ERDC/GSL TR-04-12

Geotechnical and Structures Laboratory

US Army Corps of Engineers®
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Technologies and Operational Innovations for Urban Watershed Networks Research Program

Prediction of Piping Erosion Along Middle Mississippi River Levees—An Empirical Model

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Final report

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under TOWNS Work Unit 15

ABSTRACT:

This research was conducted to address the concerns of U.S. Army Corps of Engineers (USACE) levee engineers regarding the cumulative effects of piping—the movement of sediment from a levee or its foundation by the flow of water. Piping is a levee failure mechanism that has not been analytically defined, but has been observed. Levee inspectors documented an increase in piping from the record flood of 1993 to the lesser flood of 1995 along the Mississippi River. The average net head on the study levee in 1993 was 18 ft and, in 1995, was 10 ft, yet piping incidence was 49 percent greater in 1995. These data support the view that repeated high water events have cumulative effects (increased seepage) and that deficiencies exist in seepage analysis theory. Typically, a seepage analysis is conducted in two dimensions with assumed homogeneous soil properties along a 500- to 1000-ft reach, while in reality piping is a localized failure and occurs near anomalies.

Because the current analysis is lacking three-dimensional geologic information and also time-dependent variables, an empirical approach was taken to determine site factors that are significant to piping. A database of seepage parameters was created, and correlation studies were conducted. The levee system (Prairie Du Rocher, IL) was segmented into 349 reaches of equal length (250 ft). The parameters of highest correlation to piping were previous piping locations (P_{93}), the alignment of the geomorphology and the levee footprint (G), the landside blanket thickness (Z_b), and effective grain size coefficient of the aquifer (D_{10}). Using multivariate logistical regression (Logit) and the significant parameters, two models for prediction of piping locations were developed for the study levee.

The 1993 model predicted 61 reaches as having high piping potential, while only 16 of these reaches actually piped during the 1993 flood. The 1995 model, which included the 1993 piping locations as an independent variable, predicted 26 reaches in the high category, 15 of which actually piped in 1995. The 1995 model predicted fewer reaches in the high category and, therefore, had better predictive capability than the 1993 model. The outcome of the model, prediction of potential locations of piping along these levees, shows promise for predicting piping along the Mississippi River levees in general and other rivers. Also, this research shows that previous piping incidence is the most influential factor in the prediction of future piping and as an indicator of cumulative effects. Therefore, the authors strongly suggest that a standard method for documenting piping (as presented in this report) be adopted by USACE.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
miles (U.S. statute)	1.609347	kilometers

Preface

This report was prepared for the Technologies and Operational Innovations for Urban Watershed Networks (TOWNS) Research Program sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), during the fiscal year 2004. The TOWNS Program Monitor was Mr. Henry Kitch, HQUSACE. Program Manager was Ms. Kathleen D. White, Cold Regions Research and Engineering Laboratory, U.S. Army Engineer Research and Development Center (ERDC), working under the supervision of Ms. Joan Pope, Technical Director, Flood and Coastal Damage Reduction, Coastal and Hydraulics Laboratory, ERDC.

The work was conducted under the TOWNS Work Unit "Cumulative Effects of Piping." Principal Investigator for the work unit was Ms. M. Eileen Glynn, ERDC, working under the direct supervision of Dr. Joseph Koester, Chief, Geotechnical and Earthquake Engineering Branch, Geosciences and Structures Division (GSD), ERDC. Dr. Robert Hall, Chief, GSD, provided general supervision, and Dr. David W. Pittman was Acting Director, Geotechnical and Structures Laboratory. Co-principal investigator for this work unit was Dr. Joel Kuszmaul, Department of Geology and Geological Engineering, University of Mississippi.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL James R Rowan, EN, was Commander and Executive Director.

1 Introduction

As floodwaters rise against the riverside slope of a levee, hydrostatic pressure builds within the foundation (pervious substratum sands) of the levee. High levels of hydrostatic pressure can endanger the integrity of the levee and increase the potential for failure through internal erosion or piping (U.S. Army Corps of Engineers (USACE) 1956a). This pressure creates a hydraulic gradient beneath the levee due to the difference in elevation between the floodwater height and the landside levee toe. When the river elevation becomes higher than the landside toe of a levee, a hydraulic gradient develops toward the landside. In the middle Mississippi River, the gradient causes water to be transported landward beneath the levee through pervious substratum sands and, if great enough, emerge at or near the landside levee toe as “underseepage” (USACE 1941). In other levee systems (e.g., Rock Island, IL), an excessive hydraulic gradient will cause seepage to emerge through the levee itself; this is known as “through seepage.” This study is focused on underseepage.

Alluvial sediments composing middle Mississippi River levee foundations are grouped into two broad categories: the pervious substratum composed of sands and gravels and the fine-grained top stratum composed of sandy silts, silts, and clays (Turnbull and Mansur 1959). A *critical* hydraulic gradient occurs when upward seepage forces created within the pervious substratum exceed downward resisting forces equal to the submerged unit weight of the top stratum soils landward of the levee (Terzaghi and Peck 1967). If the vertical hydraulic gradient across the top stratum exceeds this critical gradient, seepage forces may cause these soils to heave or erode at localized weak spots near the landside levee toe. Formation of sand boils (Figure 1) at weak spots along the landside levee toe indicates the process of subsurface erosion, referred to as “piping.”

Piping is defined herein as the process of actively eroding sand or other soil from underneath a levee because of excessive hydrostatic pressure and concentration of underseepage in localized channels (Turnbull and Mansur 1959). Once sand boils are formed and the process of piping begins, the hydraulic gradient required to maintain the sand boils or partial pipes is equal to or less than the critical gradient (USACE 1956a). If the hydraulic gradient does not dissipate, a continuous pipe may develop beneath the levee. Collapse of the pipe, depending on its size, could cause subsidence or catastrophic collapse of the levee. In either case, the levee may be overtopped by floodwaters and scoured away.

Figure 1. Sand boils at Trotters, MS, 1937, lower Mississippi River (USACE 1956b)

The critical gradient varies from site to site because of the natural variation in top stratum thickness and composition and because of man-made interference. In addition, the critical gradient may decrease with successive floods at sites where piping has previously occurred (USACE 1956a). Therefore, it is not possible to calculate one critical gradient per levee system, making the issue of levee stability a complex problem. Rather, critical gradients must be computed for shorter lengths of levees, referred to as reaches, which have similar geometries landside and riverside of the levee.

The USACE St. Louis District maintains approximately 240 miles[1] of mainline and tributary levees between Alton and Gale, IL, along the middle Mississippi River (USACE 1976). These levees (Figure 2) were upgraded through construction or raising during the 1940s and 1950s by the St. Louis District. The raised levees increased flood protection but also increased the potential for failure through piping by increasing the height of floodwaters against the levee.

At the time of these upgrades, relatively little was known about the foundation materials beneath the levees or the geologic setting on which they were constructed (USACE 1956a). The St. Louis District and USACE Waterways Experiment Station Geotechnical Laboratory conducted an intensive underseepage investigation along the Mississippi River and tributary levees from Alton to Gale, IL, in the 1950s. The investigation resulted in seepage control measures being designed and implemented for the upgraded levees. Control measures were considered warranted if the upward gradient through the top stratum would equal 0.85 with a river stage at the net grade of the levee. Based on this criterion, about

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page v.

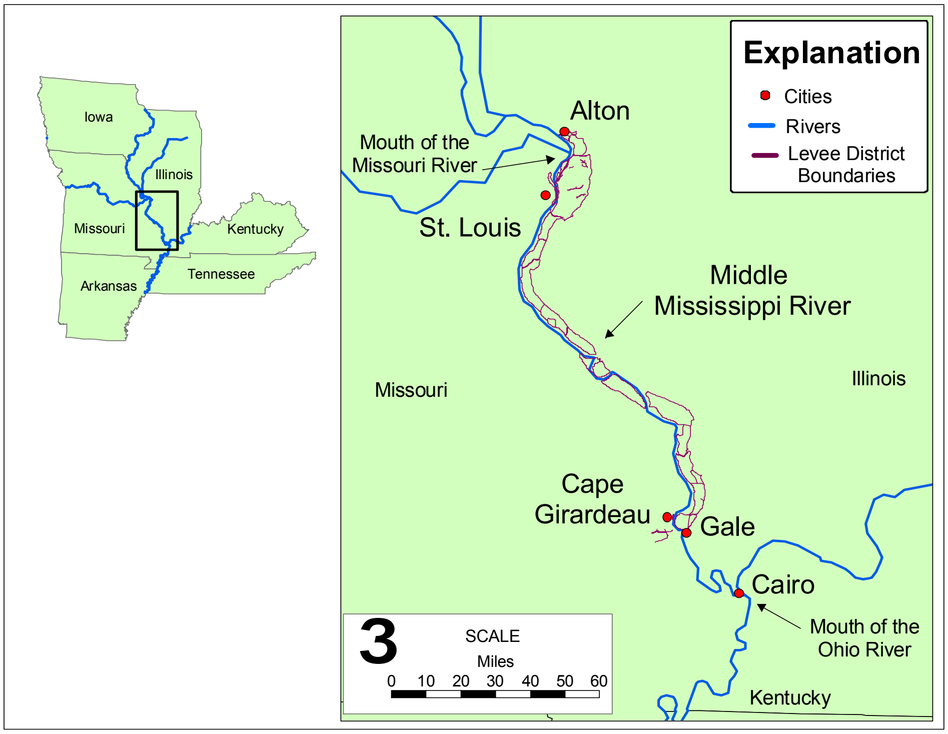

Figure 2. Levee districts shown in red, between Alton and Gale, IL, along the middle Mississippi River

2,100 relief wells and 14 landside seepage berms were planned along 70 miles of the 240 miles of levees. Piezometers were installed for monitoring purposes in areas where the need for control measures was questionable.

The St. Louis District personnel documented excessive underseepage and the formation of sand boils during the flood events of 1973, 1993, and 1995. Despite continued investigations, analyses, and the addition of control measures since the 1950s, excessive underseepage and the formation of sand boils have been increasing with subsequent flood events. For example, District personnel documented higher frequencies of sand boils during the 1995 flood than during the record flood of 1993. They also noted that sand boils tend to reoccur at the same locations, indicating a cumulative effect of internal erosion on the foundation (Sills 2000, 2001) and not a healing effect. It was also observed that sand boils frequently occurred both where control measures were employed (i.e., relief wells) and in other reaches where control measures were not warranted by previous analysis. Finally, it was surprising to District personnel that piping during the 1995 flood occurred in reaches where there was no piping during the record 1993 flood.

During the 1990s, the USACE Vicksburg District documented a worsening of piping along some of its levees in the Lower Mississippi River Valley. Specific problem areas occur along Lake Providence, LA, and Buck Chute, MS, levees, where the District has noted piping to occur at lower river stages than previously observed. This is similar to the St. Louis District observations after the record 1993 flood in the middle Mississippi River. The Vicksburg District is highly concerned that the integrity of these levees' foundations may be declining and has launched a major research study with Louisiana State University to investigate the role of piping in levee failure. The study will be completed in late 2004.

Similarly, seepage through and beneath the levees during flood events is a major concern for the USACE Sacramento District (CESPK). Recent flood events in 1986 and 1997 put a severe strain on the levee system, causing a number of levee failures that resulted in several deaths and hundreds of millions of dollars of property damage. The CESPK has noticed a deterioration of its levee system over time (USACE 2003) and is actively installing new seepage control measures. However, criteria, levels of protection, and costs are issues of intense debate, and the major costs of these control measures threaten the viability of some projects. Other USACE Districts, including Omaha, Kansas City, and Rock Island, are facing these same issues.

These observations indicate that piping has a cumulative effect of internal erosion on the foundation of levees. It is also clear that, after decades of combating piping and seepage, we have few tools to measure their effects or control their progression. The analysis principles and equations developed for design by USACE in the 1950s are still being used, but do not evaluate seepage as time dependent. These observations and others have provided the motivation for the current study that presents an innovative analysis of the piping phenomenon along the middle Mississippi River levees. The approach was to map the documented piping locations for the 1973, 1993, and 1995 flood events (Table 1) and observe the geometry, geology, and seepage characteristics of the levee at these locations to arrive at an empirical model that would statistically correlate piping incidence to these variables. The goal of the model is to establish the potential for piping along reaches of levee according to physical characteristics and past performance. Entire levee systems could be mapped, according to their potential for piping, using this model. This map would be beneficial in directing limited resources during flood fights toward the most susceptible of levee reaches. The model could also be used as a planning tool for decision makers to apply priority to levee reaches for upgrade and maintenance. In addition, the database required for the model could also act as a much-needed repository for levee geologic, geotechnical, and operation and maintenance documentation. Many times this information is scattered throughout District offices and is difficult to gather for research investigations or special analysis.

Table 1
Summary of the 1973, 1993, and 1995 Floods

Flood Year	Frequency of Occurrence	Duration, days	Estimated Damage, $	St. Louis Gage Max Crest, ft	Average Net Head Prairie Du Rocher, ft	Average Net Head Fort Chartres, ft
1973	< 50 year	77	170 million	43.3	13	13
1993	50 to 100 year	80	20 billion	49.5	18	20
1995	< 50 year	n/a	n/a	43.8	10	11

**Data taken from U.S. Coast Guard (1998), Shannon and Wilson (1995), and USACE (1976).*

2 Background

The U.S. Army Engineer Research and Development Center Geotechnical and Structures Laboratory (GSL), with the assistance of the University of Mississippi, developed a geographical information system (GIS) database specific to piping along the middle Mississippi River from Alton to Gale, IL, levees. Using this database and related software as tools to implement methods of analysis, a detailed assessment of levee performance was made at two selected sites, Prairie Du Rocher and Fort Chartres levee districts. The initial goals were to: (a) observe whether current seepage control measures are working by identifying where sand boils are occurring and (b) compare sand boil location and frequency between flood events.

The research goal is to develop an empirical model useful in correlating levee characteristics with piping for prediction purposes and levee operations and maintenance purposes. The steps necessary to achieve this goal are to:

a. Create a GIS database describing piping and levee characteristics for each 250-ft segment or reach of levee.

b. Analyze piping occurrences and their spatial arrangement.

c. Perform statistical analyses related to the spatial distribution of piping events, the location of previous piping events, and selected geotechnical related variables.

d. Establish an empirical model through regression analysis and validation to produce a categorical rank (low, medium, and high) for each analyzed levee reach based on its potential for piping during future high-water events.

Sites were nominated from within a 240-mile levee system between Alton and Gale, IL, in the St. Louis District, which includes urban, suburban, and agricultural levee districts. Of these sites nominated for the study of piping, the Prairie Du Rocher and Fort Chartres levee districts were selected for detailed analysis (Figure 3 and Table 2). These agricultural levee districts, located in Monroe and Randolph counties, IL, were selected because the site geology could be more readily detected than in urban districts.

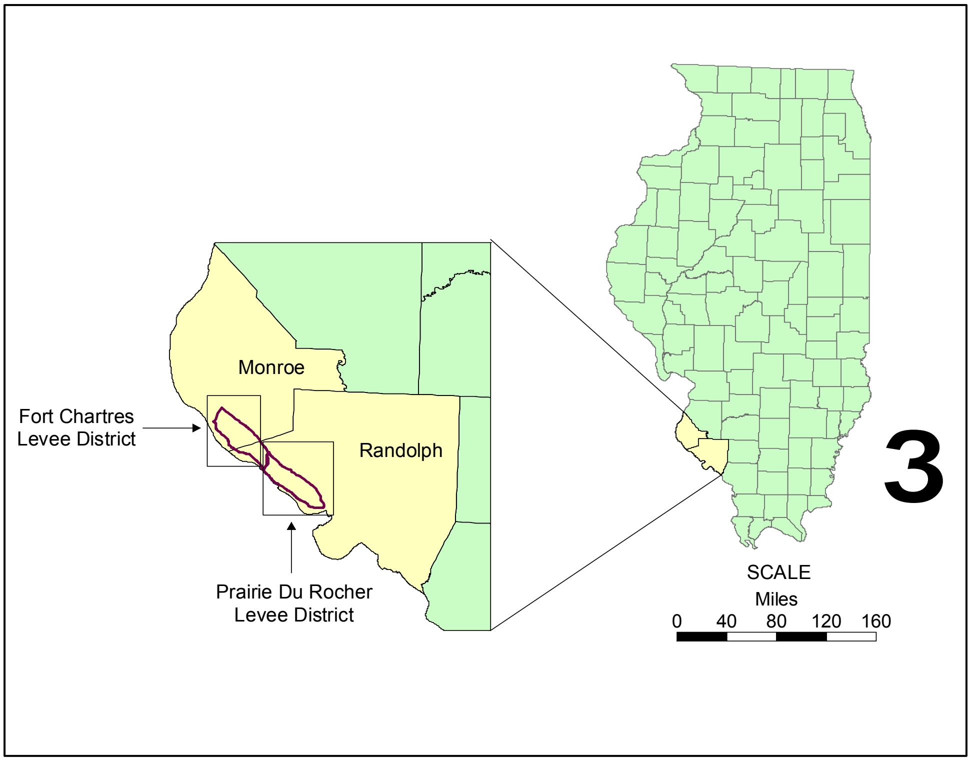

Figure 3. Locations of the Prairie Du Rocher and Fort Chartres levee districts

Table 2
Piping Summary for the 1973, 1993, and 1995 Floods

	Prairie Du Rocher Levee District			Fort Chartres Levee District		
Flood Year	**No. of 250-ft Reaches Affected by Piping**	**Percent of Levee Affected by Piping**	**Average Net Head, ft**	**No. of 250-ft Reaches Affected by Piping**	**Percent of Levee Affected by Piping**	**Average Net Head, ft**
1973	0	0	13	1	< 1	13
1993	24	5	18	18	~ 4	20
1995	49	14	10	37	~ 5	11

*Data taken from Shannon and Wilson (1995) and USACE (1993, 1995).

The floodplain of the Mississippi River located along the Prairie Du Rocher and Fort Chartres levee districts is approximately 3 miles wide. The predominant geomorphology within these districts is referred to as chutes and bars (Smith and Smith 1984). Since the 1950s, 15 floods or high-water events have occurred along the middle Mississippi River (USACE 1976 and USCG 1998). Although each of these high-water events is important, the floods of 1973, 1993, and 1995 are addressed since records of piping during these events for the Prairie Du Rocher and Fort Chartres levee districts are well documented (USACE 1976, 1993, 1995).

The flood of 1973 occurred in late April and brought floodwaters of record height to the levees along the middle Mississippi River (USACE 1976). As noted in Table 1, the average net head or height of floodwaters resting against the levees of the Prairie Du Rocher and Fort Chartres levee districts was near 13 ft. Although this flood sustained a maximum crest that was 13.3 ft above flood stage for the St. Louis, MO, gage and lasted a record 77 consecutive days, no piping was reported in the Prairie Du Rocher levee district. In Fort Chartres, piping was isolated to only a small section of the levee.

The 1993 flood tested the levees again and broke all records set by previous floods along the middle Mississippi River. This flood event occurred during the summer months, and the duration of flooding lasted 80 consecutive days (Lovelace and Strauser 1996). The height of floodwaters within the Prairie Du Rocher levee district averaged 18 ft while the average in Fort Chartres was even higher at 20 ft, with some of the levees in this district being overtopped. Because of overtopping in the Fort Chartres levee district, the entire district was inundated. The Prairie Du Rocher district suffered minor overtopping, but no levee failed as a result. In relation to piping, over 2,600 ft or approximately 4 percent of the levees within Fort Chartres were affected prior to inundation. Over 4,500 ft or approximately 5 percent of the levees within the Prairie Du Rocher levee district were affected by piping.

Although precipitation that led to the spring flood of 1995 was not directly centered over the middle Mississippi River valley, it caused floodwaters along levees within Prairie Du Rocher to rise to an average height of 10 ft (USCG 1998). The average height of floodwaters along levees within Fort Chartres was nearly 11 ft. Although floodwaters reached heights near those of the 1973 flood in which piping was only a minor problem, piping during the 1995 flood event in the Prairie Du Rocher and Fort Chartres levee districts exceeded piping in the 1993 flood. In Prairie Du Rocher, approximately 14 percent of the levees within the district were affected by piping, which was an increase of approximately 8 percent from the percentage of levees affected by piping in 1993. The number of piping observations within the Fort Chartres levee district showed an increase of approximately 5 percent from the 1993 to the 1995 flood. Table 2 provides a summary regarding the amount of levee affected by piping within these two levee districts during the 1973, 1993, and 1995 flood events. The paradox that piping incidents are more numerous during the lower intensity flooding of 1995 than the greater floods of 1973 and 1993 indicates some potential for cumulative effects that cannot be easily explained and, as mentioned, provided motivation for this study.

3 GIS Database and Piping Model Development

A GIS database of geotechnical information related to piping and seepage analysis was developed for the Prairie Du Rocher and Fort Chartres levees. Variables included in the database were those identified in previous studies and are typical and atypical for conventional seepage analyses. Source data were gathered for incorporation into the levee GIS from ERDC and USACE, St. Louis reports, U.S. Geological Survey (USGS) websites, and GPS field data obtained by the authors. Pertinent themes and theme attributes were then designed to perform a "reach-by-reach" statistical analysis of the frequency of piping. In this analysis, a reach refers to a levee segment of 250-ft length, in contrast to typical seepage studies where a "reach" refers to a length of levee having fairly uniform foundation and construction characteristics. The piping model developed herein was based on data from the Prairie Du Rocher levee district and was tested on a neighboring levee district (Fort Chartres).

The piping that occurred during the flood of 1993 was documented and described by numerous USACE engineers and local officials. These observations were summarized from field notes and compiled into a single report by the St. Louis District (USACE 1993). Using 1993 locations of piping, each 250-ft levee reach in the GIS database affected by piping was assigned a value of one, while the nonaffected levee reaches were assigned a value of zero. For levee reaches in Prairie Du Rocher, this resulted in 24 reaches being assigned a value of one and 325 reaches being assigned a value of zero. In Fort Chartres, an even smaller number of levee reaches were affected by piping, with only 18 reaches being assigned a value of one and the remaining reaches being assigned a value of zero.

USACE and local personnel also recorded piping within the Prairie Du Rocher and Fort Chartres districts during the 1995 flood. Similar to 1993, the information obtained in 1995 was compiled into another single report (USACE 1995). For the 1995 flood, 49 of the levee reaches within the Prairie Du Rocher levee district were assigned a value of one (an increase of approximately 8 percent from piping in 1993), while 37 reaches in the Fort Chartres levee district were affected by piping (an increase of approximately 5 percent from the 1993 flood). The remaining levee reaches in each district were assigned a value of zero, for no piping observed (Table 2).

Model Variables

Using the levee GIS, an assessment of piping locations within these two levee districts was undertaken for the flood events of 1993 and 1995. This study attempted to use all available variables that offered primary, measured properties of the conditions existing at or beneath the levees within the studied districts from the variables listed in Table 3.

Table 3
Piping-Related Variables

No.	Brief Variable Description	Symbol	Noted Previous Investigators
1	Net Head on the levee (ft)	H	USACE (1956a,b)
2	Transformed confining layer thickness (ft)	Z_b	Turnbull and Mansur (1959)
3	Vertical permeability of riverside and landside top blanket (cm/sec^2)	k_{br} and k_{bl}	USACE (1956a,b)
4	Effective thickness of the substratum (ft)	d	USACE (1941)
5	Ratio of horizontal permeability of the substratum with vertical permeability of the top stratum	k_h/k_v	USACE (1956a,b)
6	Distance from landside toe of the levee to effective seepage entry (ft)	s	USACE (1956a,b)
7	Distance from landside toe of the levee or berm to effective seepage exit (ft)	x_3	USACE (1956a,b; 1976)
8	Critical gradient through the top stratum landside toe of the levee	i_c	USACE (1941; 1956a,b; 1976)
9	Surface geologic deposit	based on type	Fisk (1945), USACE (1956), Kolb (1975), Smith (1988), Saucier (1994)
10	Surface geologic configuration	based on alignment with the levee	Fisk (1945), USACE (1956a,b), Kolb (1975), Saucier (1994)
11	Blocked exit	based on alignment with the levee	USACE (1976)
12	Effective grain size of aquifer	D_{10}	USACE (1956a)

Variables were selected that proved to be statistically significant in the best regression model for levee reaches in the Prairie Du Rocher levee district. This meant that a number of potentially meaningful variables were omitted because they did not prove to be statistically significant in the regression model development. For example, the location of relief wells was determined to be statistically insignificant in the Prairie Du Rocher levee district. The variables that were retained in the regression model are:

a. Transformed confining thickness of the top stratum (Z_b).

b. Effective grain size (D_{10}) of the substratum aquifer.

c. Geologic configuration of swales and abandoned channels to the levee.

Transformed confining layer thickness

Transformed confining layer thickness was found to be critically important through various underseepage and piping studies conducted for levees along the middle and lower Mississippi River during the 1950s. In his review of underseepage and piping studies, this focused mostly on levees of the Mississippi River, Wolff (2002) notes that underseepage and piping are inversely related to the thickness of the top stratum. Although the transformed confining layer thickness requires some interpretation in achieving its final values, it is considered a measured variable. In this study, estimates for this variable were derived from a set of empirical criteria adopted from Turnbull and Mansur (1959). Besides thickness, which serves to resist upward hydrostatic pressures from the pervious substratum, the heterogeneity and presence of discontinuities such as root holes within the top stratum are additional properties of the top stratum that influence the occurrence of piping (USACE 1941) but are not quantified in this study or in conventional analysis.

The data used to develop estimates of transformed confining layer thickness for the Prairie Du Rocher levee district consisted of 218 boring locations through the top stratum. Ordinary kriging estimates of confining layer thickness were obtained using the tools available in Environmental Systems Research Institute's ArcGIS 8.1 for geostatistical interpolation. Due to the orientation of boring locations and the spacing between sample locations, a circular search neighborhood incorporating 10 neighbors was used. Using the interpolated surface obtained from the application of ordinary kriging, a minimum value for transformed confining layer thickness was obtained for each levee reach. If soil borings along the levee reach existed, estimates of minimum transformed confining layer thickness from the interpolated surface were compared with these borings. In cases where true values for transformed confining layer thickness were less than those obtained from the mathematical surface, the true values were used for analysis.

Effective grain size, or D_{10}

The effective grain size for a soil sample is defined as the particle size for which 10 percent of the material by weight is smaller than that size (Dunn et al. 1980). Underseepage studies performed by USACE (1956a,b) showed a correlation between horizontal permeability of the substratum and effective aquifer grain size, or D_{10}. This relationship suggested that permeability of the pervious substratum determined through pump tests was correlated to the effective grain size (D_{10}) of the substratum. The permeability of the substratum is also a factor that influences the location and severity of piping (USACE 1956a). A more permeable substratum allows increased amounts of seepage to flow landward beneath the levee, increasing the hydrostatic pressure that can develop at the boundary between the top stratum and the pervious substratum.

Geologic configuration of swales and abandoned channels

Surface geology is a major factor influencing the location of underseepage and piping, especially in regard to levee alignment. As determined by the USACE (1956a), point bar and chutes and bar deposits are the most problematic of the various surface geologic deposits present along middle Mississippi River levees because they are the most heterogeneous deposits that compose the top stratum. This problem is also magnified by the fact that the majority of levees along the Mississippi River are founded on these types of deposits (Kolb 1975; Smith and Smith 1984).

Within point bar deposits are geomorphologic features known as swales (Figure 4), which are composed of relatively fine-grained sediments that extend below the confining layer below the top stratum. Figure 5, showing the parabolic cross section of the swales intersecting a levee profile, illustrates this. Swales serve as small-scale barriers that restrict flow sufficiently to focus underseepage within the substratum along paths adjacent to the swales. Within chutes and bar deposits are geomorphologic features known as abandoned channels, which are also fine-grained features, but they are much larger than swales. They extend deeper within the sediments than swales and have a greater aerial extent, allowing abandoned channels to serve as barriers to underseepage to a greater extent than swales.

The orientation of swales and abandoned channel deposits, also referred to as channel-fill deposits (USACE 1956b), are influential in the location of underseepage and piping, especially where they intersect the levee at an unfavorable orientation or configuration. Investigations by the USACE (1956a) and Kolb (1975) identified orientations of swale and abandoned channel deposits with the levee and described their influence on piping. The most severe cases of piping tend to occur where these features intersect the levee at an acute angle or parallel the levee toe at a short distance (Kolb 1975). These fine-grained surface features serve to decrease the exit distance for underseepage, thereby concentrating the groundwater flow close to the levee toe. This increases the local exit seepage gradient (hydraulic gradient) promoting the formation of sand boils between the landside levee toe and these elongated features (Kolb 1975). Kolb also noted that sand boils occur in the obtuse angle of the swale-levee intersection, but the distribution of sand boils in this location are more random.

A plan view of swales within each levee district was interpreted from 1-m ground resolution digital orthorectified aerial photography (USGS 1992-2000). Interpretations of swales (Figure 6) was provided by Villanueva[1] from her study of the geomorphology within the Prairie Du Rocher levee district. Using this work as a guide, swales within the Fort Chartres levee district were also identified and digitized. Although Smith and Smith (1984) had mapped abandoned channels in the middle Mississippi River, the mapping was at too large of a scale and

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[1] Villanueva, Evelyn. (2002). Geomorphic maps of Prairie Du Rocher, IL, unpublished. U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory, Vicksburg, MS.

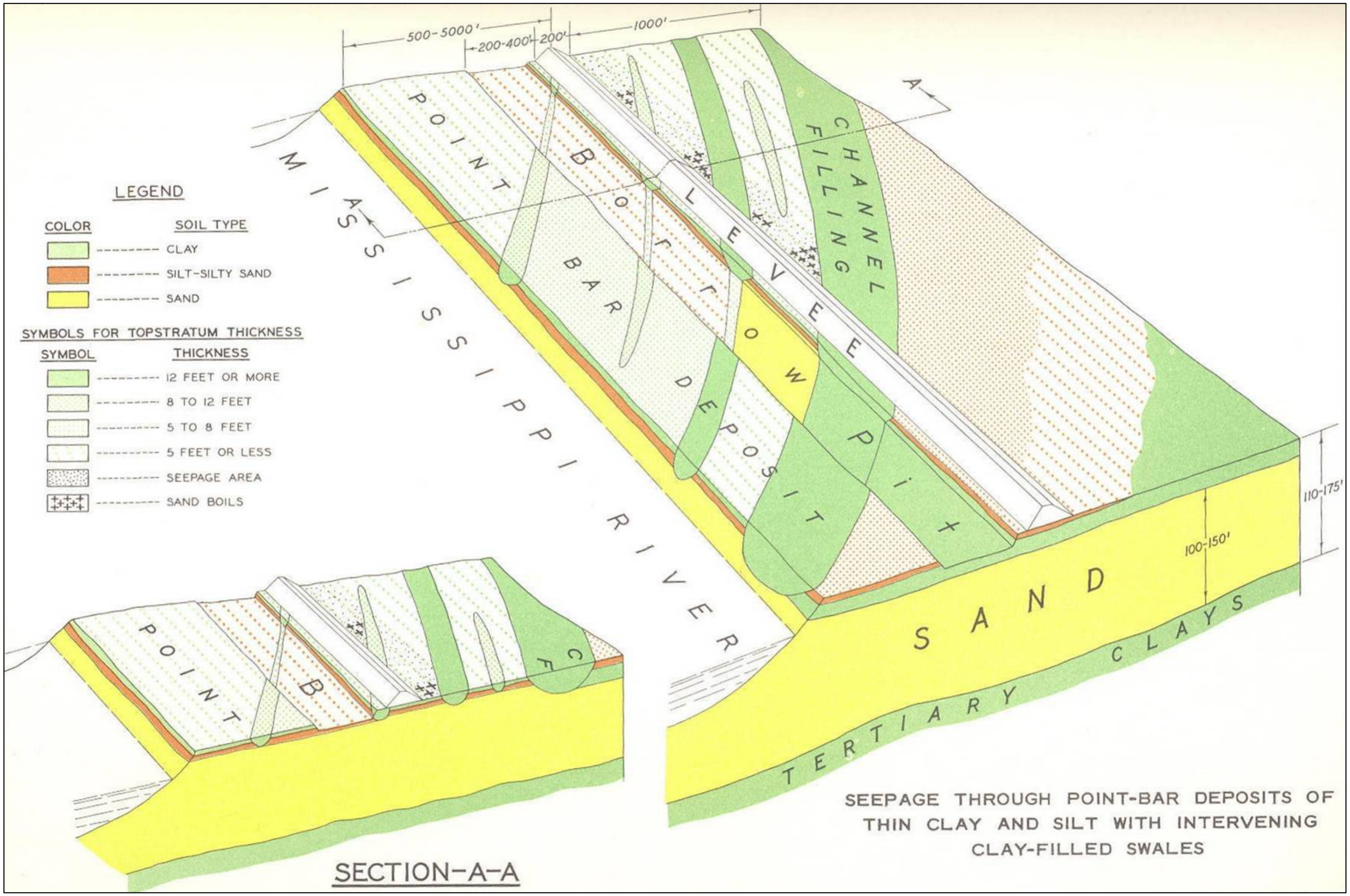

Figure 4. Influence of surface geology and levee orientation on seepage (USACE 1956a)

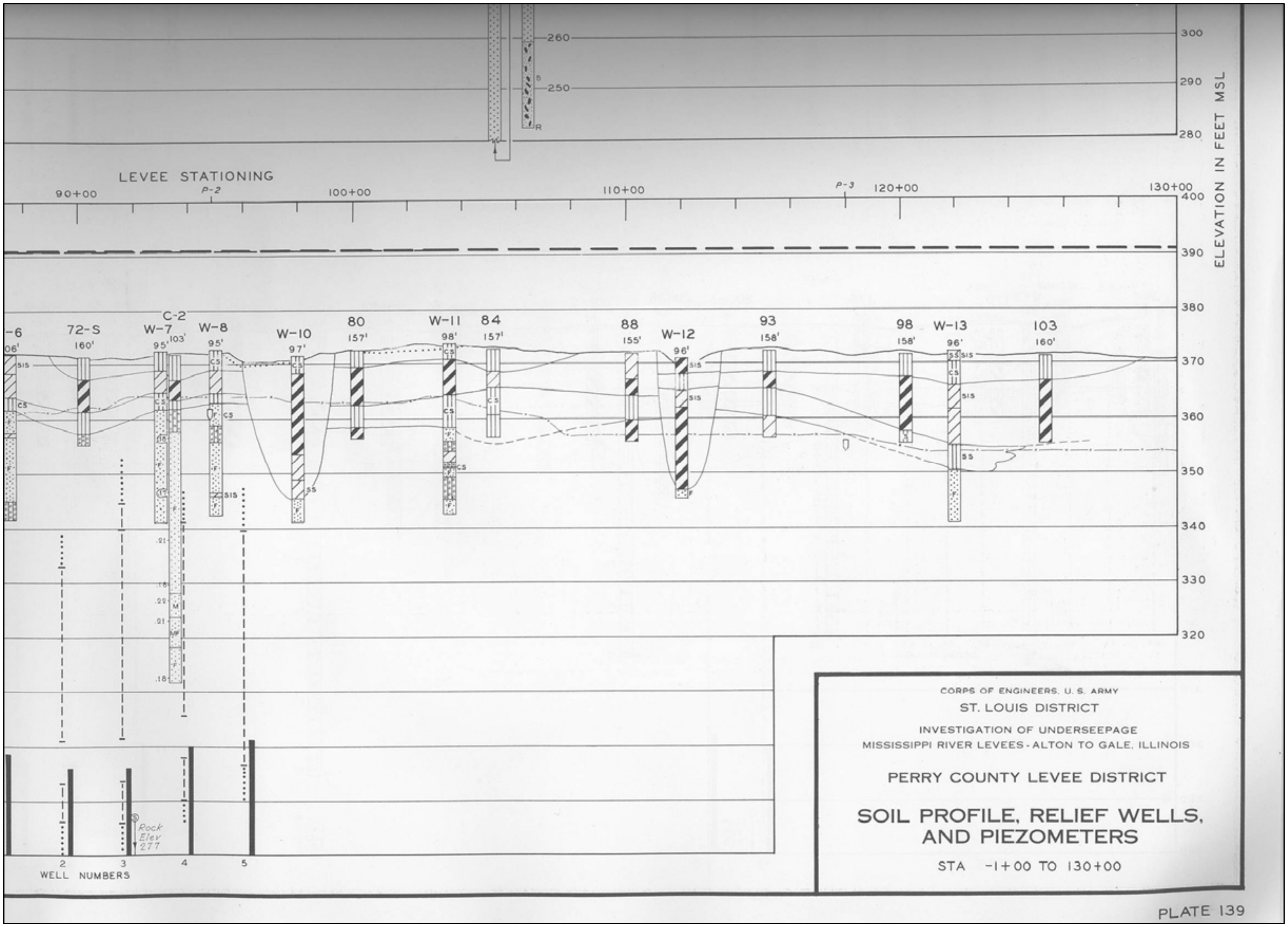

Figure 5. Typical profile developed along Mississippi River levees from Alton to Gale, IL, showing low permeability, parabolic-shaped, channel-fill deposits (USACE 1956a)

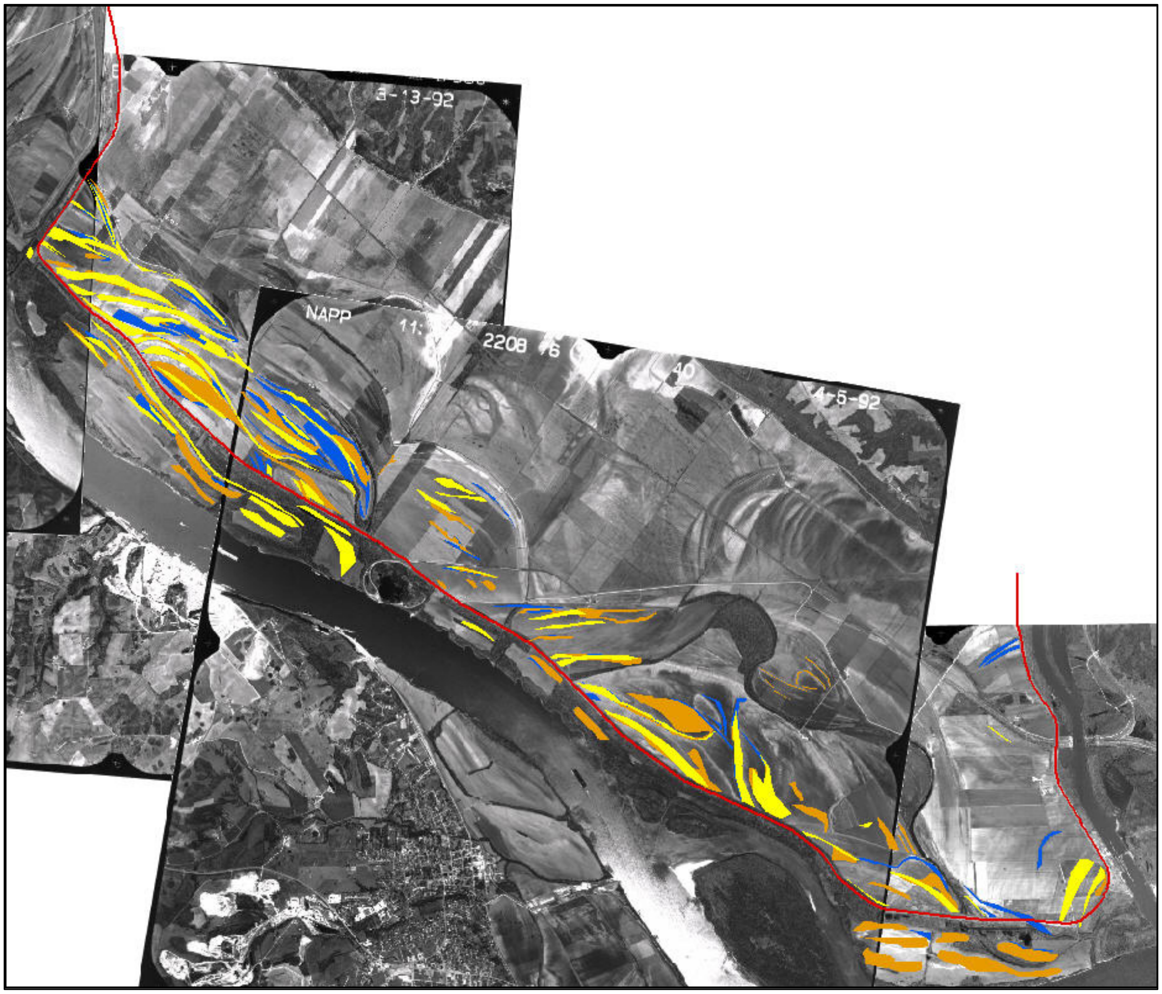

Figure 6. Detailed mapping of smaller swales, Prairie Du Rocher, IL. Colors denote swales visible in 1992, 1994, and 1996 aerial photos

therefore lacked the detail required for this model. The Smith and Smith (1984) maps did not include the ubiquitous smaller swales shown in Figure 4 that are directly related to piping. Figure 5 shows a typical profile of these features, along a section of levee between Alton to Gale mapped by USACE (1956a). Sand boils are ubiquitous adjacent to these features during high-water events as confirmed by 1973, 1993, 1995, and earlier observations.

Channel-fill deposits are recognized in the model by introducing a variable to denote the existence of unfavorable geologic conditions. Each 250-ft levee reach in the studied districts is assigned a value for this variable based on a geomorphologic interpretation of local conditions. The rankings range from zero, for levee segments having a favorable orientation, to one, for the most unfavorable or problematic swale positioning. The significance of this variable compared to the others is that swale location and aerial extent are not explicit factors in routine seepage analyses.

Regression Model Development

Logistic regression is well suited for analyses similar to this study because it is capable of predicting binary outcomes (e.g., piping, no piping) based on predictor variables that are continuous (e.g., effective grain size), discrete (e.g., geologic configuration), or a mix, as is the case here (Tabachnick and Fidell 1996). Logistic regression also makes no assumptions about the distribution of the predictor, the form of the relationship between the outcome and the predictor variables, or the frequency of occurrence of the outcome.

Stepwise linear and logistic regression were applied to the levee segments of Prairie Du Rocher to identify the variables listed in Table 3 that are statistically significant at the 95-percent confidence level for the 1993 dataset. Only the logistic regression is discussed in this report. While not all variables remained significant at this level in the models, the same variable set was retained for all models for consistency. In logistic regression, or the logit, the relation between the probability of experiencing piping within an individual levee segment i, π_i, and values of the independent variables is described by the logistic function (see, for example, Le 1998) in Equation 1:

$$\pi_i = \frac{\exp\left(\beta_0 + \beta_1 Z_b + \beta_2 D_{10} + \beta_3 G\right)}{1+\exp\left(\beta_0 + \beta_1 Z_b + \beta_2 D_{10} + \beta_3 G\right)} \qquad (1)$$

where

$\beta_0, \beta_1, \beta_2, \beta_3$ = regression coefficients

Z_b = transformed confining thickness of the top stratum

D_{10} = effective grain size

G = geologic configuration of swales and abandoned channels to the levee

Here, the independent variables of the model, Z_b, D_{10}, and G, are defined as above for each levee segment, while the coefficients β_0 through β_3 are determined in the logistic model to maximize the maximum likelihood function (see, for example, Menard 2002). The basic premise behind maximizing this function is to obtain the best estimates of the coefficients that maximize the chance of a particular set of independent variable values occurring. A problem with using logit to assign a relative risk of an event occurring is that no single, well-accepted goodness-of-fit test exists for this method. However, one goodness-of-fit test that does exist and is regarded as noteworthy by Veall and Zimmerman (1996) is pseudo-R^2 developed by McFadden (1973). An example of logistic regression modeling described by Borooah (2002) reported that acceptable McFadden pseudo-R^2 values ranged from 0.09 to 0.15.

Another method of addressing the goodness-of-fit for a logistic regression model is to assess the predictive ability of the model (Pampel 2000). This can be done in the case where the dependent variable is binary in nature by looking at the accuracy of both predicted hits (the frequency of true positive predictions) or misses (the frequency of true negative predications). In performing this comparison, a prediction rule or set of prediction rules must be adopted to interpret what exactly would be considered a hit or a miss or a predicted case of piping compared to a case of no piping (Menard 2002). These predictions will require the creation of categorical threshold values to define the most likely locations for piping occurrence from locations categorically less likely to experience piping. The establishment of two logistic regression models and associated proposed threshold values for classifying categories of piping potential is introduced in the following section. One model is created using 1993 data as a predictive tool, and one model is created using 1993 and 1995 data as a predictive tool for future piping events.

4 Model Applications

Modeling 1993 Piping Events

The first model developed for the Prairie Du Rocher (PDR-93 Logit) levee district involved the three independent variables found to be significant: transformed confining layer thickness, effective aquifer grain size, and unfavorable geologic configuration. These three independent variables were then regressed against the binary (zero for no piping and one for piping) dependent variable of 1993 piping locations using the multiple logistic regression method (Table 4).

Table 4
PDR-93 Logit Model Summary Statistics

Model Name	Model Test	Model Significance	Independent Variables	Coefficient Value	P-value
PDR-93 Logit	McFadden pseudo-R^2	0.165	Intercept	-7.7432	<0.0001
			Transformed confining layer thickness, Z_b	-0.0526	0.4630
			Effective aquifer grain size, D_{10}	26.9941	0.0010
			Unfavorable geologic configuration	1.9084	0.0010

The PDR-93 Logit with a McFadden pseudo-R^2 value of 0.165 was classified as significant. In addition, this model can be assessed based on predictive ability, but this requires the selection of arbitrary threshold values for classifying the likelihood of piping occurrence in each 250-ft levee segment. The 1993 Logit model (Equation 2) was created to provide the best possible fit for the 1993 data of the Prairie Du Rocher levee district such that these high, medium and low categories could be selected (Figure 7).

PDR-93 Logit Model:

$$\ln \frac{\pi_{93}}{1-\pi_{93}} = -7.743 - 0.0526\,Z_b + 26.99\,D_{10} + 1.908\,G \qquad (2)$$

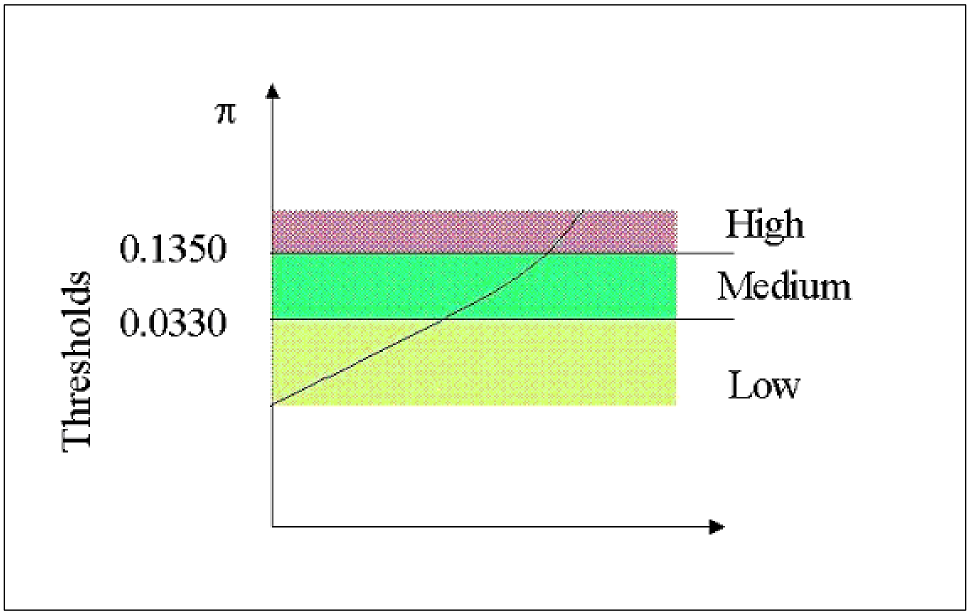

Figure 7. Best-fit high, medium, and low threshold values of the empirical model estimating piping potential, PDR-93 Logit model

Figure 8 shows the location of piping events (marked in blue) in 1993 with the color-coded levee reaches within the Prairie Du Rocher levee district. The majority of levee reaches within the high and medium categories occur near the intersection of swales with the levee and where swales run parallel to the levee.

While the 1993 Logit model was created to provide the best possible fit for the 1993 data of the Prairie Du Rocher levee district, the same model was applied to the Fort Chartres district. This application was intended to assess the ability of the model to “predict” the likelihood of 1993 piping events at a comparable site. Essential in this model application are threshold levels defined previously for the Prairie Du Rocher levee district. These thresholds were applied to the estimated piping potential, separating each 250-ft reach in the Fort Chartres levee district into a category of low, medium, or high potential for future piping incidents.

Table 5 shows a summary of the logistic regression modeling of piping potential in 1993 along with records of the actual 1993 piping occurrences. Notice that the categories of the probability of piping potential reasonably match the actual piping occurrences, with decreasing percentages of segments with respect to observed piping when high, medium, and low classes are considered.

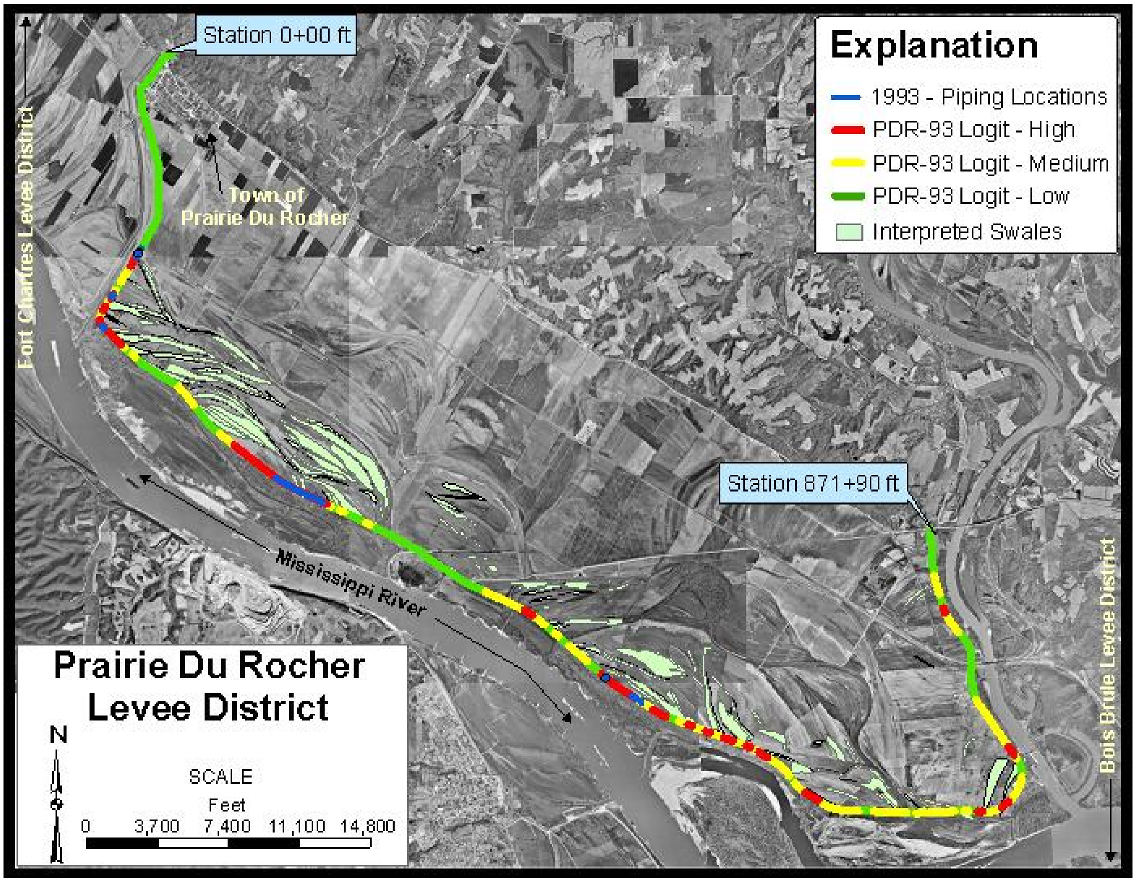

Figure 8. Coded levee reaches in relation to the location of piping in 1993 and identified swales for the Prairie Du Rocher levee district

Table 5
Results of the 1993 Logistic Regression Model and Actual 1993 Piping Events

Model	Piping Potential Assigned by Model	No. of Reaches Predicted in this Rating	No. of Reaches in This Rating That Actually Piped	Percent of Reaches in This Rating That Actually Piped
PDR-93 Logit	High	61	16	26
	Medium	111	4	4
	Low	177	4	2
	Total	349	24	7
FTC-93 Logit	High	62	7	11
	Medium	107	7	7
	Low	109	1	1
	Total	278	15	5

Modeling 1995 Piping Events

The 1995 observations of piping were used as the dependent variable in creating an additional model while using only two independent variables. The independent variables used in regression were piping locations in 1993 and the levels of predicted piping potential from the 1993 logistic regression model for each levee reach (actual values obtained for each reach). Table 6 summarizes the basic model coefficient values obtained for the 1995 logistic regression model. Equation 3 expresses the PDR-95 empirical model.

Table 6
PDR-95 Logit Model Summary Statistics

Model Name	Model Test	Model Significance	Independent Variables	Coefficient Value	P-value
PDR-95 Logit	McFadden pseudo-R^2	0.128	Intercept	-2.3532	<0.0001
			Piping Potential Values from PDR-93 Logit	2.9881	0.0880
			Piping Locations in 1993	2.3851	<0.0001

PDR-95 Logit model:

$$\ln \frac{\pi_{95}}{1-\pi_{95}} = -2.353 + 2.988\,\pi_{93} + 2.385\,P_{93} \qquad (3)$$

The importance or value of knowing where previous piping events have occurred in categorizing the piping potential of individual levee reaches was demonstrated through the statistical significance (P-value <0.0001) for the location of piping in 1993 and the large coefficient or weight assigned to this variable in the 1995 model. The large coefficient given to the locations of piping in 1993 in the model resulted from 37 percent of the piping locations between 1993 and 1995 being correlated. The authors believe this strong correlation occurred, because these pipes have not healed as once thought but have remained as preferred pathways of higher permeability, needing less gradient to reactivate in future flood events.

To determine whether the 1995 model had a better predictive ability, the ability to categorize the piping potential of individual levee reaches was calculated for both Prairie Du Rocher and Fort Chartres. Table 7 shows a summary of the logistic regression modeling of piping potential in 1995 along with records of the actual 1995 piping occurrences. Figure 9 presents the coded levee reaches in relation to the location of piping in 1995 and identified swales for the Fort Chartres district.

Two effects are noted when comparing Table 5 and Table 7: (a) there is more piping occurring in 1995 and (b) the high piping potential is predicted in fewer reaches when previous piping is considered. Thus using previous piping as an

Table 7
Results of the 1995 Logistic Regression Model and Actual 1995 Piping Events

Model	Piping Potential Assigned by Model	No. of Reaches Predicted in this Rating	No. of Reaches in This Rating That Actually Piped	Percent of Reaches in This Rating That Actually Piped
PDR-95 Logit	High	26	15	58
	Medium	123	19	15
	Low	200	15	8
	Total	349	49	14
FTC-95 Logit	High	27	15	56
	Medium	104	12	12
	Low	127	9	6
	Total	278	36	13

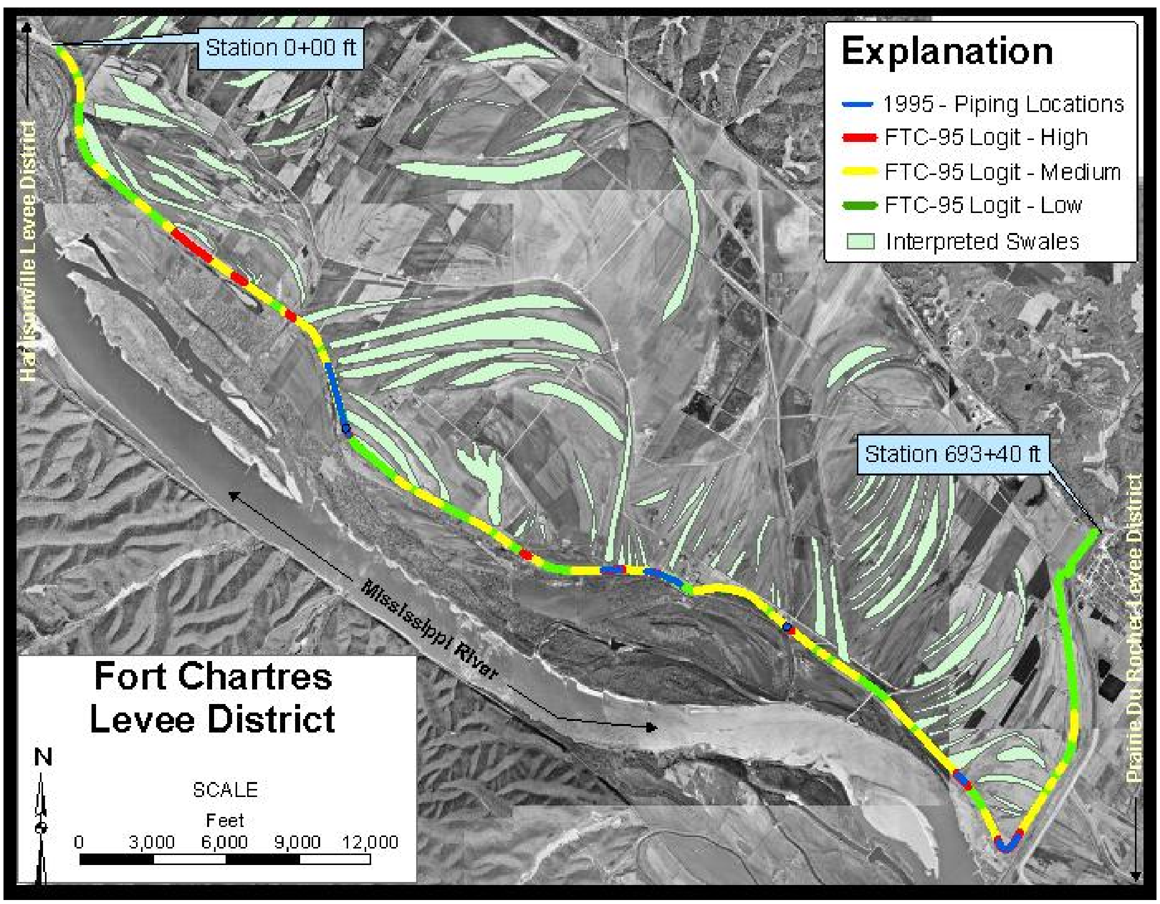

Figure 9. Coded levee reaches in relation to the location of piping in 1995 and identified swales for the Fort Chartres District

independent variable eliminates some false positives, allowing resources to be concentrated in a few critical reaches.

The success of the 1995 model is more simply illustrated by the sparse number of reaches coded red in the Fort Chartres levee map (Figure 9) versus the numerous red reaches displayed on the 1993 Prarie Du Rocher piping potential map (Figure 8). This clearly demonstrates the value of documenting previous piping locations.

Documentation of Piping Events

Piping locations must be clearly documented during high-water events to enable District engineers to evaluate the cumulative effects (progression) of erosion under the levees with each flood. This requires additional resources and commitment from the local officials and USACE engineers to standardize their methods of documenting sand boils. Preferably, engineers should document seepage at several stages during the rise in river stage, therefore the critical gradient at which sand boils occur could be better estimated. Because of recent economic hardships, USACE Districts are losing their resources to obtain this type of monitoring data.

However, piping locations are of high importance to the predictability of the empirical model developed by this study and expressed by Table 7. During the study it was painfully clear that no significant effort has been applied to standardizing the terminology (i.e., defining the severity) used to describe seepage and sand boils. Thus, the authors propose a standard form illustrated by Figure 10. This type of detailed documentation is necessary for comparisons of seepage severity to be made between flood events and to track worsening conditions of levee foundations. USACE engineers should be trained in using this standard form and should take the task seriously.

A method to identify unknown previous piping locations is an area of research that would be beneficial to this study. The ERDC is currently using new geophysical instruments that define levee soil conditions. In 2004, ERDC will perform a demonstration of these new methods on the urban levees surrounding Sacramento, CA.

Excessive Seepage or Piping Observation
Unified Piping Observation Sheet

Proposed by Joel Kuszmaul, July 2003: Based on the work of Wilson (2003) and Cunny (1987)

A. Report location of Incident (GPS location preferred, levee station is a second choice)
Limit a single observation record to conditions that are uniform and no longer than 200 ft along the levee.

Levee District in which incident is occurring: ____________________________

Option 1: GPS Coordinates

Specify Coordinate system (UTM, Lat./Long., etc.): ____________

Location of piping or underseepage observation using GPS unit:

Start of problem: ________________ ___________________

End of problem: ________________ ___________________

Opition 2: Levee Stationing

Specify distance to nearest station marker: ____________

Location of piping or underseepage observation using stationing (within 100 ft): _____________

B. Report Distance from Levee Toe

Specify location of seepage or piping condition as measured from the toe of levee

(estimate within about 10 ft): ________________

C. Report Category of Severity (use Description to determine the appropriate class, after Cunny 1987)

Select one	Class	Descriptor	Description
☐	I	Light	Area wet or still, ponded water. No obvious exit location for seepage.
☐	II	Moderate	Running water is observed at and beyond toe (or ponded water shows movement). No obvious exit location for seepage.
☐	III	Heavy	Pin boils or small (< 1 in. diam.) pipe openings. Without sand cones but with running water.
☐	IV	Sand boils	Sand boils for pipe openings > 1 in. diam. (but < 12 in. diam.) or any pipe (< 12 in. diam.) with sand cones.
☐	V	Large Boils	Sand boils with pipe openings 12 in. or more diam.

D. Condition of Water (select most appropriate category)

Select one	**Description** (if last category selected, describe condition in words)
☐	Ponded (still)
☐	Running and clear
☐	Running and muddy
☐	Running and carrying sand
☐	Running and _________________

E. Date and Time of Observation Date: _____________ Time: _____________

F. Name of person making observation: ________________________

G. Is immediate notification of District CE Liaison Required?
If a Class IV or Class V observation is noted in Item C, report observation immediately.

Figure 10. Proposed Piping Observation Sheet

5 Conclusions

The empirical models developed from this research proved effective in their ability to assess the potential for piping activity along levee reaches in the Prairie Du Rocher and Fort Chartres levee districts. The outcome of this research has improved the ability to estimate the location of future piping problems along these levees and shows promise for predicting piping along middle Mississippi River levees in general. In addition, the methods used to develop the empirical model should be transferable to other river levee systems, although the significance of some variables may change with differing river systems. The outcome of the model, prediction of potential locations of piping, can be used to prioritize levee remediation and flood fighting efforts.

Transformed confining layer thickness (Z_b), effective aquifer grain size (D_{10}), and unfavorable geologic configuration were the only variables kept as significant in their relationship with past piping incidents in the current middle Mississippi River model. In the development of these variables, each displayed unique characteristics, summarized below.

a. Unfavorable geologic configuration, determined through interpreting the location and alignment of swales, was the most significant and most influential of the variables included within the empirical models.

b. Transformed confining layer thickness, Z_b , exhibited spatial structure in the Prairie Du Rocher and Fort Chartres levee districts consistent with previous findings. The variable (Z_b) produced a negative correlation with piping locations; that is, the smaller the Z_b (the thinner the top stratum), the higher the incidence of piping.

c. Effective aquifer grain size, D_{10} , exhibited no spatial structure within either of the studied levee districts, but D_{10} is a significant variable for predicting future piping incidents.

d. Use of previous piping as a variable in logistic regression models significantly improves the ability of the model to identify likely locations of piping in subsequent flood events.

The authors strongly urge the community of practice to begin standardizing piping observations. A worksheet to assist in the description is proposed as Figure 10.

With further development, these models may provide a basis for comparing the potential for future piping incidents within reaches of separate levee districts. Such a comparison may prove useful in ranking the maintenance needs of levee districts with historical data and separate management groups.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
July 2010	Final report	

4. TITLE AND SUBTITLE
Prediction of Piping Erosion Along Middle Mississippi River Levees–An Empirical Model

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
M. Eileen Glynn, Joel Kuszmaul

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
TOWNS 15

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199
University of Mississippi, P.O. Box 1848, University, MS 38677

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/GSL TR-04-12

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

September 2004 version revised July 2010.

14. ABSTRACT
This research was conducted to address the concerns of U.S. Army Corps of Engineers (USACE) levee engineers regarding the cumulative effects of piping—the movement of sediment from a levee or its foundation by the flow of water. Piping is a levee failure mechanism that has not been analytically defined, but has been observed. Levee inspectors documented an increase in piping from the record flood of 1993 to the lesser flood of 1995 along the Mississippi River. The average net head on the study levee in 1993 was 18 ft and, in 1995, was 10 ft, yet piping incidence was 49 percent greater in 1995. These data support the view that repeated high water events have cumulative effects (increased seepage) and that deficiencies exist in seepage analysis theory. Typically, a seepage analysis is conducted in two dimensions with assumed homogeneous soil properties along a 500- to 1000-ft reach, while in reality piping is a localized failure and occurs near anomalies.

Because the current analysis is lacking three-dimensional geologic information and also time-dependent variables, an empirical approach was taken to determine site factors that are significant to piping. A database of seepage parameters was created, and
(Continued)

15. SUBJECT TERMS
Levees
Mississippi River
Mississippi River geomorphology
Soil erosion
Underseepage

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED			36	

14. ABSTRACT (Concluded).

correlation studies were conducted. The levee system (Prairie Du Rocher, IL) was segmented into 349 reaches of equal length (250 ft). The parameters of highest correlation to piping were previous piping locations (P_{93}), the alignment of the geomorphology and the levee footprint (G), the landside blanket thickness (Z_b), and effective grain size coefficient of the aquifer (D_{10}). Using multivariate logistical regression (Logit) and the significant parameters, two models for prediction of piping locations were developed for the study levee.

The 1993 model predicted 61 reaches as having high piping potential, while only 16 of these reaches actually piped during the 1993 flood. The 1995 model, which included the 1993 piping locations as an independent variable, predicted 26 reaches in the high category, 15 of which actually piped in 1995. The 1995 model predicted fewer reaches in the high category and, therefore, had better predictive capability than the 1993 model. The outcome of the model, prediction of potential locations of piping along these levees, shows promise for predicting piping along the Mississippi River levees in general and other rivers. Also, this research shows that previous piping incidence is the most influential factor in the prediction of future piping and as an indicator of cumulative effects. Therefore, the authors strongly suggest that a standard method for documenting piping (as presented in this report) be adopted by USACE.