Ohio River Levee Performance Evaluation under Flood Conditions

Purdue Geotechnical Society Workshop
West Lafayette, Indiana
April 15, 2016

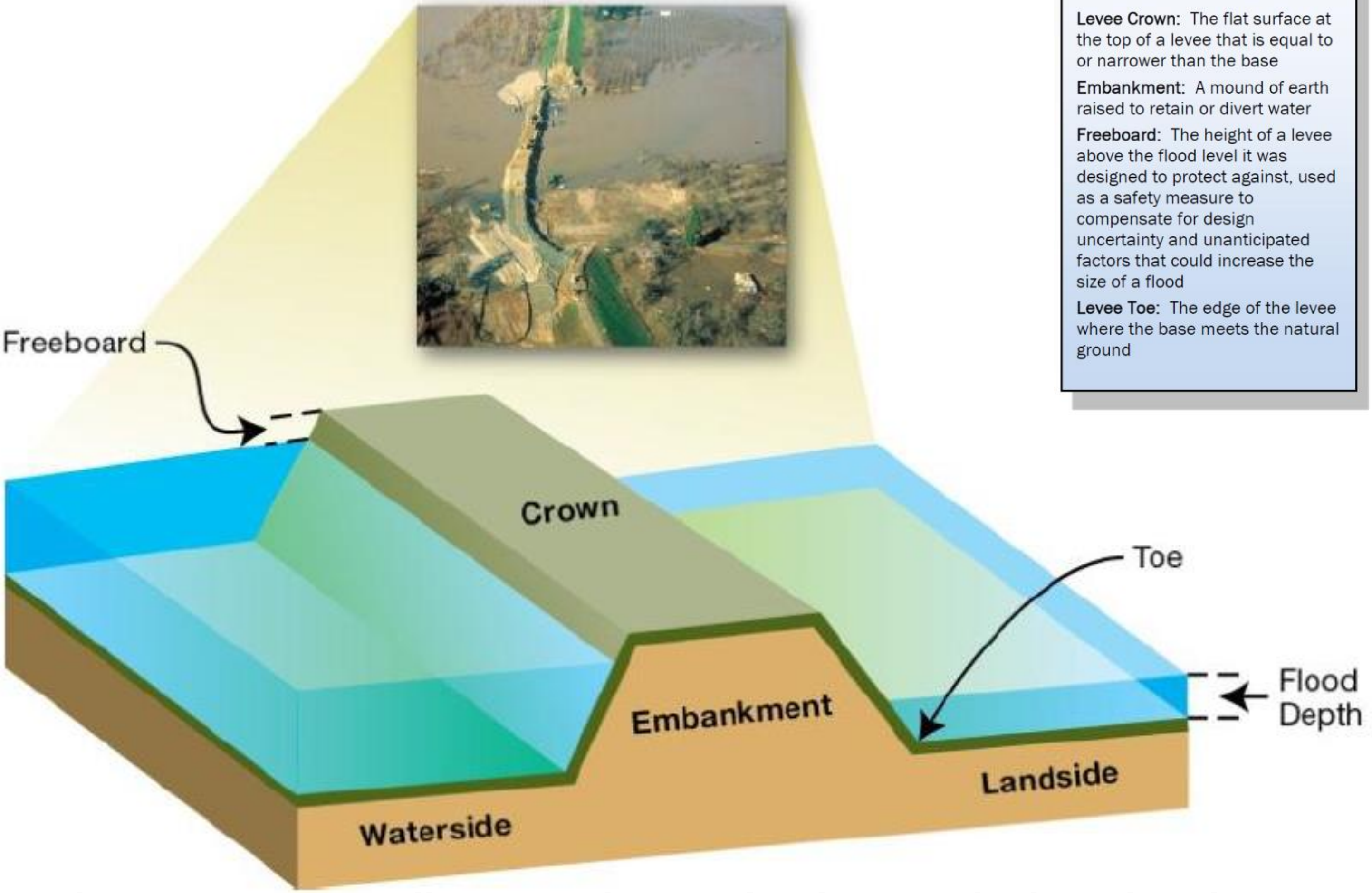
Mundell
Consulting Professionals for the Earth and the Environment

John A. Mundell, P.E., L.P.G.
MUNDELL & ASSOCIATES, INC.
Consulting Professionals for the Earth and the Environment

Talk Outline

- Levee systems in the United States
- Levee performance
- Critical data evaluation and design considerations
- Lessons learned

What is a Levee?



LEVEE COMPONENTS:

Levee Crown: The flat surface at the top of a levee that is equal to or narrower than the base

Embankment: A mound of earth raised to retain or divert water

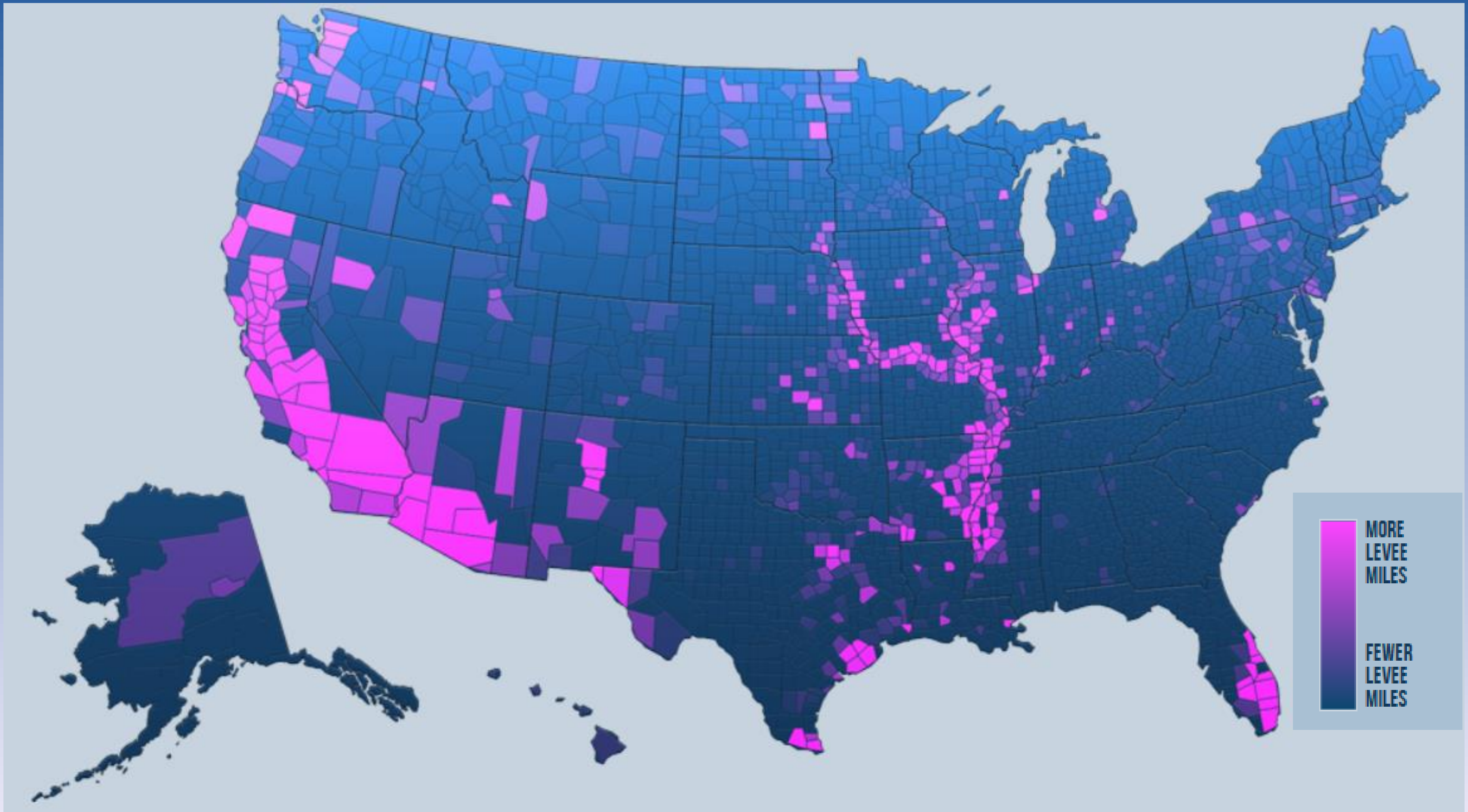
Freeboard: The height of a levee above the flood level it was designed to protect against, used as a safety measure to compensate for design uncertainty and unanticipated factors that could increase the size of a flood

Levee Toe: The edge of the levee where the base meets the natural ground

"a man-made structure, usually an earthen embankment, designed and constructed in accordance with sound engineering practices to contain, control, or divert the flow of water in order to reduce the risk from temporary flooding."

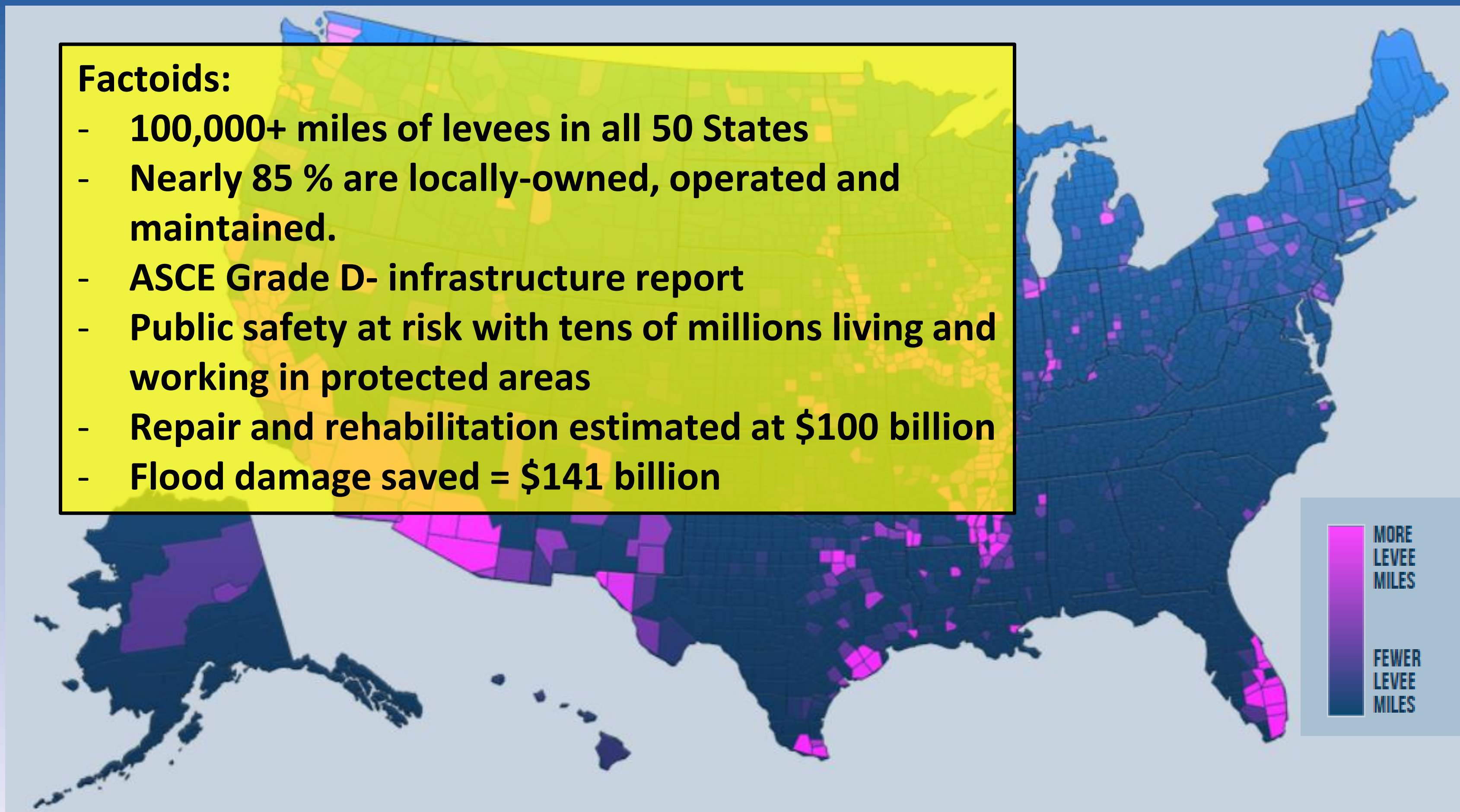
- Federal Emergency Management Agency (FEMA)

Levee Systems in the United States



Federal Emergency Management Agency's Midterm
Levee Inventory as of July 2012.

Levee Systems in the United States



Factoids:

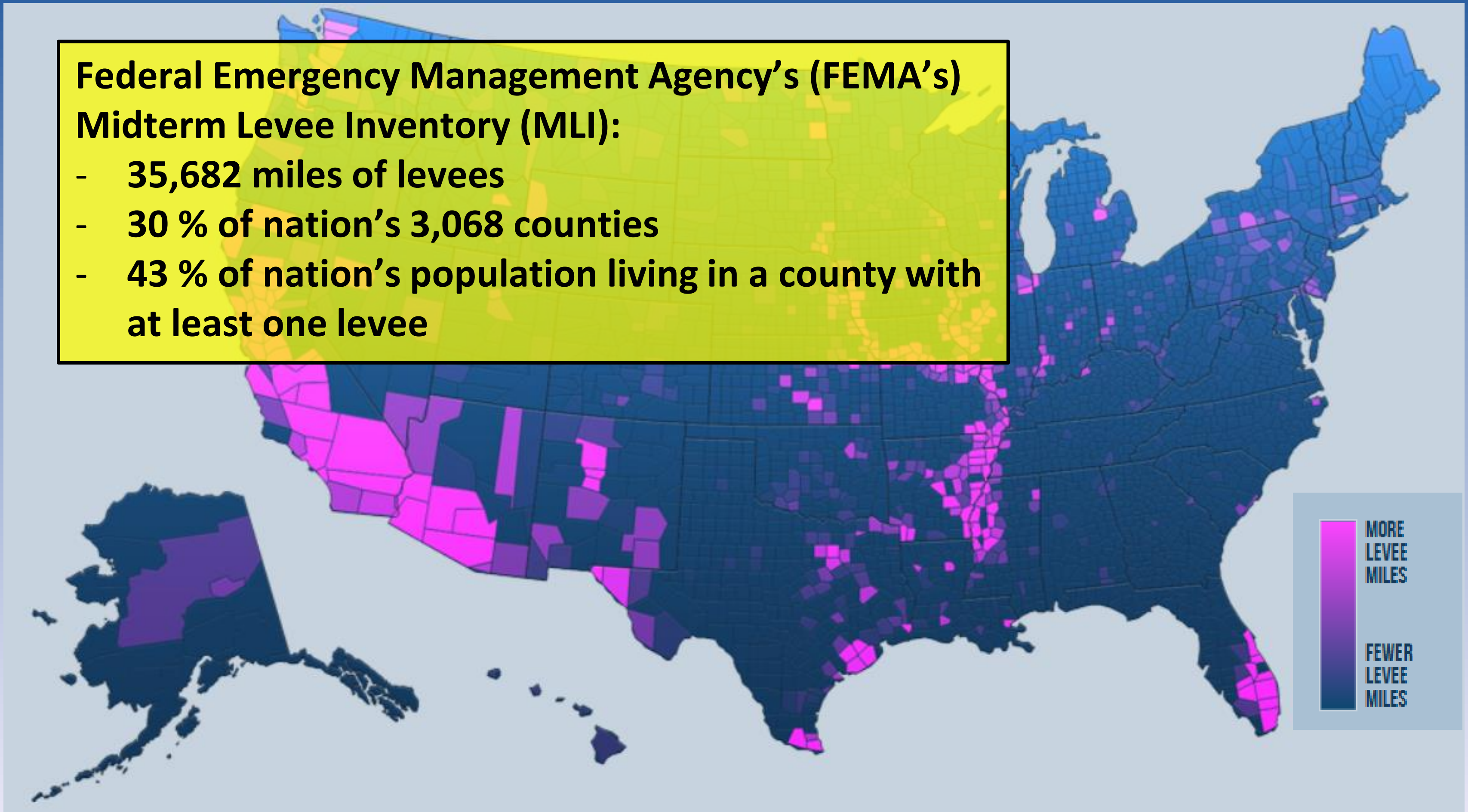
- **100,000+ miles of levees in all 50 States**
- **Nearly 85 % are locally-owned, operated and maintained.**
- **ASCE Grade D- infrastructure report**
- **Public safety at risk with tens of millions living and working in protected areas**
- **Repair and rehabilitation estimated at $100 billion**
- **Flood damage saved = $141 billion**

Federal Emergency Management Agency's Midterm Levee Inventory as of July 2012.

Levee Systems in the United States

Federal Emergency Management Agency's (FEMA's) Midterm Levee Inventory (MLI):

- **35,682 miles of levees**
- **30 % of nation's 3,068 counties**
- **43 % of nation's population living in a county with at least one levee**

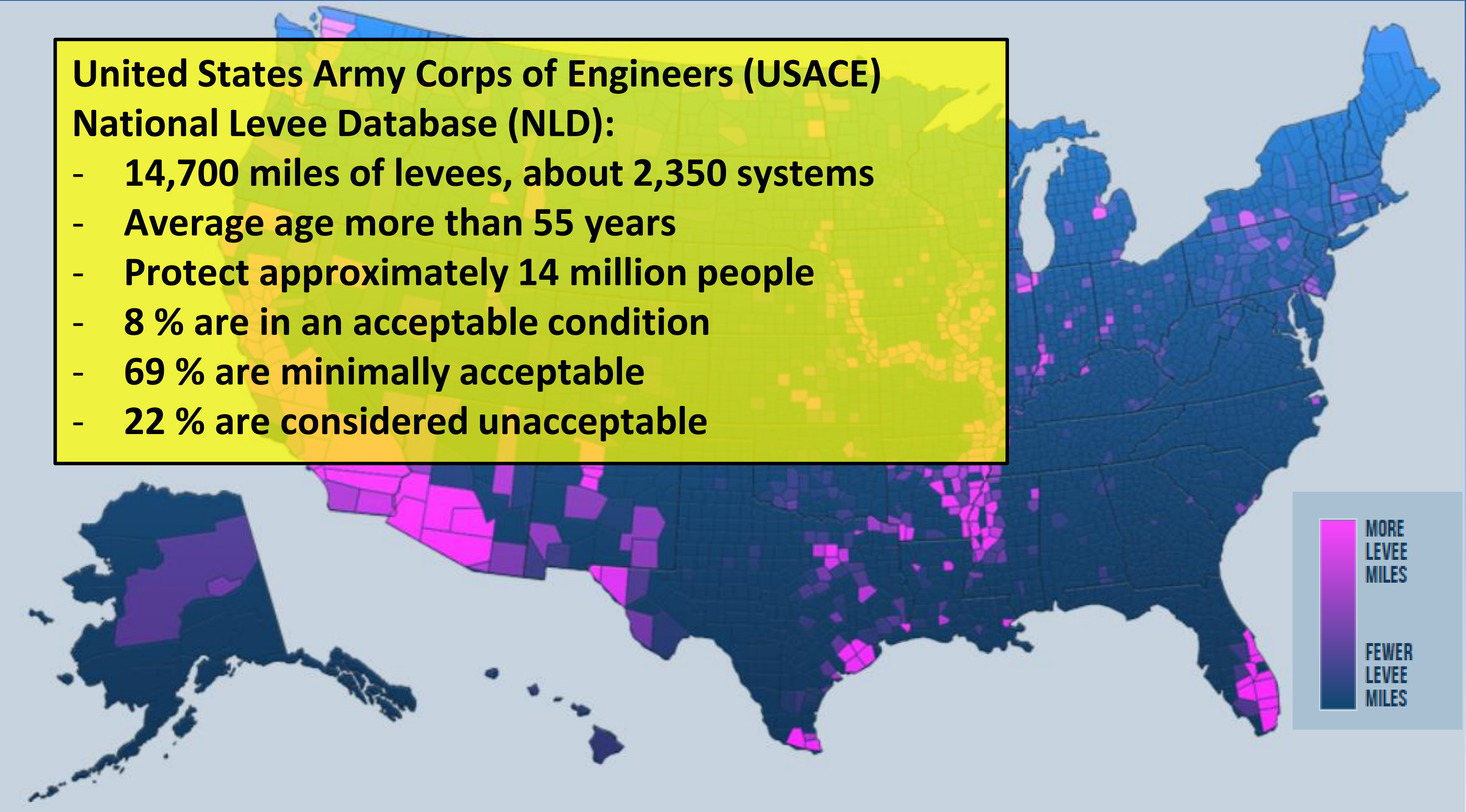


Federal Emergency Management Agency's Midterm Levee Inventory as of July 2012.

Levee Systems in the United States

United States Army Corps of Engineers (USACE) National Levee Database (NLD):

- **14,700 miles of levees, about 2,350 systems**
- **Average age more than 55 years**
- **Protect approximately 14 million people**
- **8 % are in an acceptable condition**
- **69 % are minimally acceptable**
- **22 % are considered unacceptable**



Federal Emergency Management Agency's Midterm Levee Inventory as of July 2012.

Levee Failures

Why does a levee fail?

- **Geologic Variability:** Unaccounted for soil/bedrock conditions from standard investigations – e.g., thin surficial blankets, higher permeability zones, interconnected uniform granular zones.
- **Flood load exceeds design:** Increase in seepage pressures beyond expectation, under-designed system to carry flows away from levee.
- **Maintenance activities ignored:** Embankment erosion remains unchecked; excess vegetation; relief wells plugged; animal burrow holes left, collapsed culvert penetrations; etc.

Geotechnical Analysis

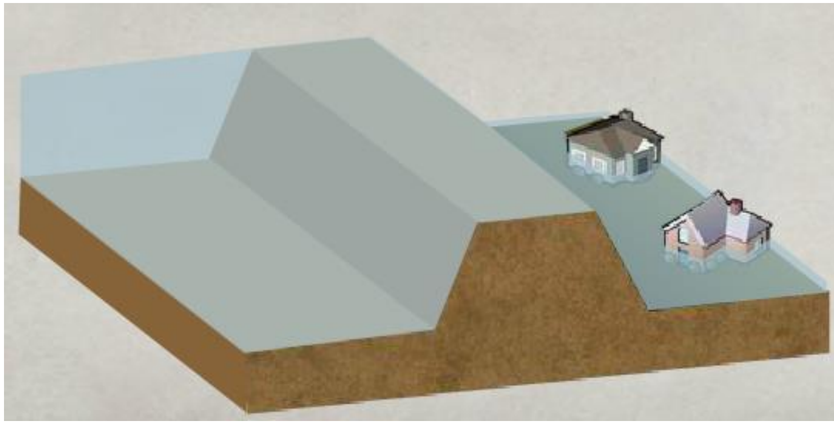
- Levee certification based on deterministic analyses and geotechnical judgment.

- Overtopping
- Slope stability
- Underseepage
- Through-seepage
- Surface erosion
- Wave attack
- Flood duration
- Seismic Stability

Identify Potential Modes of Failure Using EM 1110-2-1913, Design and Construction of Levees,"

Corps of Engineers
IWR-HEC

Failure Modes

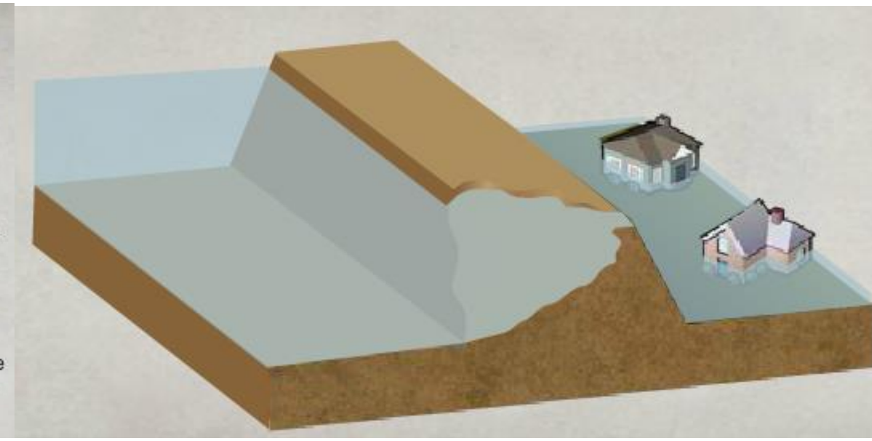


OVERTOPPING

After a heavy rain, floodwaters often rise. At times, river levels can rise to a point where they're higher than a levee's crown. As water begins to flow over its crown, the area intended to be protected will flood.

BREACHING

Breaching occurs when part of a levee gives way, creating a hole for floodwaters to pass through. A hole in a levee can be the result of burrowing animals, erosion, or slumps and cracks in the levee. Once water levels rise, the levee's weakened banks begin to erode. The levee's holes eventually turn into gaps, and as the pressure mounts, entire sections of the levee can give way.

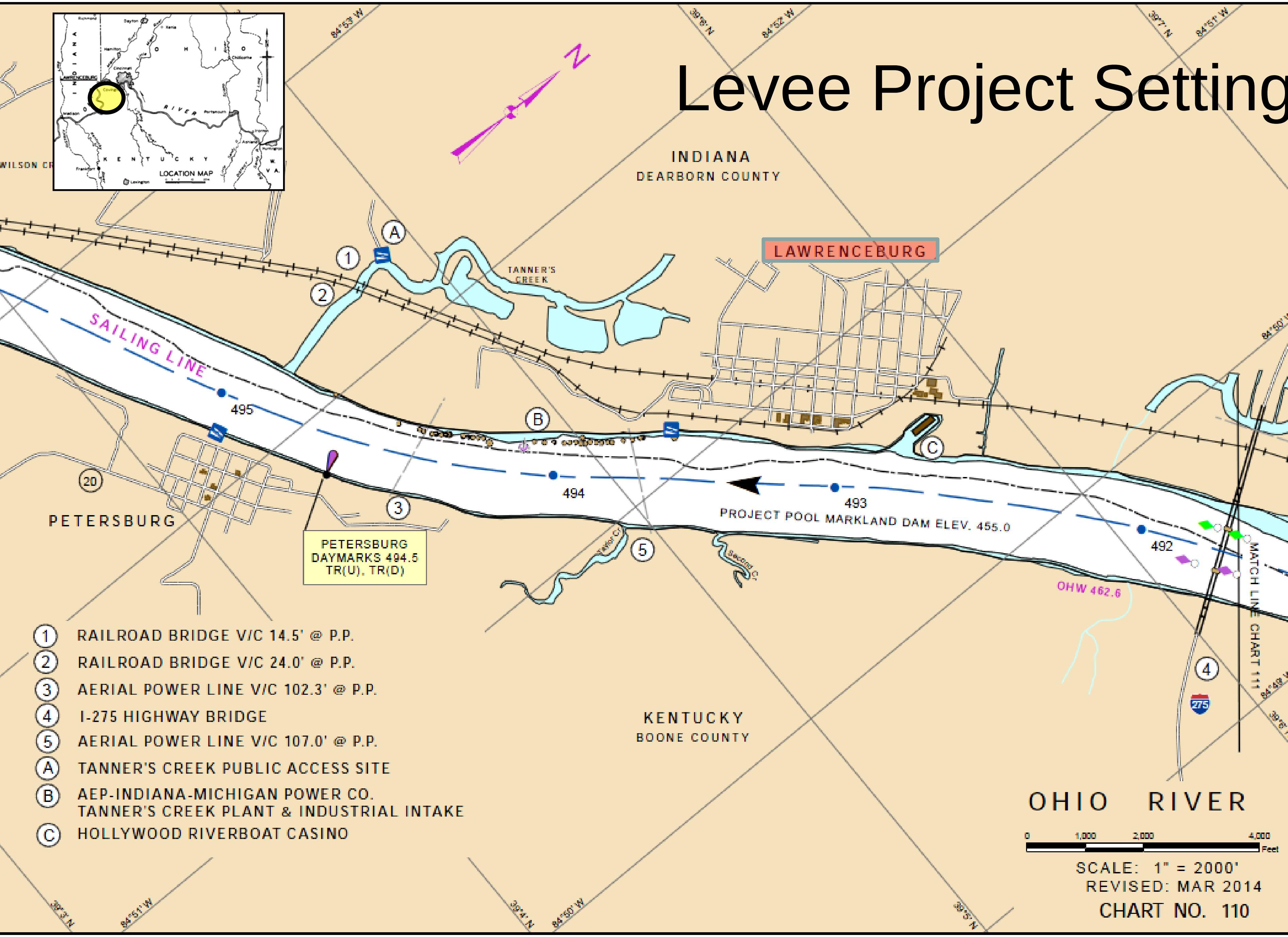


SEEPAGE

Seepage occurs when, over time, water begins to seep under or through a levee, creating weak spots in its structure. The first signs are puddles of standing water on the inboard side of the levee. Sand boils, bubbling springs at the base of the levee, also begin to form, causing the soil to become unstable, and the levee structure to be compromised. This can result in a total collapse of the levee.

Seepage

Levee Project Setting



Levee Project Characteristics

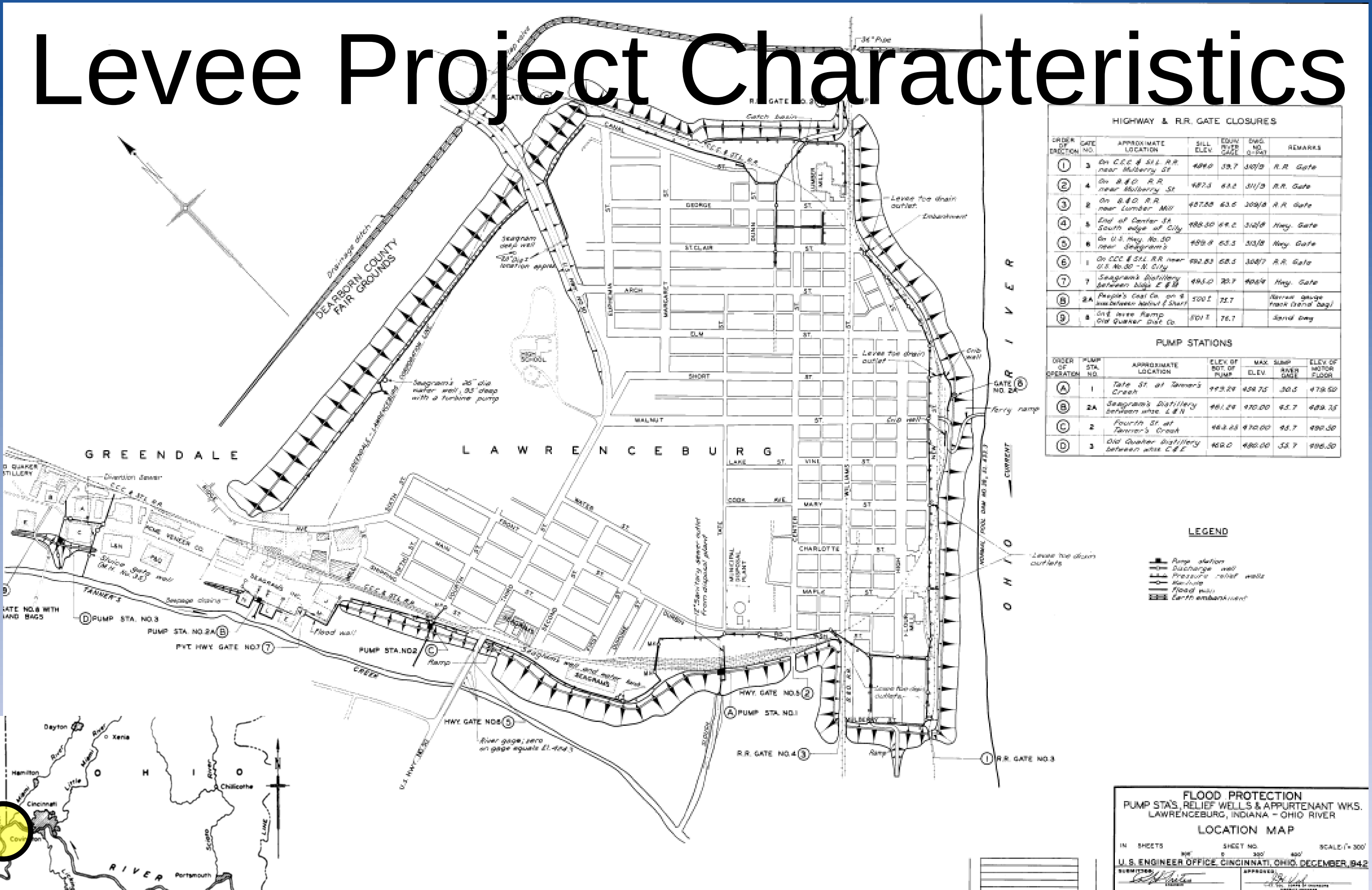
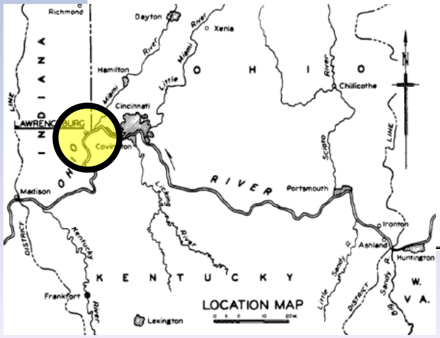


FIGURE 1. LAWRENCEBURG LEVEE HISTORICAL VICINITY MAP



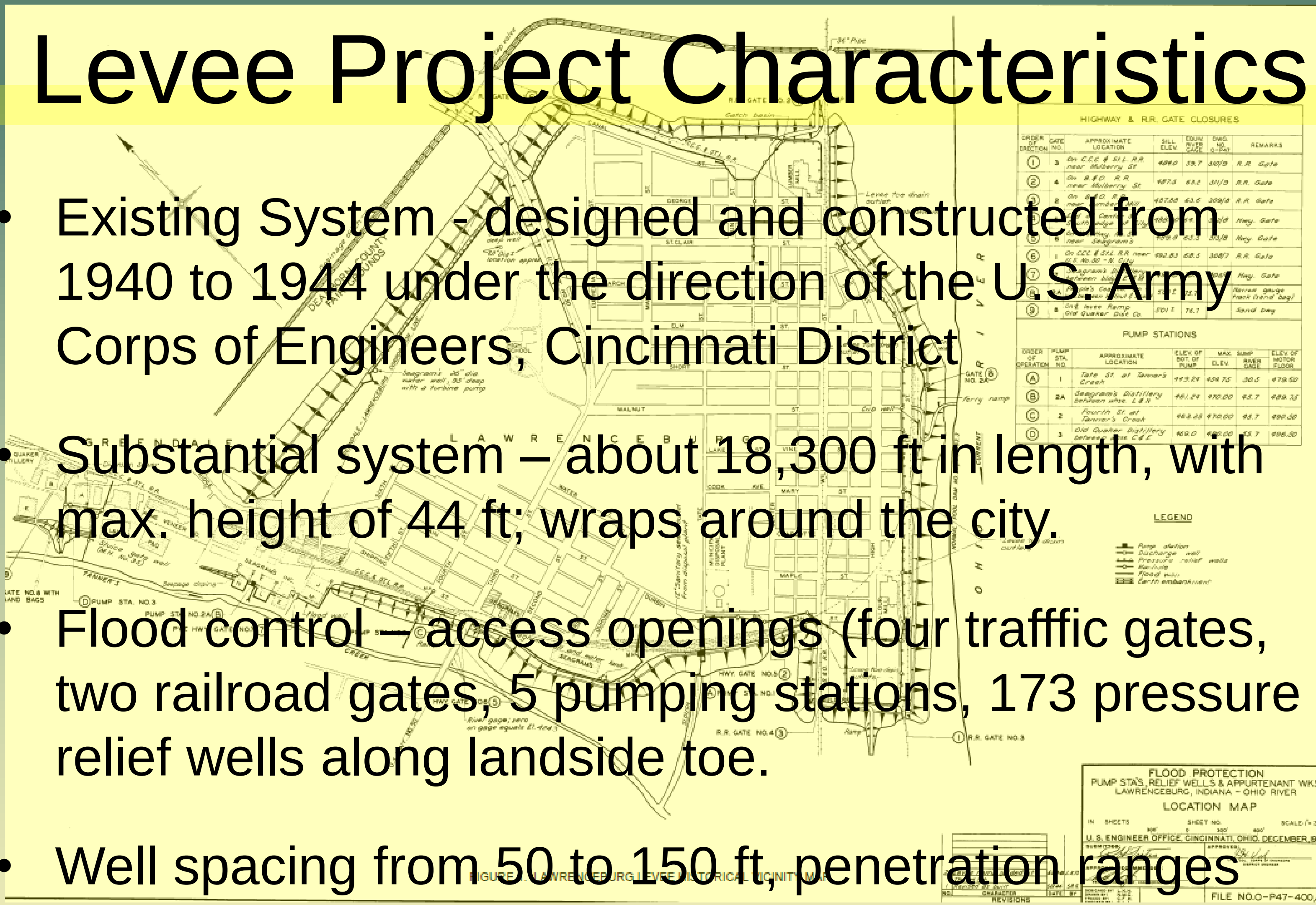
Levee Project Characteristics

- Existing System - designed and constructed from 1940 to 1944 under the direction of the U.S. Army Corps of Engineers, Cincinnati District

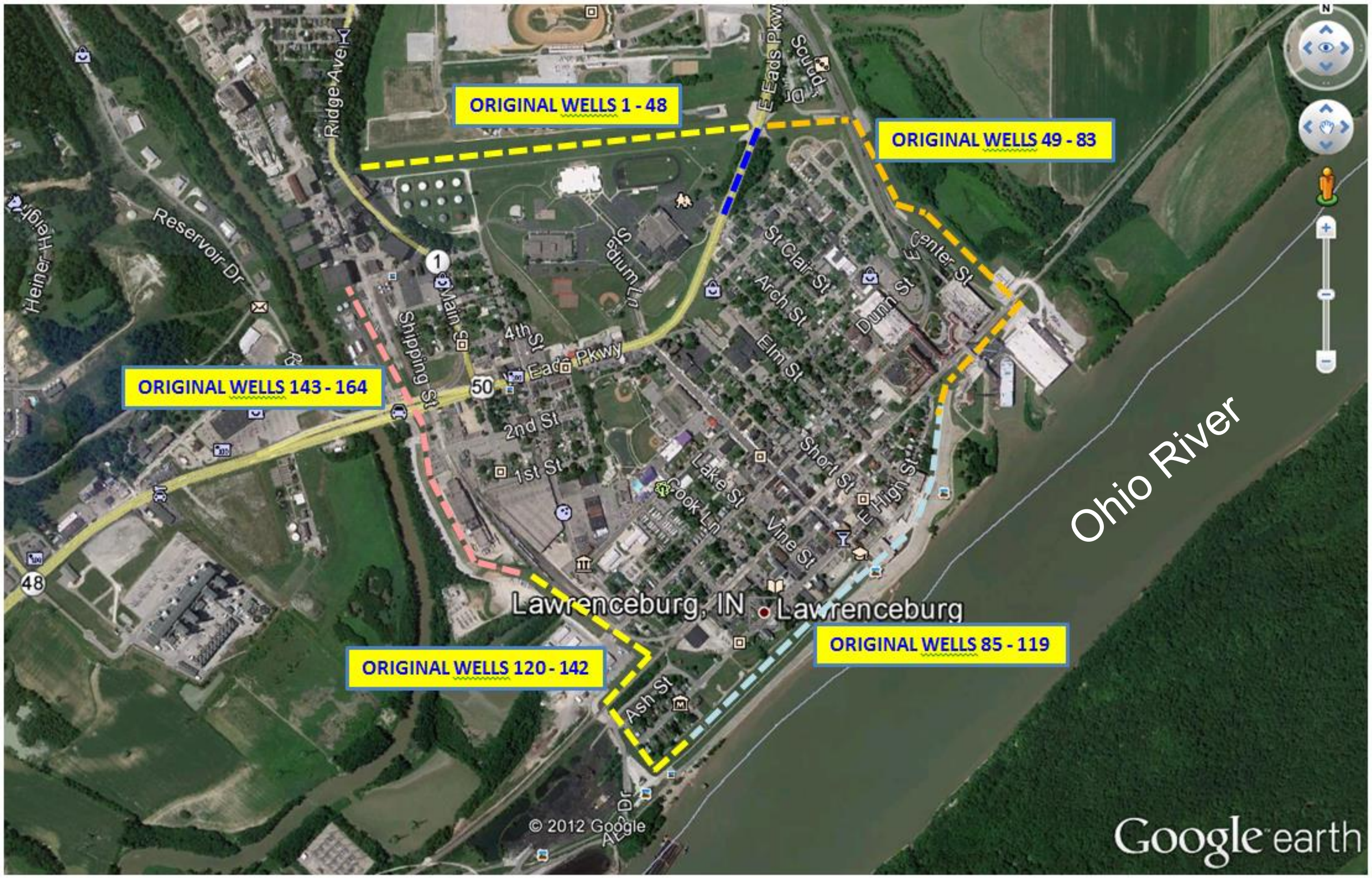
- Substantial system – about 18,300 ft in length, with max. height of 44 ft; wraps around the city.

- Flood control – access openings (four trafffic gates, two railroad gates, 5 pumping stations, 173 pressure relief wells along landside toe.

- Well spacing from 50 to 150 ft, penetration ranges from 6 to 17 percent into the aquifer.



Lawrenceburg Levee System



Levee Peer Review

How will the levee system perform under:

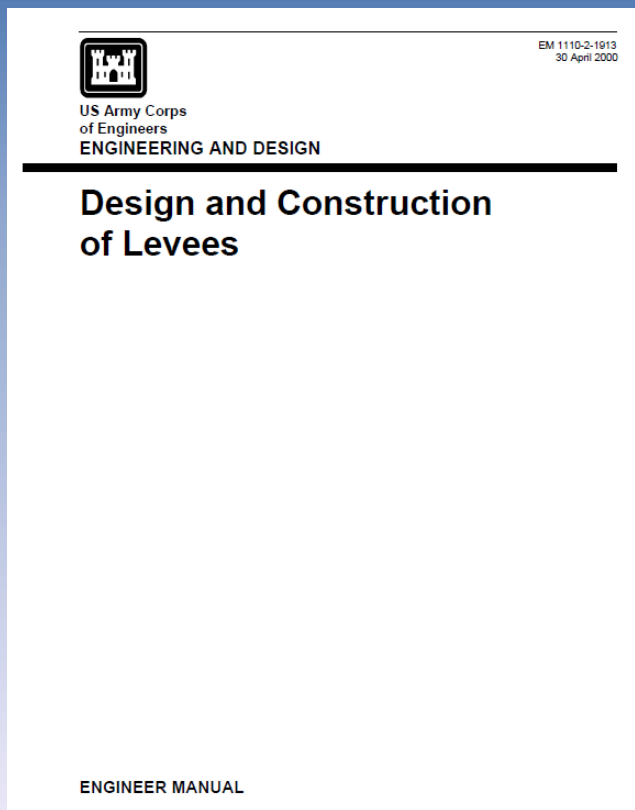
- 100-yr flood conditions (100-year flood)?
- 1937 flood conditions (500-year flood)?
- Does it provide a 1-percent-annual-chance or greater level of flood protection on the modernized National Flood Insurance Program (NFIP) maps, called Digital Insurance Rate Maps (DFIRMs).
- This is part of a certification process by a professional engineer to be eligible for FEMA accreditation and meet the criteria for a moderate-risk area on the DFIRM (no flood insurance).

Peer Review Scope

- Subsurface characterization.
- Evaluation of the geologic stratigraphy and layer hydraulic parameters assumed.
- Evaluation of the technical methodology/analysis approach.
- Evaluation of the levee geometric configuration inputs.
- Selection of performance standards (FS)
- Evaluation of reasonableness of results.
- Identification of critical issues and recommendations for additional study.

Planning and Design

U.S. Army Corps of Engineers, EM 1110-1913, EM1110-2-1914
Engineering Design Manuals for Levees and Relief Wells

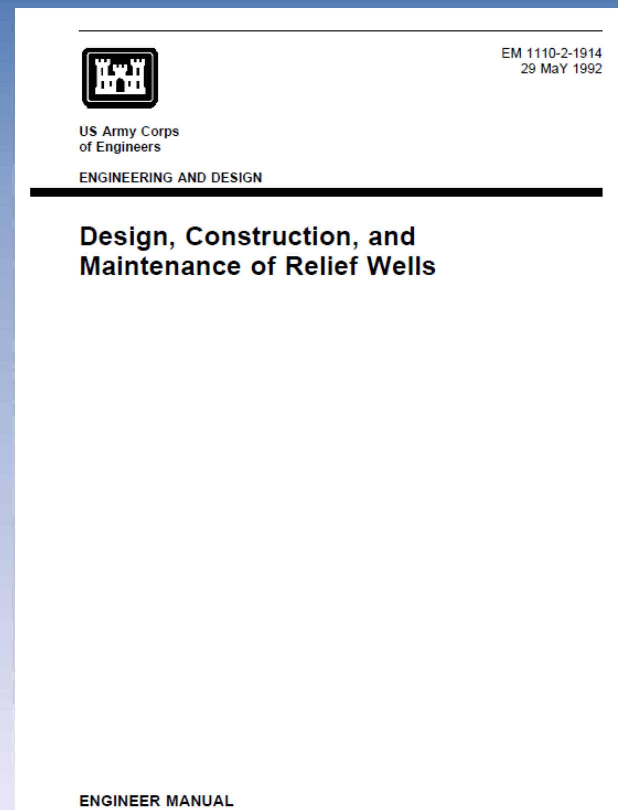


EM 1110-2-1913
30 April 2000

US Army Corps
of Engineers
ENGINEERING AND DESIGN

Design and Construction of Levees

ENGINEER MANUAL



EM 1110-2-1914
29 MaY 1992

US Army Corps
of Engineers

ENGINEERING AND DESIGN

Design, Construction, and Maintenance of Relief Wells

ENGINEER MANUAL

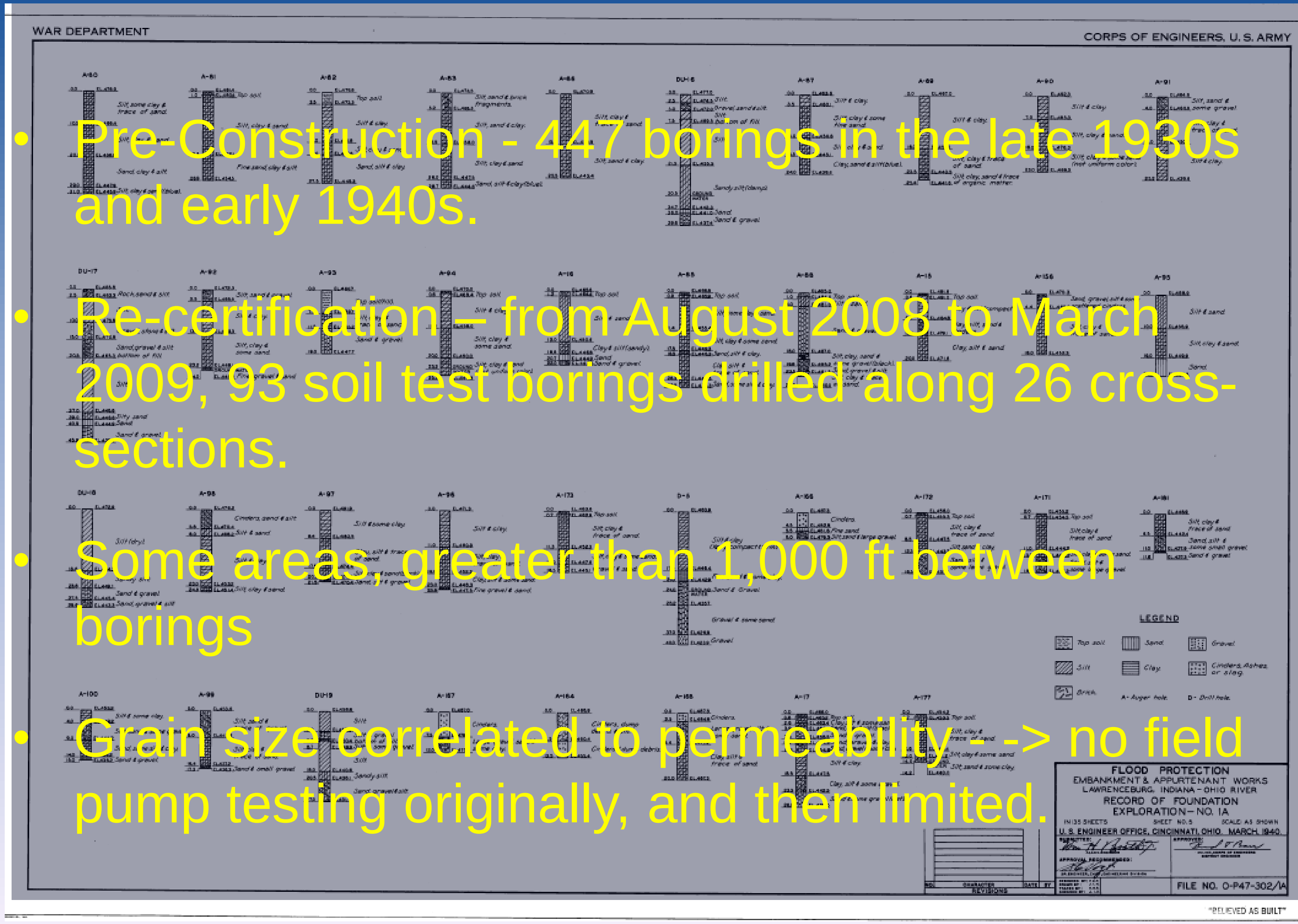
What Would GAL Say?

"If I am the one in charge of the site investigation of a project, will I foresee the cause of a potential failure?"

G. A. Leonards, CE 684 Lecture Notes, Fall 1980.

Subsurface Investigations

- Pre-Construction - 447 borings in the late 1930s and early 1940s.
- Re-certification – from August 2008 to March 2009, 93 soil test borings drilled along 26 cross-sections.
- Some areas, greater than 1,000 ft between borings
- Grain size correlated to permeability - -> no field pump testing originally, and then limited.



Findings

REVIEW AREA	AREA COMPONENTS	COMMENTS
Subsurface Characterization	Levee System Condition and Past Performance	No documentation of levee conditions or past levee performance during flood events.
	Geologic Evaluation and Basis of Test Boring Location and Spacing	Little to no description of geologic setting and conditions affecting design of subsurface investigation and seepage analysis; exceedance of recommended 1000 ft spacing between currernt cross-sections; no use of geophysical surveys to supplement information and variation expected between borings.
	Soil Laboratory Testing and Field Testing	Did not perform enough field permeability testing of pervious foundation layer testing. Did not peform enough lab tests of blanket layer samples for permeability.
	Calibration of Observed River Levels, Piezometric Readings, and Seepage Discharges	No historical correlation among Ohio River flood levels, observed water pressures and seepage quantities from levee during flood events.

Findings

REVIEW AREA	AREA COMPONENTS	COMMENTS
Subsurface Characterization	Levee System Condition and Past Performance	No documentation of levee conditions or past levee performance during flood events.
	Geologic Evaluation and Basis of Test Boring Location and Spacing	Little to no description of geologic setting and conditions affecting design of subsurface investigation and seepage analysis; exceedance of recommended 1000 ft spacing between currernt cross-sections; no use of geophysical surveys to supplement information and variation expected between borings.
	Soil Laboratory Testing and Field Testing	Did not perform enough field permeability testing of pervious foundation layer testing. Did not peform enough lab tests of blanket layer samples for permeability.
	Calibration of Observed River Levels, Piezometric Readings, and Seepage Discharges	No historical correlation among Ohio River flood levels, observed water pressures and seepage quantities from levee during flood events.

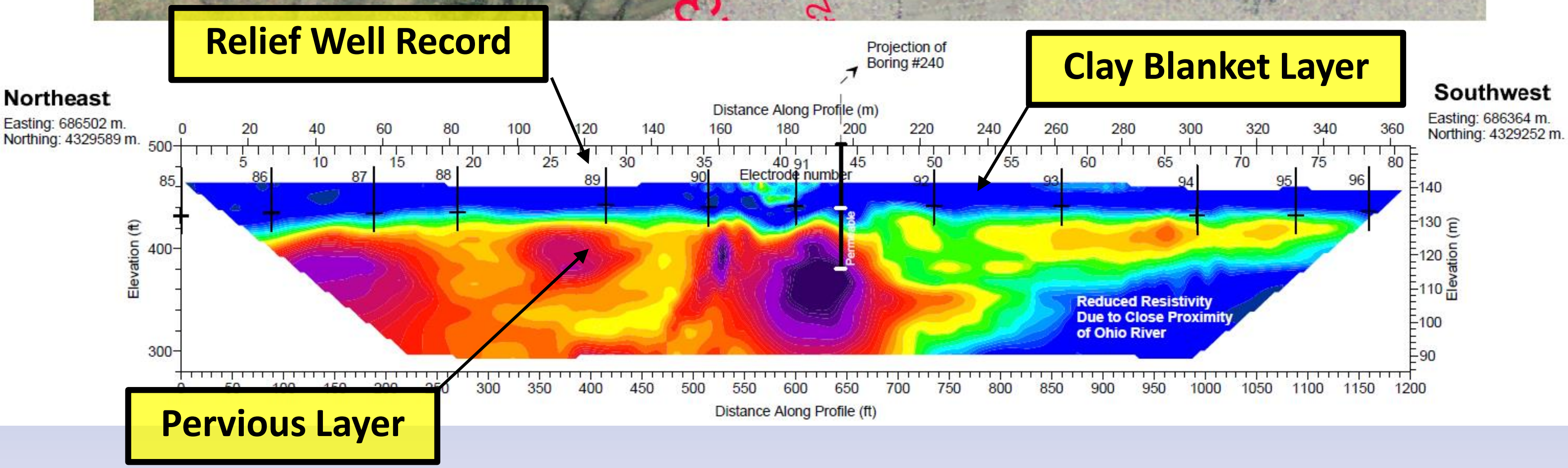
Recommendations

- **Document levee inspection and observations during flood events**
- **Perform geophysical survey; correlate with past drilling**
- **Rehabilitate and test relief wells to support permeability range and variation**
- **Use relief wells as water level monitoring points; continuous data collection to correlate water levels, River levels and seepage flows.**

Levee Inspection Documentation

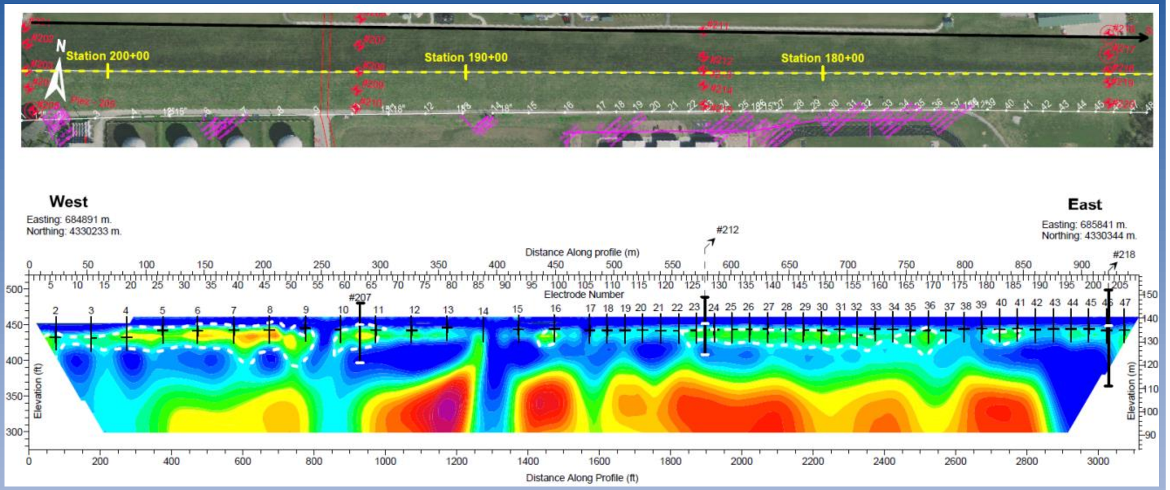
Levee Feature 1 (LF-1): Depression along dry side of levee

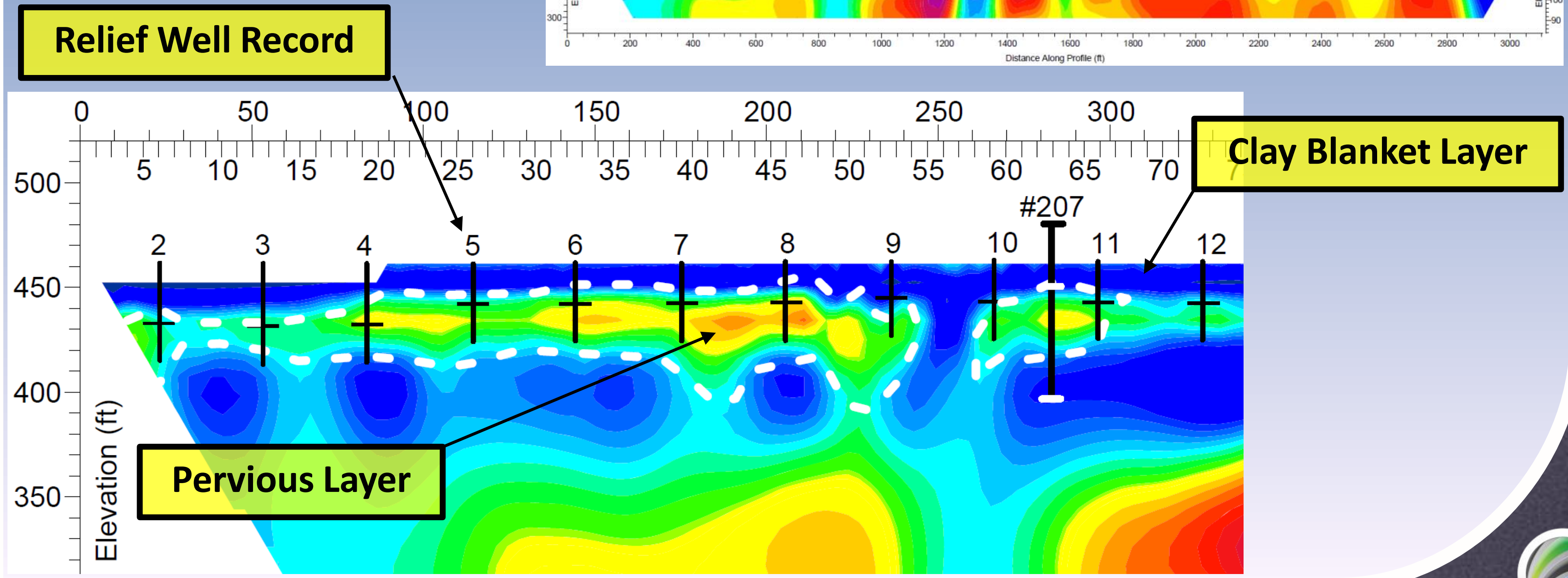
Geophysical Survey
South Levee



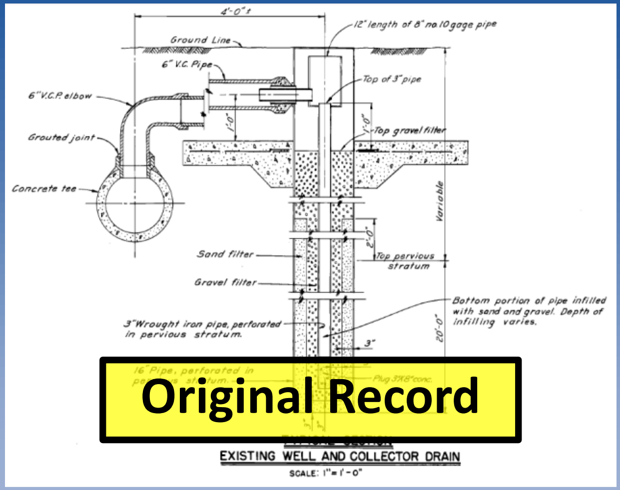
2D Resistivity Profile with Borings Provides Continuous Upper Blanket Thickness and high resistivity lower pervious zone

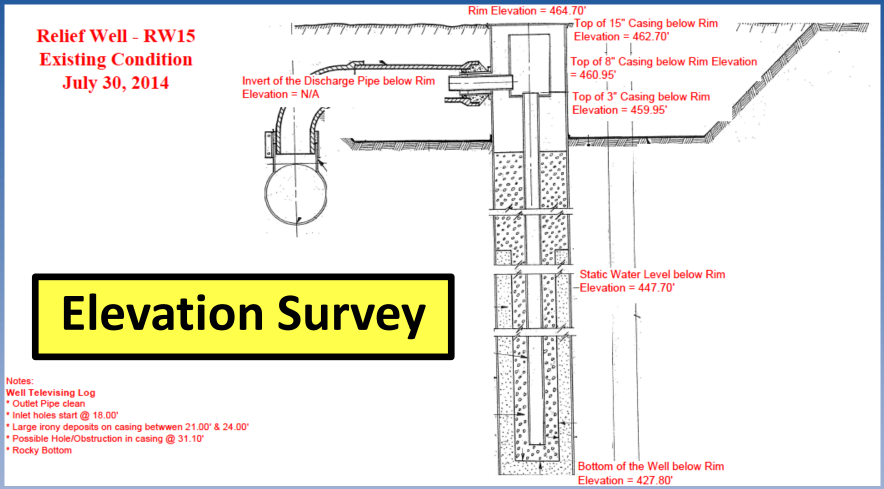
Geophysical Survey North Levee





Relief Well Rehabilitation/Documentation



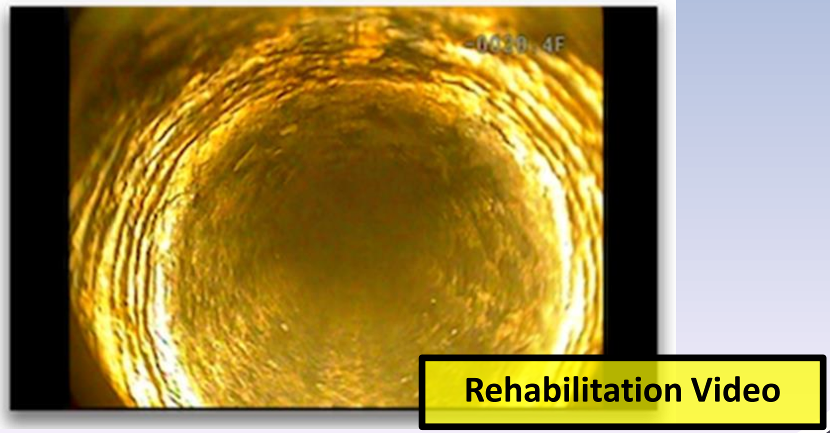


RW15 - Looking West

Post Rehabilitation

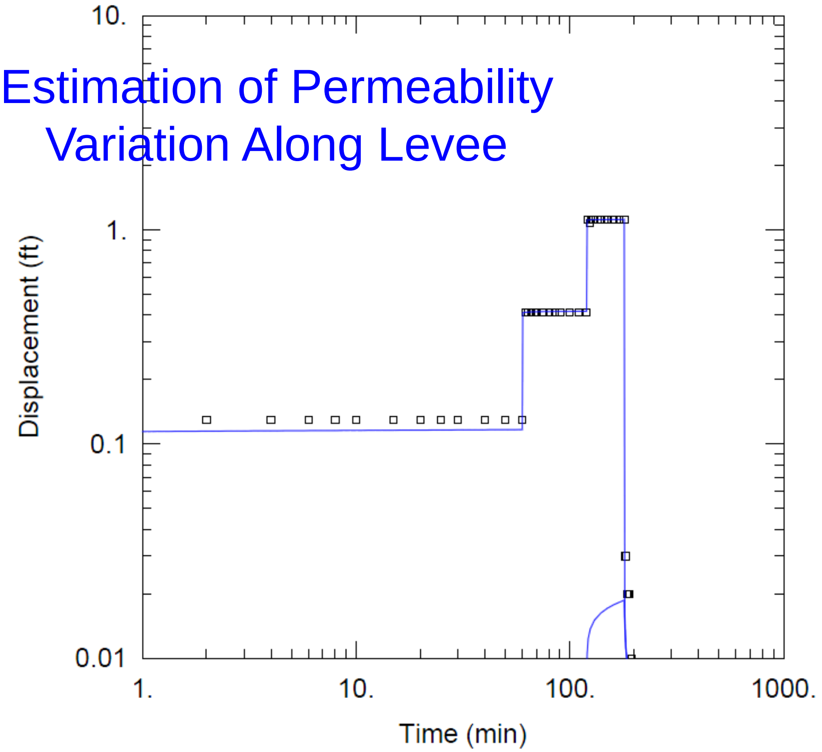
Relief Well Down Hole Televising – RW10

Casing Joint at 20.40'



Pump Testing of Relief Wells

Estimation of Permeability Variation Along Levee



WELL TEST ANALYSIS

Data Set: T:\...\RW-11 POST_Theis (1935) Confined Solutio
Date: 05/14/15 Time: 08:42:15

PROJECT INFORMATION

Company: Mundell & Associates Inc.
Client: LCD
Project: M14051
Test Well: RW-11
Test Date: 9/16/14

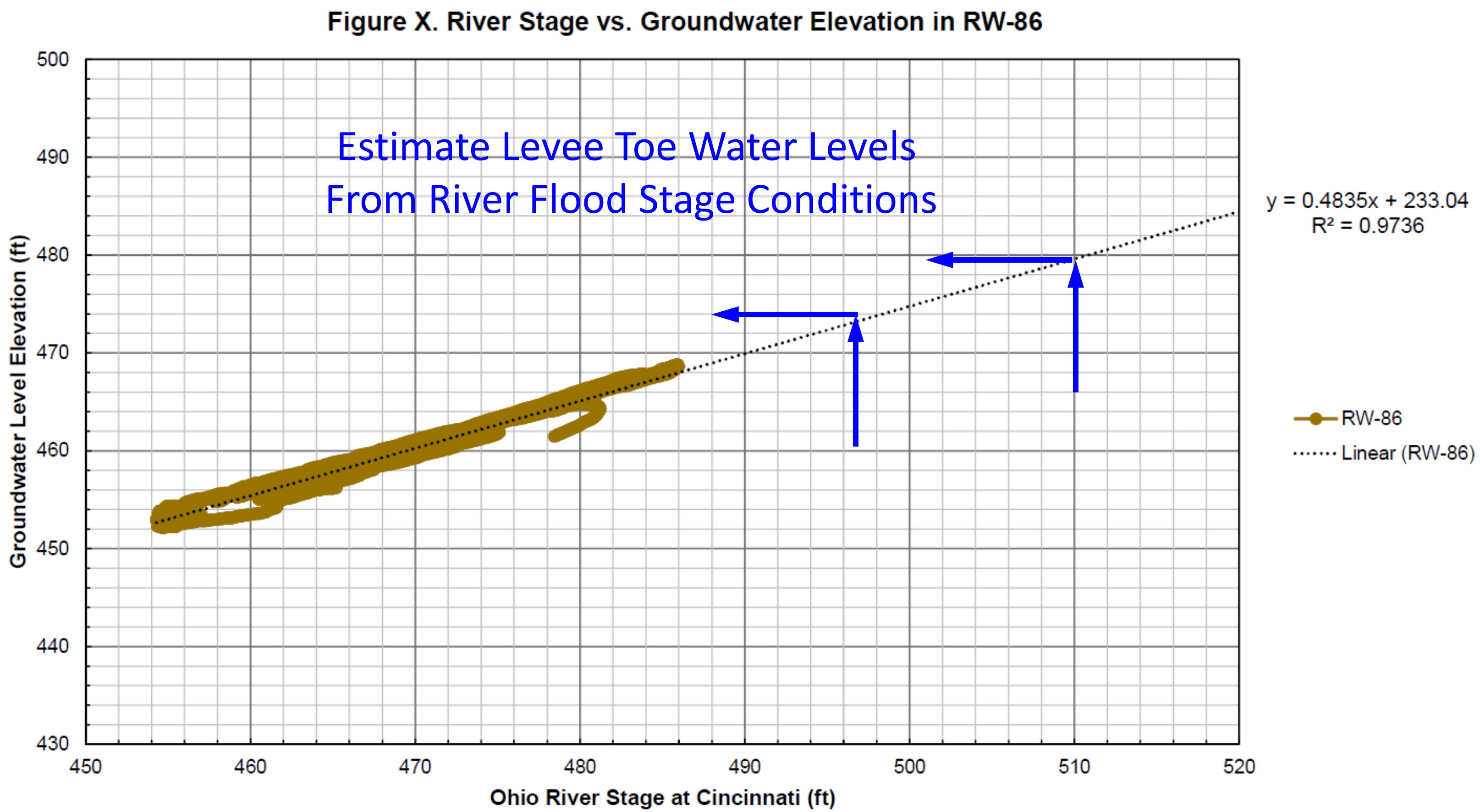
SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Step Test)

T = 1480.4 cm^2/sec
S = 0.01646
Sw = 20.
C = 0.01522 min^2/ft^5
P = 2.44

Step Test Model: Jacob-Rorabaugh
Time (t) = 1. min Rate (Q) in cu. ft/min
$s(t) = 0.1626Q + 0.01522Q^{2.44}$
W.E. = 47.02% (Q from last step)

Correlate Water Level to River Levels



What Would GAL Say?

"…Field measurements, appropriately conducted, provide the ultimate test of the validity of the theory. However, it is clear that the kinds of measurements made, where they are located, and how they are interpreted are all so dependent on the concepts derived from existing theories, that the tendency persists to 'validate' inapplicable procedures…"

G. A. Leonards, '*Investigation of Failures*', Sixteenth Terzaghi Lecture, J. Geotechnical Engineering Division, February, 1982.

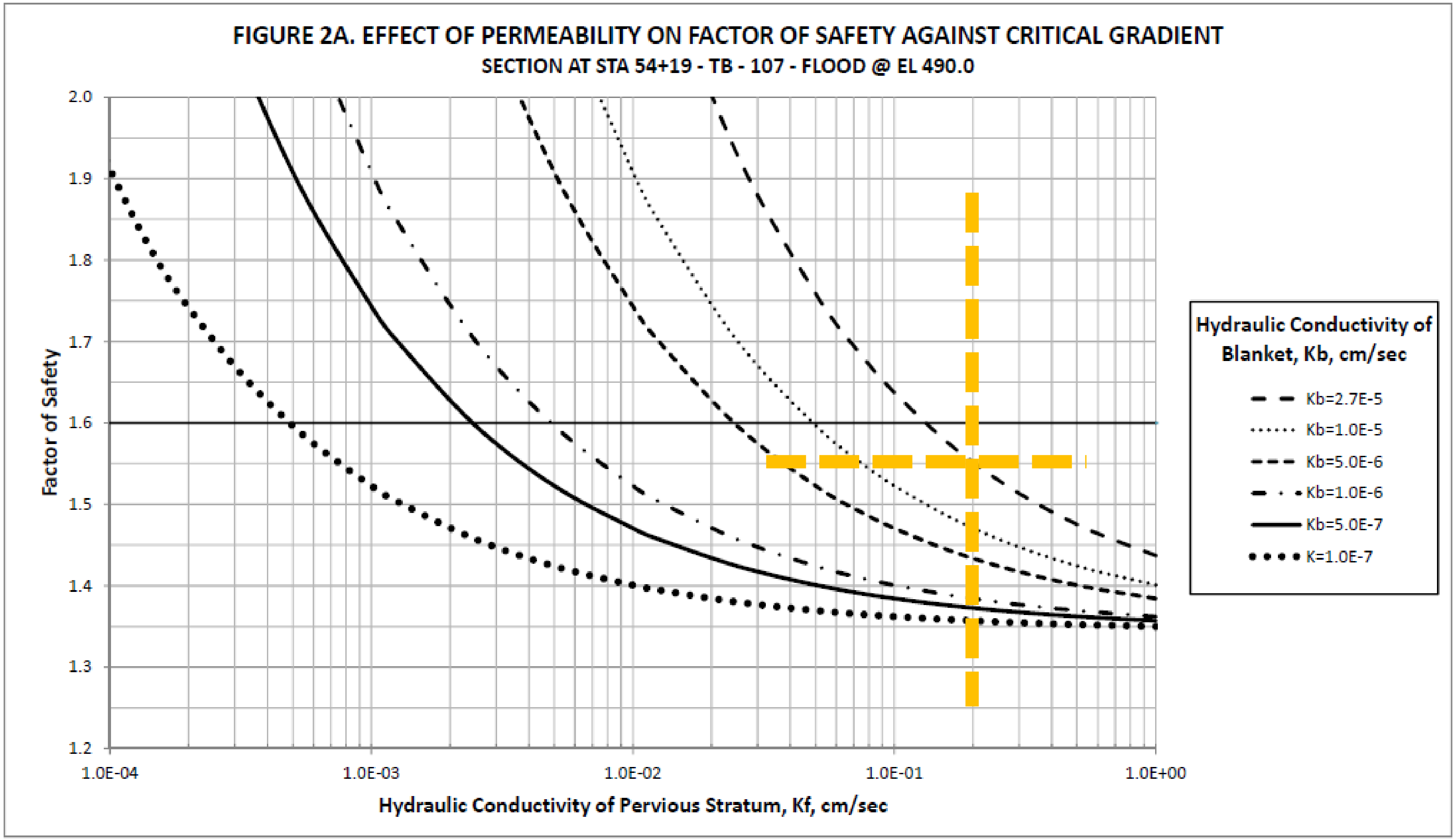
Selection of Input Parameters

- Geometric configuration inputs suitable for blanket theory analysis.
- Permeability inputs continued to evolve because of lack of direct testing; variability along levee still likely.
- Relief well analysis affected by non-linear levee configuration and existing relief well capacity.

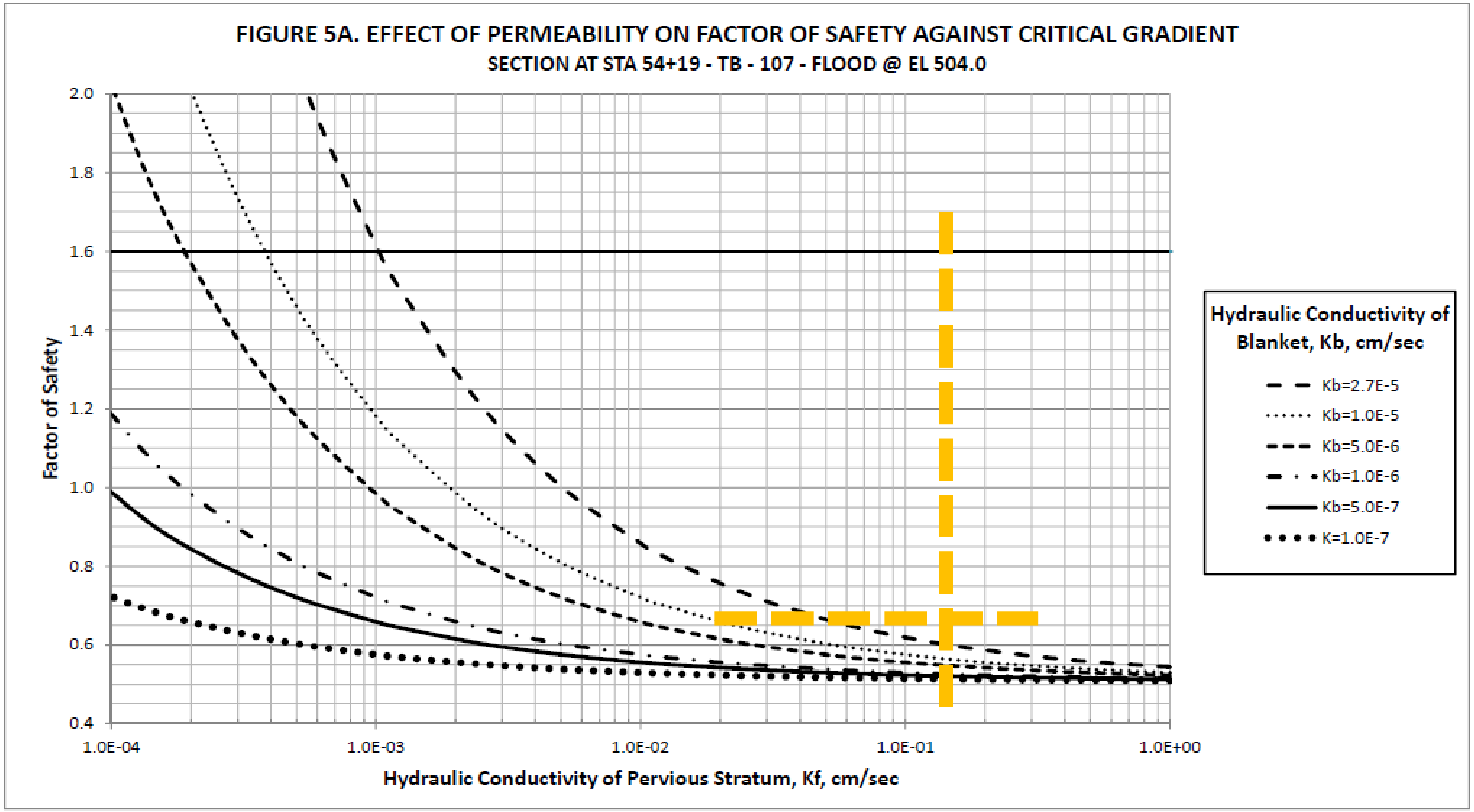
Recommendations:

- Perform sensitivity analysis to demonstrate impacts of parameter variation.
- Consider supplementary techniques to identify variations along levee (e.g., testing of relief wells and geophysics).

Sensitivity Analysis



Sensitivity Analysis



Seepage Analyses Parameter Selection

SEEPAGE ANALYSIS ASSUMPTIONS[a]

Report	Report Date	Flood Elevation, ft	Factor of Safety, Critical Gradient	Factor of Safety, Uplift	Permeability Pervious Layer cm/sec	Permeability Blanket Layer cm/sec	No. Relief Wells
Stability Assessment	June 1, 2009	490.0	2.5	1.4	0.4 - 1.1	2.7×10^{-5}	-
Installation of Phase I Relief Wells	October 23, 2009	490.0, 498.0, 501.0	2.5	1.4	0.6 - 1.0	2.7×10^{-5}	46 (21 east; 25 west)
Revised Relief Well Design	July 23, 2010	501.0	2.5; 2.0	1.4	0.3; 0.46	2.7×10^{-5}	36 (15 east; 21 west)
An Assessment of Review Comments	August 31, 2010	501.0	2.5	1.4	0.3	2.7×10^{-5}	-b
Final Relief Well Plans	June 21, 2011	501.0	2.5	1.4	0.5; 0.6	2.7×10^{-5}	36 (15 east; 21 west)
North Levee Preliminary Relief Well Analyses	June 29, 2011	501.0	2.5	1.4	0.6	2.7×10^{-5}	-
Aquifer Characteristics and Relief Well Design	September 21, 2011	493.6	1.6	1.4	0.3	2.7×10^{-5}	-c
Final Relief Well Plans	December 2, 2011	490.0, 501.0, 504.0	1.6	1.4	0.2, 0.3	2.7×10^{-6}	29 (11 east; 18 west); 28 (north)

[a]As indicated in available reports reviewed.

[b]Analysis performed to compare to USACE software; seepage block analysis.

[c]Letter seeks concurrence from USACE for selected design parameters.

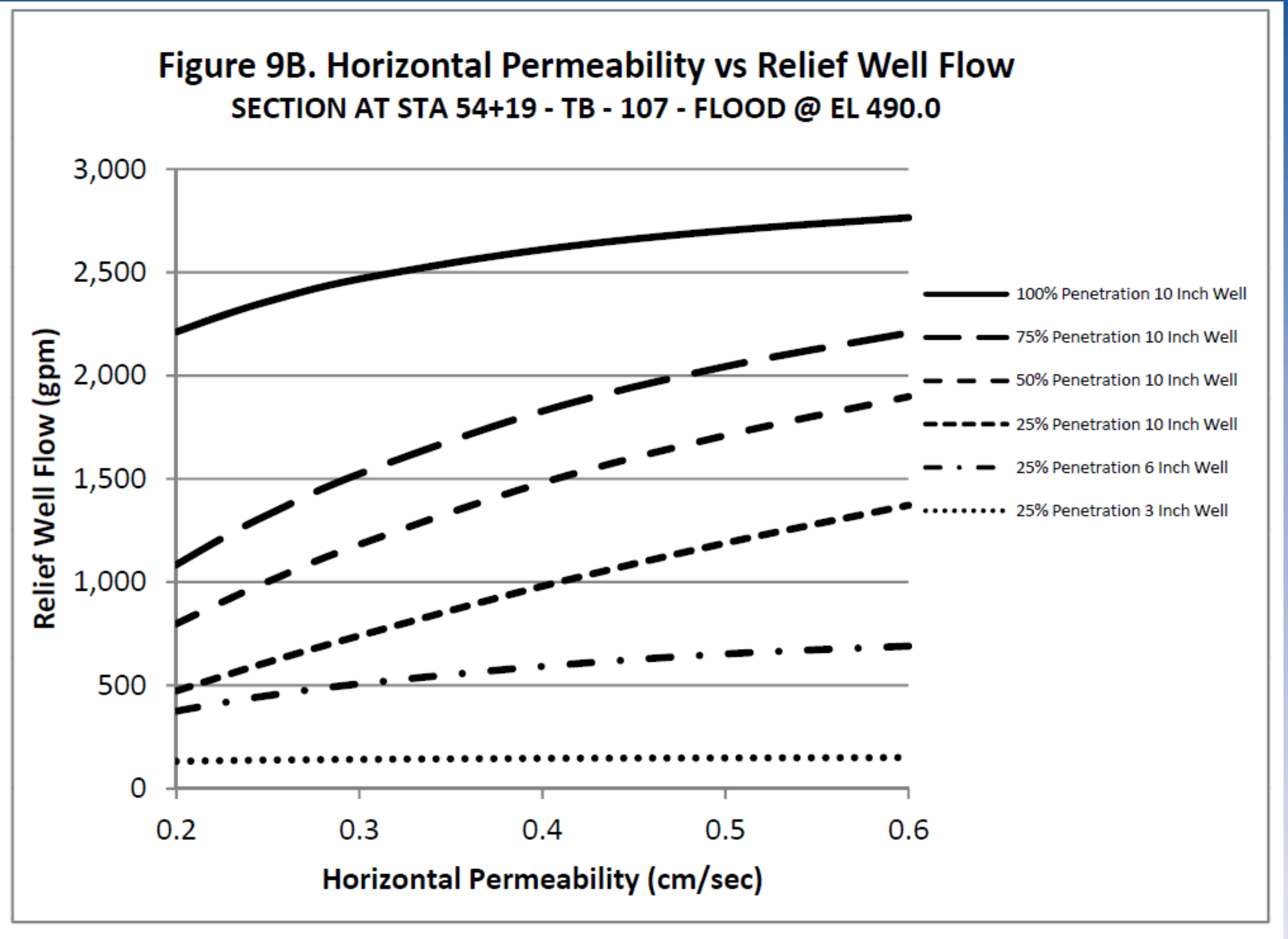
Seepage Analyses Parameter Selection

Permeability Pervious Layer cm/sec	Permeability Blanket Layer cm/sec	No. Relief Wells
0.4 - 1.1	2.7×10^{-5}	-
0.6 - 1.0	2.7×10^{-5}	46 (21 east; 25 west)
0.3; 0.46	2.7×10^{-5}	36 (15 east; 21 west)
0.3	2.7×10^{-5}	-b
0.5; 0.6	2.7×10^{-5}	36 (15 east; 21 west)
0.6	2.7×10^{-5}	-
0.3	2.7×10^{-5}	-c
0.2, 0.3	2.7×10^{-6}	29 (11 east; 18 west); 28 (north)

K Variation

No. Relief Wells

Seepage Analyses Parameter Selection



Relief Wells Flows

K Variation

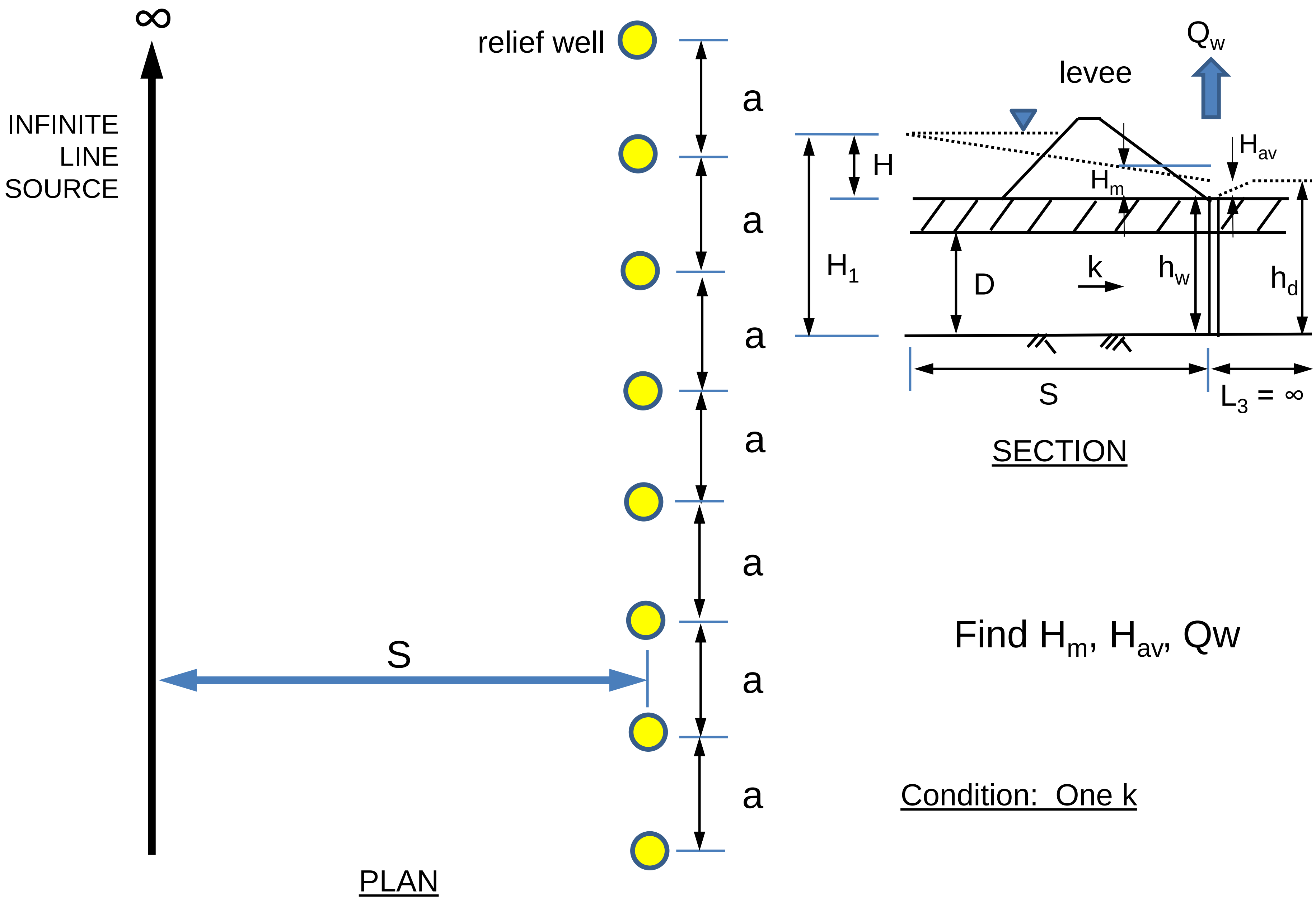


Figure 1. Infinite Line of Wells Parallel to Infinite Line Source (impervious top stratum)

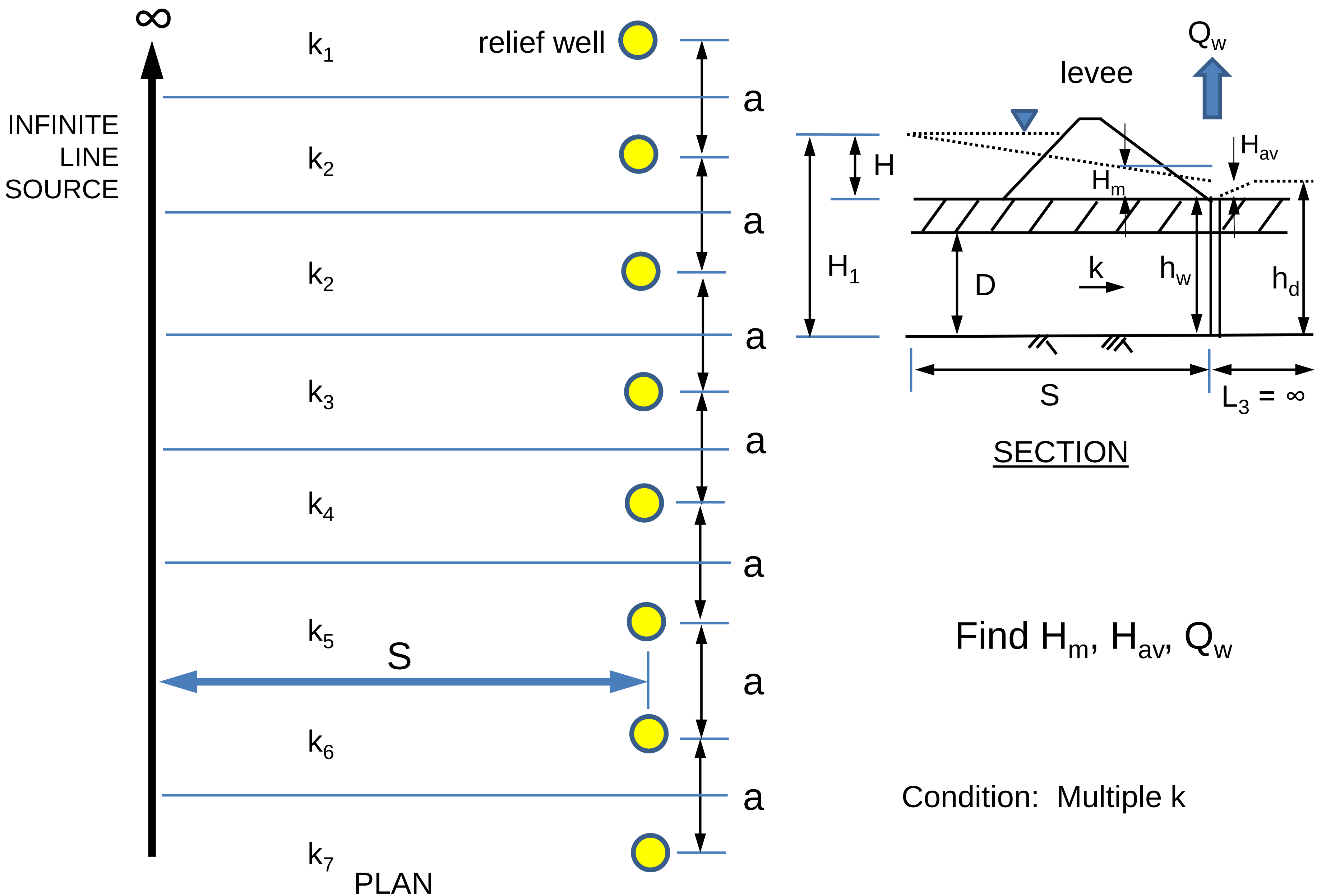


Figure 1. Infinite Line of Wells Parallel to Infinite Line Source (impervious top stratum)

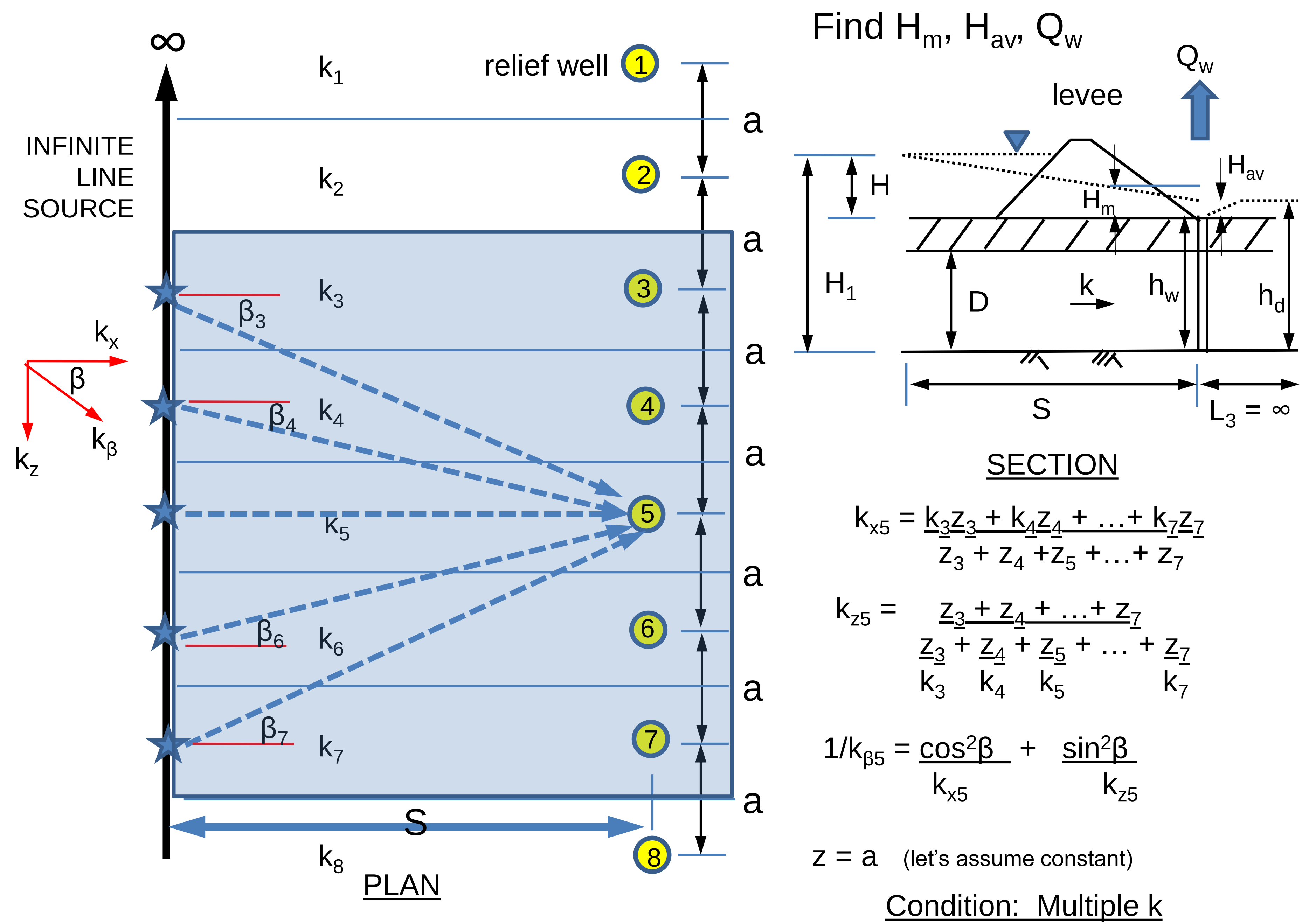


Figure 1. Infinite Line of Wells Parallel to Infinite Line Source (impervious top stratum)

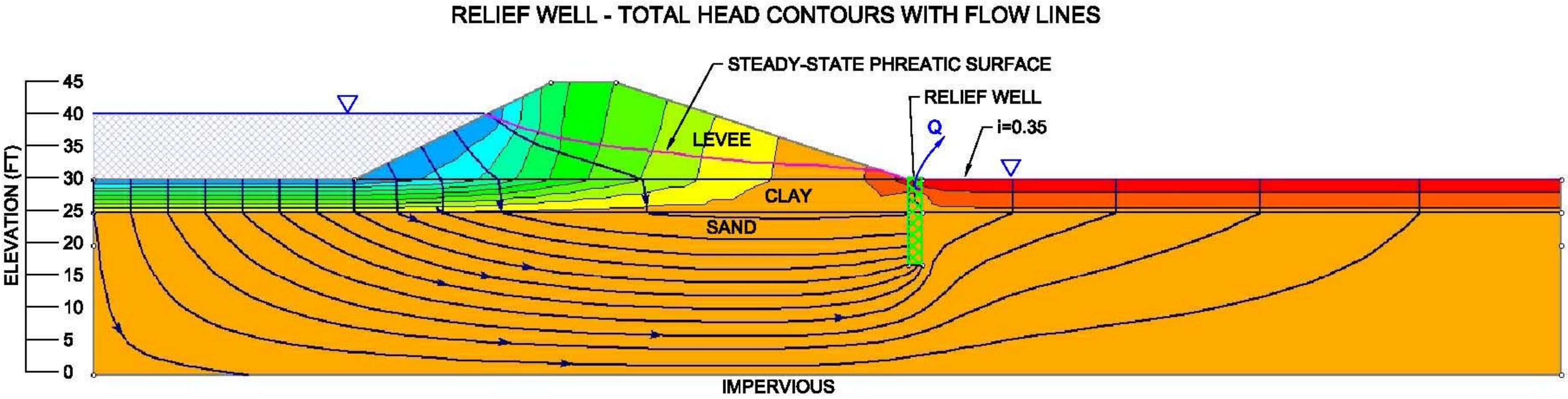
Challenges Encountered

- **Geologic Setting and Scale:** Variability of alluvial/glacial deposits; 5 mile length of levee.
- **Lack of Performance Observations:** No documentation of levee inspections, behavior during flood conditions, or water/groundwater levels or flow measurements made historically.
- **Construction/maintenance activities:** No repair or rehabilitation of existing relief well system had occurred.

Lessons Learned

- Consider the potential for failure from an incomplete investigation.
- Confirm theory with real field measurements.
- Don’t blindly use standard design methodologies without considering their impact on the results.
- Account for the potential variation of site parameters in your approach.
- Discuss your results with the original engineer when doing a peer review.

THANKS!


RELIEF WELL - TOTAL HEAD CONTOURS WITH FLOW LINES
STEADY-STATE PHREATIC SURFACE
RELIEF WELL
Q
i=0.35
LEVEE
CLAY
SAND
IMPERVIOUS
ELEVATION (FT)
45
40
35
30
25
20
15
10
5
0