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Pressure Relief Wells: Analysis of Subsurface Heterogeneity to evaluate Relief Well Locations for Mississippi River Levees

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PRESSURE RELIEF WELLS: ANALYSIS OF SUBSURFACE HETEROGENEITY TO

EVALUATE RELIEF WELL LOCATIONS FOR MISSISSIPPI RIVER LEVEES

by

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ABSTRACT

When designing pressure relief well systems, it is imperative to understand what major geomorphology and heterogenies features are present, such as buried oxbow lakes, especially when the feature is parallel to the source, such as the Mississippi River. When present, there is a notable greater increase in head pressures, especially on the landward tow of the levee. This can cause erosional features that originally thought of to have been protected from by installing pressure relief wells. When comparing the effective hydraulic conductivities of horizontal clay layers and vertical clay layers spanning the length of the model, little to no noticeable difference can be discerned, also long as the clay volume is under 30%.

ACKNOWLEDGMENTS

I would like to acknowledge and give warmest thanks to my supervisor, Dr. Katherine Grote, who made this work possible. Her guidance and advice carried me though many challenges, a pandemic, and many revisions. She has been a pillar of support throughout my collegiate career, which has culminated in pursuing a degree and career which I once thought was unattainable.

I would also like to give special thanks to Dr. J. David Rogers, who guided my direction in refence materials for topics relating to uplift pressure and relief well design along the Mississippi River.

Finally, I would like to thank my partner Eric, my cat Frankie, my parents Paige and Arthur, and my grandparents Merrill and Barbara, for their continuous support when undertaking this project. Your encouragement was what sustained me this far.

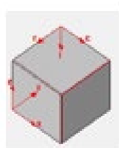
TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

LIST OF TABLES

NOMENCLATURE

Symbol	Description
b=m	Thickness of an aquifer layer
H	Net head on well system
k_f=k_e	Effective hydraulic conductivity of pervious foundation
k_h	Horizontal hydraulic conductivity of an aquifer layer
k_v	Vertical hydraulic conductivity of an aquifer layer
L_1	Distance from riverside levee toe to open seepage entrance (i.e. the river)
L_2	Width of embankment base
	Reference Cube used to help orientate between the different models

1. INTRODUCTION

1.1. BACKGROUND

Much of the Mississippi River is protected by soil levees. Often these levees are located on geology which includes a thinner layer (known as a blanket) of soil with relatively low hydraulic conductivities overlaying a deeper, more pervious soil, often known as an aquifer (Figure 1.1.)

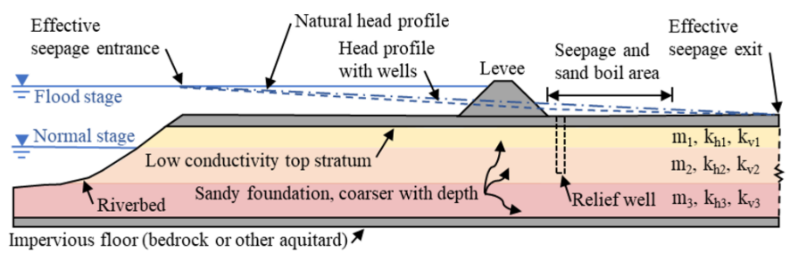


Figure 1.1 Typical Mississippi levee cross-section

When a flood occurs, a hydraulic gradient develops (seen as the blue dotted line in Figure 1.1), which causes subsurface under seepage flows towards the "dry" landward side of the levee, where blanket soils cause confined conditions with artesian heads. Excess heads at the levee tow are evaluated against the resistance provided by the landside confining blanket's effective unit weight and thickness. Suppose the driving uplift force provided by the excess head is greater than the resisting force provided by the blanket. In that case, that location may be susceptible to uplift-related breaching of the coning blanket, and internal erosion of the foundation may initiate (such as sand boils).

Given that foundation, erosion can potentially progress to levee failure under seepage, and methods for controlling it have been researched and employed for nearly a century.

Pressure relief wells are an under-seepage countermeasure studied and used by the U.S. Army Corps of Engineers (USACE) since the 1930s (USACE 1939a, 1939b). Relief wells provide a filtered exit for under seepage and can allow the problematic excess head to safely dissipate, thus limiting the potential for initiating internal erosion. Existing analytical relief well design methodology is based on experimental and theoretical work. It does not compute the maximum head landward of the well, which may govern the design, and the average is used as a conservative approximation (USACE 1955). It also does not account for any heterogeneity's underling the blanket, which could cause elevated uplift pressures. Instead, a conservative effective hydraulic conductivity (k_{eff}) is used across all levees surrounding the Mississippi River. In this paper, the existing uplift factors are evaluated and further verified with analytical and FE solutions to assess the impacts of heterogeneities under the blanket versus an effective hydraulic conductivity.

1.2. PURPOSE

The state of Missouri is hugged to the east by the Mississippi River (Figure 1.2), the second longest river in North America, housing communities, such as Mark Twain's hometown of Hannibal and the jazz central of St. Louis. Between these communities is rich and fertile farmland. To protect commercial and agricultural assets, along with the people who live within the flood plans, Missouri has built two hundred thirteen levee systems spanning two thousand thirty-eight miles. These levees are a low permeable earthen flood barrier, oftentimes covered in grass. The Army Corps of Engineers maintains much of the levees nears St. Louis, as well as two thousand one hundred forty-eight levee systems totaling fourteen thousand one hundred fifty miles within the United States. To help monitor, maintain, and design these levees, an effective hydraulic conductivity is used in calculations. This method takes into consideration the direction of groundwater flow and the hydraulic conductivities of the geology present and in essence averages them. This creates an assumption that there is homogenous geology under and around the levee systems. This method is used in a conservative manor for the Army Corps of Engineers and this project takes a closer look at how reliable using effective hydraulic conductivity is as well as the assumption of homogeneous geology. But the Mississippi River Flood Plains do not have homogenous geology. In the last 100 years, it has been witnessed to meander and change its path within the floodplain, creating features such as ox bow lakes. Over time large sections of the Mississippi River have been tamed, but its history cannot be erased. This report will investigate heterogeneities within the floodplains and the impact it has in flooding conditions verses using an effective hydraulic conductivity to design levees and placement of pressure relief wells.

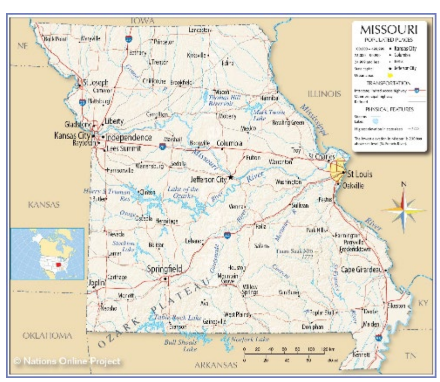


Figure 1.2 State of Missouri

Figure 1.1 illustrates a levee that could be found on the Mississippi River, which Blanket Theory can analyze. It is founded on relatively thin impervious soils underlain by deeper pervious soils where under seepage, sand boils, and internal erosion are commonly a concern. Where under seepage control is needed, a relief well system may be designed to reduce excess head. System details to provide adequate pressure relief depend on numerous parameters and are often determined using the USACE (1992) analytical design process.

Pressure Relief Wells are aptly named. When flooding conditions occur, and the pressure head exceeds the pressure exerted by the clay blanket, failure modes can be created such as sluffing, internal erosion, or sand boils, as pictured center. When a pressure relief well is installed, much like a monitoring or drinking well, the surface pump can be open once under artisanal conditions, allowing the excess head to be released in a control manor (Figure 1.3). The Army Corps of Engineers has many parameters when locating levees in need of pressure relief wells systems, but often rely on the assumption that much of the floodplains have a homogenous geology.

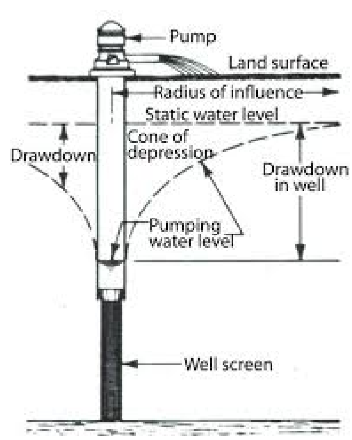


Figure 1.3 Structure of a pressure relief well

A relief well system is often placed near or at the levee toe on the landward side of a levee, as seen in Figure 1.1. Excess heads at the levee tow are evaluated against the resistance provided by the landside confining blanket's effective unit weight and thickness. Suppose the driving uplift force provided by the excess head is greater than the resisting force provided by the blanket. In that case, that location may be susceptible to uplift-related breaching of the coning blanket, and internal erosion of the foundation may initiate (such as sand boils). This location is the optimal placement of a relief well, where it can alleviate the most excess head. In a controlled situation, where k_{eff} would be used, the location of the pressure relief wells can be standardized. In situations, such as the presences of a buried oxbow feature, the excess head would no longer occur at a standard distance away from the tow of the levee and could lead to internal erosional features, such as sand boils, occurring further away from the toe of the levee.

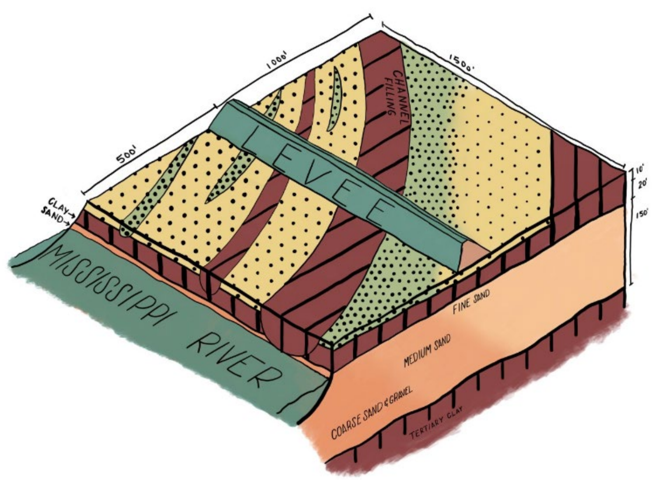


Figure 1.4 Cross section of a Mississippi levee with buried oxbow channel

Oxbows are an alluvial feature which occurs when a meandering stream or river find a shorter path of least resistance and cuts off a bend of itself (Figure 1.4). Over time, the cut off feature slowly begins to fill with clay and silt, which is more impervious than the surrounding sand, which has a higher hydraulic conductivity than the clay and silt composing the buried oxbow. The Mississippi River has the largest concentration of oxbow lakes in North America, with an estimation of 1,500 alluvial features. With a high concentration of buried oxbow lakes, the levees surrounding the Mississippi River are at a greater risk of succumbing to failure due to increased head creating internal erosion. Oxbow lakes, and their frequent occurrence along the Mississippi River are a prime example of heterogeneity within the floodplains. As a stream or river meanders, the water within the river seeks the shortest path of least resistance, causing the river to cut parts of itself off, creating oxbow lakes, as seen in the upper left photo. Over time, the oxbow lake will fill with dense clay and silt compared to the surrounding sands, and eventually turn into a buried oxbow channel. Identifying and avoiding these conditions is not always possible when building levees, so a closer examination is needed on the affects buried oxbow lakes and other heterogeneities have on levees.

2. METHODS

2.1. MODEL PARAMETERS

For this project, Groundwater Vista was used to run ModFlow V. 6. Groundwater Vista is a window graphical user interface for 3-D groundwater flow and transport modeling. ModFlow V. 6 uses Finite Difference Modeling to simulate groundwater flow, where chosen geology can be imputed into layers, rows, and columns. Other more complex versions and add on are available for ModFlow V. 6, but the standard program was used for this project.

This method was used to build two- and three- dimensional numerical models of different heterogeneities below the low hydraulic conductivity blanket with steady-state flow of confined groundwater. The base parameters for all testing parameters remained the same, to best identify how the testing parameters affect the pressure head in its respective scenario. This base parameter can best be thought of as the control scenario and is referred to as the "Parent Model" throughout this investigation.

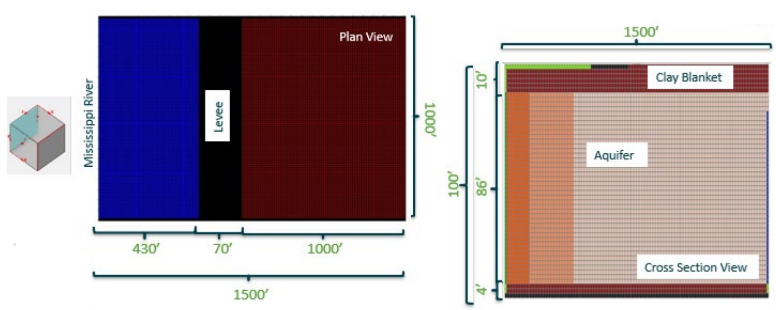


Figure 2.1 Plan and cross-sectional views of the parent model and its dimensions

Figure 2.1 illustrates the model dimensions used. The model was 1,000 feet long (L) and 1,500 feet wide (W) and 100 feet thick (B). Each cell in the ModFlow program had a dimension of 10 feet long, 10 feet wide, and 2 feet thick. This allowed for the most accurate illustration of the testing parameters without using the Grid Feature in ModFlow. It was advised not to use the Gride Feature as the flow lines from each cell are split, where cell smoothing is then required. For the scope of this investigation, this step was not required in order to create a reliable and understandable result.

Dimensions of the levee from the river, and the footprint of the levee were originally outlined in Mansur and Kaufman 1962. No-flow boundaries were set on the bottom layer of the model, along with the north and south vertical sides of the model. A no-flow boundary was also used as the footing of the levee to as it is assumed the levee would be a perfectly impervious feature (Figure 2.2). A constant head boundary was placed on the first layer (ground surface) from the source (the Mississippi River) to the levee. This constant head boundary was set at 120 feet. This boundary then extends down the model where the source, or Mississippi Riverbanks are (see Figure 2.2). A second constant head boundary was placed on the landward side of the levee to help with artificial flow mimicking a flooding event. This constant head boundary was placed form the bottom of the model to 20 feet below ground surface with a constant head of 80 feet (see Figure 2.2).

The hydraulic conductivities used were collected from Mansur and Kaufman and verified through other reports completed on Mississippi River Levees and are values used by the Army Corp of Engineers. All clay layers used a hydraulic conductivity of 0.58 feet per day. Coarse Grained sand used 255 Feet Per Day, Medium Grained Sand used 198 feet per day, and the fine-grained sand used 5.7 feet per day (see Figure 2.2).

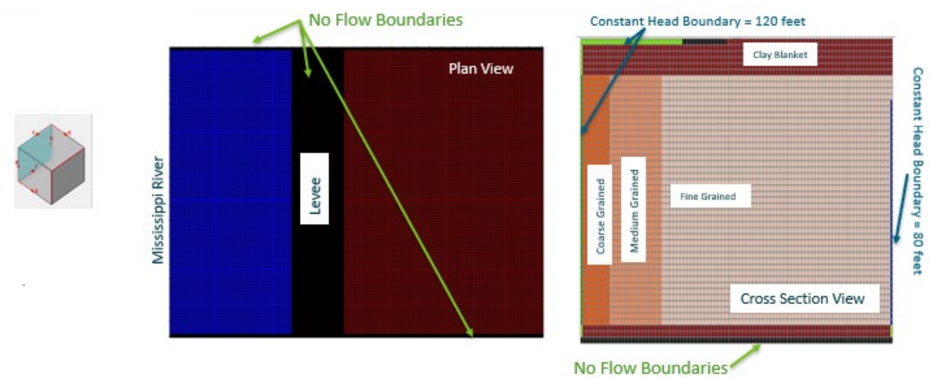


Figure 2.2 Location of no flow boundaries (left) and location of different hydraulic conductivities (right)

2.2. TESTING PARAMETERS

Four Scenarios were tested at first. The first (picture number one in Figure 2.3) examines horizontal layers with clay volumes compared to sand of 10%, 20%, and 30% (excluding the clay blanket) and examining each volume as one layer, two layers, or three layers. Looking to the table to the right, you can see the nine different scenarios composed from the three different volumes of clay verse sand in the aquifer and using different number of layers. This is repeated for Vertical layers along the length of the model (picture number 2 in Figure 2.3) and Vertical layers along the width of the model (picture number 3 in Figure 2.3). The fourth is a model of a shallow buried ox bow which only extend halfway through the model but run parallel and perpendicular to the flow of groundwater (picture number 4 in Figure 2.3). Table 1.1 shows a tabulated summary of the nine models created in this first series.

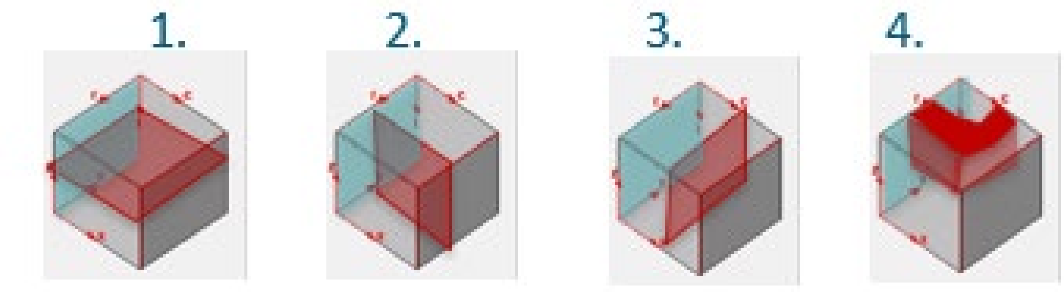


Figure 2.3 Using the reference cube, the first four testing parameters are shown

Table 1.1 Outline of what parameters were used for the first nine models created.

	10%	**20%**	**30%**
1 Layer	1 Layers @ 10%	1 Layer @ 20%	1 Layer @ 30%
2 Layers	2 Layers = 10%	2 Layers = 20%	2 Layers = 30%
3 Layers	3 Layers =10%	3 Layers = 20 %	3 Layers = 30 %

Three hypotheses were initially tested, each with three parameters:

1. Horizontal layer(s) of clay under the blanket, where the volume increases from 10%, 20% and 30% clay to sand (excluding the clay blanket). For each volume of clay, the layers increase from one, two, to three layers, all equally spaced (Figure 2.4);
2. Vertical layer(s) of clay under the blanket, along the length of the model, where the volume increases from 10%, 20% and 30% clay to sand (excluding the clay

blanket). For each volume of clay, the layers increase from one, two, to three layers, all equally spaced (Figure 2.5).

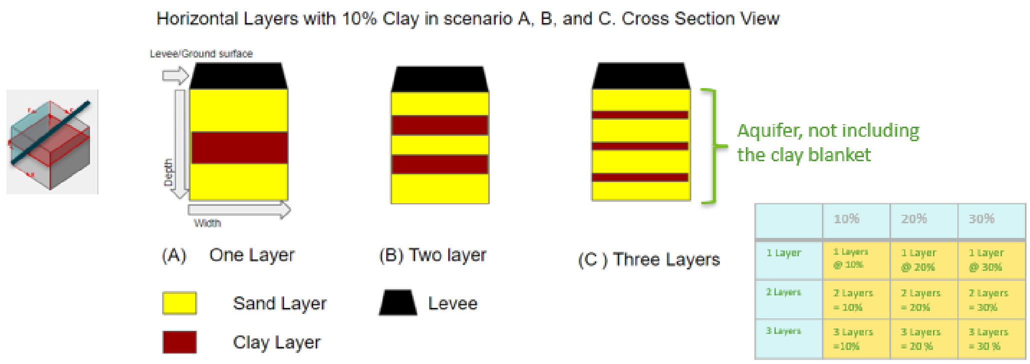


Figure 2.4 Horizontal layers testing parameters

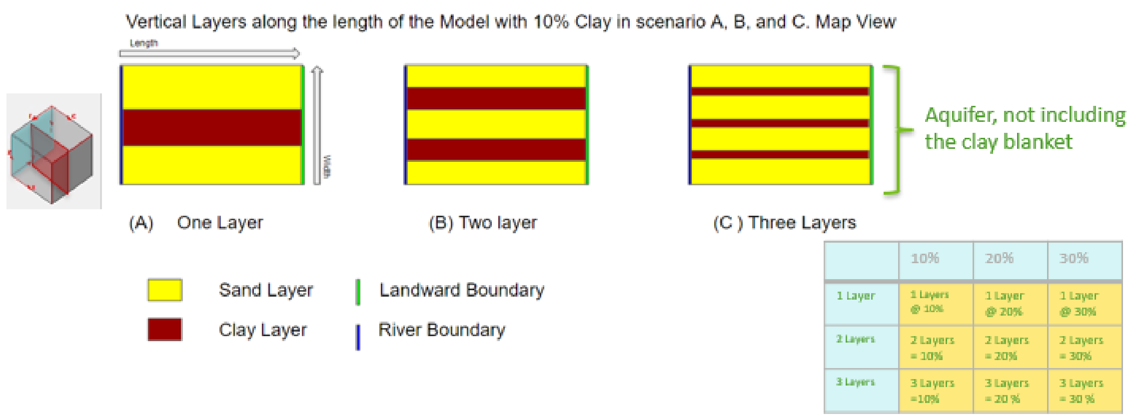


Figure 2.5 Vertical layers parallel to flow testing parameters

3. Vertical layer(s) of clay under the blanket, and along the width of the model, where the volume increases from 10%, 20% and 30% clay to sand (excluding the

clay blanket). For each volume of clay, the layers increase from one, two, to three layers, all equally spaced (Figure 2.6).

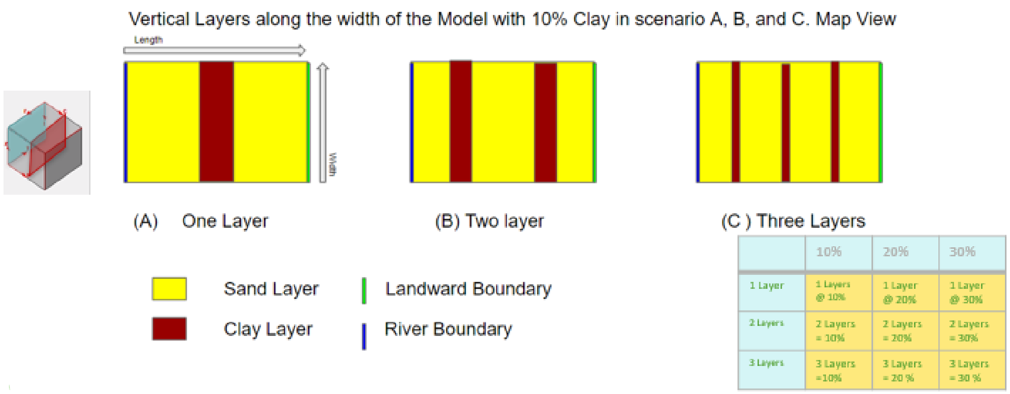


Figure 2.6 Vertical layers perpendicular to flow testing parameters

(1) The figure on the right (in Figure 2.7) was drawn after a figure commonly used by Mansur and Kaufman in several reports, but most notable in their 1962 report. It shows part of the buried oxbow channel underlying a levee. In my model, I took that ideal with a clay seam running parallel then perpendicular to the direction of flow. The buried oxbow in my model only extends halfway through the aquifer, or to a depth of fifty feet below ground surface.

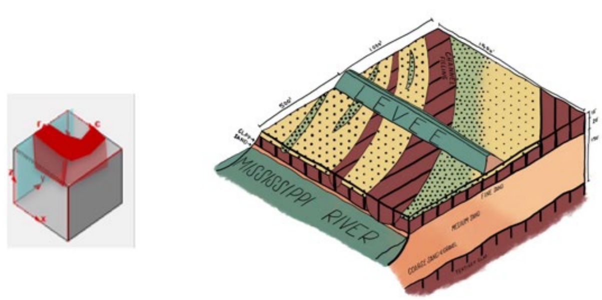


Figure 2.7 Buried oxbow channel testing parameters

2.3. EFFECTIVE HYDRAULIC PARAMETERS

The effective hydraulic conductivity was calculated for each model ran, then averaged to find a representative hydraulic conductivity for each of the of the three parameters at 10%, 20%, and 30%. Two equations were used to solve for the effective hydraulic conductivity. See Figure 2.8 and Figure 2.9 for a visual on how the effective hydraulic conductivity is calculated for each situation. Figure 2.10 shows a tabulated summary of all of the effective hydraulic conductivities used and in what situation they were used.

Eq. 1. $$k_{eff,parallel} = \frac{\sum k * b}{\sum b}$$

$k_{eff,\ parallel}$ = Effective Hydraulic conductivity with flow parallel to layers
k=hydraulic conductivity of layer
b=thickness of layer

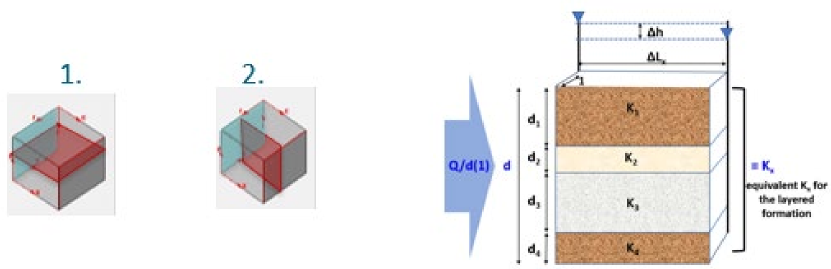
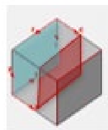


Figure 2.8 Testing parameters where $K_{eff,parallel}$ is used (right) and a diagram of how $K_{eff,parallel}$ is computed (left)

Eq. 2. $$K_{eff,Perpendicular} = \frac{\sum L}{\sum \frac{L}{K}}$$

$k_{eff,\ perpendicular}$ = Effective Hydraulic conductivity with flow parallel to layers
k=hydraulic conductivity of layer
L=Length of layer

3.



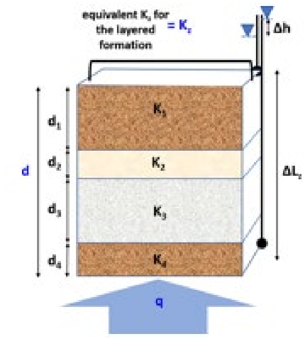
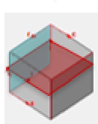


Figure 2.9 Testing parameters where $K_{eff,perpendicular}$ is used (left) and a diagram of how $K_{eff,perpendicular}$ is computed (left)

Once the effective hydrologic conductivity has been calculated, the hydraulic conductivity for the fine grain sand is replaced with the effective hydraulic conductivity and the model is run. In these scenarios, there are no clay layers besides the clay blanket at the surface of the model. Once the model has ran, the head values are downloaded and processed in excel to allow the heads to be compared between the effective hydraulic conductivity and the heterogeneity hydraulic conductivity.

By Volume Clay to Sand 10% 20% 30%

1.



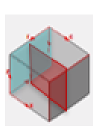
Formation	Keff (ft/day)
HA1	4.7
HA2	4.6
HA3	4.6
HA	4.6

Formation	Keff (ft/day)
HB1	4.2
HB2	4.2
HB3	4.3
HB	4.2

Formation	Keff (ft/day)
HC1	3.7
HC2	3.1
HC3	3.7
HC	3.5

Parallel

2.



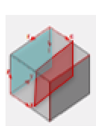
Formation	Keff (ft/day)
VLA1	5.2
VLA2	5.1
VLA3	5.1
VLA	5.1

Formation	Keff (ft/day)
VLB2	4.5
VLB3	4.7
VLB4	4.8
VLB	4.7

Formation	Keff (ft/day)
VLC1	3.4
VLC2	3.7
VLC3	4.2
VLC	3.7

Parallel

3.



Formation	Keff (ft/day)
VWA1	2.9
VWA2	2.9
VWA3	2.8
VWA	2.9

Formation	Keff (ft/day)
VWB1	2.1
VWB2	2.0
VWB3	2.1
VWB	2.0

Formation	Keff (ft/day)
VWC1	1.6
VWC2	1.6
VWC3	1.6
VWC	1.6

Perpendicular

Figure 2.10 The K_{eff} used in the nine effective hydraulic conductivity models

3. RESULTS

3.1. SUMMARY

Once the data was processes for all models ran, the only significant change in head pressure was when the vertical layers of clay ran the vertical width of the model. The following sub-sections explore the results from all tests ran. Section 3.4 explores how heterogeneity in the aquifer differ when effective hydraulic conductivity is calculated for that respective aquifer.

3.2. HORIZONTAL LAYERS

When the clay layer run horizontally though the aquifer (Figure 3.1), the overall head changes little to none when comparing all tested parameters.

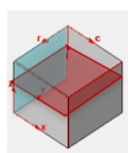


Figure 3.1 The refence cube of the placement of the horizontal layer

Once each model was completed (Figure 3.6), the head values from the surface were downloaded and graphed in excel. For the horizontal Layers Graphs, it is easily identified that there is a steady head from the river, which is at a flood stage of 120 feet (the River with a depth of 80 feet, plus an excess of 40 feet), to where the levee is (which is holding back the excess of 40 feet of water). Once on the landward side of the levee, the head drops linearly to a constant head of 80 feet 1,500 feet away from the river side.

This trend remains the same when the volume of clay is 10%, 20% and 30% (Figure 3.2-3.4). This trend also remains the same when there are regardless of the number of layers (Figure 3.2-3.4) and can be compared to the parent or the control model (Figure 3.5).

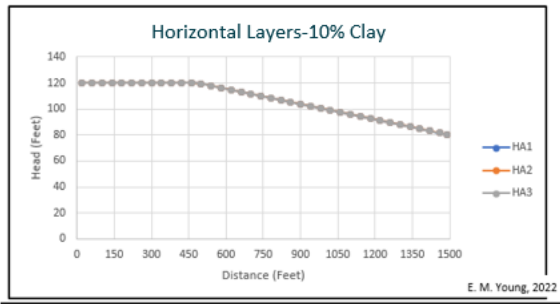


Figure 3.2 Comparison of horizontal layers when 1,2, and 3 layers are present. all layers for each model total 10% total clay volume

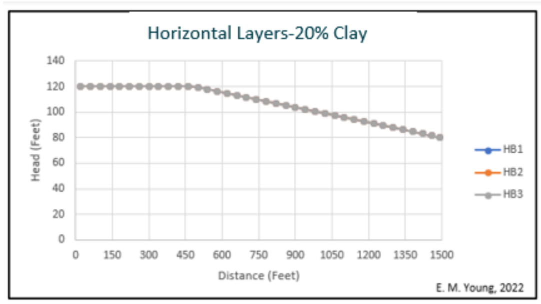


Figure 3.3 Comparison of horizontal layers when 1,2, and 3 layers are present. all layers for each model total 20% total clay volume

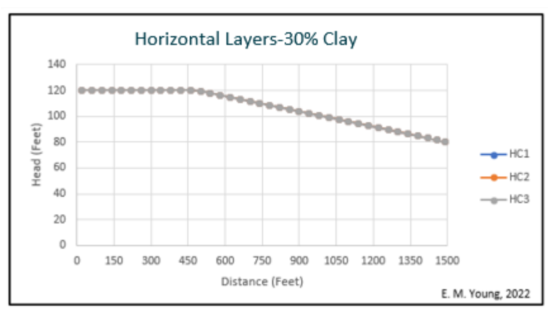


Figure 3.4 Comparison of horizontal layers when 1,2, and 3 layers are present. all layers for each model total 30% total clay volume

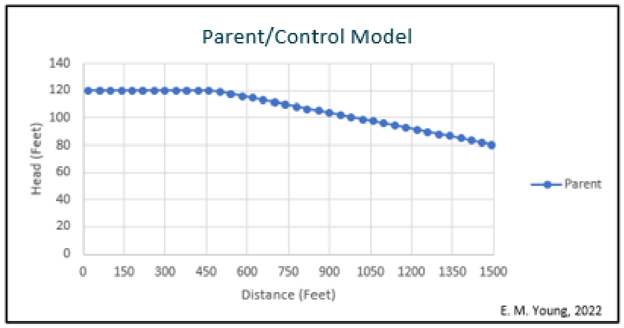


Figure 3.5 The parent, also known as the control model pressure head results for reference

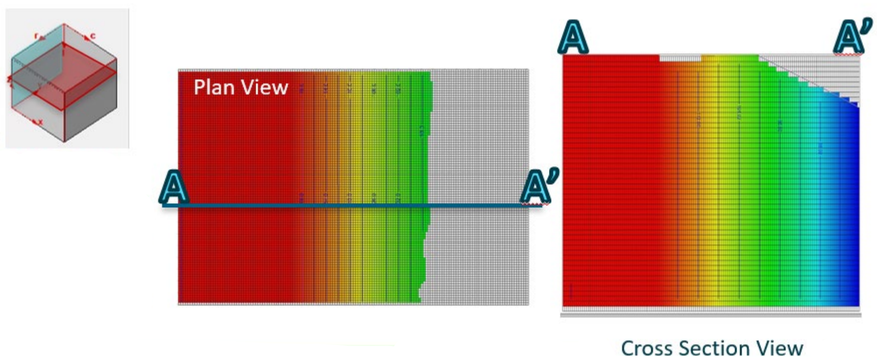


Figure 3.6 The model pressure heads result in plan and cross-sectional view

3.3. VERTICAL LAYERS PARALLEL TO FLOW

When the clay layer run vertically though the aquifer along the length of the model (Figure 3.7), the overall head changes little to none when comparing all tested parameters. Once each model was completed (Figure 3.12), the head values from the surface were downloaded and graphed in excel. For the horizontal Layers Graphs, it is easily identified that there is a steady head from the river, which is at a flood stage of 120 feet (the River with a depth of 80 feet, plus an excess of 40 feet), to where the levee is (which is holding back the excess of 40 feet of water). Once on the landward side of the levee, the head drops linearly to a constant head of 80 feet 1,500 feet away from the river side. This trend remains the same when the volume of clay is 10%, 20% and 30% (Figure 3.8 – 3.10). This trend also remains the same when there are regardless of the number of layers (Figure 3.8 – 3.10) and can be compared to the parent or the control model (Figure 3.11).

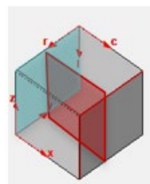


Figure 3.7 The reference cube of the vertical layer parallel to groundwater flow

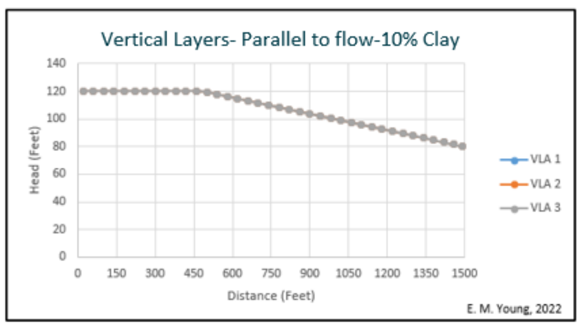


Figure 3.8 Comparison of vertical layers perpendicular to groundwater flow, when 1, 2, or 3 layers are present. all layers for each model total 10% total clay volume

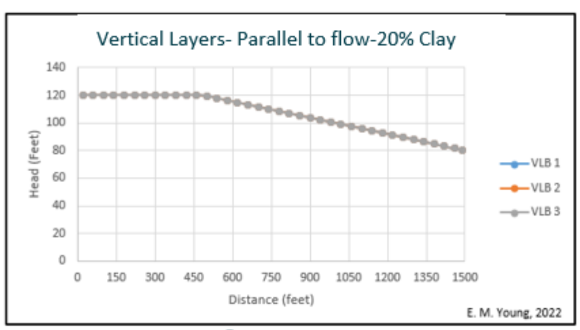


Figure 3.9 Comparison of vertical layers perpendicular to groundwater flow, when 1, 2, or 3 layers are present. all layers for each model total 20% total clay volume

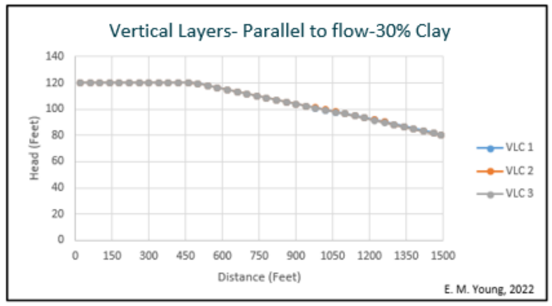


Figure 3.10 Comparison of vertical layers perpendicular to groundwater flow, when 1, 2, or 3 layers are present. all layers for each model total 30% total clay volume

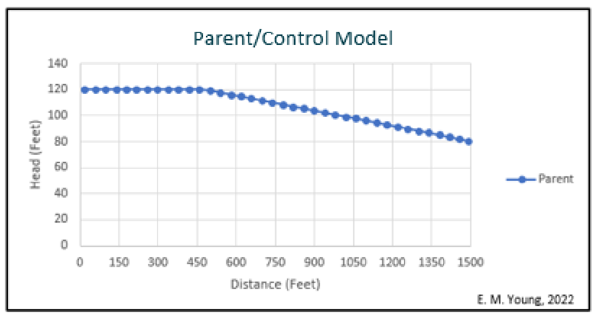


Figure 3.11 The parent also known as the control model pressure head results for reference

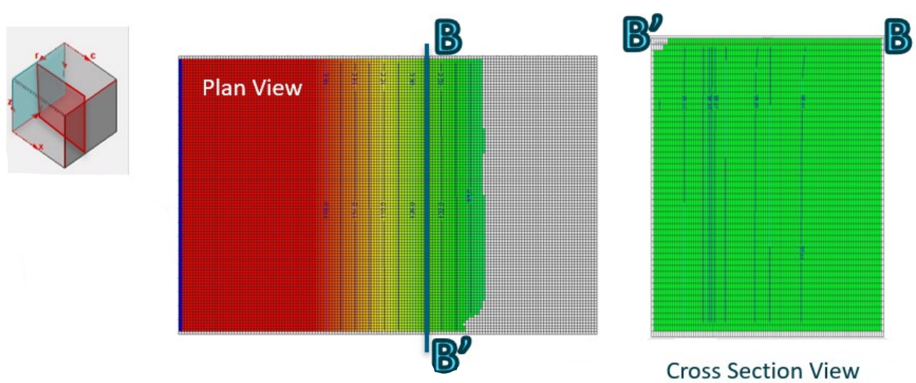


Figure 3.12 The model pressure heads result in plan and cross-sectional view

3.4. VERTICAL LAYERS PERPENDICULAR TO FLOW

When the clay layer run vertically though the aquifer along the width of the model (Figure 3.13), the overall head changes little to none when comparing all tested parameters.

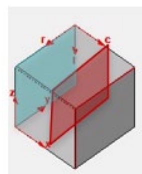


Figure 3.13 Reference cube of the vertical clay layer perpendicular to flow

Once each model was completed, the head values from the surface were downloaded and graphed in excel. For the horizontal Layers Graphs, it is easily identified that there is a steady head from the river, which is at a flood stage of 120 feet (the river with a depth of 80 feet, plus an excess of 40 feet), to where the levee is (which is holding back the excess of 40 feet of water). Once on the landward side of the levee, the head drops linearly to a constant head of 80 feet 1,500 feet away from the river side (Seen in Figure 3.18, using Figure 3.19 for a reference cube). This trend remains the same when the volume of clay is 10%, 20% and 30% (Figure 3.14-3.16). This trend also remains the same when there are regardless of the number of layers (Figure 3.14-3.16) and can be compared to the parent or the control model (Figure 3.17).

3.5. BURIED OXBOW FEATURE

Here is a look at the buried oxbow feature design (Figure 3.20 and Figure 3.21). The plan view snip was taken under the clay blanket and show the oxbow lake starting

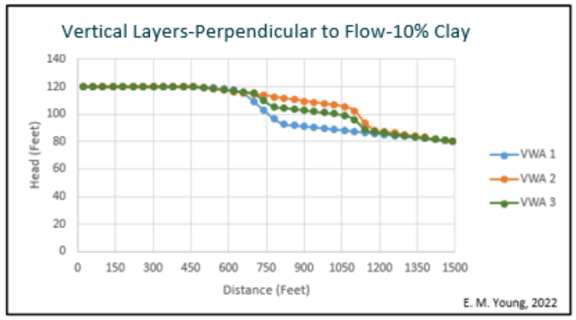


Figure 3.14 Comparison of vertical layers perpendicular to flow when 1, 2, or 3 layers are present. all layers for each model total 10% total clay volume.

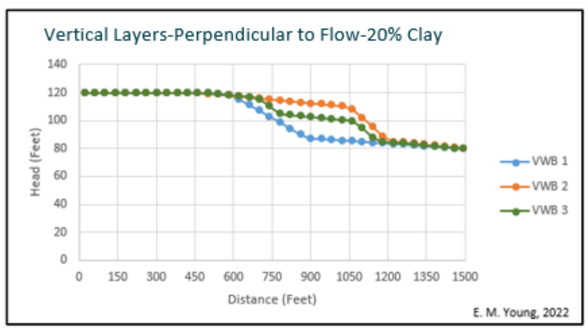


Figure 3.15 Comparison of vertical layers perpendicular to flow when 1, 2, or 3 layers are present. all layers for each model total 20% total clay volume.

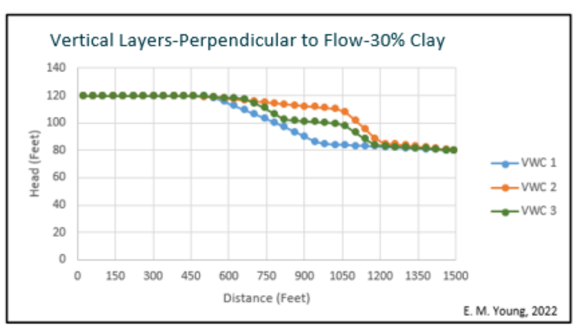


Figure 3.16 Comparison of vertical layers perpendicular to flow when 1, 2, or 3 layers are present. all layers for each model total 30% total clay volume.

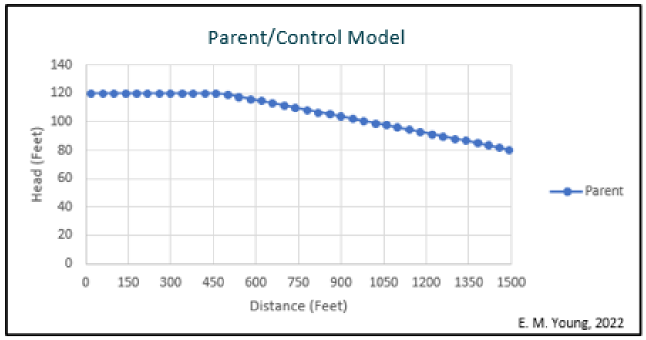


Figure 3.17 The parent model also known as the control model pressure head results for reference

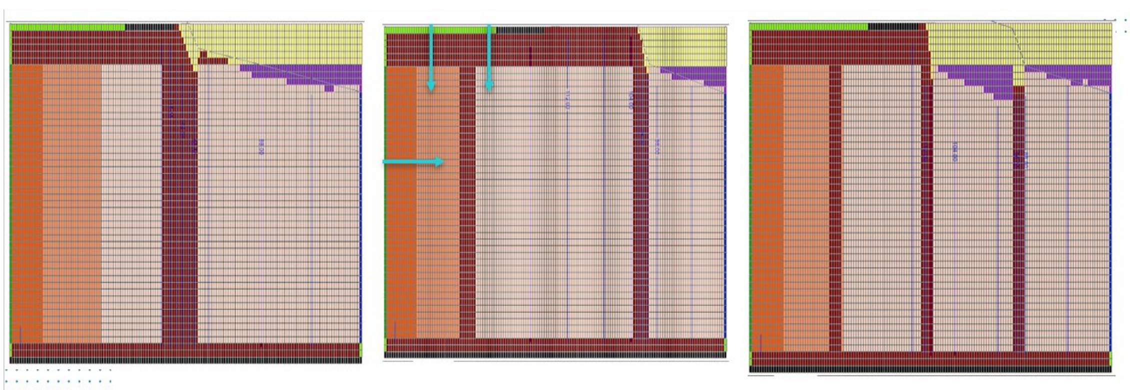


Figure 3.18 Three cross-sections taken when there is 1, 2, and 3 clay layers present perpendicular to flow

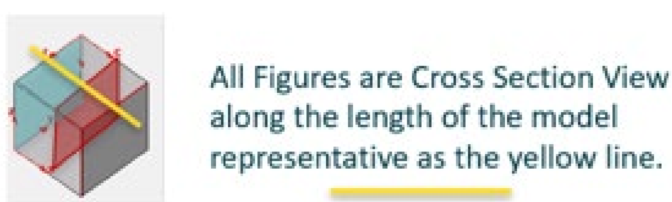


Figure 3.19 Using the reference cube, the yellow line shows where the cross-sections from 3.18 were completed

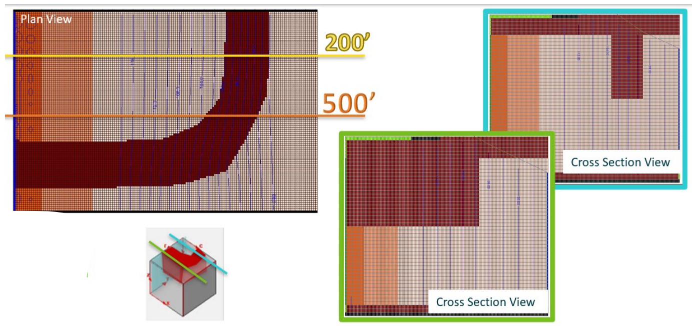


Figure 3.20 Images of the buried oxbow feature, please refer to the reference cube for the cross-section locations

parallel then turning perpendicular to the groundwater flow. This is to represent a buried oxbow that may not be easily identified form the ground surface. The two cross section boarders correspond to the cross-section line on the gray cube (Figure 3.20). The cross section in Green shows the clay layers when parallel to flow, and the cross section in blue shoe when the clay layer is perpendicular. Do note the two-hundred-foot line and the five-hundred-foot line. This is where pressure head values were collected for the following graphs.

The overall graphs from the oxbow lakes are very similar to the parent model, with relatively little change across the model (Figures 3.22-3.25). If the oxbow lake extended the full length of the model, it would expect more variation in head, than what is currently present. Figure 3.26 shows the model results and the lake of great pressure head change once the model processed the buried oxbow feature.

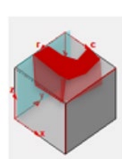


Figure 3.21 The reference cube for the orientation of the buried oxbow feature

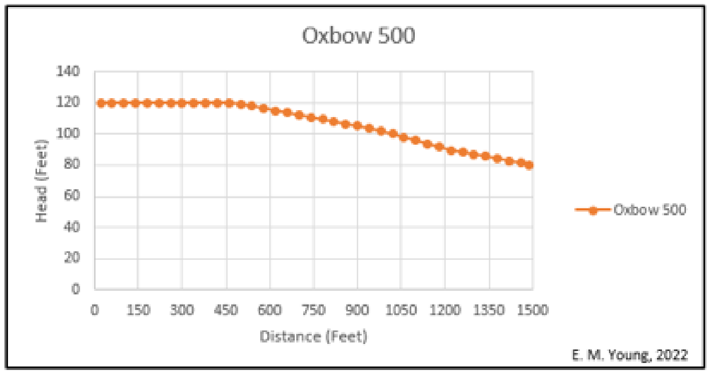


Figure 3.22 The pressure head at the 500’ cross-section line from Figure 3.20

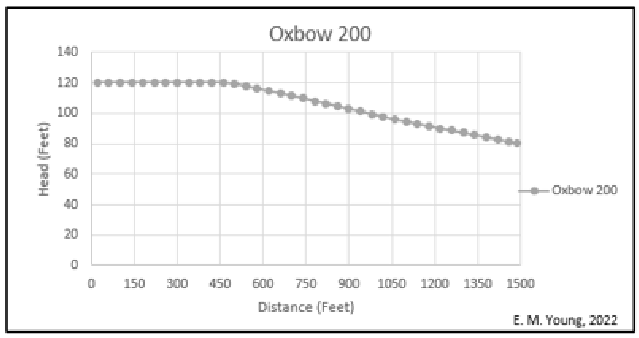


Figure 3.23 The pressure head at the 200’ cross section line from Figure 3.20

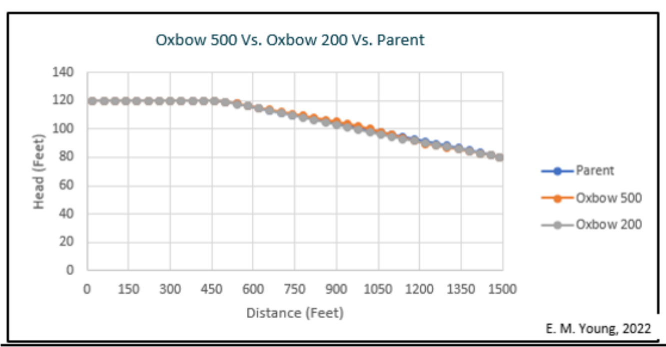


Figure 3.24 Comparison of the pressure head from the 500’ cross-section, 200’ cross-section, and the parent (also known as the control model)

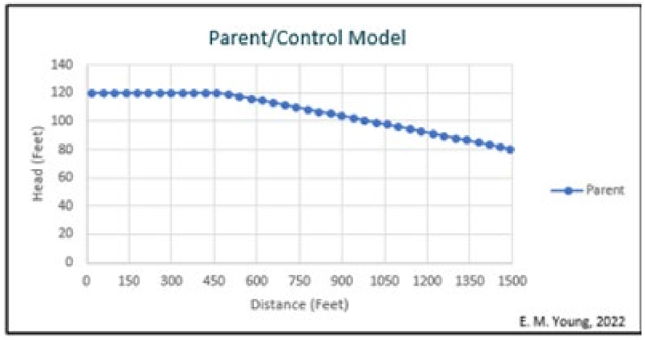


Figure 3.25 The parent also known as the control model pressure heads

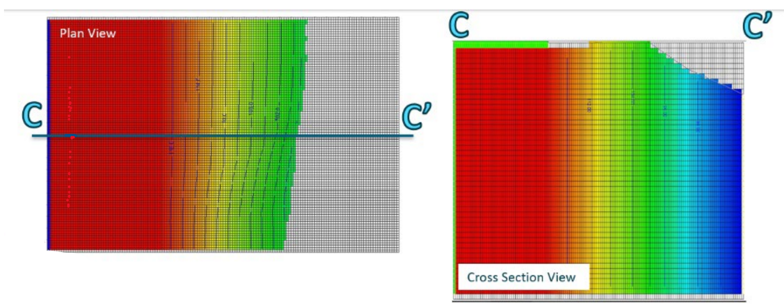


Figure 3.26 The plan and cross-sectional view of the pressure head produced from the buried oxbow model

3.6. EFFECTIVE HYDRAULIC CONDUCTIVITY

The overall effective hydraulic conductivities for all nine models look very similar, and look similar the parent model, which has no added clay layers, but does have different hydraulic conductivities thought-out the model (Figure 3.27). Now let's compare the effective hydraulic conductivities to the original three situations we started out with.

The overall effective hydraulic conductivities for all nine models look very similar, and look similar the parent model, which has no added clay layers, but does have different hydraulic conductivities thought-out the model. Now let's compare the effective hydraulic conductivities to the original three situations we started out with (Figure 3.28).

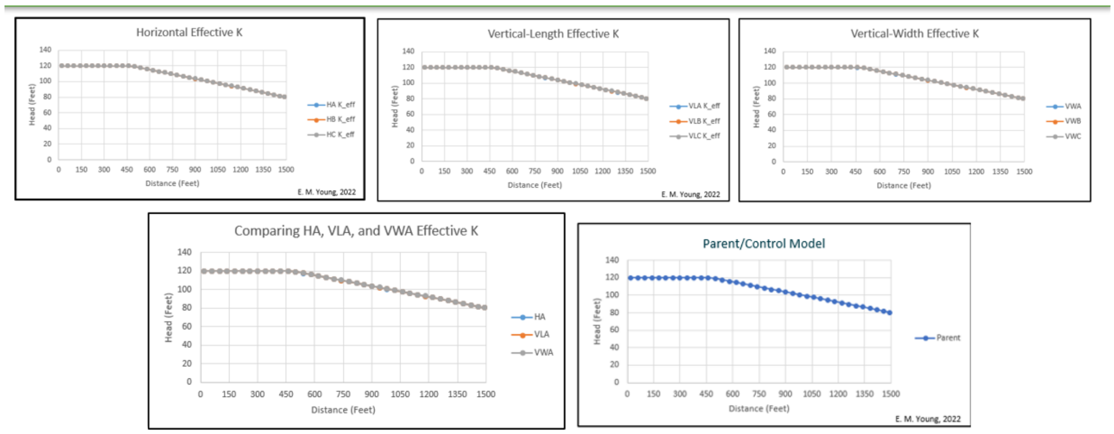


Figure 3.27 Comparison of the horizontal, vertical-parallel to flow, vertical-perpendicular to flow, and the parent (control) model

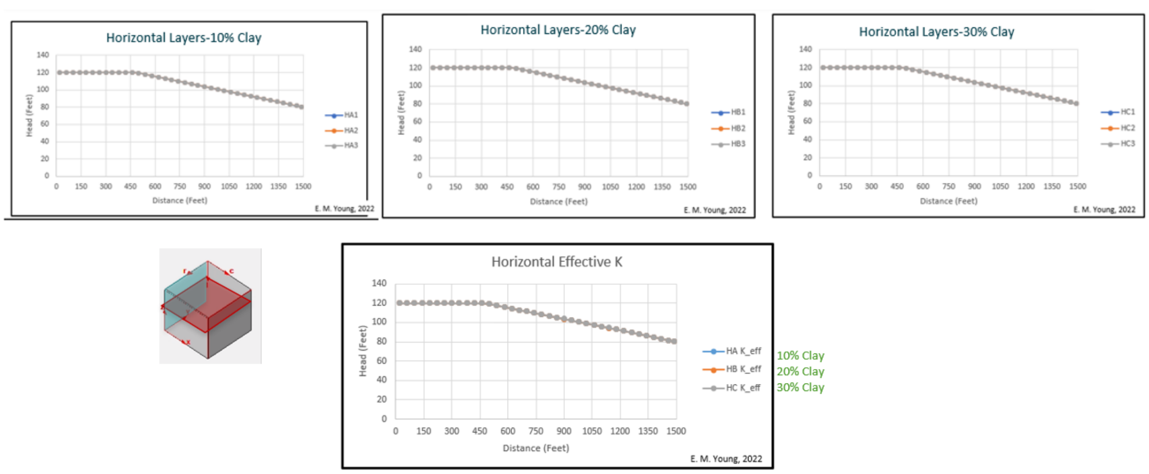


Figure 3.28 Comparison of horizontal layers at 10%, 20%, and 30%

For the Vertical layers spanning the length of the model (Figure 3.29), the pressure head look to be very similar to the effective hydraulic conductivities, this could be due to the fact the layer is parallel to the direction of flow, so the clay layer itself does not have a huge effect on the pressure head so when applied to the effective hydraulic conductivity, the vertical layer would still not have an effect to the results.

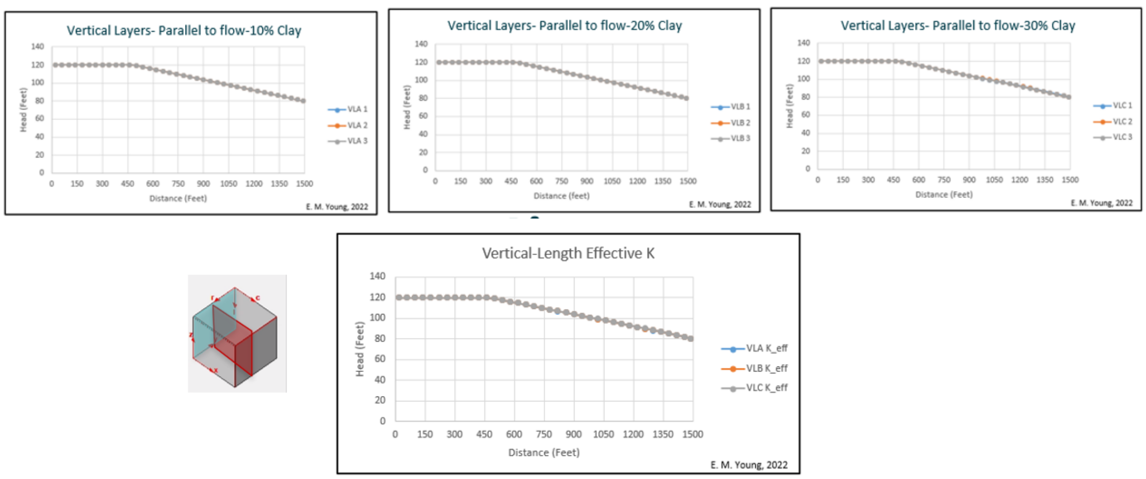


Figure 3.29 Comparison of vertical clay layers parallel to flow at 10%, 20%, and 30% total clay volume

And again, this vertical layer spanning the width of the model does cause pressure head differences due to the location of the vertical clay layers (Figure 3.30). But when you apply the effective hydraulic conductivity, the placement of the clay layers no longer seems to matter, and the overall effective hydraulic conductivity is not very different from the parent model. If the effective hydraulic conductivity is design to be very conservative, this over estimation would prevent many modes of failures for the levees. This does leave us with a set of levees that could be drastically over engineered potentially wasting millions of dollars in maintaining unnecessary pressure relief wells.

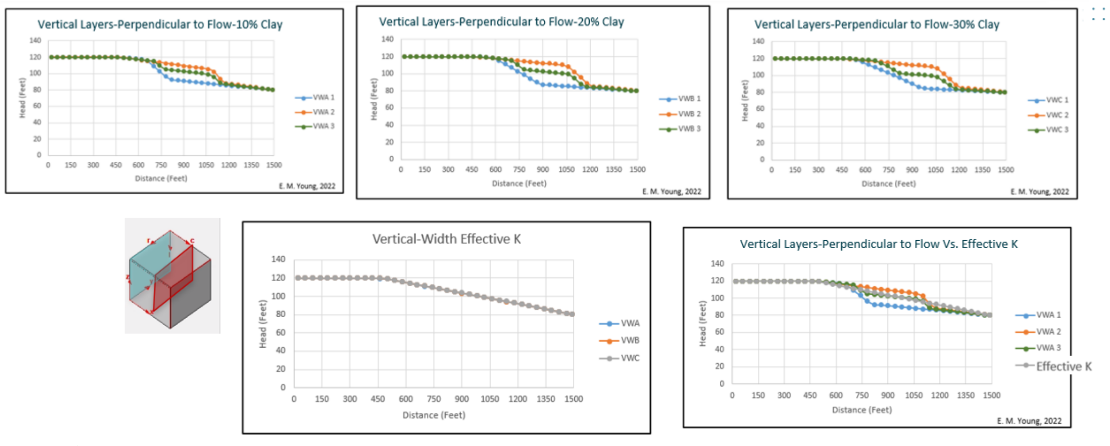


Figure 3.30 Comparison of all vertical layer perpendicular to flow at 10%, 20%, and 30% total clay volume.

To summarize, effective hydraulic conductivity is not affected greatly by horizontal clay seams, less than 30% volume, nor by vertical clay seams, spanning perpendicular of a levee and less than 30%.

4. CONCLUSION

When designing pressure relief well systems, it is imperative to understand what major geomorphology and heterogenies features are present, such as buried oxbow lakes, as when the feature is parallel to the source, such as the Mississippi River, there is a notable greater increase in head pressures, especially on the landward tow of the levee. This can cause erosional features that originally thought of to have been protected from by installing pressure relief wells. When comparing the effective hydraulic conductivities of horizontal clay layers and vertical clay layers spanning the length of the model, little to no noticeable difference can be discerned, also long as the clay volume is under 30%. Dams or levees are often located on geology which includes a thinner layer (known as a blanket) of soil with relatively low hydraulic conductivity overlaying deeper, more pervious foundation soils as illustrated in Figure 1.1. During a flood, a hydraulic gradient develops which causes subsurface under seepage flows towards the “dry” landward side of the levee, where blanket soils cause confined conditions with artesian heads. Excess heads at the levee toe are evaluated against the resistance provided by the effective unit weight and thickness of the landside confining blanket. If the driving uplift force provided by the excess head is greater than the resisting force provided by the blanket, then that location may be susceptible to uplift-related breaching of the confining blanket and internal erosion of the foundation may initiate (often observed in the field as sand boils). Given that foundation erosion can potentially progress to levee failure, under seepage and methods for controlling it have been researched and employed for nearly a century.

APPENDIX

HORIZONTAL LAYERS MODELS

HA 1: 10% Clay, One Layer

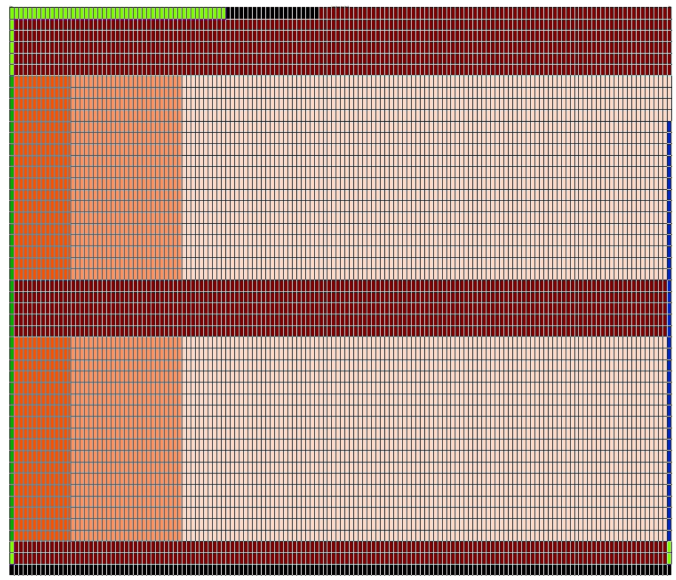


Figure A.1. Before Modflow Program was Ran, Plan View

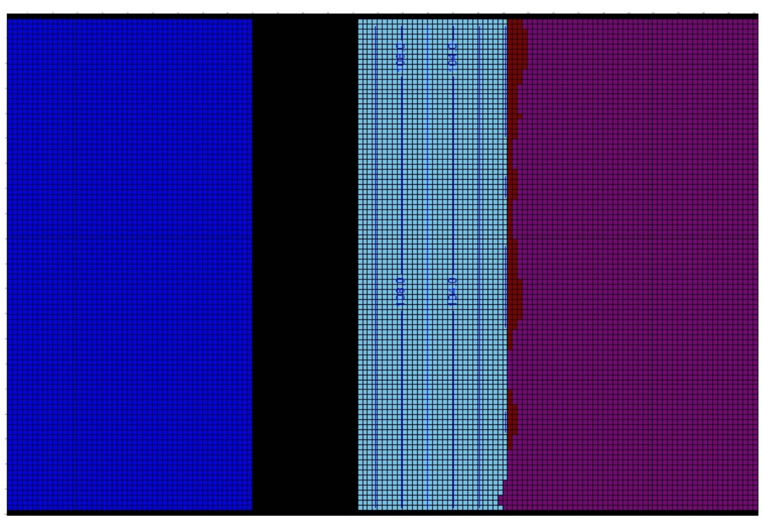


Figure A.2. After ModFlow Program was Ran, Plan View

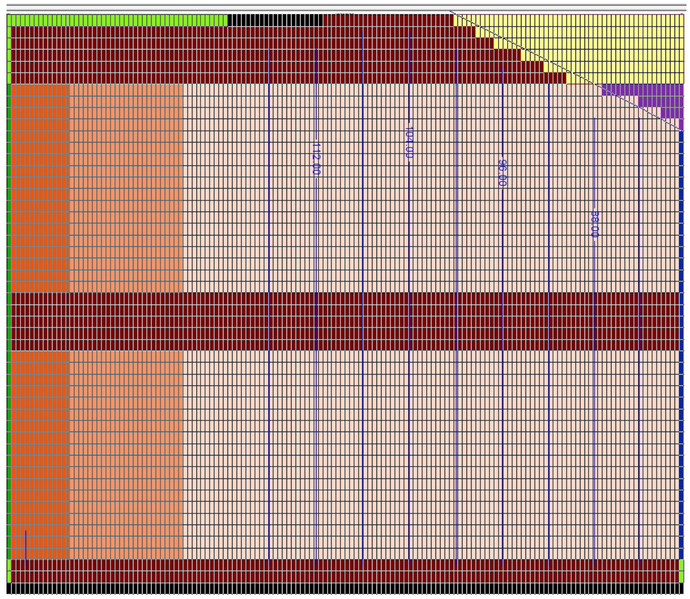


Figure A.3. After ModFlow Program was Ran, Cross-Section View

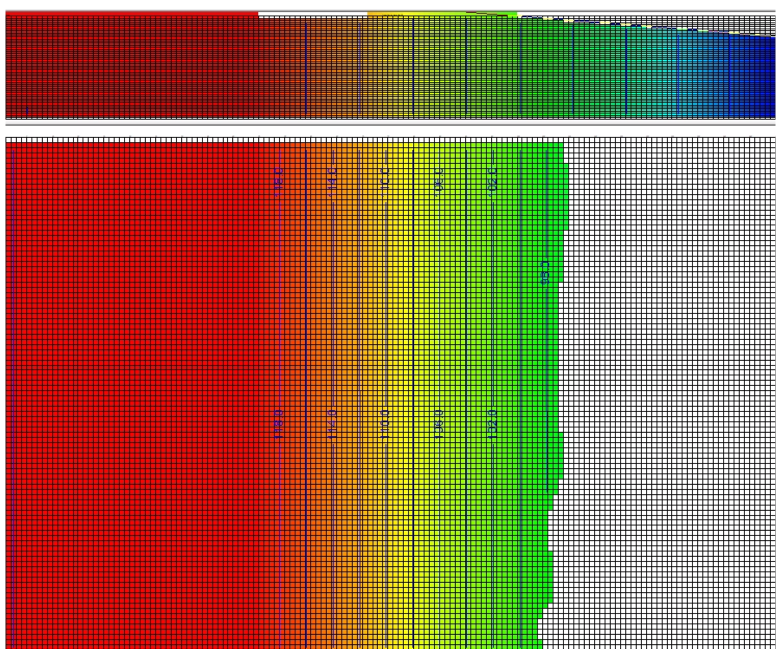


Figure A.4. After ModFlow Program was Ran, Color Flood, Plan View

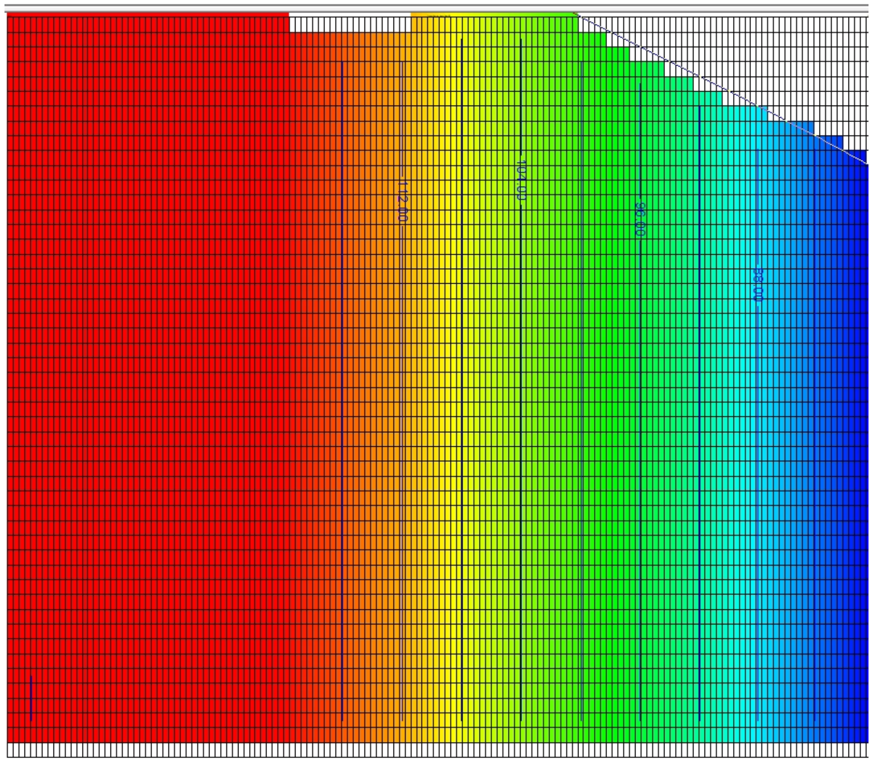


Figure A.5. After ModFlow Program was Ran, Color Flood, Cross-Section View

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VITA

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While Young was completing her graduate degree at Missouri University of Science and technology, she was awarded the Dr. Oboh-Ikuenobe Leadership Award from the Department of Geoscience and Geological and Petroleum Engineering in May of 2021. Throughout her colligate career she remained an active member in the Association of Environmental & Engineering Geologist of Missouri-St. Louis.

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