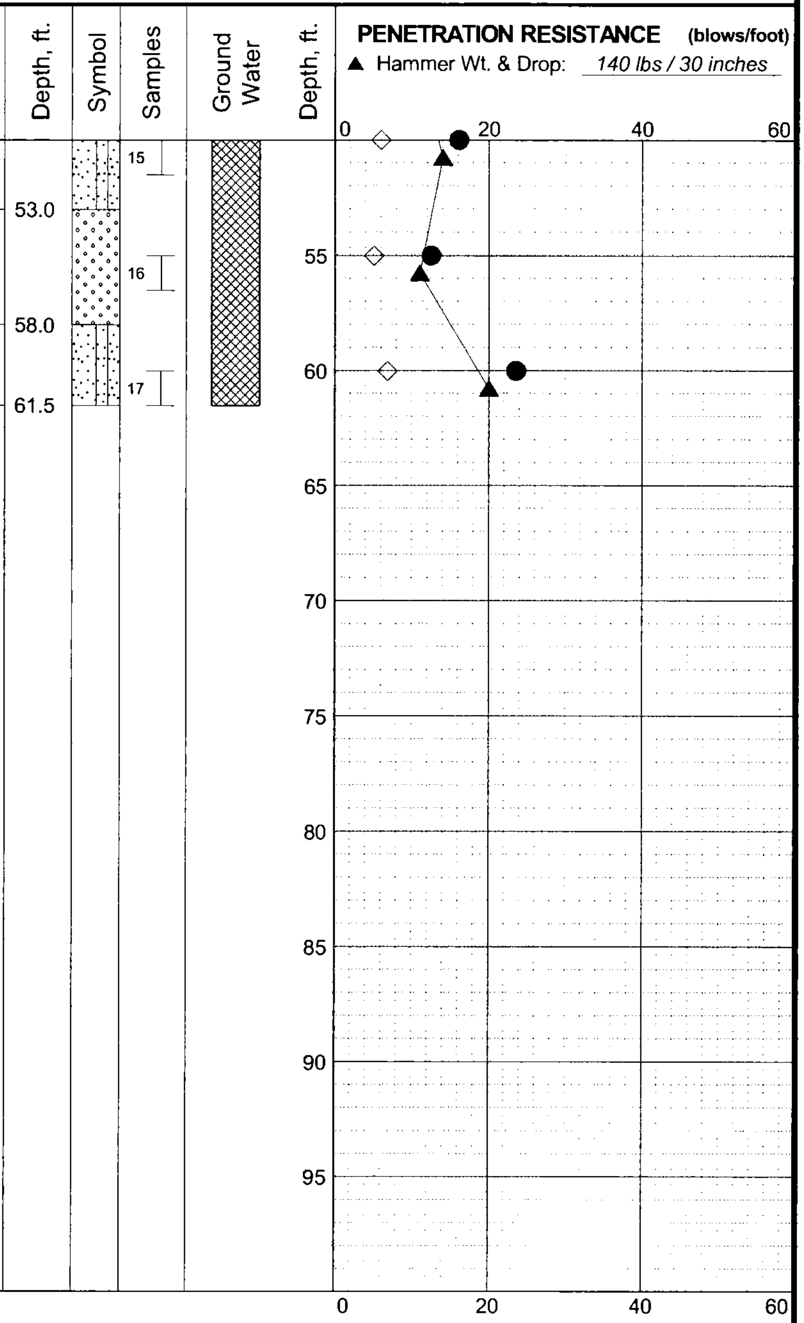
FIG. A-3
Sheet 1 of 2

Total Depth:	*61.5 ft.*	Northing:	*~ 525,954 ft.*	Drilling Method:	*Mud Rotary*	Hole Diam.:	*5 in.*
Top Elevation:	*~*	Easting:	*~ 1,268,368 ft.*	Drilling Company:	*Holocene Drilling*	Rod Diam.:	*NWJ*
Vert. Datum:		Station:	*~*	Drill Rig Equipment:	*B-61 Mobile Truck*	Hammer Type:	*Automatic*
Horiz. Datum:	*NAD83*	Offset:	*~*	Other Comments:			

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

53.0	Medium dense, gray, slightly silty, fine gravelly SAND; wet; (Ha[g]) SW-SM.
58.0	Medium dense, gray, slightly silty, fine to medium SAND; wet; (Ha[cd]) SP-SM.
61.5	BOTTOM OF BORING COMPLETED 10/16/2009



LEGEND

* Sample Not Recovered
⌶ Standard Penetration Test
Ｓ 3" O.D. Thin-Walled Tube

▯ Piezometer Screen and Sand Filter
▧ Bentonite-Cement Grout
▩ Bentonite Chips/Pellets
▨ Bentonite Grout

◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├─●─┤ Liquid Limit
Natural Water Content

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

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LOG OF BORING DD1-1 Levee

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FIG. A-3
Sheet 2 of 2

MASTER LOG E 21-21199.GPJ SHAN WIL.GDT 6/1/10 Log: EVP Rev: JKN Typ: CLP

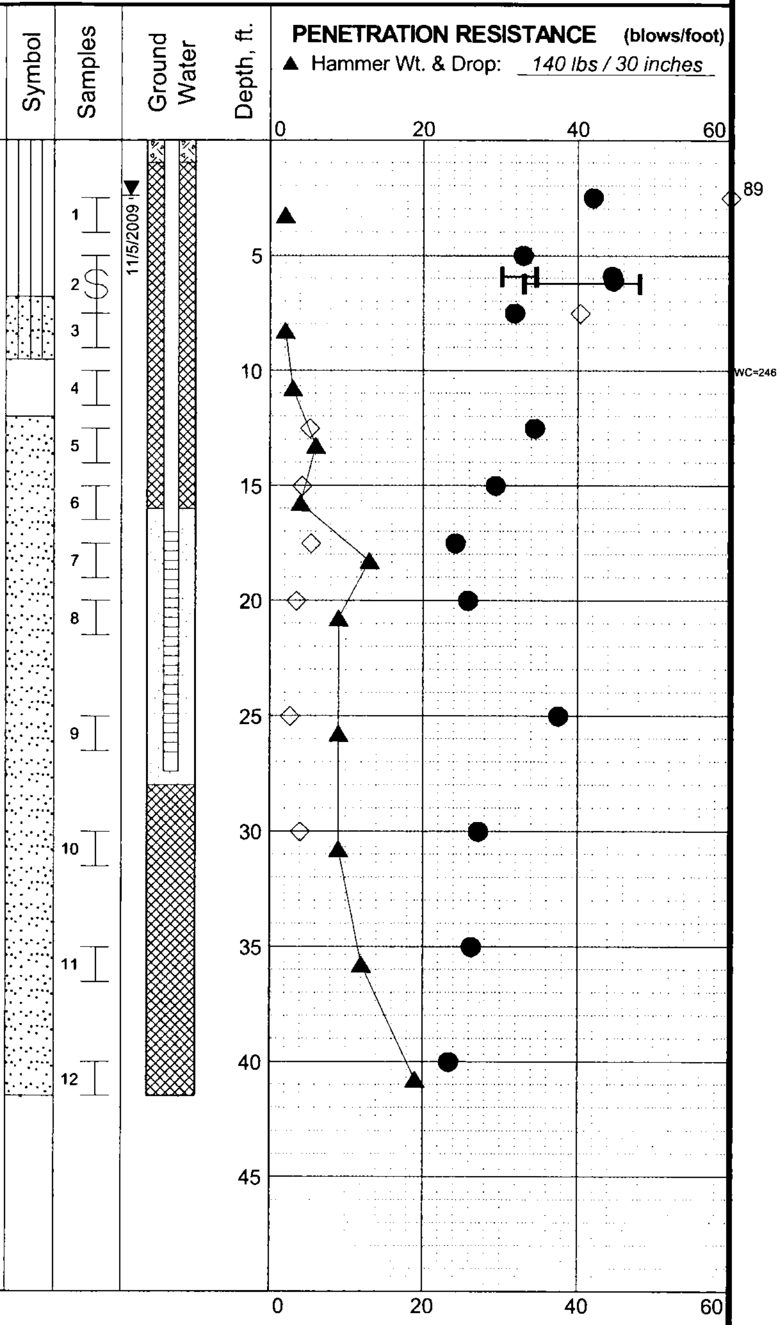
Total Depth: 41.5 ft.
Top Elevation: ~
Vert. Datum:
Horiz. Datum: NAD83
Northing: ~ 508,726 ft.
Easting: ~ 1,263,857 ft.
Station: ~
Offset: ~
Drilling Method: Mud Rotary
Drilling Company: Holocene Drilling
Drill Rig Equipment: BK-81 Truck
Other Comments:
Hole Diam.: 5 in.
Rod Diam.: NWJ
Hammer Type: Automatic

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

SOIL DESCRIPTION	Depth, ft.
Soft, brown, trace to slightly clayey, slightly fine sandy SILT; moist; scattered roots, iron-oxide staining; (Ha[ob]) ML.	6.8
Very loose, brown, silty, fine SAND; wet; scattered roots, trace of iron-oxide staining; (Ha[ob]) SM.	9.5
Soft, brown WOOD; moist; horizontal grain; (WOOD).	12.0
Loose to medium dense, gray, trace to slightly silty, fine medium SAND; wet; trace to scattered wood fragments, scattered mica flakes; (Ha[cd]) SP/SP-SM.	41.5

BOTTOM OF BORING
COMPLETED 10/19/2009



◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├─●─┤ Liquid Limit
Natural Water Content

LEGEND

* Sample Not Recovered
I Standard Penetration Test
$ 3" O.D. Thin-Walled Tube
☐ Piezometer Screen and Sand Filter
▧ Bentonite-Cement Grout
▩ Bentonite Chips/Pellets
▨ Bentonite Grout
▼ Ground Water Level in Well

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD1-2 Landward

June 2010 21-1-21199-002

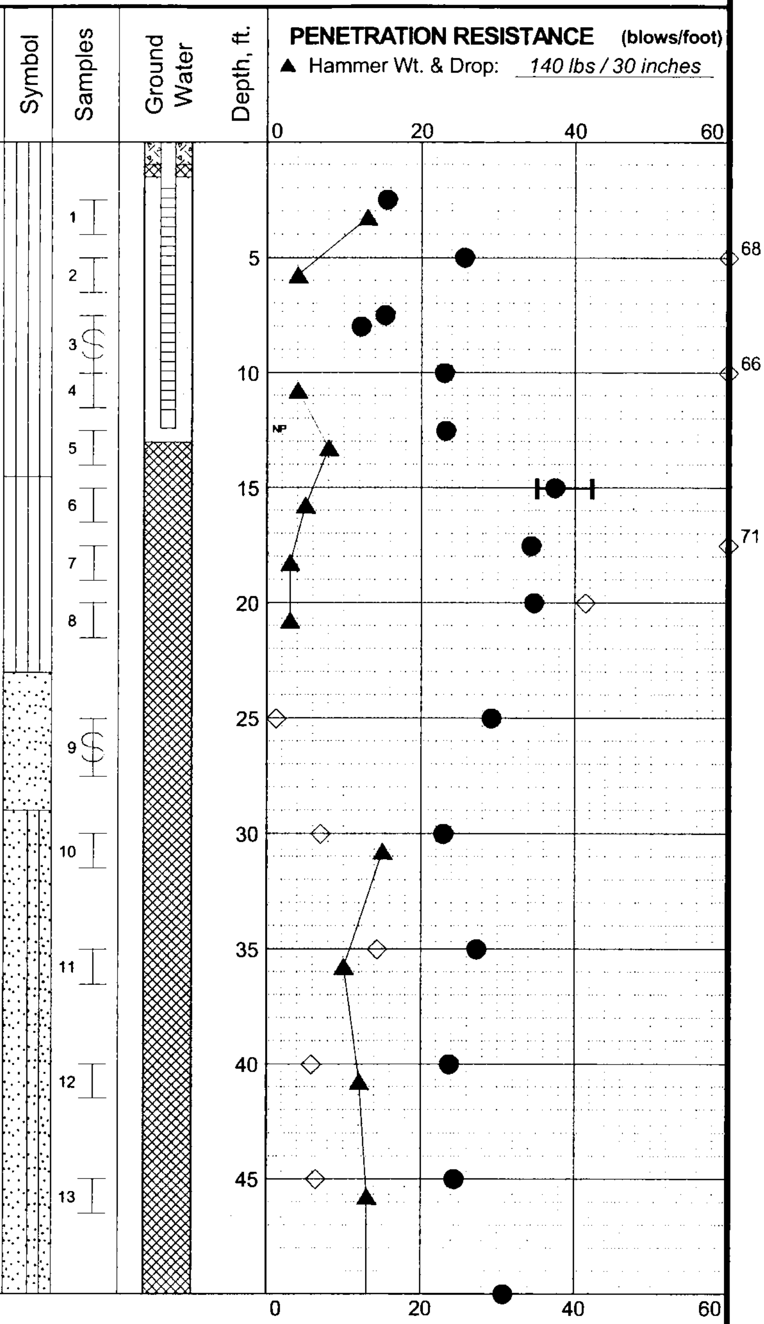
SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-4

Total Depth:	61.5 ft.	Northing:	~ 508,713 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,263,901 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	BK-81 Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION *Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.*	Depth, ft.
Loose to medium dense, brown, fine sandy SILT; moist; trace of organics, locally trace of clay, local slightly silty sand zones; (Hf) ML. - Iron-oxide-stained seams below 12 feet.	
Interbedded, very loose to loose and soft to medium stiff, brown, fine sandy SILT, slightly fine sandy SILT, trace of clay, and silty, fine SAND; moist; scattered organics and wood, trace of iron-oxide-stained seams; (Ha[ob]) ML/SM.	14.5
Gray, fine SAND, trace of silt; wet; stratified; (Ha[cd]) SP.	23.0
Loose to medium dense, gray, slightly silty to silty, fine to medium SAND; wet; trace of organics, locally trace of fine gravel; (Ha[cd]) SP-SM/SM. - Scattered wood fragments at 35 feet.	29.0

CONTINUED NEXT SHEET



LEGEND

- * Sample Not Recovered
- Ⅰ Standard Penetration Test
- $ 3" O.D. Thin-Walled Tube

- ⊟ Piezometer Screen and Sand Filter
- ▧ Bentonite-Cement Grout
- ⊠ Bentonite Chips/Pellets
- ▨ Bentonite Grout

◇ % Fines (<0.075mm)

● % Water Content

Plastic Limit ├─●─┤ Liquid Limit

Natural Water Content

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD1-2 Levee

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

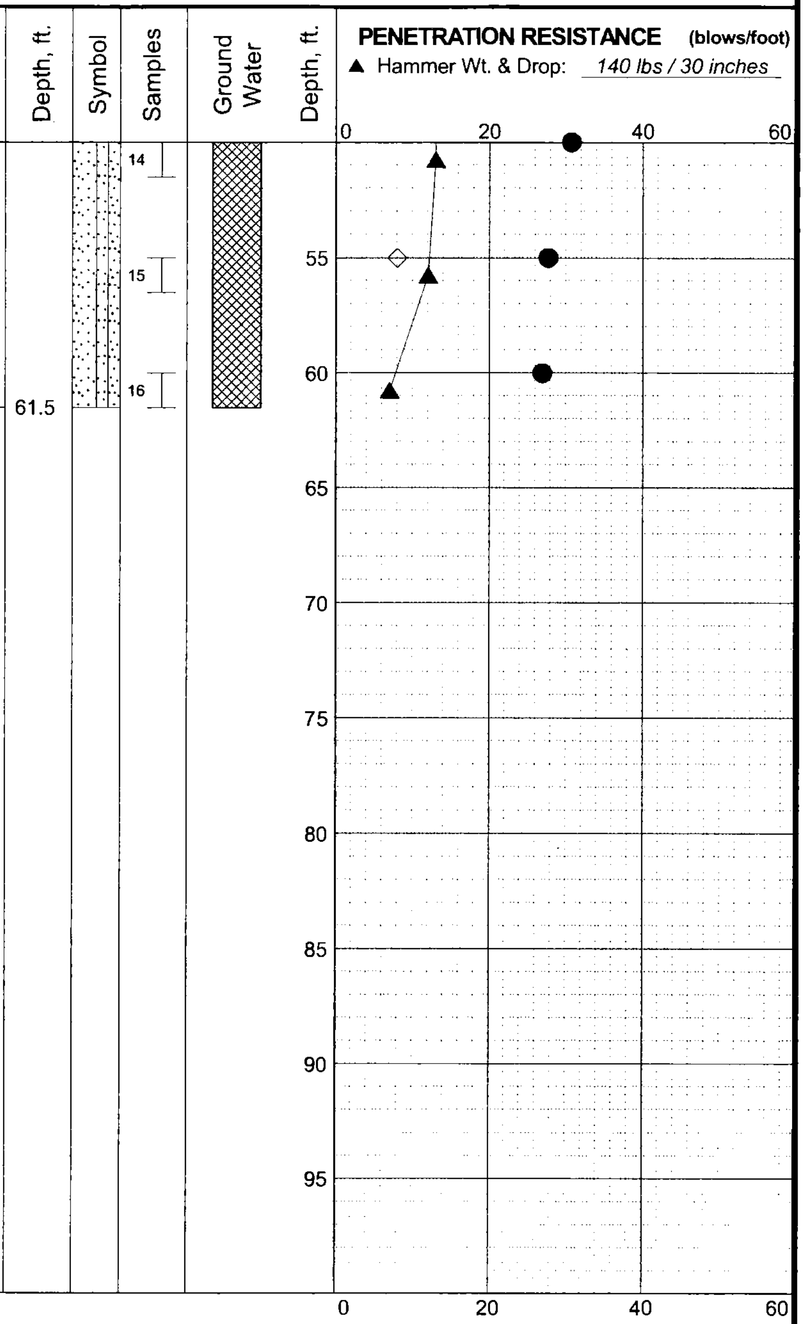
FIG. A-5
Sheet 1 of 2

Total Depth:	61.5 ft.	Northing:	~ 508,713 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,263,901 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	BK-81 Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

BOTTOM OF BORING
COMPLETED 10/20/2009



LEGEND

- * Sample Not Recovered
- I Standard Penetration Test
- $ 3" O.D. Thin-Walled Tube
- ▯ Piezometer Screen and Sand Filter
- ▨ Bentonite-Cement Grout
- ▩ Bentonite Chips/Pellets
- ▧ Bentonite Grout

◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├─●─┤ Liquid Limit
Natural Water Content

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD1-2 Levee

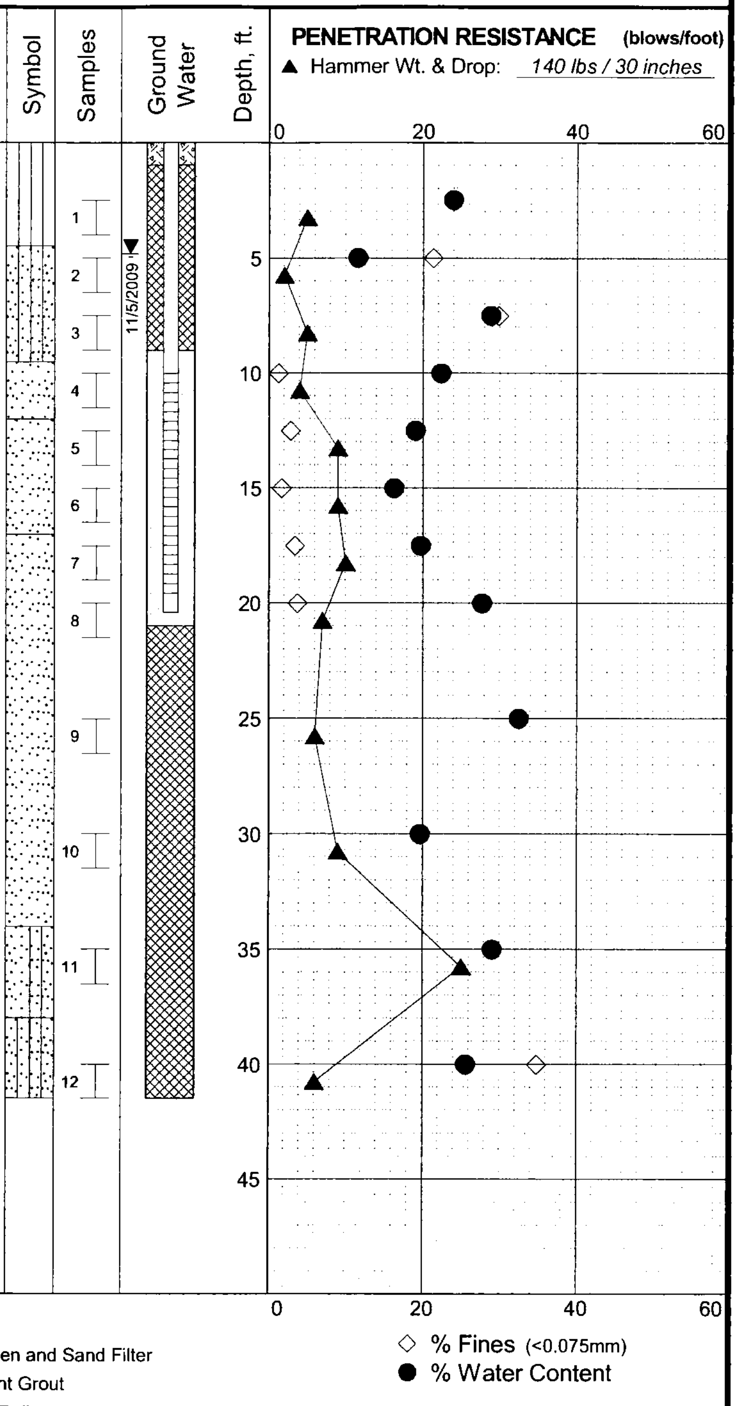
June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-5
Sheet 2 of 2

Total Depth:	41.5 ft.	Northing:	~ 507,123 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,269,522 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	BK-81 Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION *Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.*	Depth, ft.
Loose, brown, slightly fine sandy SILT; moist; scattered organics; (Topsoil) ML.	4.5
Very loose to loose, brown and gray, silty, fine SAND; wet; (Ha[ob]) SM.	9.5
Loose, gray SAND, trace of silt and fine gravel; wet; (Ha[cd]) SP.	12.0
Loose, gray, fine gravelly SAND, trace of silt; wet; (Ha[g]) SP.	17.0
Loose, gray, trace to slightly fine gravelly SAND, trace of silt; wet; local slightly silty layers at 25 feet; (Ha[cd]) SP.	34.0
Medium dense, gray, slightly silty, fine SAND, trace of fine gravel; wet; scattered shell fragments; (He) SP-SM.	38.0
Loose, gray, silty, fine to medium SAND, trace of clay; wet; trace of shell fragments; (He) SM.	41.5
BOTTOM OF BORING COMPLETED 10/20/2009	



LEGEND

* Sample Not Recovered
⌶ Standard Penetration Test
▯ Piezometer Screen and Sand Filter
▧ Bentonite-Cement Grout
▩ Bentonite Chips/Pellets
▨ Bentonite Grout
▼ Ground Water Level in Well

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD3-1 Landward

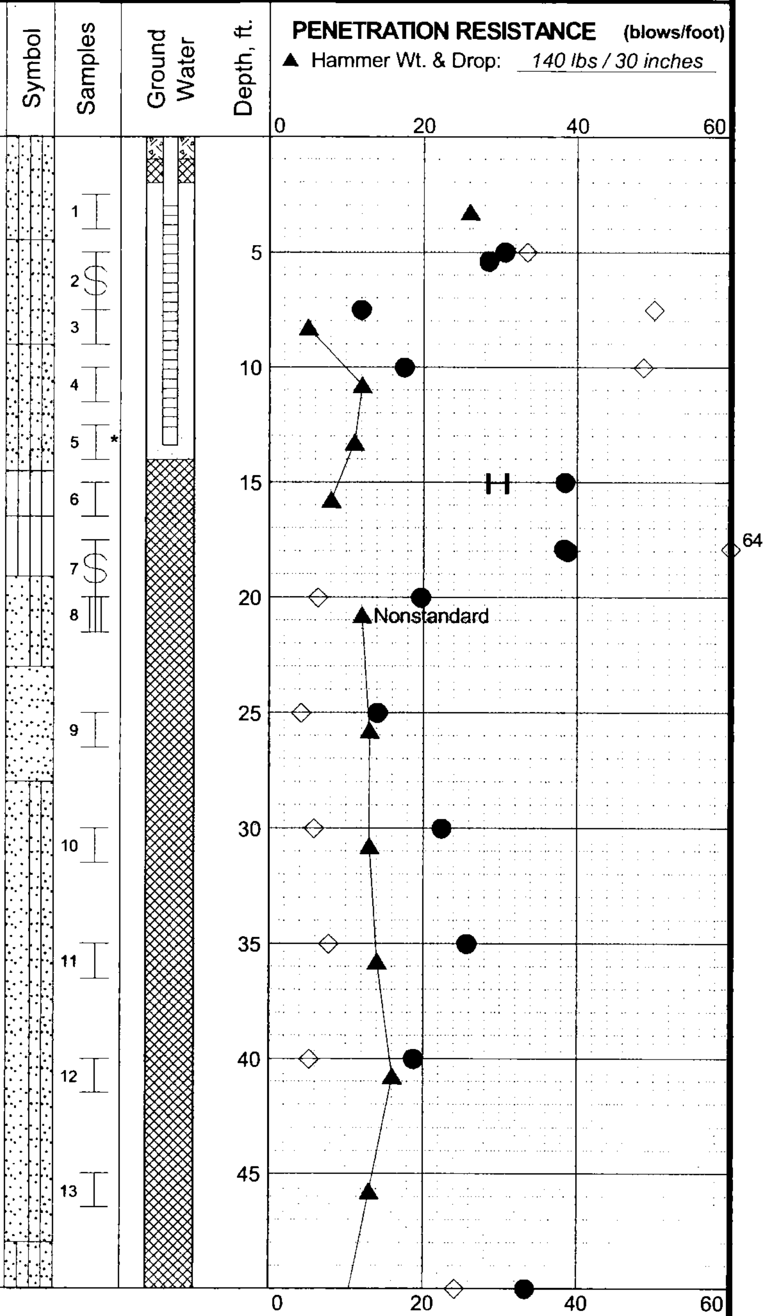
June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-6

Total Depth: 61.5 ft.
Top Elevation: ~
Vert. Datum:
Horiz. Datum: NAD83
Northing: ~ 507,134 ft.
Easting: ~ 1,269,453 ft.
Station: ~
Offset: ~
Drilling Method: Mud Rotary
Drilling Company: Holocene Drilling
Drill Rig Equipment: BK-81 Truck
Other Comments:
Hole Diam.: 5 in.
Rod Diam.: NWJ
Hammer Type: Automatic

SOIL DESCRIPTION *Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.*	Depth, ft.
Medium dense, gray, slightly clayey, slightly gravelly, silty SAND; moist; scattered roots; (Hf) SM.	
Loose, brown, silty, fine SAND to fine sandy SILT, trace of fine gravel; moist; trace of organics; (Hf) SM/ML.	4.5
Medium dense, gray-brown, silty, fine SAND; moist; scattered fine sandy silt seams; (Hf) SM.	9.0
Medium stiff, brown, slightly clayey SILT, trace of fine sand; wet; faint iron-oxide mottles; (Ha[ob]) ML.	14.5 16.5
Gray and orange, fine sandy SILT grading to silty, fine SAND; wet; iron-oxide mottling, stratified, trace of fine roots; (Ha[ob]) ML/SM.	19.1
Medium dense, gray, slightly silty SAND, trace of fine gravel; wet; (Ha[cd]) SP-SM.	23.0
Medium dense, gray, fine gravelly SAND, trace of silt; wet; (Ha[g]) SP.	
Medium dense, gray, trace of fine gravel to slightly fine gravelly, slightly silty SAND; wet; (Ha[cd]) SP-SM/SW-SM.	28.0
CONTINUED NEXT SHEET	48.0



LEGEND

- * Sample Not Recovered
- Ⅰ Standard Penetration Test
- $ 3" O.D. Thin-Walled Tube
- Ⅲ 3" O.D. Split Spoon Sample
- ⊟ Piezometer Screen and Sand Filter
- ▧ Bentonite-Cement Grout
- ▩ Bentonite Chips/Pellets
- ▨ Bentonite Grout

◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├─●─┤ Liquid Limit
Natural Water Content

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD3-1 Levee

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-7
Sheet 1 of 2

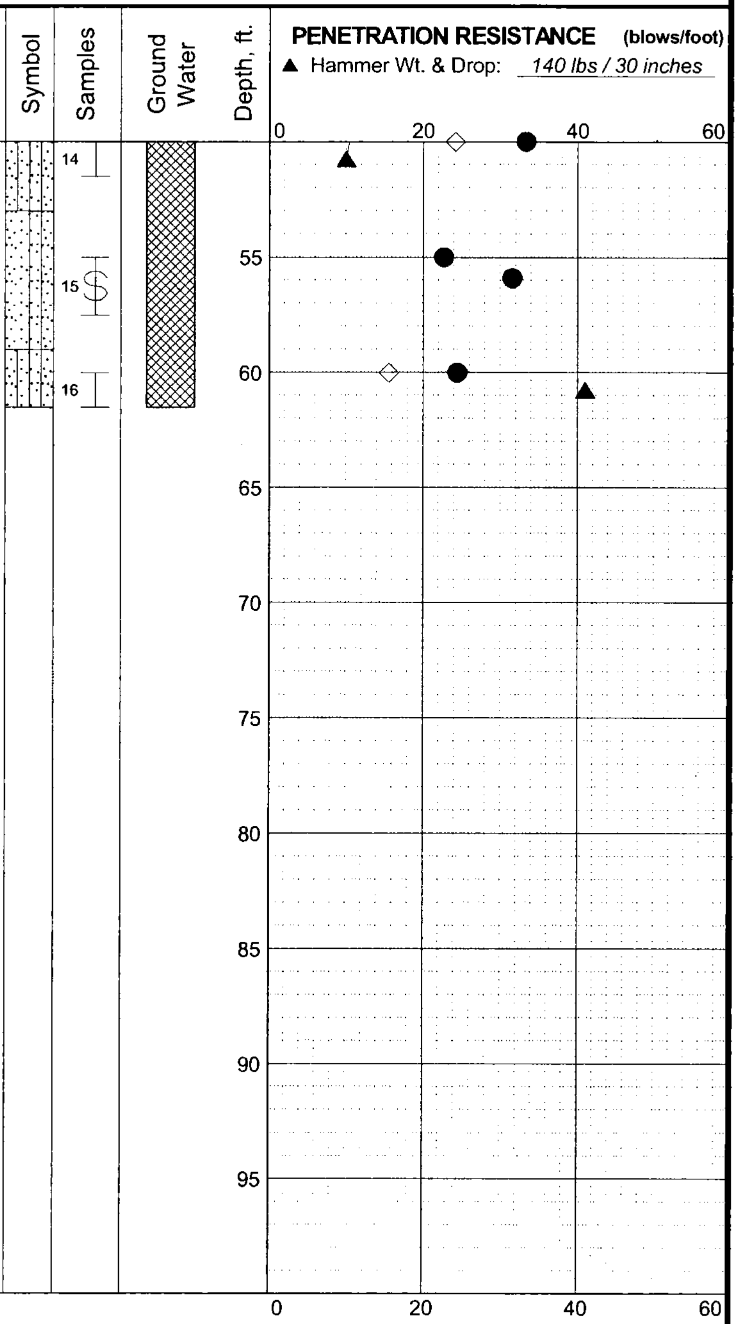
Total Depth:	61.5 ft.	Northing:	~ 507,134 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,269,453 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	BK-81 Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

SOIL DESCRIPTION	Depth, ft.
Medium dense, gray, silty, fine to medium SAND; wet; trace of shells and organics; (He) SM.	53.0
Gray, trace of silt to slightly silty, fine to medium SAND; wet; trace of shell fragments, scattered coarse wood fragments; (Ha[cd]/He) SP-SM/SP.	59.0
Dense, gray, silty, fine to medium SAND; wet; (Ha[cd]) SM.	61.5

BOTTOM OF BORING
COMPLETED 10/21/2009



◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├─●─┤ Liquid Limit
Natural Water Content

LEGEND

*	Sample Not Recovered
I	Standard Penetration Test
$	3" O.D. Thin-Walled Tube
‖	3" O.D. Split Spoon Sample
▯	Piezometer Screen and Sand Filter
▧	Bentonite-Cement Grout
▩	Bentonite Chips/Pellets
▨	Bentonite Grout

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD3-1 Levee

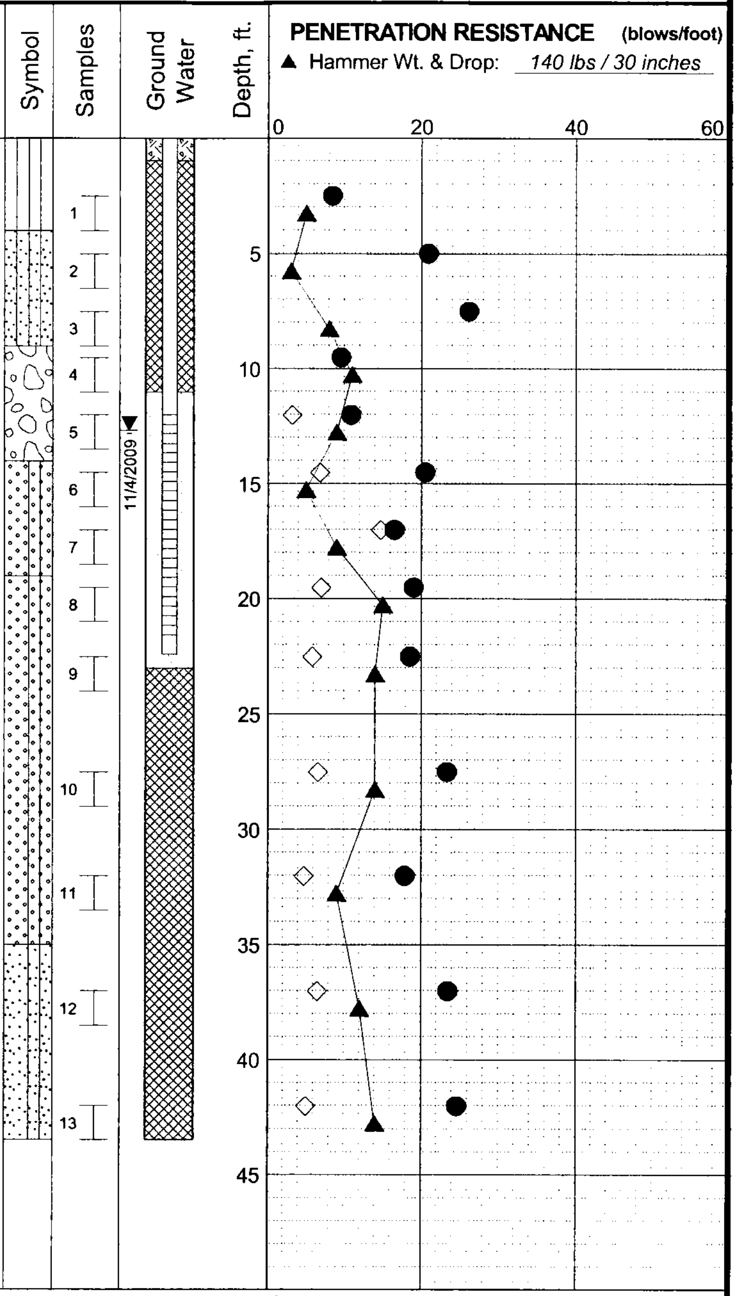
June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-7
Sheet 2 of 2

Total Depth: 43.5 ft.
Top Elevation: ~
Vert. Datum:
Horiz. Datum: NAD83
Northing: ~ 530,262 ft.
Easting: ~ 1,277,725 ft.
Station: ~
Offset: ~
Drilling Method: Mud Rotary
Drilling Company: Holocene Drilling
Drill Rig Equipment: B-61 Mobile Truck
Other Comments:
Hole Diam.: 5 in.
Rod Diam.: NWJ
Hammer Type: Automatic

SOIL DESCRIPTION *Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.*	Depth, ft.
Loose, brown, slightly fine sandy SILT; moist; trace of fine roots; (Ha[ob]) ML.	4.0
Very loose to loose, brown, silty, fine SAND; moist; scattered iron-oxide-stained seams; (Ha[cd]) SM.	9.0
Loose to medium dense, brown, sandy, fine GRAVEL, trace of silt to gravelly SAND, trace of silt; wet; strong iron-oxide staining below 12 feet, rounded to subrounded gravel; (Ha[g]) GP/SW.	14.0
Loose, gray, slightly silty, slightly fine gravelly SAND to silty SAND, trace of fine gravel; wet; scattered silty sand seams, scattered iron-oxide-stained and dark brown layers below 17 feet, trace of organics; (Ha[cd]) SW-SM/SM.	19.0
Loose to medium dense, gray, trace to slightly silty, trace of fine gravel to fine gravelly SAND; wet; (Ha[cd]) SW-SM/SP.	35.0
Medium dense, gray, slightly silty, fine to medium SAND, trace of fine gravel; wet; (Ha[cd]) SP-SM.	43.5
BOTTOM OF BORING COMPLETED 10/9/2009	



LEGEND

* Sample Not Recovered
⌶ Standard Penetration Test
▭ Piezometer Screen and Sand Filter
▨ Bentonite-Cement Grout
▩ Bentonite Chips/Pellets
▧ Bentonite Grout
▼ Ground Water Level in Well

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD17-1 Landward

June 2010
21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-8

Total Depth:	63.5 ft.	Northing:	~ 530,351 ft.	Drilling Method:	Mud Rotary
Top Elevation:	~	Easting:	~ 1,277,702 ft.	Drilling Company:	Holocene Drilling
Vert. Datum:		Station:	~	Drill Rig Equipment:	B-61 Mobile Truck
Horiz. Datum:	NAD83	Offset:	~	Other Comments:	

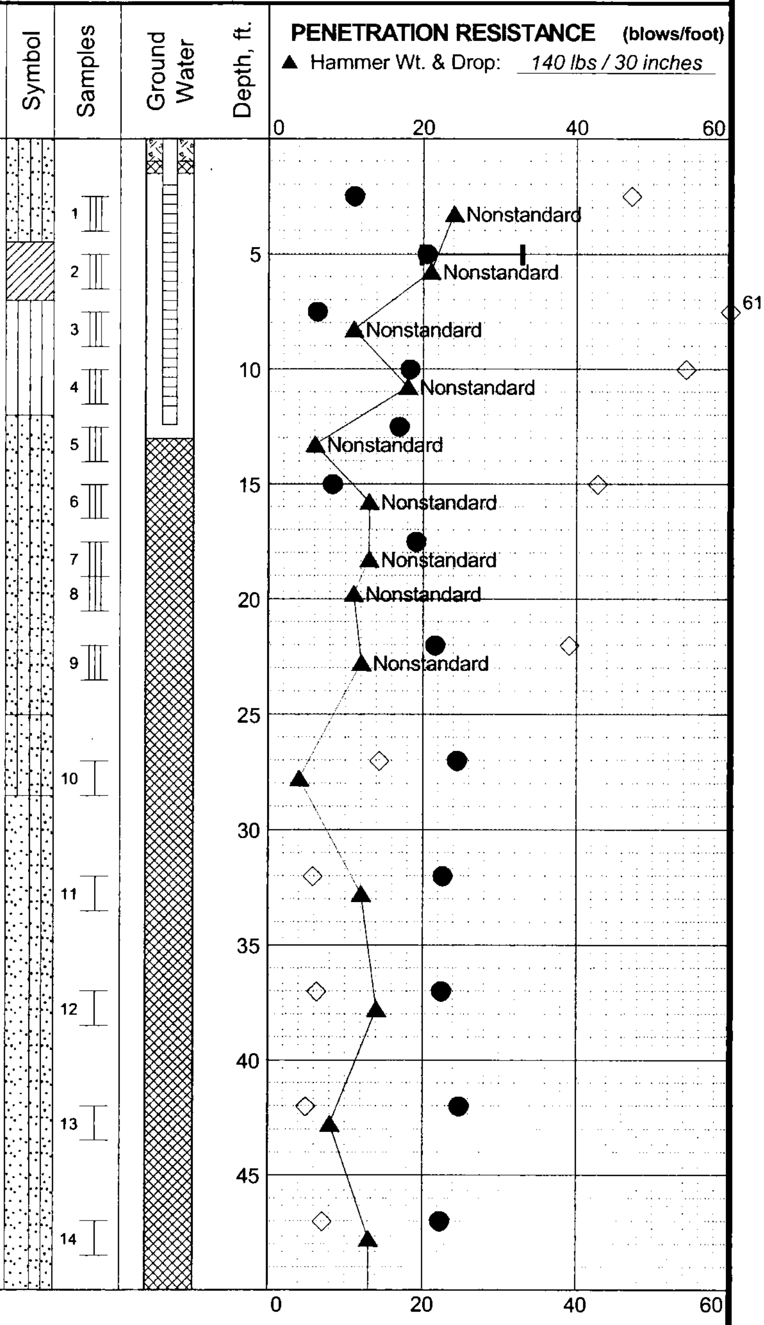
Hole Diam.: 5 in.
Rod Diam.: NWJ
Hammer Type: Automatic

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

SOIL DESCRIPTION	Depth, ft.
Medium dense, brown, slightly clayey, fine gravelly, silty SAND; moist; iron-oxide mottles, trace of fine roots; (Hf) SM.	4.5
Very stiff, brown, silty CLAY, trace of sand and gravel and medium dense, fine sandy SILT; moist; trace of organics; (Hf) CL/ML.	7.0
Medium dense, brown, fine sandy SILT; moist; scattered slightly fine sandy to fine sandy silt layers; (Hf) ML.	12.0
Loose to medium dense, brown and gray, silty, fine SAND, trace of fine gravel; moist; (Ha[ob]) SM.	25.0
Loose, brown, silty, fine to medium SAND; moist; (Ha[cd]) SM.	28.5
Loose to medium dense, gray, trace of silt to slightly silty, fine to medium SAND, trace of fine gravel; wet; (Ha[cd]) SP-SM/SP/SW-SM. - Slightly silty sand layer at 47 feet.	

CONTINUED NEXT SHEET



LEGEND

*	Sample Not Recovered
Ⅲ	3" O.D. Split Spoon Sample
I	Standard Penetration Test
◫	Piezometer Screen and Sand Filter
▧	Bentonite-Cement Grout
▩	Bentonite Chips/Pellets
▨	Bentonite Grout

◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├──●──┤ Liquid Limit
Natural Water Content

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD17-1 Levee

June 2010
21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-9
Sheet 1 of 2

Log: EVP Rev: JKN Typ: CLP

Total Depth: 63.5 ft.
Top Elevation: ~
Vert. Datum:
Horiz. Datum: NAD83

Northing: ~ 530,351 ft.
Easting: ~ 1,277,702 ft.
Station: ~
Offset: ~

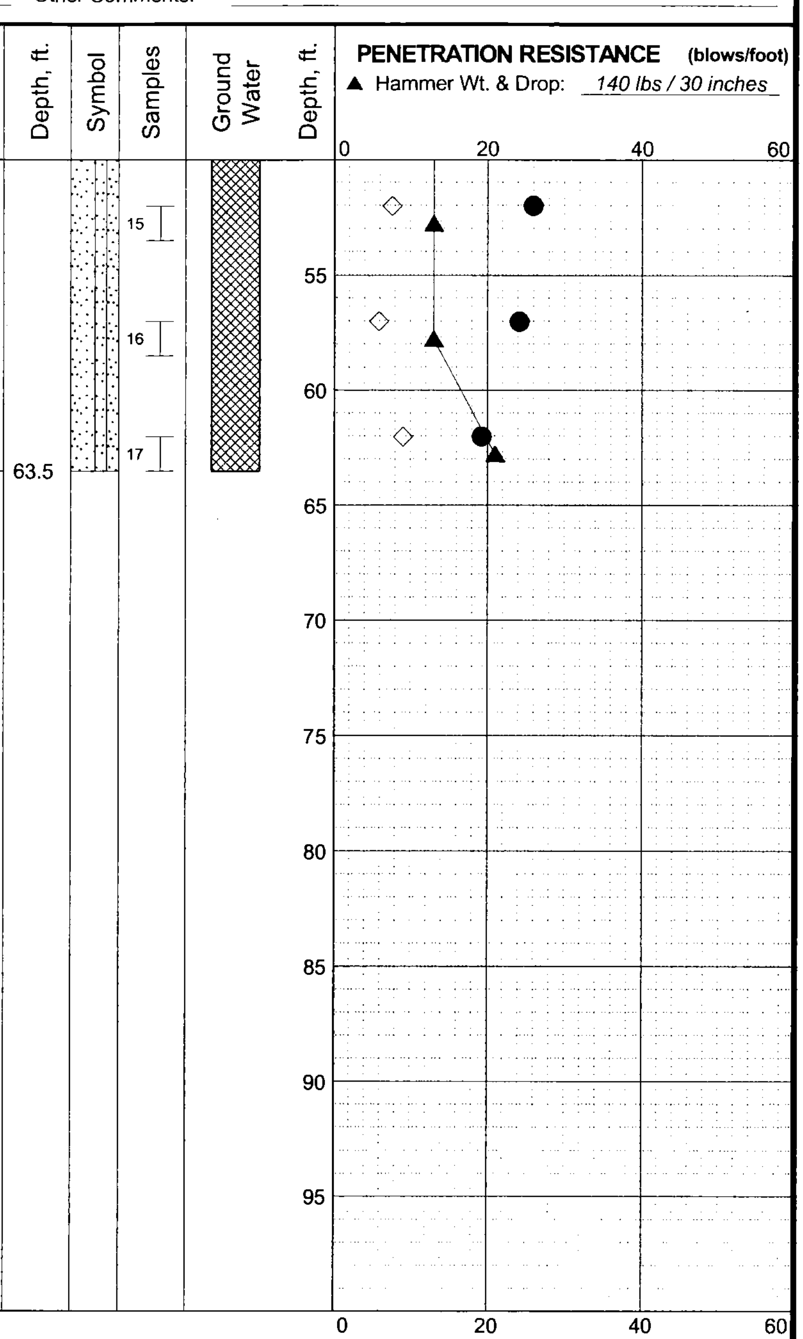
Drilling Method: Mud Rotary
Drilling Company: Holocene Drilling
Drill Rig Equipment: B-61 Mobile Truck
Other Comments:

Hole Diam.: 5 in.
Rod Diam.: NWJ
Hammer Type: Automatic

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

BOTTOM OF BORING
COMPLETED 10/9/2009



LEGEND

* Sample Not Recovered
Ⅲ 3" O.D. Split Spoon Sample
⌶ Standard Penetration Test

⊟ Piezometer Screen and Sand Filter
▧ Bentonite-Cement Grout
▩ Bentonite Chips/Pellets
▨ Bentonite Grout

◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├─●─┤ Liquid Limit
Natural Water Content

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD17-1 Levee

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
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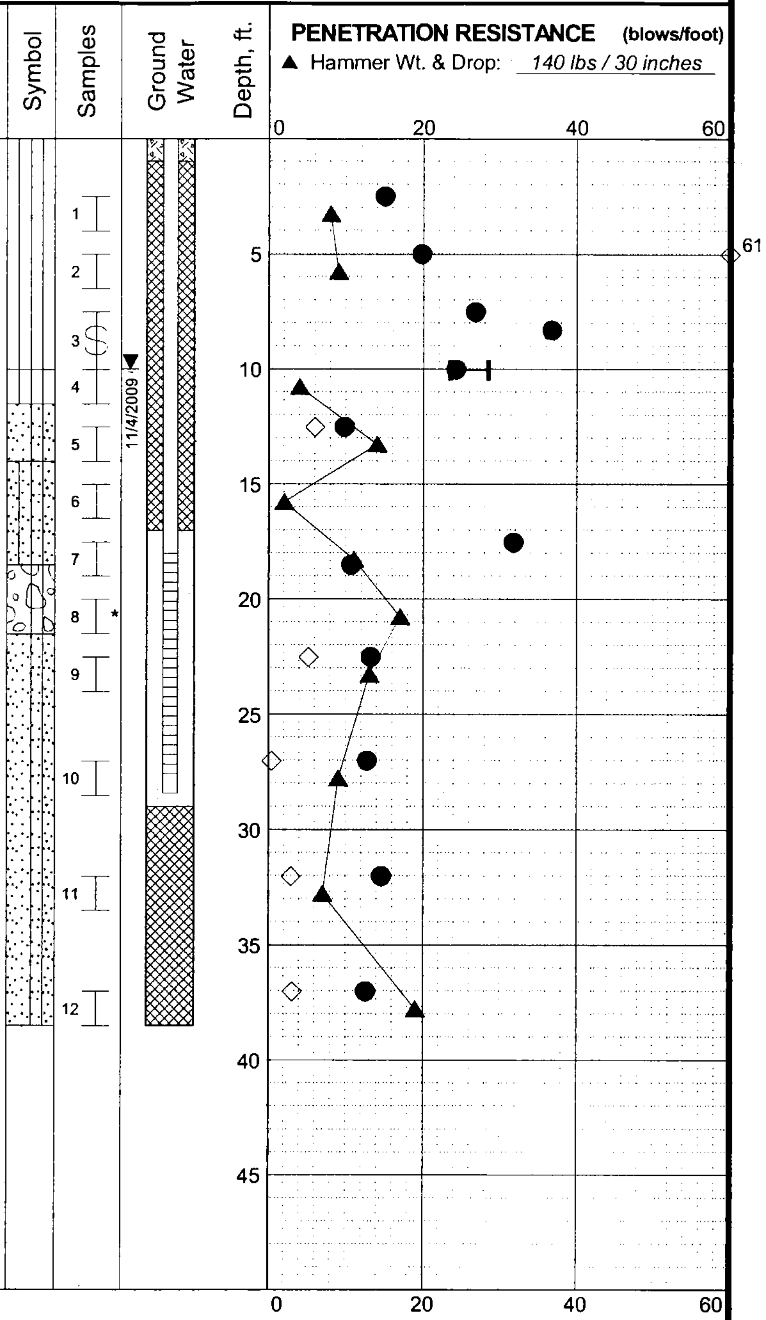
FIG. A-9
Sheet 2 of 2

MASTER LOG E 21-21199.GPJ SHAN WIL.GDT 6/1/10 Log: EVP Rev: JKN Typ: CLP

Total Depth:	38.5 ft.	Northing:	~ 531,266 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,270,707 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	B-61 Mobile Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION *Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.*	Depth, ft.
Loose, mottled brown and gray, fine sandy SILT, trace of clay; moist; scattered iron-oxide staining, slightly fine gravelly sand layer at 9.1 feet; (Ha[ob]) ML.	
Soft, brown, slightly clayey, fine sandy SILT; wet; trace of organics; (Ha[ob]) ML.	10.0
	11.5
Medium dense, brown, slightly silty, fine gravelly SAND; moist; scattered silt pockets; (Ha[cd]) SP-SM.	14.0
Very loose to medium dense, brown and gray, silty, fine SAND to slightly fine sandy SILT, trace of clay; wet; (Ha[ob]) SM/ML.	18.5
Medium dense, gray-brown, slightly silty, sandy GRAVEL; wet; scattered silty, fine sand seams; (Ha[g]) GP-GM.	21.5
Loose to medium dense, gray, trace of silt to slightly silty, fine gravelly SAND and sandy GRAVEL, trace of silt; wet; (Ha[g]) SP-SM/GW/SP.	
BOTTOM OF BORING COMPLETED 10/9/2009	38.5



Log: EVP Rev: JKN Typ: CLP

LEGEND

- * Sample Not Recovered
- I Standard Penetration Test
- $ 3" O.D. Thin-Walled Tube

- ▭ Piezometer Screen and Sand Filter
- ▧ Bentonite-Cement Grout
- ▩ Bentonite Chips/Pellets
- ▨ Bentonite Grout
- ▼ Ground Water Level in Well

- ◇ % Fines (<0.075mm)
- ● % Water Content

Plastic Limit ├──●──┤ Liquid Limit
Natural Water Content

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD17-2 Landward

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-10

NOTES

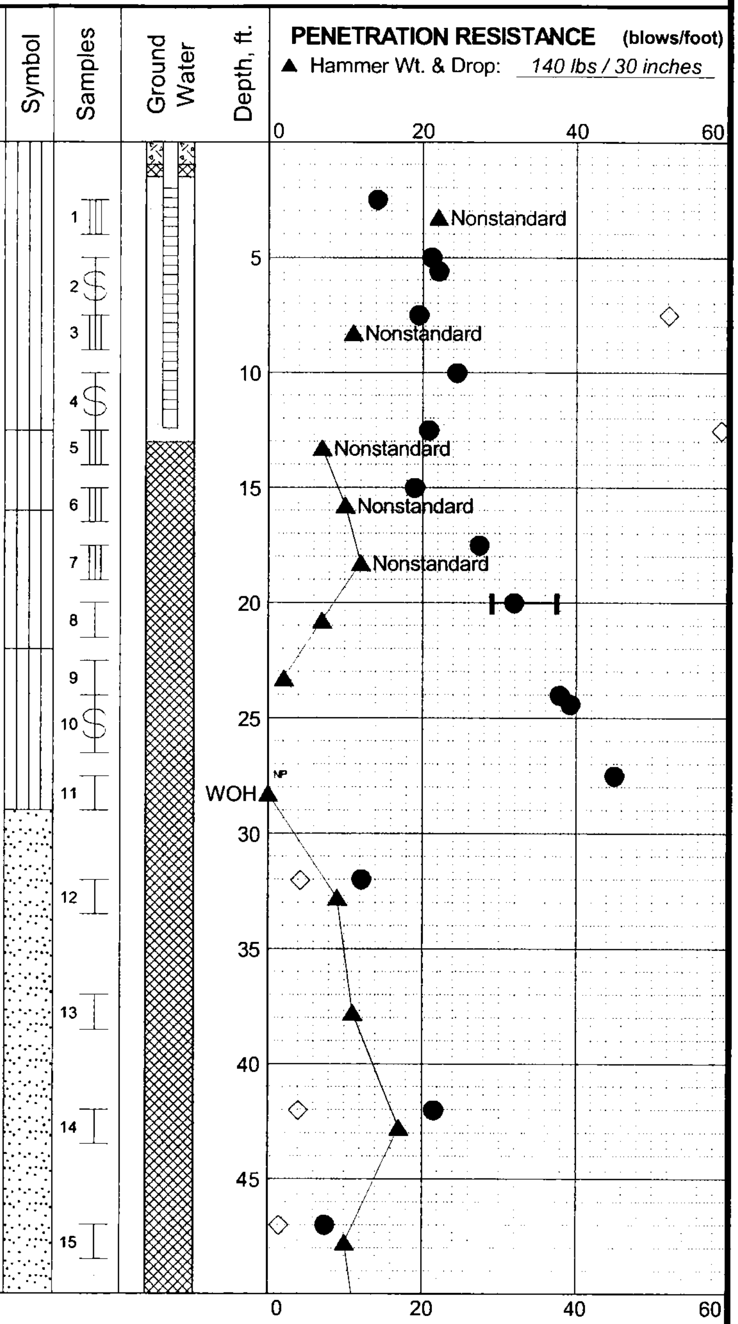
1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

MASTER LOG E 21-21199.GPJ SHAN WIL.GDT 6/1/10

Total Depth:	63.5 ft.	Northing:	~ 531,153 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,270,679 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	JWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	B-61 Mobile Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.	Depth, ft.
Medium dense, brown and gray, fine sandy SILT to silty, fine SAND; moist; slightly gravelly above 7.5 feet, locally trace of clay, trace of organics, trace of slightly clayey silt pockets; (Hf) ML/SM.	
Loose, brown, fine sandy SILT; moist; trace of iron-oxide staining; (Ha[ob]) ML.	12.5
Medium stiff to stiff, brown, trace to slightly clayey, trace to slightly fine sandy SILT; moist; faintly laminated, trace of roots, scattered iron-oxide stains, silty fine sand seams above 20 feet; (Ha[ob]) ML.	16.0
Very soft, gray, trace to slightly fine sandy SILT, trace of clay; wet; scattered silty fine sand seams and layers; (Ha[ob]) ML.	22.0
Loose to medium dense, gray, gravelly SAND, trace of silt to sandy GRAVEL, trace of silt; wet; locally trace of wood fragments; (Ha[g]) SP/GW.	29.0

CONTINUED NEXT SHEET



LEGEND

- * Sample Not Recovered
- 3" O.D. Split Spoon Sample
- 3" O.D. Thin-Walled Tube
- Standard Penetration Test
- Piezometer Screen and Sand Filter
- Bentonite-Cement Grout
- Bentonite Chips/Pellets
- Bentonite Grout

◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├──●──┤ Liquid Limit
Natural Water Content

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD17-2 Levee

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-11
Sheet 1 of 2

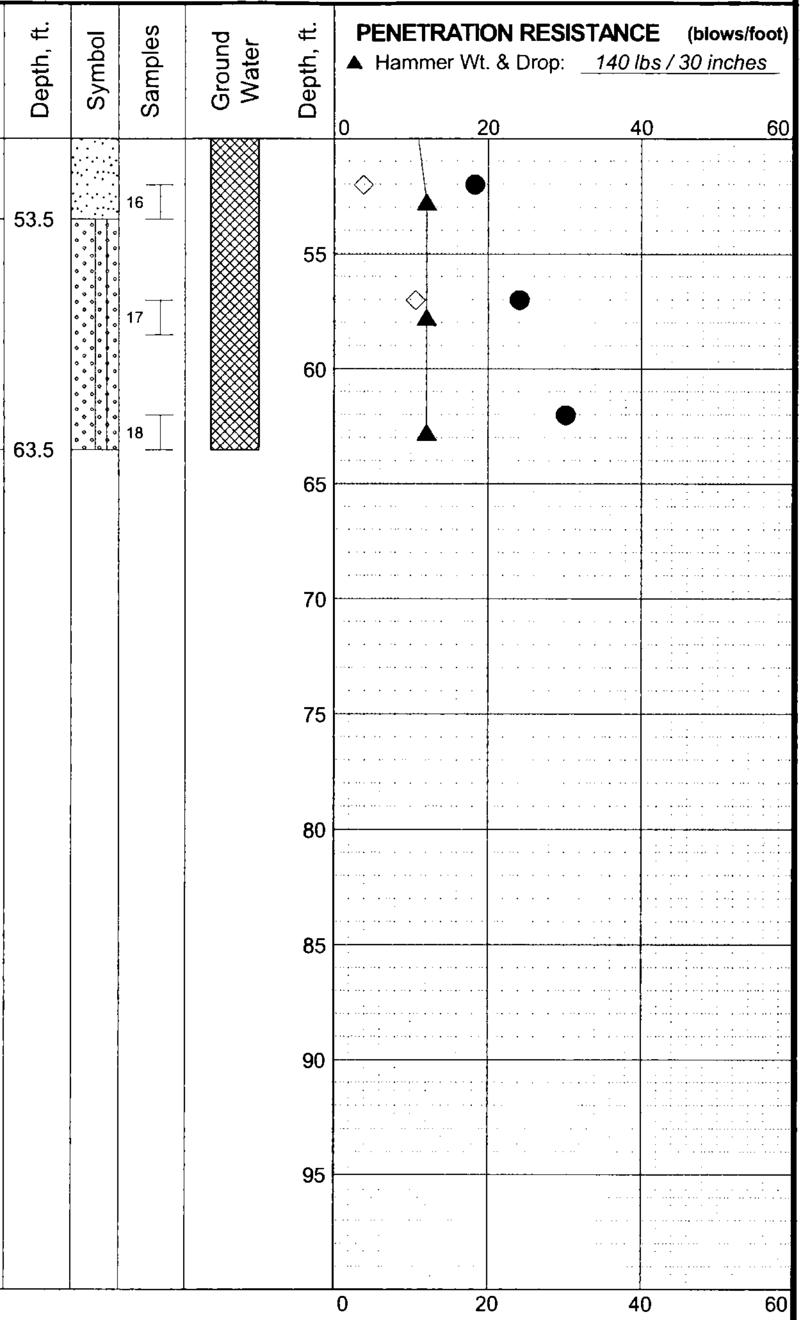
Total Depth:	63.5 ft.	Northing:	~ 531,153 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,270,679 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	JWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	B-61 Mobile Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

Medium dense, gray, slightly silty SAND, trace of fine gravel; wet; (Ha[cd]) SW-SM.

BOTTOM OF BORING
COMPLETED 10/13/2009



◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├──●──┤ Liquid Limit
Natural Water Content

LEGEND

- * Sample Not Recovered
- Ⅱ 3" O.D. Split Spoon Sample
- Ⅱ 3" O.D. Thin-Walled Tube
- Ⅰ Standard Penetration Test
- ⊟ Piezometer Screen and Sand Filter
- ▧ Bentonite-Cement Grout
- ▩ Bentonite Chips/Pellets
- ▨ Bentonite Grout

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD17-2 Levee

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-11
Sheet 2 of 2

MASTER LOG E 21-21199.GPJ SHAN WIL.GDT 6/1/10 Log: EVP Rev: JKN Typ: CLP

Total Depth:	51.5 ft.	Northing:	~ 525,350 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,272,695 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	B-61 Mobile Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

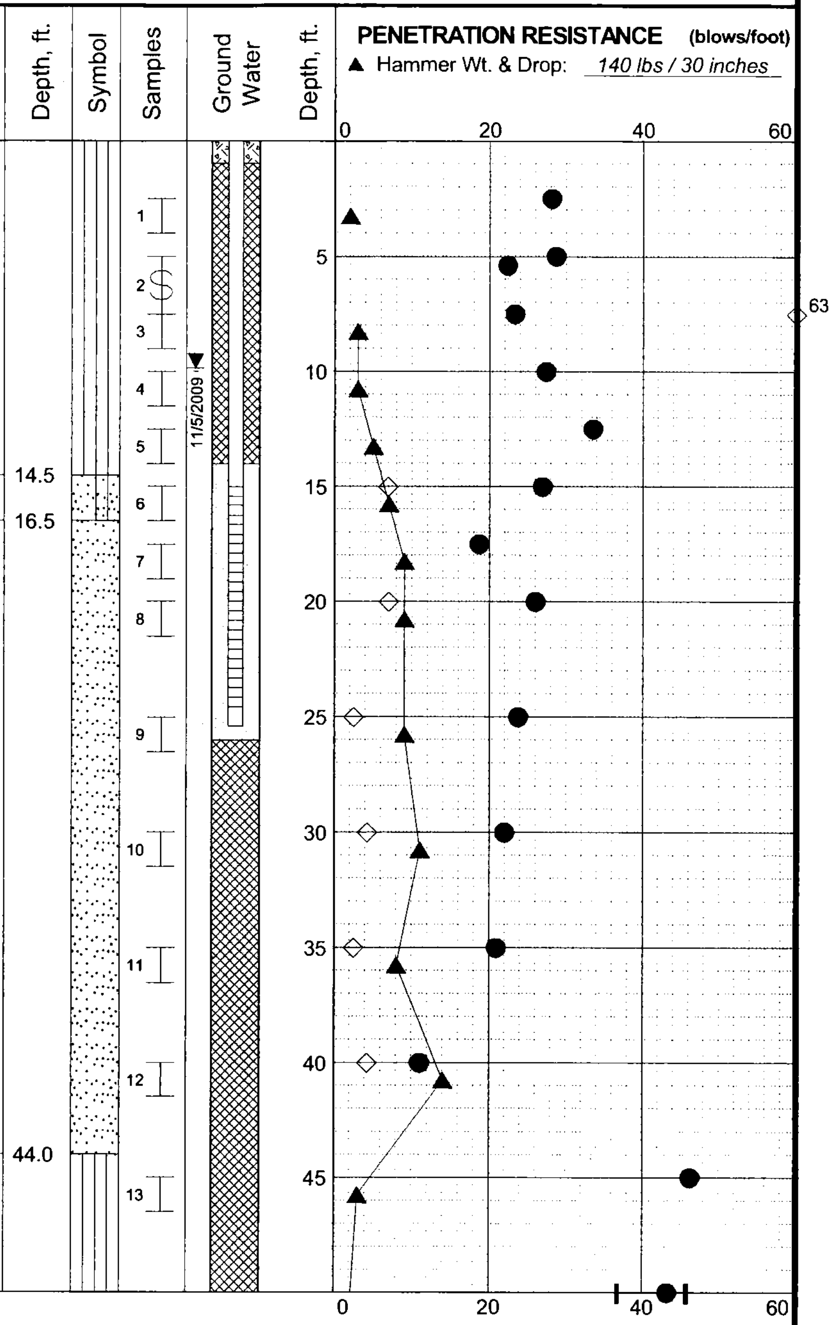
Interbedded, very loose to loose, brown and gray, fine sandy SILT to slightly silty and silty, fine SAND; moist; iron-oxide-stained seams, laminated, slightly clayey silt layers above 5 feet; (Ha[ob]) ML/SM/SP-SM.

Loose, orange-brown, slightly silty, fine to medium SAND, trace of fine gravel; wet; iron-oxide-stained; (Ha[cd]) SP-SM.

Loose to medium dense, gray, trace of silt to slightly silty, trace of gravel to gravelly SAND; wet; (Ha[cd]) SP/SW-SM.

Soft, gray, slightly clayey to clayey SILT; wet; scattered wood fragments and scattered to numerous organics; (Ha[ob]) ML.

CONTINUED NEXT SHEET



LEGEND

- * Sample Not Recovered
- Ⅰ Standard Penetration Test
- $ 3" O.D. Thin-Walled Tube
- ▭ Piezometer Screen and Sand Filter
- ▧ Bentonite-Cement Grout
- ▩ Bentonite Chips/Pellets
- ▨ Bentonite Grout
- ▼ Ground Water Level in Well

◇ % Fines (<0.075mm)

● % Water Content

Plastic Limit ├─●─┤ Liquid Limit

Natural Water Content

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD17-3 Landward

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

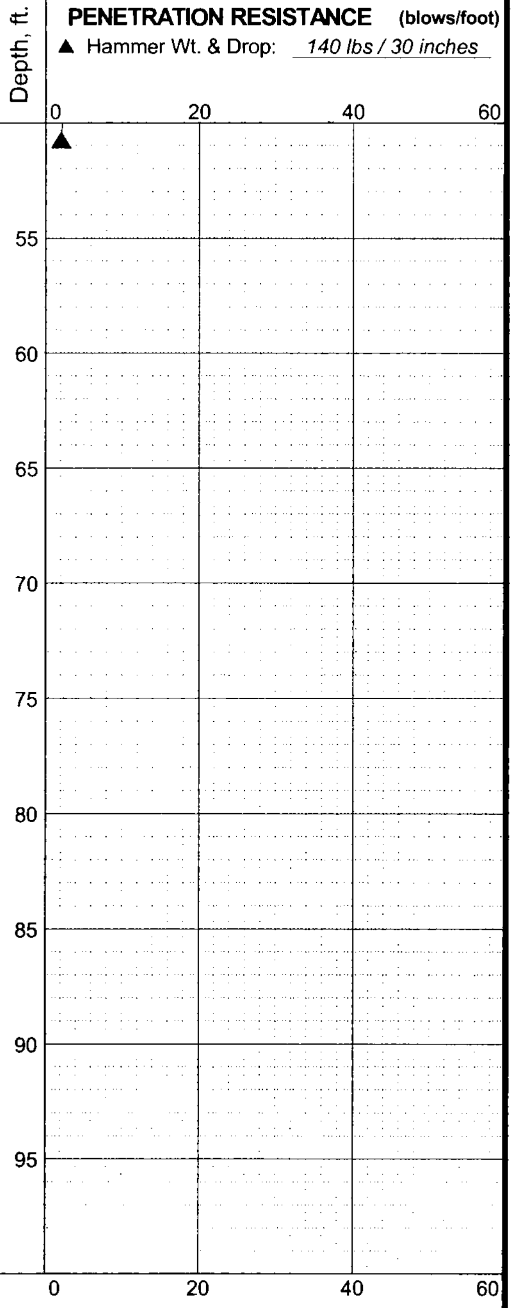
FIG. A-12
Sheet 1 of 2

Log: EVP Rev: JKN Typ: CLP

MASTER_LOG_E 21-21199.GPJ SHAN_WIL.GDT 6/1/10

Total Depth:	51.5 ft.	Northing:	~ 525,350 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,272,695 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	B-61 Mobile Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION *Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.*	Depth, ft.	Symbol	Samples	Ground Water
			14	⊠
BOTTOM OF BORING COMPLETED 10/15/2009	51.5			



◇ % Fines (<0.075mm)

● % Water Content

Plastic Limit ├──●──┤ Liquid Limit

Natural Water Content

LEGEND

- * Sample Not Recovered
- I Standard Penetration Test
- S 3" O.D. Thin-Walled Tube
- ▯ Piezometer Screen and Sand Filter
- ▨ Bentonite-Cement Grout
- ⊠ Bentonite Chips/Pellets
- ▧ Bentonite Grout
- ▼ Ground Water Level in Well

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD17-3 Landward

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-12
Sheet 2 of 2

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

MASTER LOG E 21-21199.GPJ SHAN WIL.GDT 6/1/10 Log: EVP Rev: JKN Typ: CLP

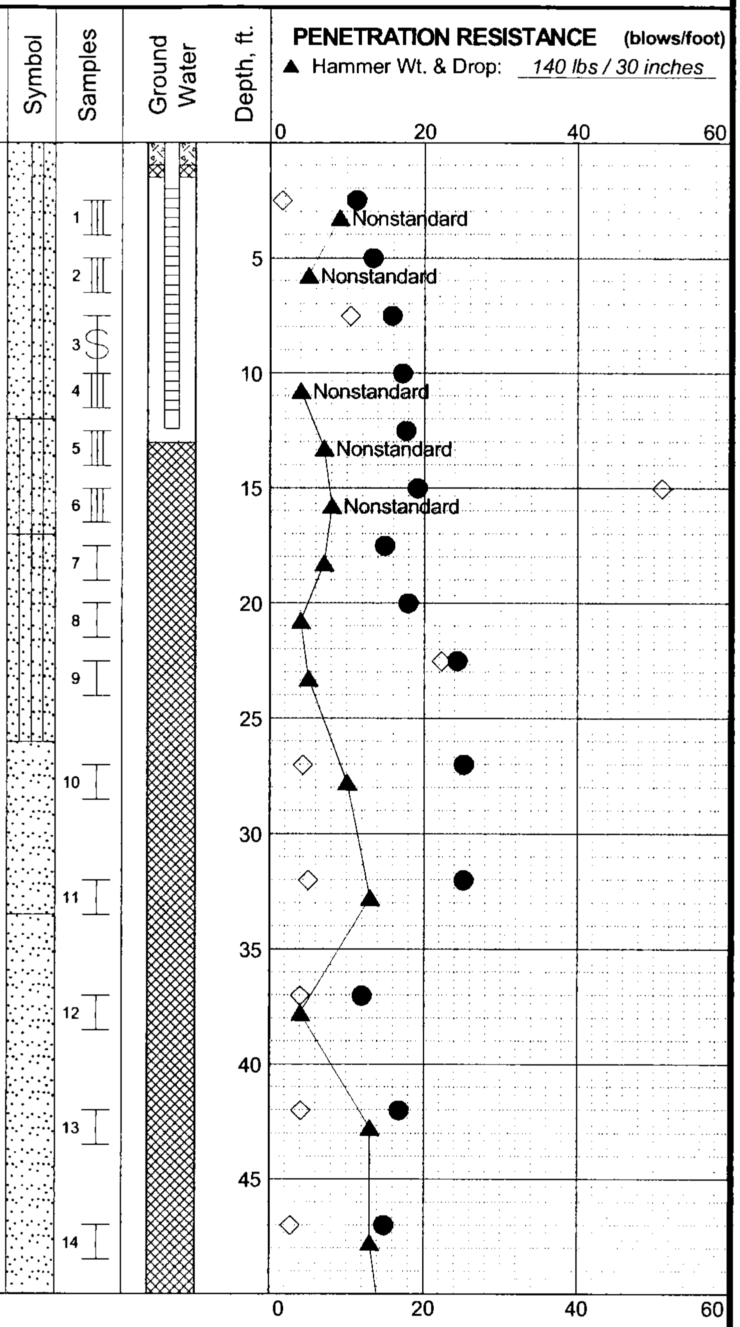
Total Depth:	66 ft.	Northing:	~ 525,290 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,272,702 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	B-61 Mobile Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

SOIL DESCRIPTION	Depth, ft.
Loose, brown, trace to slightly silty, fine SAND; moist; locally trace of gravel, trace of organics, scattered silty clay clasts above 5 feet, scattered fine sandy silt layers below 10 feet; (Hf) SP-SM/SP.	
Loose, gray-brown, silty, fine SAND to fine sandy SILT; moist; laminated, faint iron-oxide-stained seams, scattered fine sandy silt layers below 15 feet; (Ha[ob]) SM/ML.	12.0
Loose, gray, silty, fine SAND; moist; (Ha[ob]) SM.	17.0
Medium dense, gray, trace to slightly silty, trace to slightly fine gravelly, fine to medium SAND; wet; (Ha[cd]) SP/SP-SM.	26.0
Loose to medium dense, gravelly SAND, trace of silt and sandy GRAVEL, trace of silt; wet; (Ha[g]) SP/GW/SW.	33.5

CONTINUED NEXT SHEET



◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├──●──┤ Liquid Limit
Natural Water Content

LEGEND

*	Sample Not Recovered	◫	Piezometer Screen and Sand Filter
Ⅲ	3" O.D. Split Spoon Sample	▧	Bentonite-Cement Grout
$	3" O.D. Thin-Walled Tube	⊠	Bentonite Chips/Pellets
⌶	Standard Penetration Test	▨	Bentonite Grout

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD17-3 Levee

June 2010　　21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-13
Sheet 1 of 2

MASTER LOG E 21-21199.GPJ SHAN WIL.GDT 6/1/10　Log: EVP　Rev: JKN　Typ: CLP

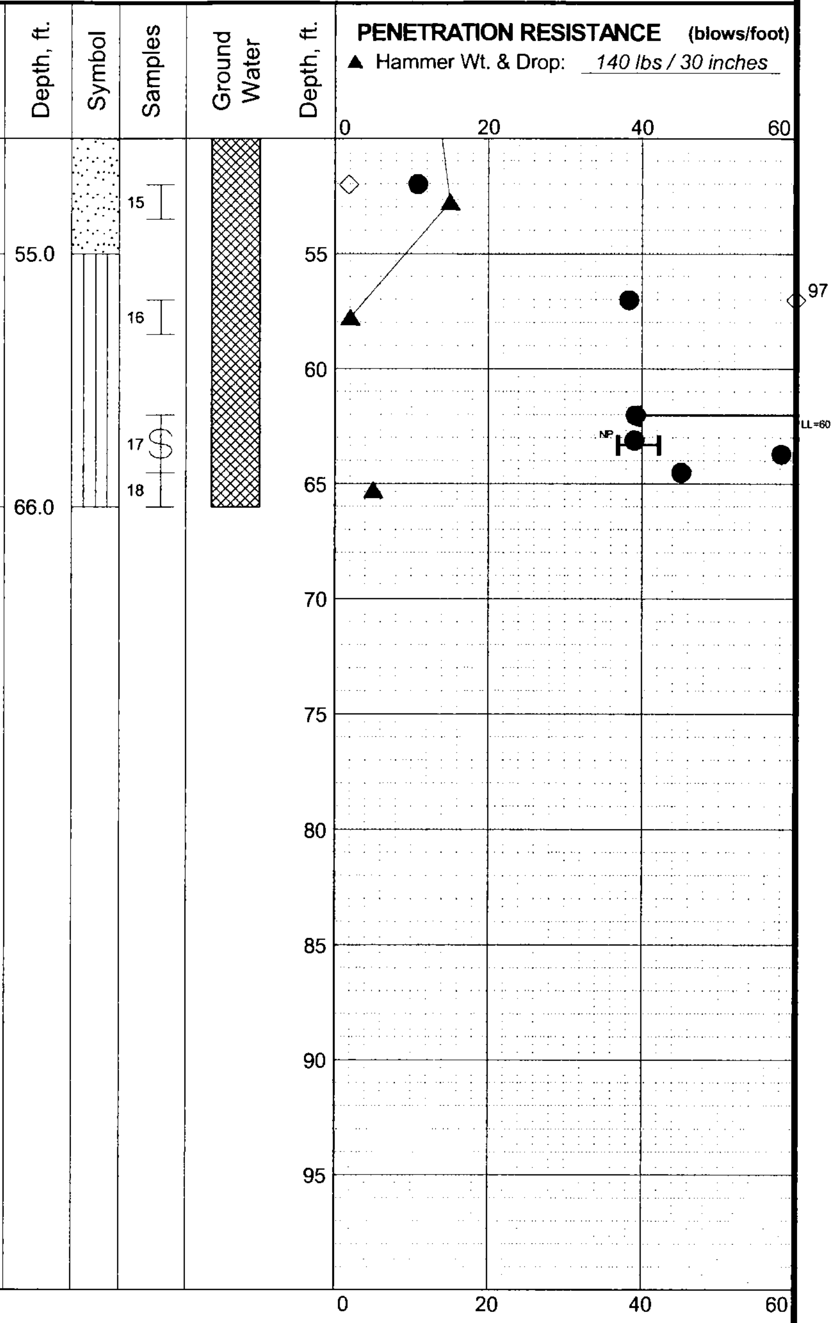
Total Depth: 66 ft.
Top Elevation: ~
Vert. Datum:
Horiz. Datum: NAD83
Northing: ~ 525,290 ft.
Easting: ~ 1,272,702 ft.
Station: ~
Offset: ~
Drilling Method: Mud Rotary
Drilling Company: Holocene Drilling
Drill Rig Equipment: B-61 Mobile Truck
Other Comments:
Hole Diam.: 5 in.
Rod Diam.: NWJ
Hammer Type: Automatic

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

Soft to medium stiff, gray, slightly clayey to clayey SILT, trace of fine sand and SILT; wet; trace to scattered organics; (Ha[ob]) ML.

BOTTOM OF BORING
COMPLETED 10/14/2009



◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├──●──┤ Liquid Limit
Natural Water Content

LEGEND

- * Sample Not Recovered
- Ⅲ 3" O.D. Split Spoon Sample
- $ 3" O.D. Thin-Walled Tube
- Ⅰ Standard Penetration Test
- ⊟ Piezometer Screen and Sand Filter
- ▧ Bentonite-Cement Grout
- ▩ Bentonite Chips/Pellets
- ▨ Bentonite Grout

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD17-3 Levee

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-13
Sheet 2 of 2

MASTER LOG E 21-21199.GPJ SHAN WIL.GDT 6/1/10 Log: EVP Rev: JKN Typ: CLP

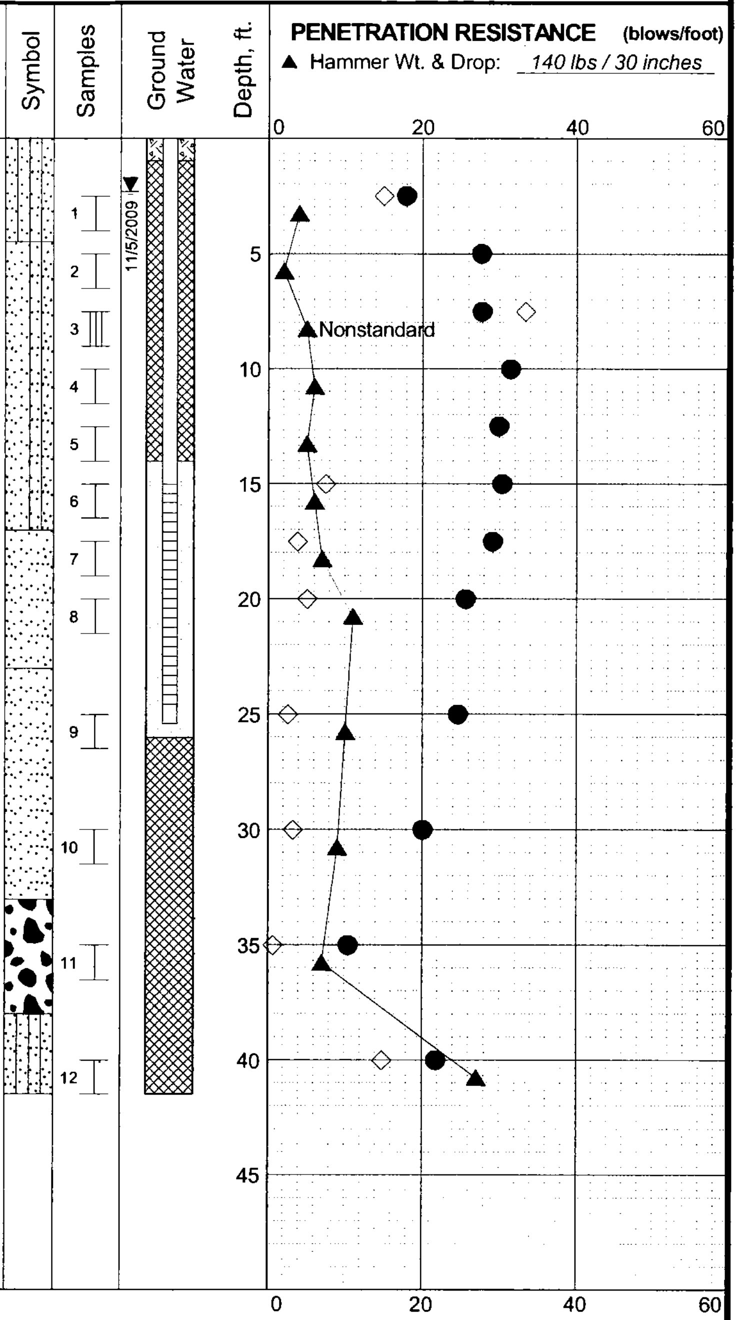
Total Depth:	41.5 ft.	Northing:	~ 504,871 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,268,661 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	BK-81 Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

SOIL DESCRIPTION	Depth, ft.
Loose, gray-brown, silty, fine SAND; moist; scattered roots; (Ha[ob]) SM.	4.5
Very loose to loose, gray, slightly silty to silty, fine to medium SAND; wet; trace of organics, moist above 7 feet; (Ha[cd]) SP-SM/SM.	17.0
Loose to medium dense, gray, trace to slightly silty, fine to medium SAND; wet; (Ha[cd]) SP/SP-SM.	23.0
Loose, gray, trace to slightly gravelly SAND, trace of silt; wet; (Ha[cd]) SP.	33.0
Loose, gray, sandy GRAVEL, trace of silt; wet; (Ha[g]) GW.	38.0
Medium dense, gray, silty, fine to medium SAND; wet; numerous shell fragments; (He) SM.	41.5

BOTTOM OF BORING
COMPLETED 10/21/2009



◇ % Fines (<0.075mm)
● % Water Content

LEGEND

- * Sample Not Recovered
- Ɪ Standard Penetration Test
- Ɪ 3" O.D. Split Spoon Sample
- ▯ Piezometer Screen and Sand Filter
- ▨ Bentonite-Cement Grout
- ▩ Bentonite Chips/Pellets
- ▧ Bentonite Grout
- ▼ Ground Water Level in Well

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD22-1 Landward

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

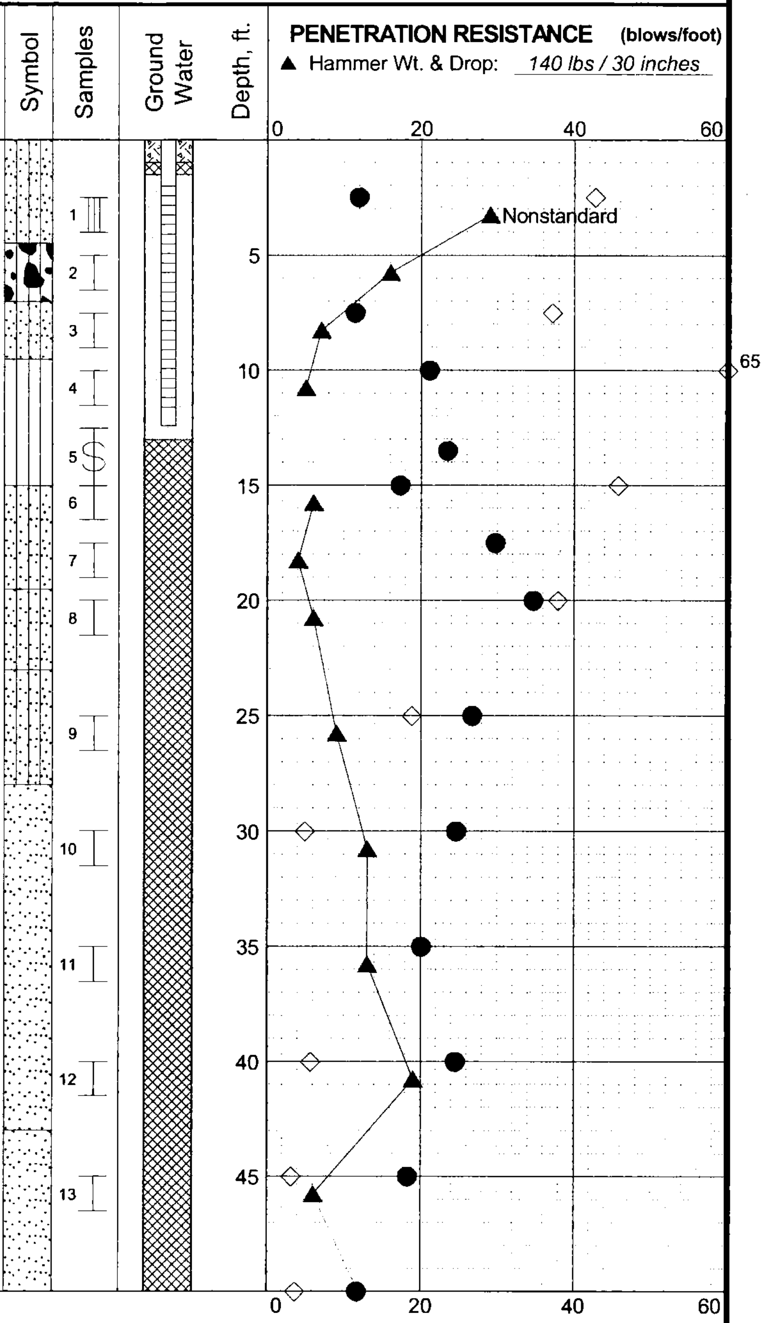
FIG. A-14

MASTER LOG E 21-21199.GPJ SHAN WIL.GDT 6/1/10 Log: EVP Rev: JKN Typ: LKN

Total Depth:	61.5 ft.	Northing:	~ 504,876 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,268,717 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	BK-81 Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION *Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.*	Depth, ft.
Medium dense, brown, slightly clayey, gravelly, silty SAND; moist; (Hf) SM.	4.5
Medium dense, gray-brown, silty, sandy GRAVEL, trace of clay; moist; scattered slightly clayey pockets; (Hf) GM.	7.0
Loose, gray-brown, silty, fine SAND; wet; (Hf) SM.	9.5
Loose, brown, fine sandy SILT to silty, fine SAND; moist; clayey silt pockets, intermixed, scattered roots above 13 feet; (Hf) ML/SM.	15.0
Loose, gray-brown, silty, fine SAND; moist; laminated, iron-oxide-stained seams, scattered silt layers; (Ha[ob]) SM.	19.5
Loose, gray-brown, silty, fine SAND; wet; strongly iron-oxide-stained layers; (Ha[ob]) SM.	23.0
Loose, gray, silty, fine to medium SAND; wet; (Ha[ob]) SM.	28.0
Medium dense, gray, trace to slightly silty, fine to medium SAND, trace of fine gravel; wet; (Ha[cd]) SP/SP-SM.	43.0
Loose to medium dense, gray, fine gravelly SAND, trace of silt; wet; (Ha[g]) SP/SW.	

CONTINUED NEXT SHEET



◇ % Fines (<0.075mm)
● % Water Content

LEGEND

*	Sample Not Recovered
Ⅲ	3" O.D. Split Spoon Sample
I	Standard Penetration Test
$	3" O.D. Thin-Walled Tube
⊞	Piezometer Screen and Sand Filter
▧	Bentonite-Cement Grout
▩	Bentonite Chips/Pellets
▨	Bentonite Grout

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD22-1 Levee

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-15
Sheet 1 of 2

Total Depth: 61.5 ft.
Top Elevation: ~
Vert. Datum:
Horiz. Datum: NAD83

Northing: ~ 504,876 ft.
Easting: ~ 1,268,717 ft.
Station: ~
Offset: ~

Drilling Method: Mud Rotary
Drilling Company: Holocene Drilling
Drill Rig Equipment: BK-81 Truck
Other Comments:

Hole Diam.: 5 in.
Rod Diam.: NWJ
Hammer Type: Automatic

SOIL DESCRIPTION

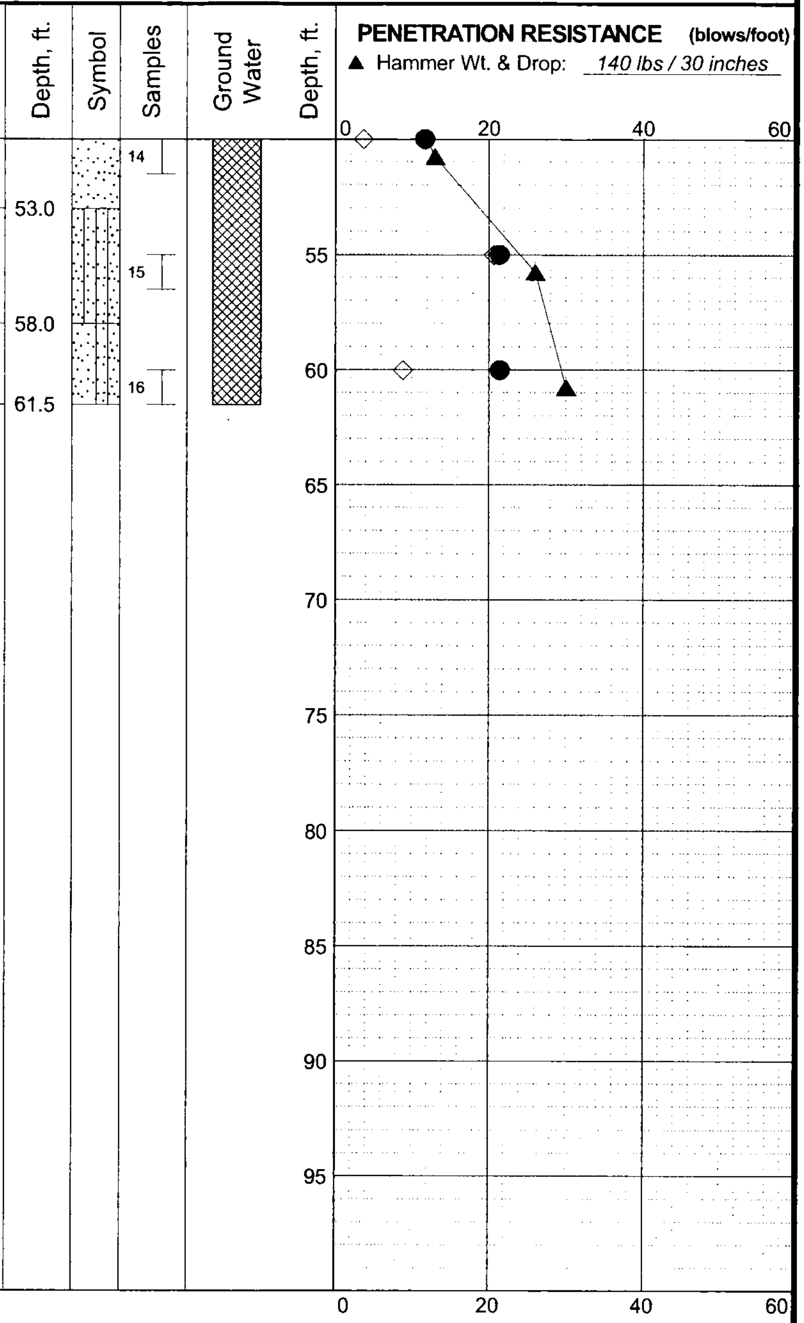
Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

53.0 Medium dense, gray, silty, fine to medium SAND, trace of clay; wet; scattered shell fragments; (He) SM.

58.0 Medium dense, gray, slightly silty, fine to medium SAND; wet; trace of shell fragments; (He) SP-SM.

61.5

BOTTOM OF BORING
COMPLETED 10/22/2009



◇ % Fines (<0.075mm)
● % Water Content

LEGEND

- * Sample Not Recovered
- 𝕀 3" O.D. Split Spoon Sample
- I Standard Penetration Test
- ⌶ 3" O.D. Thin-Walled Tube
- ⊟ Piezometer Screen and Sand Filter
- ▧ Bentonite-Cement Grout
- ▩ Bentonite Chips/Pellets
- ▨ Bentonite Grout

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD22-1 Levee

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-15
Sheet 2 of 2

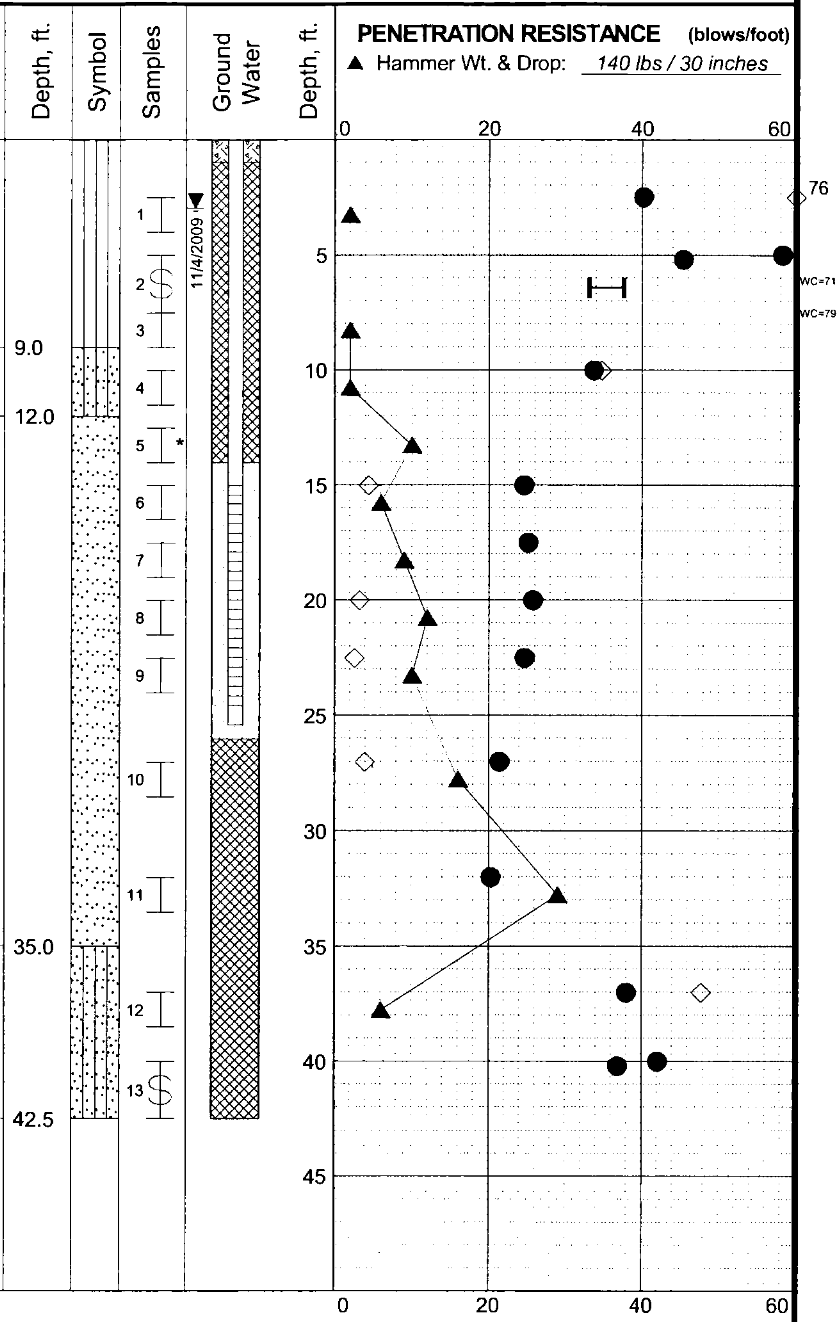
MASTER LOG E 21-21199.GPJ SHAN WIL.GDT 6/1/10 Log: EVP Rev: JKN Typ: LKN

Total Depth:	42.5 ft.	Northing:	~ 502,793 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,259,501 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	BK-81 Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

SOIL DESCRIPTION	Depth, ft.
Very loose, gray and brown, slightly fine sandy to fine sandy SILT, trace of clay to soft, slightly clayey SILT; wet; scattered iron-oxide-stained seams, peat seam at 5.9 feet, numerous wood fragments and coarse organics below 6 feet, laminated; (Ha[ob]) ML.	9.0
Very loose, gray, silty, fine SAND; wet; laminated, scattered organics; (Ha[ob]) SM.	12.0
Loose to medium dense, gray, fine to medium SAND, trace of silt and fine gravel; wet; trace of organics; (Ha[cd]) SP.	35.0
Loose, gray, silty, fine SAND to fine sandy SILT; wet; scattered fine organics, laminated, scattered slightly clayey to clayey seams, slightly silty, fine sand below 41.5 feet; (Ha[ob]) SM/ML.	42.5
BOTTOM OF BORING COMPLETED 10/22/2009	



LEGEND

- * Sample Not Recovered
- I Standard Penetration Test
- $ 3" O.D. Thin-Walled Tube
- ▯ Piezometer Screen and Sand Filter
- ▨ Bentonite-Cement Grout
- ▩ Bentonite Chips/Pellets
- ▧ Bentonite Grout
- ▼ Ground Water Level in Well

◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├─●─┤ Liquid Limit
Natural Water Content

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD22-2 Landward

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

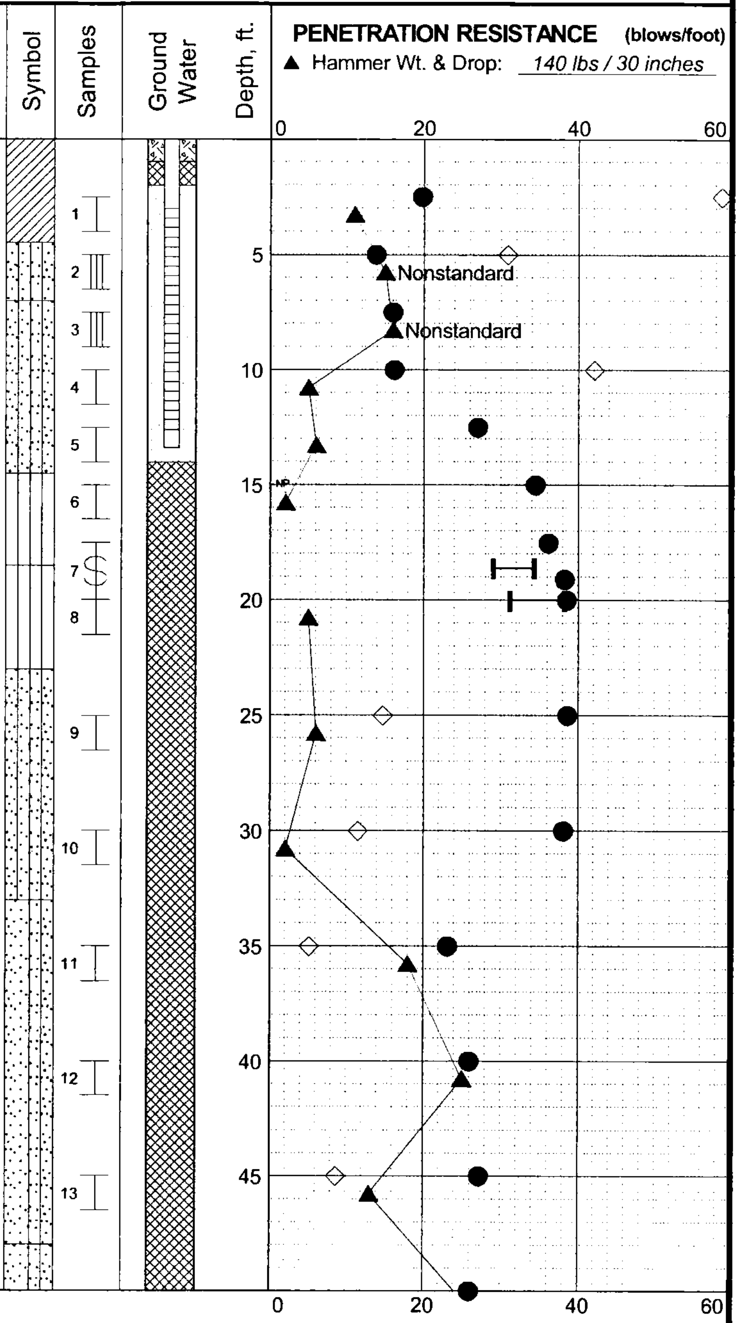
FIG. A-16

MASTER LOG E 21-21199.GPJ SHAN WIL.GDT 6/1/10 Log: EVP Rev: JKN Typ: LKN

Total Depth:	61.5 ft.	Northing:	~ 502,860 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,259,493 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	BK-81 Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

SOIL DESCRIPTION *Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.*	Depth, ft.
Stiff, brown and gray, slightly fine gravelly, sandy, silty CLAY; moist; trace of iron-oxide-stained pockets, scattered clayey sand pockets, trace of roots; (Hf) CL.	4.5
Medium dense, brown, fine gravelly, silty SAND; moist; intermixed, locally trace of clay, trace of iron-oxide stains; (Hf) SM.	7.0
Loose to medium dense, brown, silty, fine SAND; moist; fine sandy silt layers below 12 feet, locally trace of gravel; (Hf) SM.	14.5
Soft, brown, slightly fine sandy SILT; wet; trace of organics, scattered silty, fine sand seams and layers, trace of iron-oxide staining; (Ha[ob]) ML.	18.5
Medium stiff, gray, clayey SILT, trace of fine sand; wet; trace of organics, laminated, iron-oxide-stained seams, scattered dark brown, organic-rich partings, scattered slightly fine sandy silt seams; (Ha[ob]) ML.	23.0
Very loose to loose, gray, slightly silty to silty, fine to medium SAND; wet; numerous organics, scattered wood fragments; (Ha[cd]) SM/SP-SM.	33.0
Medium dense, gray, slightly silty SAND, trace of fine gravel; wet; (Ha[cd]) SP-SM. - Scattered large wood fragments and silty clay seams at 45 feet.	48.0

CONTINUED NEXT SHEET



LEGEND

- * Sample Not Recovered
- Ɪ Standard Penetration Test
- Ⅲ 3" O.D. Split Spoon Sample
- $ 3" O.D. Thin-Walled Tube
- ◫ Piezometer Screen and Sand Filter
- ▧ Bentonite-Cement Grout
- ⊠ Bentonite Chips/Pellets
- ▨ Bentonite Grout

◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├─●─┤ Liquid Limit
Natural Water Content

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD22-2 Levee

June 2010 21-1-21199-002

SHANNON & WILSON, INC.
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FIG. A-17
Sheet 1 of 2

Total Depth:	61.5 ft.	Northing:	~ 502,860 ft.	Drilling Method:	Mud Rotary	Hole Diam.:	5 in.
Top Elevation:	~	Easting:	~ 1,259,493 ft.	Drilling Company:	Holocene Drilling	Rod Diam.:	NWJ
Vert. Datum:		Station:	~	Drill Rig Equipment:	BK-81 Truck	Hammer Type:	Automatic
Horiz. Datum:	NAD83	Offset:	~	Other Comments:			

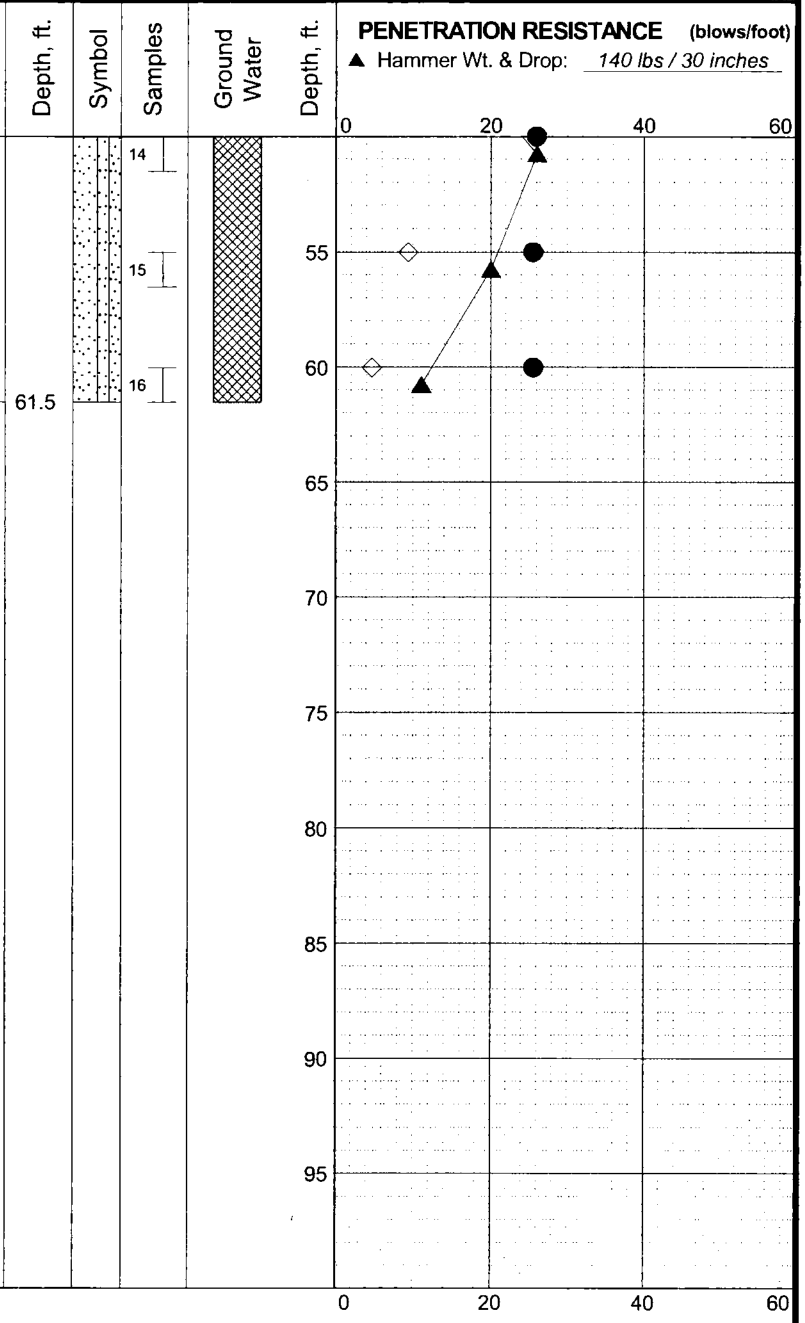
SOIL DESCRIPTION

Refer to the report text for a proper understanding of the subsurface materials and drilling methods. The stratification lines indicated below represent the approximate boundaries between material types, and the transition may be gradual.

Medium dense, gray, trace to slightly silty, fine to medium SAND; wet; (Ha[cd]) SP-SM/SP.

- Trace of wood fragments at 60 feet.

BOTTOM OF BORING
COMPLETED 10/23/2009



LEGEND

* Sample Not Recovered	Piezometer Screen and Sand Filter
Standard Penetration Test	Bentonite-Cement Grout
3" O.D. Split Spoon Sample	Bentonite Chips/Pellets
3" O.D. Thin-Walled Tube	Bentonite Grout

◇ % Fines (<0.075mm)
● % Water Content
Plastic Limit ├─●─┤ Liquid Limit
Natural Water Content

NOTES

1. Refer to KEY for explanation of symbols, codes, abbreviations and definitions.
2. The stratification lines represent the approximate boundaries between soil types, and the transition may be gradual.
3. The discussion in the text of this report is necessary for a proper understanding of the nature of the subsurface materials.
4. Groundwater level, if indicated above, is for the date specified and may vary.
5. USCS designation is based on visual-manual classification and selected lab testing.

Skagit River Levee General Investigation
Skagit County, Washington

LOG OF BORING DD22-2 Levee

June 2010 21-1-21199-002

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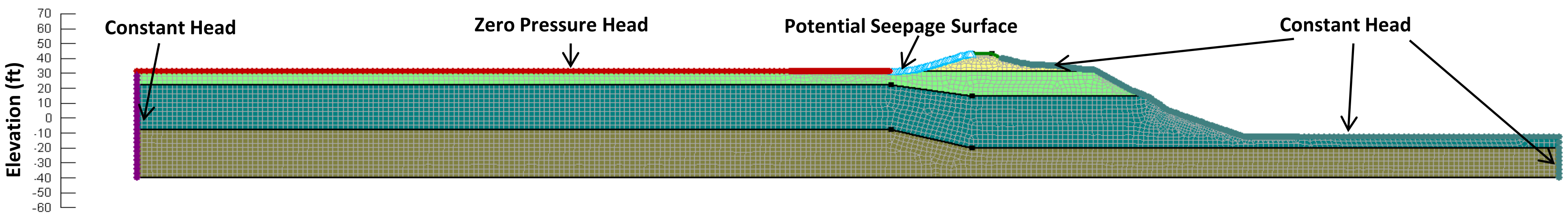
FIG. A-17
Sheet 2 of 2

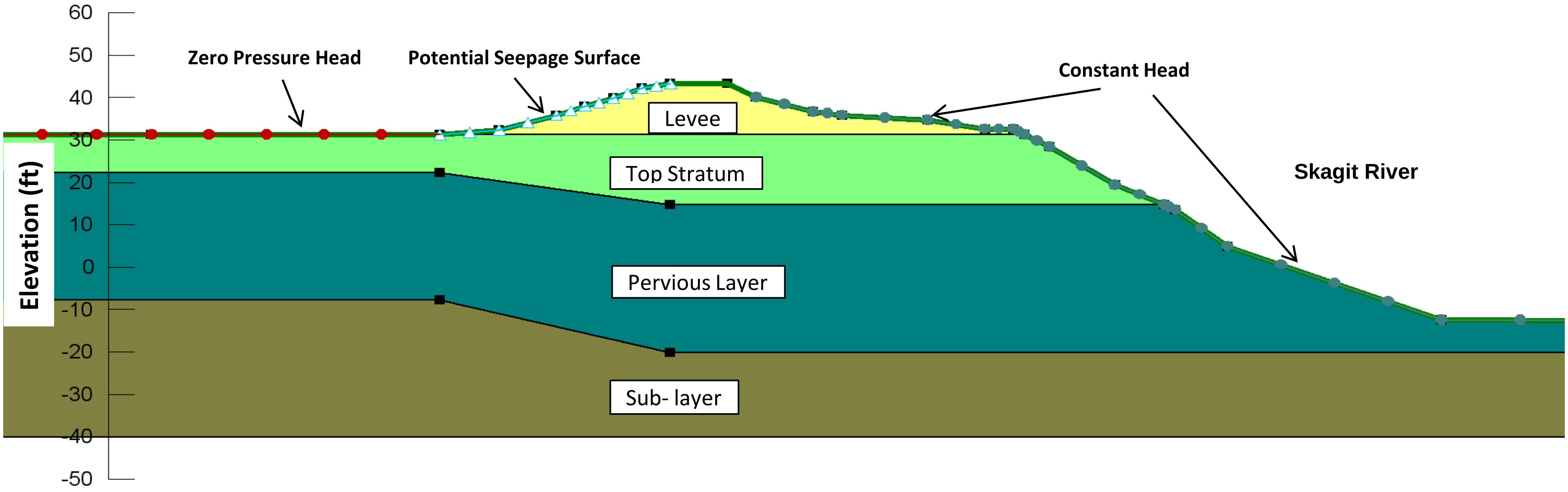
APPENDIX B

SAMPLE SEEP/W AND SLOPE/W ANALYSES

Complete Model



Detail



Notes:

1. Horizontal equals vertical.

Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DD17-1 CROSS SECTION
SEEPAGE ANALYSIS
BOUNDARY CONDITIONS

January 2011 21-1-21199-003

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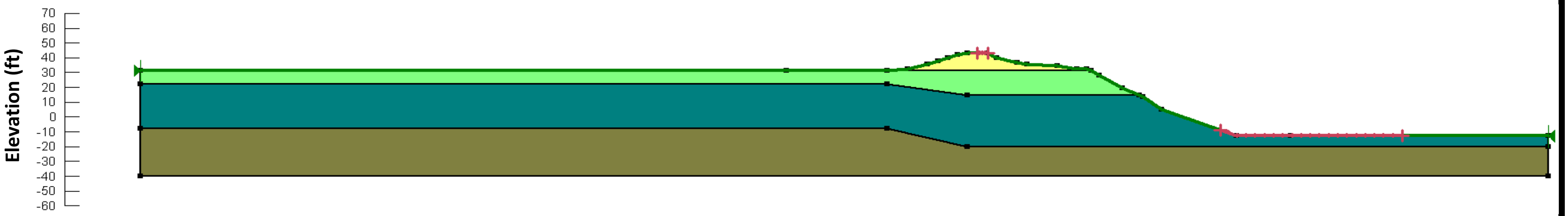
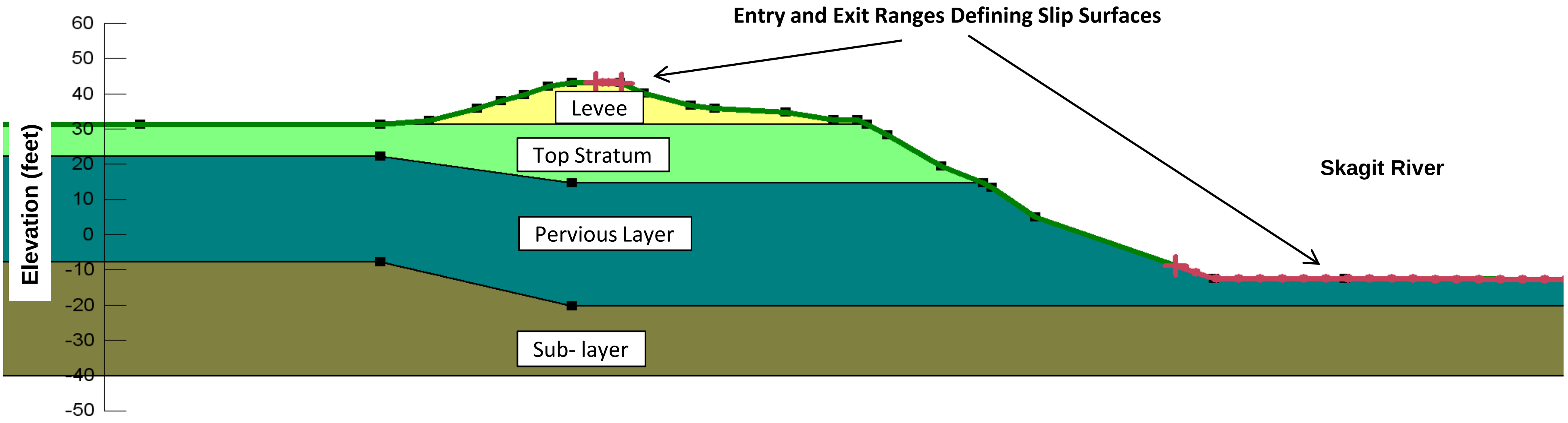
FIG. B-1

FIG. B-1

Complete Model



Detail



Notes:

1. Horizontal equals vertical.

Skagit River Levee General Investigation
Levee Risk and Reliability Analysis
Skagit County, Washington

DD17-1 CROSS SECTION
LIMIT EQUILIBRIUM ANALYSIS
GEOMETRY AND SEARCH CRITERIA

January 2011 21-1-21199-003

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FIG. B-2

FIG. B-2

APPENDIX C

IMPORTANT INFORMATION ABOUT YOUR GEOTECHNICAL/ENVIRONMENTAL REPORT

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

Attachment to and part of Report 21-1-21199-003

Date: January 31, 2011
To: Mr. Daniel E. Johnson
U.S. Army Corps of Engineers,
Seattle District

IMPORTANT INFORMATION ABOUT YOUR GEOTECHNICAL/ENVIRONMENTAL REPORT

CONSULTING SERVICES ARE PERFORMED FOR SPECIFIC PURPOSES AND FOR SPECIFIC CLIENTS.

Consultants prepare reports to meet the specific needs of specific individuals. A report prepared for a civil engineer may not be adequate for a construction contractor or even another civil engineer. Unless indicated otherwise, your consultant prepared your report expressly for you and expressly for the purposes you indicated. No one other than you should apply this report for its intended purpose without first conferring with the consultant. No party should apply this report for any purpose other than that originally contemplated without first conferring with the consultant.

THE CONSULTANT'S REPORT IS BASED ON PROJECT-SPECIFIC FACTORS.

A geotechnical/environmental report is based on a subsurface exploration plan designed to consider a unique set of project-specific factors. Depending on the project, these may include: the general nature of the structure and property involved; its size and configuration; its historical use and practice; the location of the structure on the site and its orientation; other improvements such as access roads, parking lots, and underground utilities; and the additional risk created by scope-of-service limitations imposed by the client. To help avoid costly problems, ask the consultant to evaluate how any factors that change subsequent to the date of the report may affect the recommendations. Unless your consultant indicates otherwise, your report should not be used: (1) when the nature of the proposed project is changed (for example, if an office building will be erected instead of a parking garage, or if a refrigerated warehouse will be built instead of an unrefrigerated one, or chemicals are discovered on or near the site); (2) when the size, elevation, or configuration of the proposed project is altered; (3) when the location or orientation of the proposed project is modified; (4) when there is a change of ownership; or (5) for application to an adjacent site. Consultants cannot accept responsibility for problems that may occur if they are not consulted after factors which were considered in the development of the report have changed.

SUBSURFACE CONDITIONS CAN CHANGE.

Subsurface conditions may be affected as a result of natural processes or human activity. Because a geotechnical/environmental report is based on conditions that existed at the time of subsurface exploration, construction decisions should not be based on a report whose adequacy may have been affected by time. Ask the consultant to advise if additional tests are desirable before construction starts; for example, groundwater conditions commonly vary seasonally.

Construction operations at or adjacent to the site and natural events such as floods, earthquakes, or groundwater fluctuations may also affect subsurface conditions and, thus, the continuing adequacy of a geotechnical/environmental report. The consultant should be kept apprised of any such events, and should be consulted to determine if additional tests are necessary.

MOST RECOMMENDATIONS ARE PROFESSIONAL JUDGMENTS.

Site exploration and testing identifies actual surface and subsurface conditions only at those points where samples are taken. The data were extrapolated by your consultant, who then applied judgment to render an opinion about overall subsurface conditions. The actual interface between materials may be far more gradual or abrupt than your report indicates. Actual conditions in areas not sampled may differ from those predicted in your report. While nothing can be done to prevent such situations, you and your consultant can work together to help reduce their impacts. Retaining your consultant to observe subsurface construction operations can be particularly beneficial in this respect.

A REPORT'S CONCLUSIONS ARE PRELIMINARY.

The conclusions contained in your consultant's report are preliminary because they must be based on the assumption that conditions revealed through selective exploratory sampling are indicative of actual conditions throughout a site. Actual subsurface conditions can be discerned only during earthwork; therefore, you should retain your consultant to observe actual conditions and to provide conclusions. Only the consultant who prepared the report is fully familiar with the background information needed to determine whether or not the report's recommendations based on those conclusions are valid and whether or not the contractor is abiding by applicable recommendations. The consultant who developed your report cannot assume responsibility or liability for the adequacy of the report's recommendations if another party is retained to observe construction.

THE CONSULTANT'S REPORT IS SUBJECT TO MISINTERPRETATION.

Costly problems can occur when other design professionals develop their plans based on misinterpretation of a geotechnical/environmental report. To help avoid these problems, the consultant should be retained to work with other project design professionals to explain relevant geotechnical, geological, hydrogeological, and environmental findings, and to review the adequacy of their plans and specifications relative to these issues.

BORING LOGS AND/OR MONITORING WELL DATA SHOULD NOT BE SEPARATED FROM THE REPORT.

Final boring logs developed by the consultant are based upon interpretation of field logs (assembled by site personnel), field test results, and laboratory and/or office evaluation of field samples and data. Only final boring logs and data are customarily included in geotechnical/environmental reports. These final logs should not, under any circumstances, be redrawn for inclusion in architectural or other design drawings, because drafters may commit errors or omissions in the transfer process.

To reduce the likelihood of boring log or monitoring well misinterpretation, contractors should be given ready access to the complete geotechnical engineering/environmental report prepared or authorized for their use. If access is provided only to the report prepared for you, you should advise contractors of the report's limitations, assuming that a contractor was not one of the specific persons for whom the report was prepared, and that developing construction cost estimates was not one of the specific purposes for which it was prepared. While a contractor may gain important knowledge from a report prepared for another party, the contractor should discuss the report with your consultant and perform the additional or alternative work believed necessary to obtain the data specifically appropriate for construction cost estimating purposes. Some clients hold the mistaken impression that simply disclaiming responsibility for the accuracy of subsurface information always insulates them from attendant liability. Providing the best available information to contractors helps prevent costly construction problems and the adversarial attitudes that aggravate them to a disproportionate scale.

READ RESPONSIBILITY CLAUSES CLOSELY.

Because geotechnical/environmental engineering is based extensively on judgment and opinion, it is far less exact than other design disciplines. This situation has resulted in wholly unwarranted claims being lodged against consultants. To help prevent this problem, consultants have developed a number of clauses for use in their contracts, reports and other documents. These responsibility clauses are not exculpatory clauses designed to transfer the consultant's liabilities to other parties; rather, they are definitive clauses that identify where the consultant's responsibilities begin and end. Their use helps all parties involved recognize their individual responsibilities and take appropriate action. Some of these definitive clauses are likely to appear in your report, and you are encouraged to read them closely. Your consultant will be pleased to give full and frank answers to your questions.

The preceding paragraphs are based on information provided by the
ASFE/Association of Engineering Firms Practicing in the Geosciences, Silver Spring, Maryland