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ABSTRACT

The paper presents the results of the geotechnical evaluation of the existing conditions of the local flood protection of Topeka, the state capital of Kansas. The existing levee system constructed by the U.S. Army Corps of Engineers consists of 6 levees units along the north and south bank of the Kansas River and tributaries, Soldier Creek and Shunganunga Creek. The geotechnical evaluation of the existing conditions of the levee system was based on all available geotechnical data and on the past performance of the system. The critical reaches of each levee unit were identified based on the geotechnical conditions and levee geometry. The geotechnical levee system response to river stage loading was evaluated. Geotechnical information included subsurface investigation performed for the design and construction of the levee, geotechnical information obtained for subsequent levee modification, and cone penetrometer tests and laboratory testing performed on selected samples collected from additional borings drilled in areas considered critical or known to experience excessive underseepage during previous flooding events. Uncertainty analyses were performed to define the existing condition of the Topeka Levee System. The system response was determined by evaluating the foundation and embankment materials and assigning values for the probability moments of the random variables considered in the analyses. The performance functions considered for the risk analyses were slope stability and underseepage piping stability. The internal erosion due to seepage through the embankment was not considered, the levee embankments being constructed of cohesive fill. A set of conditional-probability-of-failure versus floodwater-elevation graphs were developed as related to underseepage piping stability and slope stability for the long-term seepage. Reliability analysis was performed using Taylor's Series Method. In the Taylor method, random variables were quantified by their expected mean values, standard deviations, and correlation coefficients.

INTRODUCTION

Topeka, the capital city of the state of Kansas, is located on the north eastern part of Kansas, on the Kansas River. The city is protected by a series of levees constructed along the north and south banks of Kansas River and its tributaries Soldier Creek and Shunganunga Creek. The Topeka levee system consists of six (6) levee units including approximately 40 miles of levees along the Kansas River and approximately 3 miles of tie back levees, 0.7 miles of floodwall, 9.2 miles of improved channel on Soldier Creek, 5.5 miles of improved channel on Shunganunga Creek, and 2.6 miles of improved and enlarged channel along the Kansas River. The levee system also includes floodwalls, pumping plants, gated outlets for drainage structures, sandbag gaps and ponding areas. The 6 levee units are as follows:

<u>Soldier Creek Unit.</u> The Soldier Creek Unit consists of a channel and levees located along Soldier Creek north and south bank, beginning at Kansas River mile 81.9 and extending northwesterly to the vicinity of the Silver Lake channels and levees. The Soldier Creek unit includes 17.9 miles of levee, 9.2 miles of channel improvement, approximately 4.3 miles of tributary tie back levees along the left bank of Soldier Creek, and 35 drainage structures. The project was designed in 1958 and constructed between the years 1958 and 1962.

<u>North Topeka Unit.</u> The North Topeka Levee Unit is located along the left bank of the Kansas River beginning on Soldier Creek and extending upstream along the left bank of the Kansas River to approximate river mile 82. The flood protection unit includes 9.3 miles of earthen levee, 3 relief wells, 3 pumping plants, 15 drainage structures, one sandbag gap, and one stoplog gap. The North Topeka Unit was designed in 1961 and constructed between 1964 and 1967 for the purpose of protecting the North Topeka area.

<u>Waterworks Unit.</u> The Waterworks Levee Unit is located along the right bank of the Kansas River to provide protection for the western side of Topeka. The levee unit includes 1,998 feet of earthen levee and 1,662 feet of floodwall with 9 relief wells for underseepage control, 4 drainage structures for the interior drainage control, and 1 sandbag and 4 stoplog gaps.

The project was designed in 1957 and constructed during 1959.

Auburndale Unit. The Auburndale Flood Levee Unit is located east of the Waterworks unit along the right bank of the Kansas River. The unit uses the Interstate I-70 embankment in lieu of a right bank levee between the Waterworks Unit at the upper end and the South Topeka Unit at the lower end. This unit also includes the Waite Street Levee and an 850-foot sub-levee, which serves as the upstream boundary for a ponding area. The entire length of the earthen levee section is 1.3 miles and includes 15 relief wells for underseepage control, 2 pumping plants and 4 drainage structures for interior drainage control and discharge of the relief well system, and one sandbag gap. The unit was designed in 1958 and constructed between the years 1961 and 1962.

South Topeka Unit. The South Topeka Levee Unit is located along the right bank of the Kansas River between the Auburndale Unit at the west upper end (river mile 85.5) and Santa Fe Railroad bridge at mile 83.8 at the lower end. The unit consists of 1.4 miles of earthen levee, 1,944 feet of floodwall and includes 2 stoplog gaps. Underseepage is controlled by 27 relief wells with the water collected from the relief well system and interior drainage discharged into the Kansas River by 5 pumping plants and 15 drainage structures. The unit was designed in 1966 and constructed between the years of 1970 and 1973.

Oakland Unit. The Oakland Flood Levee Unit is located along the Kansas River downstream of South Topeka Unit and continuing along left bank of Shunganunga Creek. Flood protection consists of 10 miles of earthen levee, one sandbag gap, and 5.5 miles of channel improvement. Underseepage is controlled by underseepage berms and 22 relief wells. The collected interior drainage and relief well water is discharged into the Kansas River by 2 pumping plants and 48 drainage structures. The Oakland Unit was designed in 1960 and constructed during the period between 1965 and 1969.

SUBSURFACE CONDITIONS

The Topeka area is located within the Eudora-Muir soils association. A review of available geological information indicates that part of the study area is situated in an area of alluvial deposition and erosion at the confluences of Soldier Creek with the Kansas River and Shunganunga Creek with the Kansas River. The efforts to control the flooding are done with a series of upstream flood control dams and levees. Subsurface investigations indicate that the composition and thickness of the natural blanket in the Topeka area generally conforms to that found elsewhere in Kansas River Valley. The natural surface impervious blanket consists of sandy silts from 10 to 20 feet thick overlaying a deposit of sands and gravels 40 to 80 feet thick, which become coarser with depth. A fairly consistent weak layer of organic material has been found along Soldier Creek, near the base of the excavated channel.

Local bedrock in the project area is comprised of the Upper Pennsylvanian limestone and shale formation which may be found at approximate depths of 60 to 80 feet below existing natural ground surface.

LEVEE DESIGN FEATURES

The basic levee section was constructed with a 10' crown width, with generally 1V on 3H riverside and landside slopes. The average height of the levees varies between 12 and 16 feet, with the maximum height of 26 feet on the Auburndale unit. Seepage control measures consist of underseepage berms, buried seepage collector system, relief wells and area fill where necessary. Typical locations of existing underseepage controls are located where the natural blanket is thin in a localized area. Stability berms were used for levee sections with heights greater than 10 feet to provide a minimum factor of safety of 1.1 for riverward slope to satisfy the rapid drawdown conditions of the river stage. A factor of safety of 1.4 was required for the landside levee slope considering steady seepage during the design river stage. For the existing soil conditions, the limiting height, or spring point appears to be 10 feet.

ASSESSMENT OF LEVEE INTEGRITY

The current levee system is in good condition with no presently identifiable problem areas. The entire levee system has performed well during past flood events. The seepage and stability berms have performed as designed over the years. The levee is well maintained and there were no unapproved utility penetrations decreasing the levee safety and stability.

GEOTECHNICAL UNCERTAINTY ANALYSES – GENERAL CONSIDERATIONS

Geotechnical failure was identified as the failure of the embankment slope resulting from the river flowing to landside areas of the levee with resulting economic damages. Further, geotechnical failure may occur when river stages reach an elevation at or below the top of the levee. Within this range, geotechnical failure modes are excessive seepage leading to a piping condition and slope instability.

Uncertainty analyses were performed to define the existing condition of the Topeka Levee system. The response curves were evaluated by assessing the foundation and embankment materials and assigning values for the probability moments of the random variables considered in the analyses. The First-Order-Second-Moment (FOSM) method, as recommended in U. S. Army Corps of Engineers engineering technical letter ETL 1110-2-556, “Risk-Based Analysis in Geotechnical Engineering for Support of Planning Studies” dated 28 May 1999. The ETL , was followed during the evaluation of the existing conditions of each levee unit. In this approach, the uncertainty in performance is taken to be a function of the uncertainty in model parameters. The standard deviations of a performance function were estimated based on the expected values (means) and the standard deviation of the random variable means. The performance functions considered were slope stability and underseepage piping stability. The final result of the FOSM is a reliability index, Beta (β), representing the amount of standard deviation of the performance function by which the expected value exceeds the limit state. The limit state for the slope stability and underseepage piping stability was defined using a factor of safety of 1.0. The standard deviation and variance of the performance function were calculated from the standard deviation and variance of the foundation and embankment parameters using the Taylor's series method based on a Taylor's series expansion of the performance function about the expected values. The partial derivatives were calculated numerically using an increment of plus and minus one standard deviation centered on the expected value. The variance of the performance function was obtained by summing the products of the partial derivatives of the performance function considering the variance of the corresponding parameters. For the existing condition of the levee, the probability of slope or underseepage piping failure (Pr_f) was expressed as a function of the river water elevation and other factors including soil strengths, permeabilities, and subsurface stratification. Reliability (R) is defined as:

$$R = (1-Pr_f) \tag{1}$$

A set of conditional-probability-of-failure versus floodwater-elevation graphs were developed as related to underseepage piping stability and slope stability for the long-term seepage condition**.** Sudden drawdown conditions may result in levee slope failure but it is unlikely to provide flooding of the area. Such failure happens when the water in the river is at a low elevation. Therefore it was not considered in this analysis.

The combined geotechnical conditional probability of failure, considering the probability of failure due to underseepage failure, and slope stability is

$$Pr(f) = 1 - ((1-Pr(f)_{us})*((1-Pr(f)_{st})) \tag{2}$$

Where: $Pr(f)$ = total probability of failure

$Pr(f)_{us}$ = probability of failure due to underseepage

$Pr(f)_{st}$ = probability of failure due to slope stability (in steady state condition)

The probability of geotechnical failure of a levee is conditional on the uncertainties associated with hydrologic and hydraulic aspects of determining the water surface profile during a flood. These uncertainties can be combined with the geotechnical uncertainties and utilized in the Flood Damage Assessment model. This was accomplished, for economic purposes, through estimation of two index elevations for each levee reach within the study area. These index elevations are defined as follows:

- The Probable Non-Failure Point (PNP) is the water elevation below which it is highly likely that the levee would not fail.
- The Probable Failure Point (PFP) is the water elevation above which it is highly likely that the levee would fail.

The terms "highly likely that the levee would fail" is defined by the ETL as having 85% probability of occurrence. Therefore, the probability of non-failure at the PNP is 15% and the probability of failure at the PFP is 85%. A linear distribution is assumed in the economic model between the PNP and PFP.

UNDERSEEPAGE RELIABILITY

Subsurface conditions for every levee unit were developed based on subsurface investigations including recent Cone Penetration Tests (CPT) performed at selected locations. The impervious blanket thickness, blanket material, and aquifer thickness and materials were determined for each characteristic reach of every levee unit. The levee height, impervious blanket and aquifer thicknesses and the permeability ration between the aquifer horizontal permeability and blanket vertical permeability used in the analysis were based on the standard deviation and the coefficient of variation of these elements for each specific reach and for the entire levee unit. Underseepage analysis was performed using the blanket theory. The analyses assumed 50% relief well efficiency to determine the amount of artesian pressure to be used between relief wells if relief wells were constructed within a certain reach. The critical reach was determined for each levee unit by calculating the underseepage factor of safety for the existing conditions at the toe of the levee. The underseepage factor of safety is defined as the ratio between the actual gradient at the levee toe obtained by analysis and the computed critical gradient (FS = i_0/i_{cr}). If the factor of safety was deemed unsatisfactory, i.e. had a factor of safety of less than 1.0, an uncertainty analysis was performed for that particular reach. In the uncertainty analysis, the maximum exit gradient at the landside toe of the levee was considered as the performance function and the value of the critical gradient, assumed to be 0.84, considered the limit state. The hydraulic gradient obtained in the foundation sand at the base of the impervious blanket was utilized in the stability analysis to assist in defining the steady state condition of the landside slope.

Reliability analysis was performed using the Taylor's Series Method. In the Taylor method, random variables are quantified by their expected values, standard deviations, and correlation coefficients. These variables were used in the generalized equation for underseepage analysis as follows:

$$X_3 = \sqrt{z * d * \left(\frac{k_f}{k_b}\right)} \tag{3}$$

$$i_o = \frac{h_0}{D_b} = \frac{H\left(\frac{k_f}{k_b} D_f D_b\right)}{D_b \left[C_R \frac{e^{2L_R} - 1}{e^{2L_R} + 1} + x_2 + \left(\frac{K_f}{K_{bL}} D_f D_{bL} \right) \right]} \tag{4}$$

Where

$$h_0 = \frac{H * L_e}{L_1 + L_2 + L_e} \quad (5)$$

$$L_1 = C_R * \frac{e^{2L_R} - 1}{e^{2L_R} + 1} \quad (6)$$

$$Pr(F) = P(i_{critical} < i_o) \quad (7)$$

Where: X_3 = C_R = effective exit distance
z = D_f = blanket thickness
d = D_b = aquifer thickness
k_f = horizontal permeability of the aquifer
k_b = vertical permeability of the blanket
k_f/k_b = permeability ratio between horizontal permeability of the aquifer and vertical permeability of the impervious blanket
L_R = actual length of the riverside blanket
L_L = actual length of landside blanket assumed infinite (∞)
H = total head on levee
H_0 = water head at the landside levee toe
i_0 = upward seepage gradient through the natural blanket
L_1 = effective length of the riverside blanket
L_2 = X_2 = base width of natural blanket beneath the levee embankment (X_2)
L_e = C_R when the landside length of the natural blanket is assumed infinite

Thus, an equation is used to calculate seepage gradient for a range of water levels on the riverside of the levee.

Permeability ratios of the blanket landside (K_L) and riverside (K_R) values were obtained by studying the classification information listed on the available boring logs and CPT.

Soldier Creek

The unit consists of the improved Soldier Creek channel and levees on both banks to contain the designed flood event, and tie back levees on the left bank of the creek. Foundation soils consist of a natural blanket with an average thickness of 23 feet overlaying a deposit of poorly graded sand averaging 20 feet in thickness. The composition of the natural blanket varies from clays (CL, CH) to silty sands, but primarily of lean clays. A weak layer of fat clay was mapped between stations 180+00 and 213+00 as substantiated by slides along the original channel. An extensive cinder fill overlaying the impervious blanket between stations 222+00 and 245+00 required the construction of a riverside seepage cut-off trench. Landside underseepage berms exist between station 397+50 and the levee end, relief wells for an existing Goodyear Plant between stations 205+00 and 206+00, and the existence of the thick impervious blanket indicates that underseepage instability was expected for this unit during initial design. The underseepage evaluation shows no instability along the Soldier Creek levee unit.

North Topeka Unit

This unit, constructed along the left bank of the Kansas River, includes 9.3 miles of earthen levee with heights varying between 2 feet and 21 feet. The natural blanket for the entire levee unit, consisting predominantly silt, varies in thickness from 1 to 23 feet, with an average thickness of 12 feet. The coefficient of variation in the thickness of the natural blanket has been calculated to be 39.4% with a standard deviation of 4.8 feet. Underseepage is controlled by landside underseepage berms between stations 83+00 and 220+00. Cut-off trenches are present between stations 205+00 and 462+50 at locations where the blanket is overlain by a sand layer or by existing pervious fill. Three (3) relief wells were placed at station 392+05 where the natural impervious blanket had been excavated for the basement of a warehouse building. Underseepage analyses for the reach between stations 205+00 to 298+00 evaluating the existing conditions indicate underseepage factors of safety less than 1.0 for a river stage at the existing levee crest and were considered critical for reliability evaluation. The assumed soil material parameters and their statistical descriptors are listed in table 1:

Table 1 North Topeka Unit

Parameter	**Mean**	**Coef. of Variation**	**Standard Deviation**
Thickness of Pervious material (ft)	70	22%	15
Landside permeability (K_L) ratio	300	40%	120
Depth of blanket (ft)	6.7	32%	2.1

Uncertainty analyses performed for this reaches resulted in the following curve:

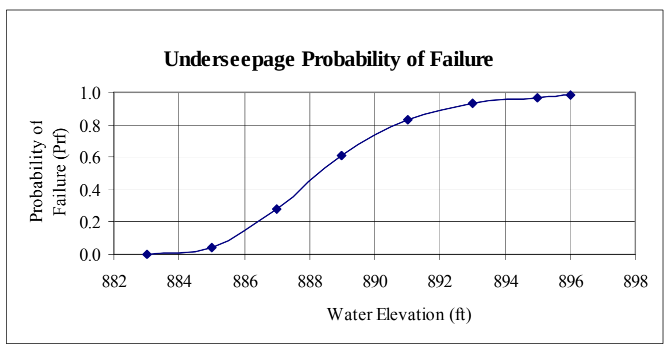

Fig. 2 North Topeka Unit Station 246+00 to 250+00

The critical water stage for highly likely (85 percent) probability of failure for the reach between stations 205+00 and 298+00 is at elevation 892 feet. The top of the levee in this reach is at elevation 896 feet.

Waterworks Unit.

The Waterworks Unit, located on the right bank of the Kansas River, consists of 1,998 feet of earthen levee and 1,662 feet of floodwall. The floodwall is constructed on a foundation soil consisting of an impervious blanket varying in thickness from 9 to 13 feet, overlaying a layer of very fine sand, which becomes progressively coarser with depth. The average impervious blanket thickness is 9.6 feet with a coefficient of variation of 28.2% and a standard deviation of 2.7 feet. Nine (9) relief wells provide underseepage control along the floodwall reach. A landside fill controls the underseepage along the levee embankment reach. Underseepage analyses considering the existing conditions indicated factors of safety less than 1.0 for a river stage at the levee crest for the reaches between stations 33+00 and 40+00. The assumed soil material parameters and their statistical descriptors for this critical reach are listed in table 2.

Table 2. Waterworks Unit

Parameter	Mean	Coef. of Variation	Standard Deviation
Thickness of Pervious material (ft)	40	25%	10
Landside permeability (K_L) ratio	500	40%	200
Depth of blanket (ft)	7.3	20%	1.5

Uncertainty analyses performed at this reach resulted in the following curve shown on Figure 3.

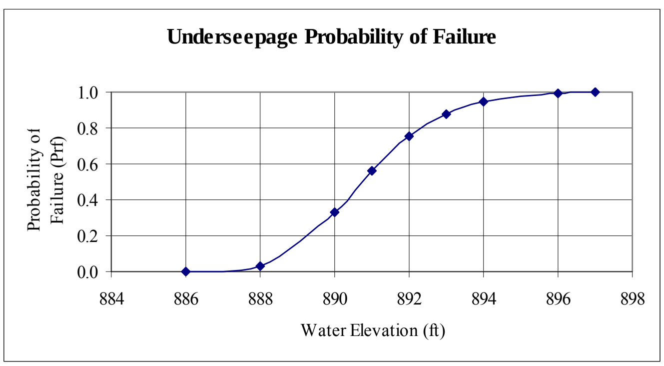

Fig. 3 Waterworks Unit

The critical water stage for highly likely (85 percent) probability of failure within this reach is elevation 892.5 feet. Top of the levee is at elevation 897.

Auburndale Unit

The Auburndale Unit is located along the right bank of the Kansas River east of the Waterworks Unit. The Interstate I-70 embankment is used as the right bank levee between the Waterworks Unit at the upper end and the South Topeka Unit at the lower end. Foundation soils below the levee embankment consist of an impervious blanket of silt or sandy silts varying in thickness between 8 and 14 feet. Near the bluff line, a clay blanket overlays the poorly graded foundation sand to a depth of up to 45 feet. A layer of impervious fill was placed on the highway landside slope to control through seepage in the embankment. Fifteen (15) relief wells are located between stations 2+00 and 17+50. A riverside impervious cut-off trench was keyed 1 foot into the impervious blanket between stations 80+00 and 137+00. Due to the high level of underseepage control, pump tested high efficiency of relief wells, width of the levee crown, and thickness of blanket, risk and uncertainty analyses were not considered to be required.

South Topeka Unit

The South Topeka Unit is located along the right bank of the Kansas River and consists of 1.4 miles of earthen levee, and 1,944 feet of floodwall founded on an impervious blanket varying in thickness between 5 and 24 feet, with an average of 15.5 feet. The standard deviation of the blanket thickness is 5 feet and the coefficient of variation 32.4%. The blanket consisting of silty clays and silty sands overlays a sand deposit more than 80 feet thick. Fill placed on the top of the natural blanket between station 50+00 and 74+30 contains debris, rock, rubble, and sand requiring the construction of riverside cut-off trenches to reduce seepage. Between station 74+30 and 93+90, a 6 to 7 foot thick layer of debris required construction of 27 relief wells for underseepage control. The blanket beneath this fill averages only a few feet in thickness and appears to be entirely missing between stations 77+50 and 80+50. A seepage interceptor drain and relief wells were placed between stations 74+05 and 93+25. The interceptor was designed to control underseepage flow along a void detected at the base of the pile cap. The void was measured as 1/16" at the sheet pile cut-off wall and 3/4" at the toe. Underseepage analyses considering the existing conditions and a factor of safety less than 1.0 was computed for a river stage at the levee crest for the reaches between stations 0+00 and 72+20 where no relief wells exist. The assumed soil material parameters and their statistical descriptors for this critical reach are listed in table: 3

Table 3 South Topeka Unit

Parameter	Mean	Coef. of Variation	Standard Deviation
Thickness of Pervious material (ft)	80	20%	16
Landside permeability(K_L) ratio	400	40%	160
Depth of blanket (ft)	11.3	40%	6

Uncertainty analyses, performed for this reach resulted in the following curve:

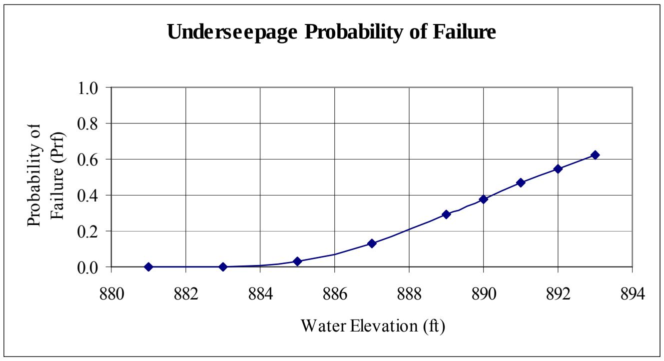

Fig. 4 South Topeka Unit

The critical water stage for highly likely (85 percent) probability of failure within this reach is above the crest of the levee of elevation 893 feet.

Oakland Unit

The Oakland Unit is located along the Kansas River downstream of the South Topeka Unit and along left bank of Shunganunga Creek. The Oakland Unit consists of 10 miles of earthen levee and 5.5 miles of channel improvements. Foundation soils of this flood protection unit contain an impervious blanket that can be divided into three general areas considering blanket material and blanket thickness. The blanket in the upper reach, between stations 0+00 to 60+00, consists of clay-type material varying from silty clay to fat clay. Blanket thickness ranges between 20 and 30 feet. The middle reach, between stations 60+00 and 285+00, is overlain by an impervious silt blanket having a thickness of between 2 and 30 feet. The blanket thickness between stations 200+00 and 245+00 is very thin; having a thickness of between 0 and 4 feet. The reach along Shunganunga creek, from station 285+00 to the end, has a substantial blanket consisting of lean to fat clays with a thickness of between 20 and 35 feet. Underlying foundation sands possess a thickness ranging between 10 and 60 feet. Sands vary in grain size from very fine to medium in the upper half of the aquifer to coarser near the top of bedrock. The entire foreshore area between station 0+00 and approximate station 40+00 contains deposits of fill material consisting of waste material, debris, cinders, and rubble. A riverside cut-off trench exists between stations 0+00 and 523+20, constructed to reduce the seepage through the levee foundation. Relief wells between stations 205+00 and 237+50 control the underseepage. Underseepage analyses indicate factors of safety less than 1.0 for the reaches between stations 60+00 and 85+55 with a river stage at the levee crest. A relief well between stations 200+00 and 245+00, considering 50 percent efficiency, increases the underseepage stability to an acceptable level of greater than 1.0. The assumed soil material parameters and their statistical descriptors for this critical reach are listed in table 4.

Table 4 Oakland Unit

Parameter	Mean	Coefficient of Variation	Standard Deviation
Thickness of Pervious material (ft)	40	37%	15
Landside permeability (K_L) ratio	600	40%	240
Depth of blanket (ft)	7.0	31.%	2.2

Uncertainty analyses performed for the reach between stations 60+00 and 85+55 resulted in the following curve shown on Figure 5. The critical water stage for highly likely (85 percent) probability of failure for the reach between stations 64+00 and 80+00 is elevation 880.5 feet, with the top of the levee being at elevations 884 feet.

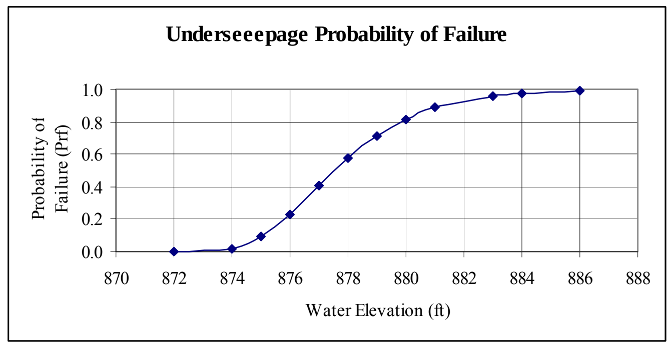

Fig. 5 Oakland Unit

SLOPE STABILITY RELIABILITY

A risk analysis was performed on a basic typical section of the levee embankment for each unit, at reaches considered critical due to the levee height or foundation conditions. A sensitivity study was done to determine which parameters in the slope stability calculations were most influential. For this study, those variables are soil strength in the embankment, soil strength in the foundation material such as cohesive soils and cohesionless soils. Statistical descriptors for these variables were determined using available site-specific information and published statistical data as in the underseepage study. Conditions analyzed for stability analyses considered steady state seepage condition along the landside slope for levees located on the Kansas River. When steady state conditions were analyzed, the water pressure in the sand layer underlying the natural impervious blanket was computed by underseepage analysis for every flood stage considered in calculations. Soil strength parameters used in the stability analyses were the drained soil parameters determined for the original flood control project design. The only new subsurface investigation performed to refine the understanding of existing conditions involved cone penetration testing (CPT) at selected locations. The coefficient of variation for soil strength parameters were obtained using methodologies outlined in ETL 1110-2-556. The limit equilibrium computer program "UTEXAS3" used to perform the stability analyses assuming circular failure surfaces. The embankment was modeled as homogeneous constructed of compacted impervious clay. All analyses consisted of running a search routine to identify the critical failure surface using the Spencer's Method. Three random variables were defined for each unit. Stability analyses were performed for different assumed river stages.

Soldier Creek Unit

The Soldier Creek Unit consisting of a low height levee(6 to 8 feet) along the Soldier Creek Channel, has the stability factors of safety higher than 1.4 for a steady state conditions with the water at the levee crest and therefore the reliability analysis was not considered as a mode of failure.

North Topeka Unit

The North Topeka Unit was analyzed assuming steady state seepage conditions and that the aquifer layer under the impervious blanket is being pressurized by the hydraulic gradient determined during underseepage analyses for different river stage elevations and different blanket thicknesses. The impervious blanket thickness is 5 feet or less. Soil properties are shown as the Expected Values in Table 5. The Standard Deviation and Coefficient of Variation determined from the uncertainty analyses are also provided in Table 5.

Table 5 North Topeka Random Variables

Parameter	Expected Value (mean)	Standard Deviation	Coefficient of Variation (%)
Clay Material Phi Angle (deg.)	26.5	1.7	10.0
Foundation Sand Phi Angle (deg.)	32	3.2	12.0
Clay Blanket Thickness (feet)	6.7	2.0	21.6

The probability that the factor of safety for slope stability is less than 1.0 for increasing river stages is shown by the curve presented in Figure 6.

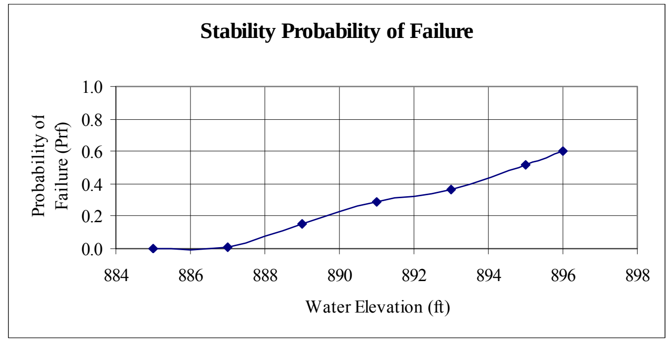

Figure 6 North Topeka Unit

Waterworks Unit

The Waterworks Flood Protection Unit was analyzed for the steady state condition considering the aquifer layer underneath the impervious blanket as being pressurized by the hydraulic gradient developed during underseepage analyses for different river stage elevations and different blanket thicknesses. The original design soil properties are shown as the Expected Values in Table 6. The Standard Deviation and Coefficient of Variation determined from the uncertainty analyses are also provided in Table 6.

Table 6 Waterworks Random Variables

Parameter	Expected Value (mean)	Standard Deviation	Coefficient of Variation (%)
Clay Material Phi Angle (deg.)	26.5	2.7	10.0
Foundation Sand Phi Angle (deg.)	32	3.8	12.0
Foundation clay Thickness (feet)	7.0	1.5	21.4

The probability that the factor of safety for slope stability is be less than 1.0 for increasing river stages is indicated by the curve presented in Figure 7. The elevation corresponding to highly likely (85 %) probability of failure is 893 feet, the top of levee is at elevation 897 feet.

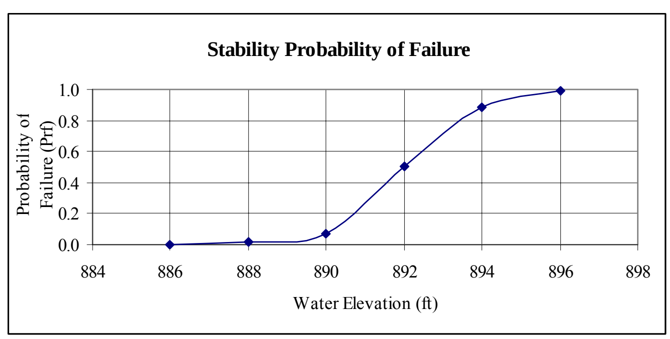

Figure7 Waterworks Unit

Auburndale Unit.

No stability analyses were performed for this levee unit since the foundation conditions and the height of the levee did not yield to any obvious weak reaches. The impervious blanket is thicker than 8 feet throughout and consists of silt or sandy silts having an internal friction angle of 26.5 degrees, as recommended for the original design. The levee was overbuilt to accommodate the highway requirements on the top. The levee height does not exceed 15 feet. Relief wells are provided to control foundation pressures. Critical failure surfaces for steady state seepage conditions will not penetrate the impervious blanket. Considering all these conditions, no instabilities were deemed to exist within this unit.

South Topeka Unit.

The South Topeka Levee Unit was analyzed for steady state seepage conditions considering the aquifer layer underneath the impervious blanket as being pressurized by the hydraulic gradient determined during underseepage analyses for different river stage elevations. Original design soil properties are shown as the Expected Values in Table 7. The Standard Deviation and Coefficient of Variation determined from the uncertainty analyses are also provided in Table 7.

Table 7 South Topeka Random Variables

Parameter	**Expected Value (mean)**	**Standard Deviation**	**Coefficient of Variation (%)**
Fill Material Phi Angle (deg.)	24.0	2.4	10.0
Embankment Fill Phi Angle (deg.)	26.5	2.7	10.0
Foundation Clay Phi Angle (deg.)	22.0	2.2	10.0

The probability that the factor of safety for slope stability is be less than 1.0 for increasing river stages is indicated by the curve presented in Figure 8.

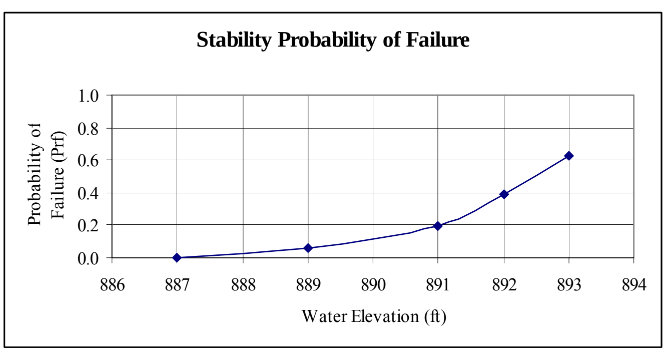

Figure 8 South Topeka

Oakland Unit

The Oakland Levee Unit was analyzed for the steady state seepage condition considering the aquifer layer underneath the impervious blanket as being pressurized by the hydraulic gradient determined during underseepage analyses for different river stage elevations. Original design soil properties are provided as the Expected Values in Table 8. The Standard Deviation and Coefficient of Variation determined from the uncertainty analyses are also provided in Table 8.

Table 8 – Oakland Levee Unit Random Variables

Parameter	**Expected Value (mean)**	**Standard Deviation**	**Coefficient of Variation (%)**
Embankment Phi Angle (deg.)	26.5	2.5	10.0
Foundation Clay Phi Angle (deg.)	19.0	2.0	10.0
Foundation Sand Phi Angle (deg.)	32.0	4.0	12.0

The probability that the factor of safety for slope stability is be less than 1.0 for increasing river stages is indicated by the curve presented in Figure 9.

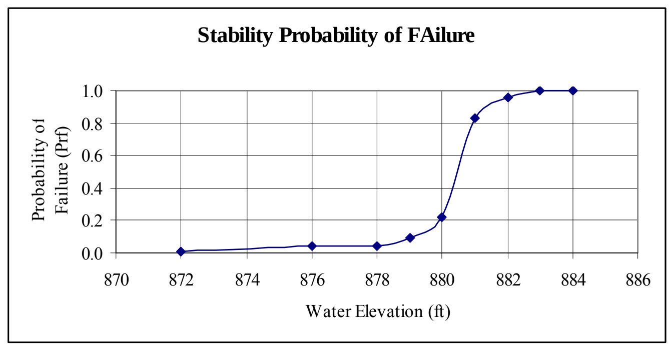

Figure 9 Oakland Unit

COMBINED PROBABILITY OF FAILURE

The total conditional probability of failure as a function of floodwater elevation has been developed by combining the probability of failure functions for two failure modes; underseepage piping and slope instability. The reliability is the probability of no failure due to each failure mode considered in the calculations. The total probabilities of failure function computed for each critical levee unit are as follows.

Soldier Creek Levee Unit.

The probability of failure was not determined since neither underseepage nor stability for steady state conditions were considered critical. The levee crest elevation along Soldier Creek varies between 919 and 886 feet and the Soldier Creek Channel bottom varies between elevations 880 and 873 feet.

North Topeka Unit

The combined probability of failure for the critical sections between stations 246+00 and 250+00 is illustrated in Fig. 10. The highly likely (85 percent) probability of failure for this reach occurs for a flood stage of elevation 890.5 feet. The levee crest elevation varies within this reach between elevations 895.6 and 896.0 feet.

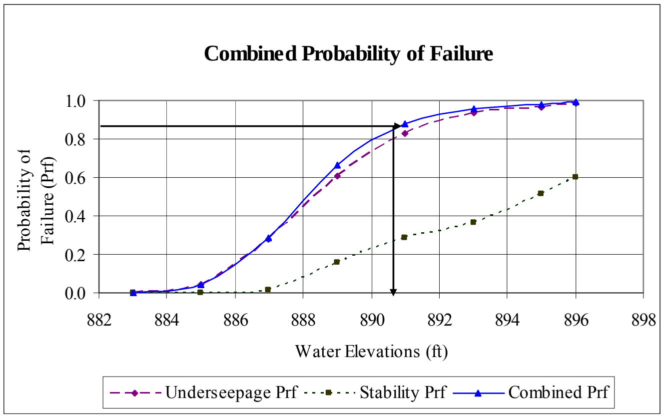

Figure 10 North Topeka Unit, Combined Probability of Failure

Waterworks Levee Unit.

The combined probability of failure for the critical section between stations 16+62 and 33+50 is illustrated by the curve shown in Figure 11. The highly likely (85 percent) probability of failure for this reach occurs for a flood stage of elevation 892 feet. The levee crest elevation varies between 897.0 and 897.6 feet.

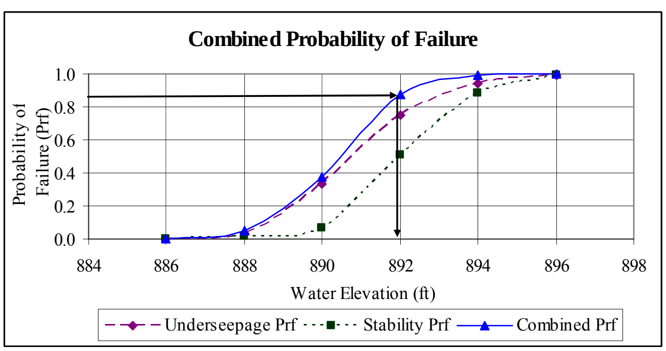

Figure 11 Waterworks Unit, Combined Probability of Failure

South Topeka Levee Unit.

The combined probability of failure for the critical section between stations 0+00 and 73+00 is illustrated in Figure 12. The highly likely (85 percent) probability of failure for this reach occurs for a flood stage of elevation 893 feet corresponding to the elevation of the levee crest.

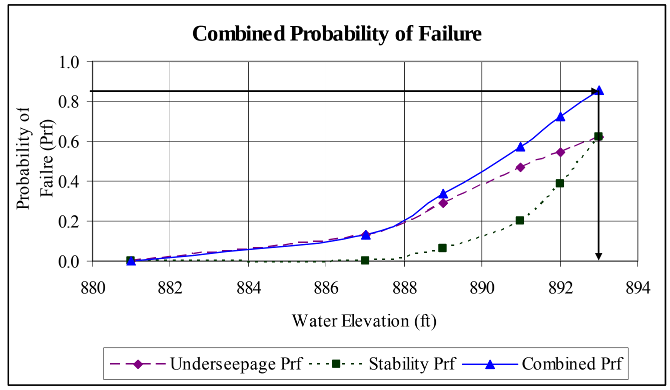

Figure 12 South Topeka Unit, Combined Probability of Failure

Oakland Levee Unit.

The combined probability of failure for the critical section between stations 64+00 and 80+00 is illustrated by the curve shown in Figure 13. The highly likely (85 percent) probability of failure for this reach occurs at a flood stage of elevation 880 feet. The levee crest elevation at this reach is 886 feet.

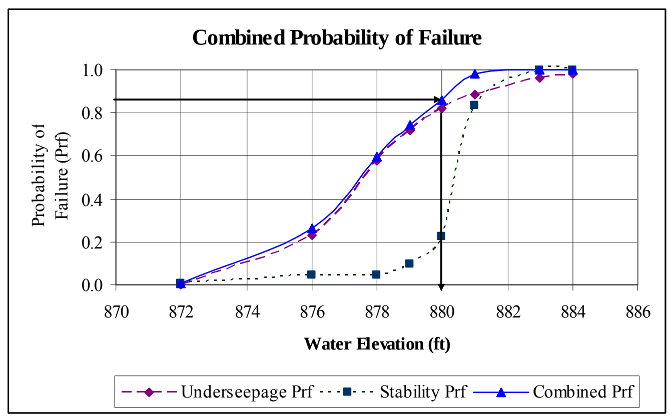

Figure 13 Oakland Levee Unit Combined Probability of Failure

CONCLUSION OF RISK AND UNCERTAINTY ANALYSIS

Based on the uncertainty analyses of the individual units of the Topeka Flood Protection System, critical reaches of the Topeka levee system have been identified and are summarized in Table 9.

Table 9 Critical Reaches for Topeka Flood Control Project

Levee Unit	Critical Station Range	Average Levee Crest Elevation	Flood Stage for 85% Probability of Failure	Freeboard Distance to Levee Crest @ 85% Failure Probability
Soldier Creek	N/A	N/A	N/A	N/A
North Topeka	246+00 to 250+00	896.0	890.5	5.5
Waterworks	16+62 to 33+50	892.0	892.0	5.0
Auburndale	N/A	N/A	N/A	N/A
South Topeka	0+00 to 73+00	893.0	893.0	0.0
Oakland	64+00 to 80+00	880.0	880.0	6.5

The geotechnical order of higher risk based on the combined risk and uncertainty analysis is shown in Table 10.

Table 10 Combined Geotechnical Risk and Uncertainty Analysis

Levee Unit	Levee Unit Reach	Nature of Risk	Damages	Nature of Cost
North Topeka	246+00 to 260+00	• Slope Failure • Loss of Levee	• Property • Loss of Lives	• Dollars • Loss of Lives
Waterworks	16+62 to 33+50	• Slope Failure • Loss of Levee	• Loss of water plant • Loss of Lives	• Utility Loss • Loss of Lives
Oakland	64+00 to 80+00	• Potential loss of full levee	• Property • Loss of Lives	• Flooding •Levee Repair
South Topeka	0+00 to 73+00	• Levee Toe Slide • Loss of Levee	• Property • Loss of Life	• Levee Repair Costs • Loss of Life
Soldier Creek	13+00 to 130+00	• Bank slides	• Channel Flow Impacts • Bank Scour	• Repair of Flood Damages

REFERENCES

The references used for risk based analyses are as follows:

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