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A GIS-BASED STRATEGY FOR MANAGING LEVEE
SIMULATION DATA

by

Jeffrey R. Handy

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Civil and Environmental Engineering

Brigham Young University

August 2008

BRIGHAM YOUNG UNIVERSITY

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ABSTRACT

A GIS-BASED STRATEGY FOR MANAGING LEVEE SIMULATION DATA

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Department of Civil and Environmental Engineering

Master of Science

Understanding and improving the state of the nation's levees has become a national priority following the devastating events surrounding Hurricanes Katrina and Rita. Federal legislation passed in 2007 created a new national *Committee on Levee Safety* and spurred the development of the National Levee Database, a central repository of information relating to the location and state of levees across the United States (Water Resources Development Act, 2007). One of the major goals in developing such a database is to improve the safety of America's levees. The National Levee Database, however, does not include features for storing seepage and slope stability data related to numerical analyses of levees. These data are critical in analyzing current levee conditions and predicting future failure scenarios, thus providing a path for further improving the safety of levees.

The Levee Analyst is a new GIS data model and set of geoprocessing tools that make it possible to store and manipulate model data associated with seepage and slope stability analyses. The data model provides a concise structure for storing large amounts of levee seepage and slope stability data and also provides a structure that is expandable and compatible with the National Levee Database. The Levee Analyst combines the capabilities of various software systems in providing a data model and suite of tools that assists in further understanding and analyzing the state of America's levees.

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I also owe much to my wife Amber who has stood beside and supported me as I have worked on my thesis, all while being pregnant with our son Will. I could not have done it without you. My thanks also go to my family and my wife's family, for their love and support.

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1 Introduction

Levees are earthen embankments constructed along waterways to protect adjacent lands from flooding. Outside of the United States, levees are often referred to as dikes. Levees have been constructed for centuries and continue to play an integral part in protecting farms and homes from flood waters. Levees are seen across the United States and around the world, constructed along mighty rivers like the Mississippi River and also along small streams prone to seasonal flooding.

The United States Army Corps of Engineer's (USACE) *Engineering and Design - Design and Construction of Levees* manual defines a levee as “an embankment whose primary purpose is to furnish flood protection from seasonal high water and which is subject to water loading for periods of only a few days or weeks a year” (USACE, 2000). Levees play a key role in protecting life and property during seasonal high waters, hurricanes, storm surges, and other weather-related events.

Levees can be classified into two main categories, agricultural levees and urban levees (USACE, 2000). Agricultural levees are constructed to provide protection for lands used for agricultural purposes, whereas, urban levees are constructed to protect residential, commercial, and industrial facilities (USACE, 2000). In urban areas where space is limited, floodwalls are also used to protect lands from flooding, but differ from levees in that they are constructed of concrete (FEMA, 2006).

In September of 2005, the Federal Emergency Management Agency (FEMA) formed the *Interagency Levee Policy Review Committee* to review current levee policy and to make recommendations for policy change. The committee's findings were published in a 2006 report entitled *The National Levee Challenge: Levees and the FEMA Flood Map Modernization Initiative*, in which they note that levees do not eliminate the risk of flooding, but instead only reduce the risk. Instead of being viewed as flood protection structures, levees should be regarded as flood risk reduction structures (FEMA, 2006). Although designed and constructed to standards necessary to protect life and property, levees are susceptible to catastrophic failures due to natural events, poor maintenance, and changing conditions. The USACE notes the four principal causes of failure in levees are: overtopping; surface erosion; internal erosion (i.e. piping); and slides within the levee embankment or foundation soils (USACE, 2000). In managing and monitoring levees, one of the primary goals is to analyze current conditions to predict and remediate potential problems and weaknesses in levees. This understanding helps levee managers to improve protection, minimize risk, and properly maintain levees.

1.1 Hurricane Katrina

On August 29, 2005, Hurricane Katrina slammed into the Gulf Coast 20 miles east of downtown New Orleans as a strong Category 3 (on the 5-point Saffir-Simpson scale) hurricane (Knabb et al, 2005). At its peak, Hurricane Katrina was a Category 5 hurricane and measured as one of the strongest storms on record with a central pressure of 902 millibars (Knabb et al, 2005). At landfall, Hurricane Katrina had sustained winds of 125 mph and these strong winds caused storm surges ranging from 10 to 16 feet in

Lake Pontchartrain, situated on the north shore of New Orleans (Knabb et al, 2005). A significant portion of New Orleans is below sea level and relies on a series of levees and floodwalls to protect the city from flooding. Hurricane Katrina's massive storm surge caused several of the levees protecting New Orleans to overtop and fail due to erosion. As the levees failed, water from Lake Pontchartrain rushed into the city, filling 80% of the city with water. In some areas the water reached depths of 20 feet and it took 43 days to fully pump out flood waters from New Orleans (Knabb et al, 2005).

Beyond the horrendous damage to property caused by the hurricane winds, storm surge, and subsequent flooding, was the devastating loss of life. In total, over 1,800 casualties are related to the events surrounding Hurricane Katrina, with a large portion of these casualties occurring in New Orleans (Knabb et al, 2005). To date, Hurricane Katrina ranks as one of the deadliest U.S. hurricanes in history (Knabb et al, 2005). The tragic events of Hurricane Katrina, witnessed real-time on television sets around the world, brought urgency to the need to evaluate the current state and conditions of America's levees.

1.2 National Levee Database

Following the flooding and disaster seen in New Orleans and along the Gulf Coast following Hurricanes Katrina and Rita, the American Society of Civil Engineers (ASCE), FEMA, and the USACE, among others, began calling on Congress to enact legislation to establish a national program to encourage levee safety and to develop a national inventory of levees similar to the National Inventory of Dams (Landers, 2007). In response to the calls for action, Congress provided \$30 million to the USACE to begin

developing a national levee database and to perform an inventory of the nation's levees (Water Resources Development Act, 2007). An initial survey of the levees in the USACE's network was completed in July of 2006 (USACE, n.d.) and work began on gathering information for this national levee database in 2006 (Landers, 2007).

Further legislation has organized and further funded efforts to evaluate and oversee the development of national levee safety program. The 110th Congress of the United States passed the Water Resources Act into law on November 9, 2007. This law, also know as the National Levee Safety Act, establishes a 16-member *Committee on Levee Safety*, including the Secretary of the Army, the Administrator of FEMA, eight representatives of state levee safety agencies, two levee experts from the private sector, two representatives from local and regional government agencies with expertise in levees, and two representatives from Indian tribes with expertise on levee safety. The *Committee on Levee Safety* is charged with developing recommendations for a national levee safety program and a plan for implementing the program. The overriding goal of the national levee safety program is to ensure the protection of human life and property through levees by developing technologically, economically, socially, and environmentally feasible programs.

One of the charges of the *Committee on Levee Safety* is to develop a database of the levees in the United States known as the National Levee Database (NLD). The database will include the location of all federal levees and non-federal levees, the general condition of each levee, an estimate of the number of structures, and the population protected by the levee and at risk if the levee were to fail or if the levee were overtopped by water. Upon completion, the information in the NLD will be available to federal, state,

and local agencies and the location of the levees will be available to the public. The complete assessment of the nation's levees is expected to take five years. As part of the Water Resources Act of 2007, Congress appropriated \$20 million annually for 2008 to 2013 for the inspection and inventory of levees. This inspection and inventory program will include all federal levees, federally constructed but non-federally operated and maintained levees, and levees participating in the federal Rehabilitation and Inspection Program (RIP). In total some 2,000 levees encompassing over 13,000 miles worth of levees will be included in the database (USACE, n.d.).

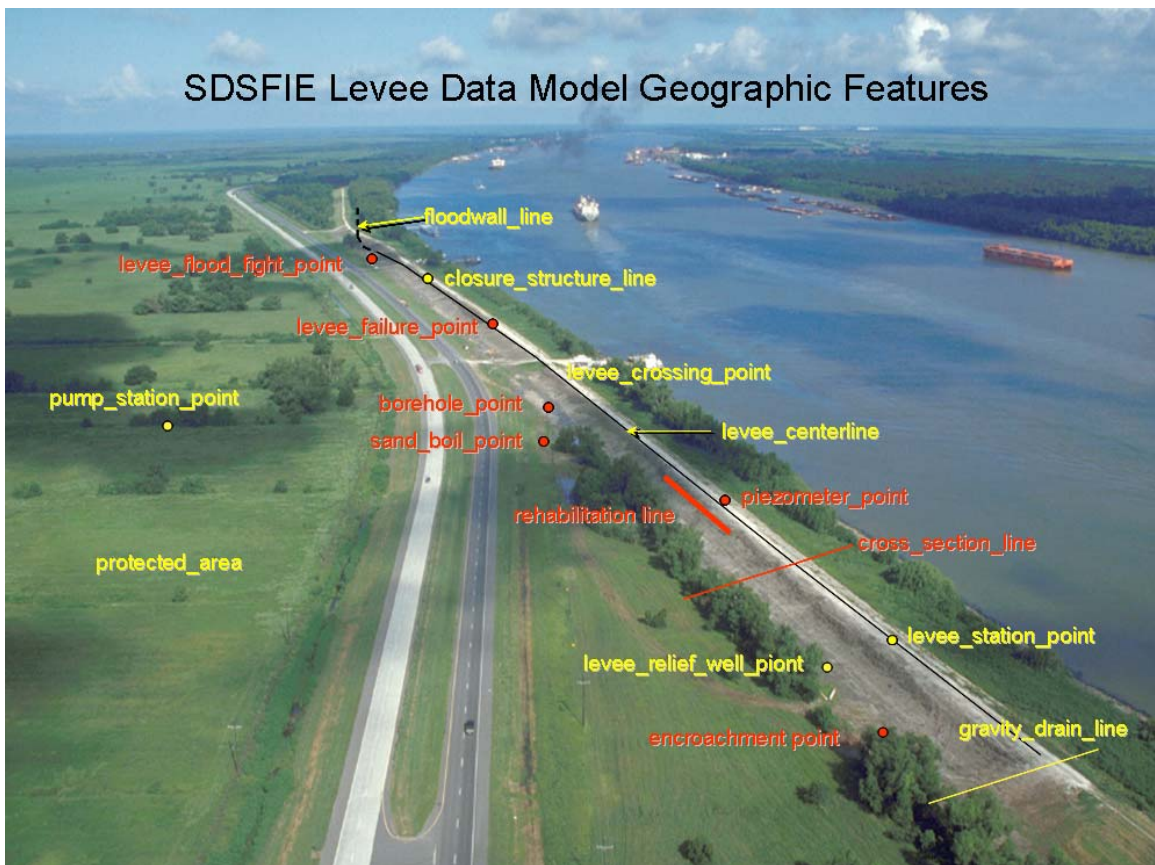


Figure 1-1 Key geographic levee features found in the National Levee Database (Adopted from the CAD-BIM Technology Center website)

The data model defining the schema for the NLD is currently available online for download from the Spatial Data Standards for Facilities, Infrastructure, and Environment (SDSFIE) website. The SDSFIE is a steering group made up of members of the Armed Forces and the USACE and is responsible for establishing the Department of Defense's standards for facilities, infrastructure, environment and civil works. The key geographic levee features included in the NLD are seen in Figure 1-1.

1.3 Arc Hydro and Arc Hydro Groundwater

The NLD provides a data model schema and GIS database that will be used to store information relating to America's levees. Over the past decade several organizations and agencies have developed different data models to represent and store geospatial data. Two of these data models, the Arc Hydro (Maidment, 2002) and Arc Hydro Groundwater (Strassberg et al, 2007) data models, have influenced the design and implementation of the Levee Analyst and the Levee Analysis Data Model.

In 2001, the Arc Hydro data model was developed by Dr. David Maidment of the University of Texas at Austin in collaboration with ESRI and the Consortium of Universities for the Advancement of Hydrologic Sciences (Maidment, 2002). This data model is used to store information relating to surface water systems and also includes a set of geoprocessing tools developed by ESRI for performing hydrologic and hydraulic analyses within ArcGIS. In 2005, Dr. Gil Strassberg, Dr. David Maidment, and Dr. Norm Jones developed an extension to the Arc Hydro data model for representing groundwater, the Arc Hydro Groundwater data model (Strassberg et al, 2007). The Arc Hydro Groundwater data model also includes a companion set of ArcGIS geoprocessing tools

for analyzing groundwater. These data models provide two examples of using a GIS geodatabase combined with the geoprocessing capabilities available in ArcGIS to archive geospatial data and also perform a series of advanced analyses. The Levee Analyst uses the same approach in providing a GIS data structure and a set of ArcGIS geoprocessing tools that allow a user to archive levee seepage and slope stability information and also perform analyses on information stored in the geodatabase.

1.4 Research Objectives

Although the NLD includes features and tables to store most information relating to levees, providing a central location for storing massive amounts of information about levees, the NLD does not include a structure for storing seepage and slope stability models associated with cross sections along a levee. The Levee Analyst was developed to fill this gap and provide a central location to store levee seepage and slope stability data.

As part of my research, my goals were to develop a data model for storing levee seepage and slope stability model data, yet also provide a data model that is compatible with the NLD. I also set out to develop a set of ArcGIS geoprocessing tools to aid in archiving and analyzing levee model data. In developing this data model and geoprocessing toolkit, I wanted to develop a simple, but extensible platform which could be used aiding the management of levee seepage and slope stability data, providing another resource for improving the state of the nation's levees.

2 Levee Analyst

The Levee Analyst is a geographic information system (GIS) data model and a set of ArcGIS geoprocessing tools designed to help manage, analyze, and archive levee seepage and slope stability simulation data. Also included in the Levee Analyst is a tool within the Groundwater Modeling System (GMS) (Owens et al, 1996) software package for automatically archiving SEEP2D seepage (Biedenharn and Tracy, 1987) and UTEXAS slope stability (Wright, 1999) analyses to a database.

The data model used by the Levee Analyst is called the Levee Analysis Data Model (LADM), and is a GIS geodatabase including feature classes, relationship classes, and tables for storing information associated with cross sections along a levee centerline where seepage and/or slope stability simulations have been constructed. The LADM is designed to be compatible with the NLD and provides a simple data structure for storing levee seepage and slope stability data.

The Levee Analyst has been designed in a generic fashion allowing it to support different types of seepage and slope stability simulations; however, the preliminary tools have been developed based on the SEEP2D and UTEXAS models supported in GMS. One of the advantages of the Levee Analyst is that it leverages existing software packages into a simple, but expandable platform that provides a central location for managing levee seepage and slope stability simulations. Another advantage of the Levee

Analyst is that it requires levee managers to pre-compute at small increments of river stage a series of seepage and slope stability analyses, thus providing a series of possible levee scenarios that can be used in analyzing current levee conditions.

An additional archival tool was developed as part of the Levee Analyst within a future release of GMS which allows a user to automatically archive SEEP2D and UTEXAS simulations to the database. In order to fully understand this additional tool available in the Levee Analyst and the role it can play in assisting levee managers and agencies manage and evaluate seepage and slope stability analyses, a brief description of GMS and the supported SEEP2D and UTEXAS models is necessary.

2.1 Groundwater Modeling System (GMS)

The Groundwater Modeling System (GMS) is a comprehensive software package used to create computer simulations of groundwater problems. GMS was developed by the Engineering Computer Graphics Laboratory (ECGL) at Brigham Young University with the support of the Department of Defense, the Department of Energy, and the Environmental Protection Agency (Owens et al, 1996). GMS provides a complete set of tools for every aspect of groundwater modeling, including site characterization, model development, and post-processing, calibration, and graphical visualization. The most current release of GMS, Version 6.5, provides a graphical interface for two models specifically applicable to levee analysis, SEEP2D and UTEXAS.

2.1.1 SEEP2D

SEEP2D is a 2-D finite element seepage model developed in 1974 by Dr. Fred Tracy of the United State Army Waterways Experiment Station in Vicksburg, Mississippi

(Biedenharn and Tracy, 1987). SEEP2D is designed to model cross sections of embankments, such as earthen dams and levees. The following conditions can be modeled using SEEP2D (Jones, 1999):

- Isotropic and anisotropic soil properties
- Confined and unconfined flow for profile models
- Saturated/unsaturated flow for unconfined profile models
- Confined flow for plan (areal) models
- Flow simulation in saturated and unsaturated zones
- Heterogeneous soil conditions
- Axisymmetric models such as flow from a well
- Drains

GMS provides a pre- and post-processing graphical user interface for SEEP2D. Within GMS, a user can input model geometry, material properties, and boundary conditions prior to running SEEP2D. After running SEEP2D, GMS can display flow lines, equipotential lines, total head contours, and pore pressures (Jones, 1999).

2.1.2 UTEXAS

UTEXAS is a slopes stability program developed by Dr. Stephen G. Wright of the University of Texas at Austin (Wright, 1999). UTEXAS utilizes the limit equilibrium method for computing factors of safety. UTEXAS is widely used in industry to analyze levees, dams, and any other earthen embankment where mass wasting may be of concern (Aquaveo, 2008). The most current release of GMS, Version 6.5, incorporates UTEXAS into the interface and allows the user to create UTEXAS input files and launch UTEXAS.

GMS can then be used to visualize model results, including the critical surface and the factor of safety.

3 Levee Analysis Data Model

The Levee Analysis Data Model (LADM) is a relational data model for storing levee centerlines, levee cross sections, and seepage and slope stability analyses. The data model includes feature classes, relationship classes, coded-value domains, and tables that provide a schema for storing information in the database and also create a standard set of field names necessary for using the tools in the Levee Analyst. Figure 3-1 shows the structure of the data model as it is seen in ArcCatalog.

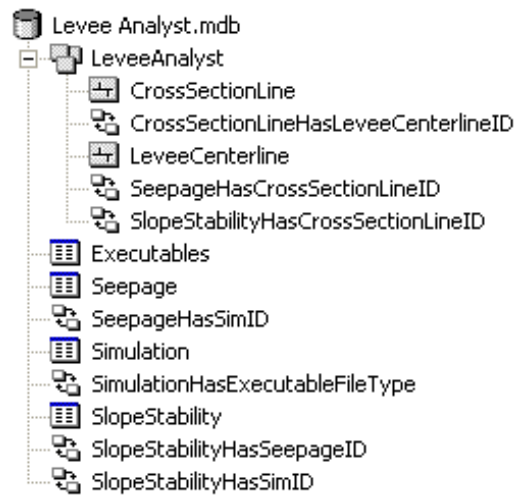


Figure 3-1 Levee Analysis data structure as seen in ArcCatalog

Figure 3-2 depicts the entire Levee Analysis Data Model, including all of the included feature classes, tables, coded-value domains, and relationships. The feature

classes included in the Levee Analysis data model include the *LeveeCenterline* and *CrossSectionLine* features classes, and the tables included in the data model are the *Executables*, *Seepage*, *Simulation*, and *Slope Stability* tables.

3.1 HydroIDs and HydroCodes

Before describing each of the classes and tables within the Levee Analysis Data Model, a description of the HydroIDs and HydroCodes is necessary. In a typical database structure, each new record within a class or table is assigned an object identifier (ObjectID or OID) used to identify the record within the class or table. However this object identifier is not unique across the different features or tables within the database. In order to provide an internal unique identifier, the *HydroID* field was added to the feature classes in the LADM. A unique HydroID is assigned to each new feature, aiding in the data archiving and retrieval process.

The *HydroCode* field was also added to the feature classes in the LADM. Often different agencies or companies will have a unique method of identifying features, such as a type of code or combination of numbers and text. The *HydroCode* field allows the user to associate this unique external identifier with the feature. The *HydroID* and *HydroCode* fields were added to provide for greater internal and external verification of features within the database based on the user-assigned identifiers. These two fields also serve to make the LADM compatible with the Arc Hydro Groundwater data model and tools.

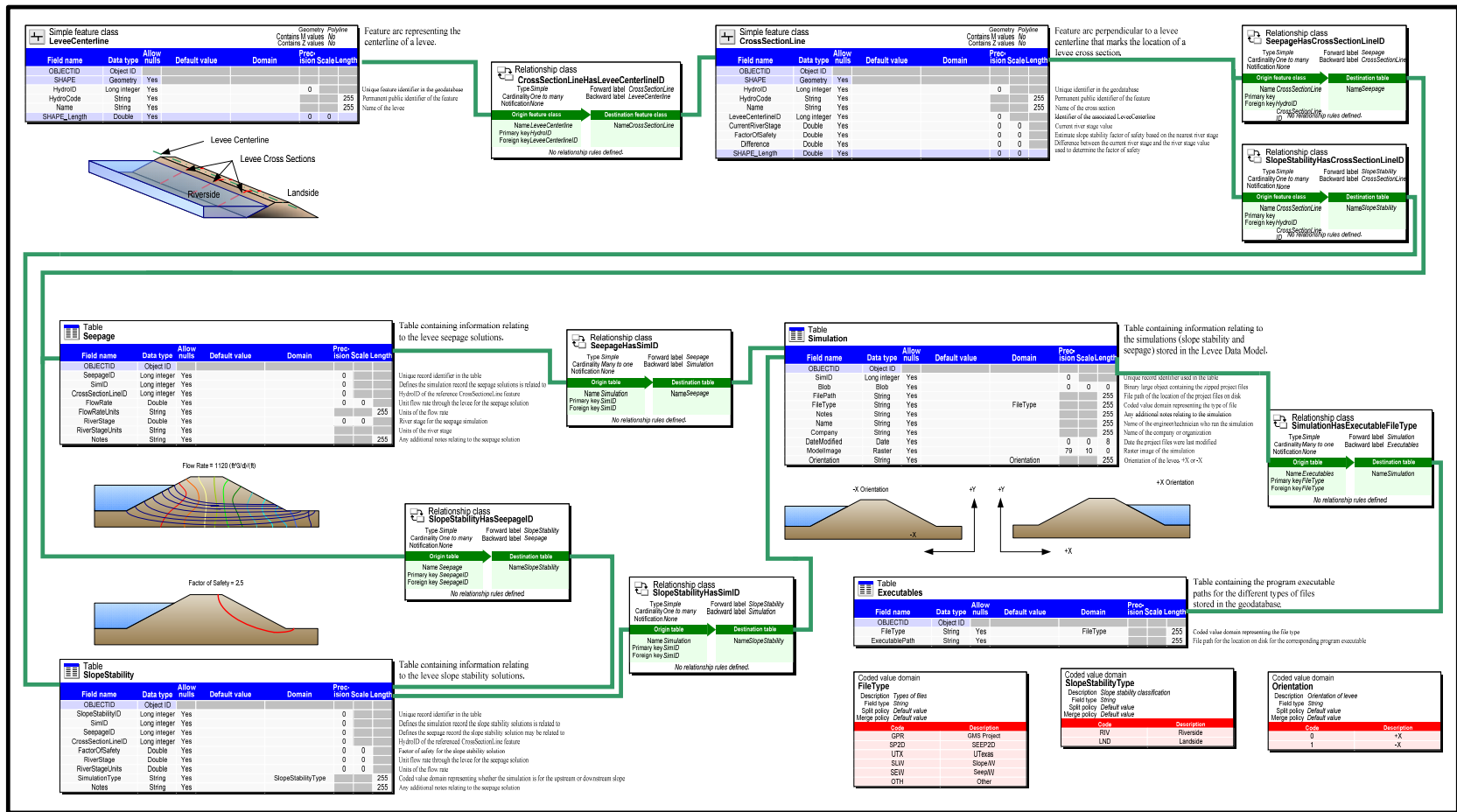


Figure 3-2 Levee Analysis Data Model

3.2 Levee Centerline Feature Class

Two key geographic features found in the NLD are included in the LADM: levee centerlines and the levee cross sections. The centerline runs parallel to the length of the structure and the cross sections run perpendicular to the centerline and mark the locations where seepage and/or slope stability analyses information is available.

Figure 3-3 depicts the orientation of the levee centerline and levee cross section feature arcs along a levee. As is seen in the image, multiple cross sections can be associated with a single levee centerline.

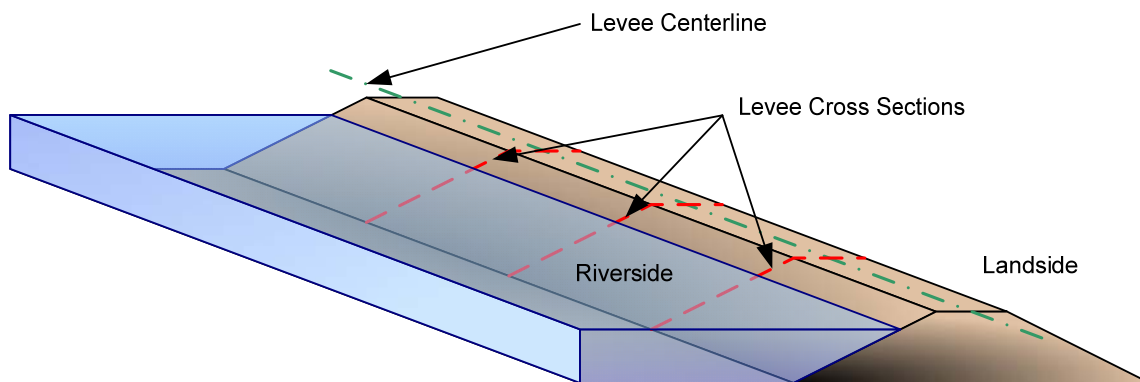


Figure 3-3 Orientation of levee centerlines and cross sections

The *LeveeCenterline* feature class is used to store polylines representing the location of centerlines of different levee structures to be stored in the database. Each record within the class represents a different levee and is assigned a unique HydroID. The *LeveeCenterline* feature class includes a *HydroCode* field for assigning an external

identifier to the feature. A *Name* field is also included to allow the user to specify a common name used for the levee. Figure 3-4 depicts the fields and the field data types in the *LeveeCenterline* feature class.

Simple feature class		Geometry <i>Polyline</i>				
LeveeCenterline		Contains M values	No			
		Contains Z values	No			
Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale Length
OBJECTID	Object ID					
SHAPE	Geometry	Yes				
HydroID	Long integer	Yes			0	
HydroCode	String	Yes				255
Name	String	Yes				255
SHAPE_Length	Double	Yes			0	0

Feature arc representing the centerline of a levee.

Unique feature identifier in the geodatabase
Permanent public identifier of the feature
Name of the levee

Figure 3-4 Fields in the *LeveeCenterline* feature class

3.3 Levee Cross Section Feature Class

In the NLD, the levee cross sections are polylines perpendicular to the flood control structure detailing the elevations along the lines. In the LADM, the *CrossSectionLine* feature class also contains polylines situated perpendicular to the levee; however, in the LADM, the levee cross sections represent locations along the levee for which a user has constructed seepage and slope stability analysis simulations. These seepage and slope analyses are stored in separate tables, the *Seepage* and *Slope Stability* tables, which allows the user to better organize and manage the different types of simulations. As Figure 3-5 depicts, multiple seepage and slopes analyses can be related to a single cross section in the *CrossSectionLine* feature class. The *CrossSectionLine* feature class is independent from the cross feature class found in the NLD; however, the

CrossSectionLine feature class has been designed to allow the cross section features in the NLD to be imported into the LADM feature class.

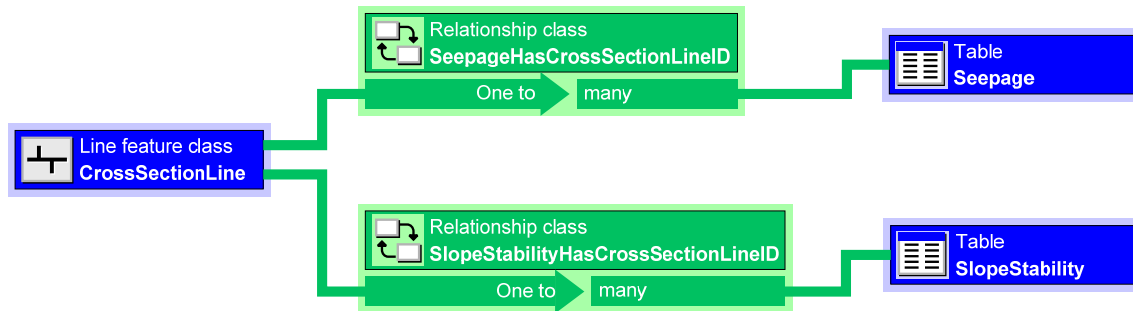


Figure 3-5 Relationship between the *CrossSectionLine* feature class and the *Seepage* and *Slope Stability* tables

As with the *LeveeCenterline* feature class, the *CrossSectionLine* feature class includes *HydroID*, *HydroCode*, and *Name* fields. A *LeveeCenterlineID* field is included to store the *HydroID* of the related levee centerline. Figure 3-6 details the structure of the *CrossSectionLine* feature class.

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale Length	
OBJECTID	Object ID						
SHAPE	Geometry	Yes					
HydroID	Long integer	Yes			0		Unique identifier in the geodatabase
HydroCode	String	Yes			0	255	Permanent public identifier of the feature
Name	String	Yes			0	255	Name of the cross section
LeveeCenterlineID	Long integer	Yes			0		Identifier of the associated LeveeCenterline
CurrentRiverStage	Double	Yes			0	0	Current river stage value
FactorOfSafety	Double	Yes			0	0	Estimate slope stability factor of safety based on the nearest river stage
Difference	Double	Yes			0	0	Difference between the current river stage and the river stage value used to determine the factor of safety
SHAPE_Length	Double	Yes			0	0	

Figure 3-6 Fields in the *CrossSectionLine* feature class

The *CrossSectionLine* feature class also includes three fields that a user might not initially populate as they enter data into the database, the *CurrentRiverStage*, the

FactorOfSafety, and the *Difference* fields. These fields are populated by different ArcGIS geoprocessing tools included in the Levee Analyst toolkit. The *CurrentRiverStage* field is used to store the current river stage of the river or water body controlled by the levee. The *FactorOfSafety* field is used to store the nearest slope stability factor of safety based on the current river stage, and the *Difference* field is used to store the difference between the current river stage head and the head value of the nearest factor of safety. A more detailed explanation of how these fields are used will follow in the descriptions of the *Add Current River Stage* and *Query Factor of Safety* geoprocessing tools.

3.4 Simulation Table

In designing the LADM, it was necessary to determine an efficient method for storing summary seepage and slope stability information, in addition to the location of the seepage and slope stability simulation files used by the analysis codes. To aid in managing this data, the *Simulation* table was developed to store summary metadata and the location of the seepage and slope stability simulation setup files. Each record in the table contains information relating to one file archive associated with a simulation. However the design of the table allows a single record within the *Simulation* table to be related to multiple seepage and/or slope stability simulations, signifying that multiple seepage and/or slope stability simulations may be saved as part of a single file archive, as is the case in GMS with SEEP2D and UTEXAS simulations. Figure 3-7 depicts the relationships between the *Seepage* and *Slope Stability* tables and the *Simulation* table and Figure 3-8 details the fields included in the *Simulation* table.

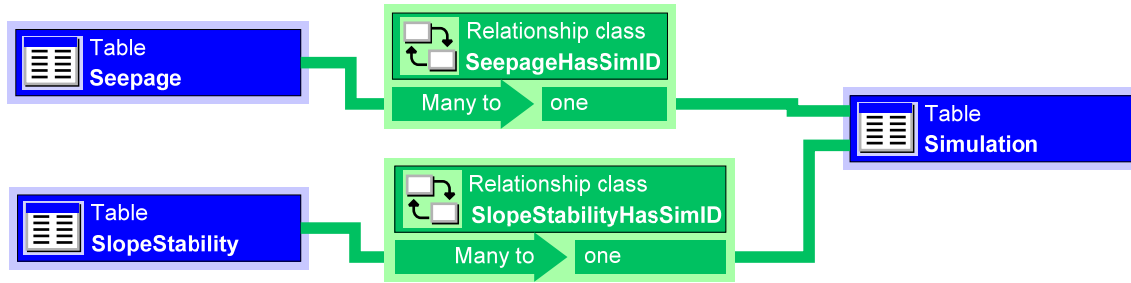


Figure 3-7 Relationships between the *Seepage* and *Slope Stability* tables and the *Simulation* table

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	
OBJECTID	Object ID							
SimID	Long integer	Yes			0			Unique record identifier used in the table
Blob	Blob	Yes			0	0	0	Binary large object containing the zipped project files
FilePath	String	Yes					255	File path of the location of the project files on disk
FileType	String	Yes		FileType			255	Coded value domain representing the type of file
Notes	String	Yes					255	Any additional notes relating to the simulation
Name	String	Yes					255	Name of the engineer/technician who ran the simulation
Company	String	Yes					255	Name of the company or organization
DateModified	Date	Yes			0	0	8	Date the project files were last modified
ModellImage	Raster	Yes			79	10	0	Raster image of the simulation
Orientation	String	Yes		Orientation			255	Orientation of the levee, +X or -X

Figure 3-8 Fields in the *Simulation* table

The *Simulation* table includes a *SimID* field that stores a unique identifier for each record included in the table. This SimID relates the simulation records with associated records in the *Seepage* and *Slope Stability* tables. A *Blob* field is also included in the *Simulation* table. A blob, or a *binary large object*, can be used to store a myriad of objects, such as images, PDFs, or zipped files. The *Blob* field in the *Simulation* table is used to store a zipped folder containing the files necessary for the related seepage and/or slope stability simulation. In the preliminary data model design and testing, the *Blob* field has been used to store a zipped file containing a GMS project file and the associated SEEP2D and UTEXAS simulation files. This field could be used to store a seepage or

slope stability analysis file from another program, such as Seep/W (Krahn, 2004) or Slope/W (Krahn, 2004).

The *FilePath* field stores the full file path of the location of the seepage and/or slope stability simulation and the *FileType* field holds a coded-value representing the type of file stored. Figure 3-9 shows the values in the *FileType* coded-value domain. These initial values contained in the domain do not constitute all of the available seepage or slope stability file types, and the user is free to add other file types to the coded-value domain in order to represent different types of seepage and slope stability simulation files stored in the geodatabase.

Coded value domain	
FileType	
Description	<i>Types of files</i>
Field type	<i>String</i>
Split policy	<i>Default value</i>
Merge policy	<i>Default value</i>
Code	Description
GPR	GMS Project
SP2D	SEEP2D
UTX	UTexas
SLW	Slope/W
SEW	Seep/W
OTH	Other

Figure 3-9 *FileType* coded-value domain

The *Simulation* table also contains several fields for storing general metadata about the seepage and/or slope stability simulation. A *Notes* field is included to add any additional notes to the simulation record. A *Name* field is available to store the name of the engineer or technician who performed the seepage and/or slopes stability simulation. The *Company* field is used to store the name of the company or organization archiving the levee seepage or slope stability information. In order to maintain a record of when the

simulations are changed or updated, a *DateModified* field is included to store the date the simulation was last modified.

Also included in the *Simulation* table is a *ModellImage* raster field to store an image of the seepage and/or slope stability simulation, allowing the user to quickly visualize the simulation. Figure 3-10 shows an image of a *Simulation* table with a raster loaded into the *ModellImage* raster field.

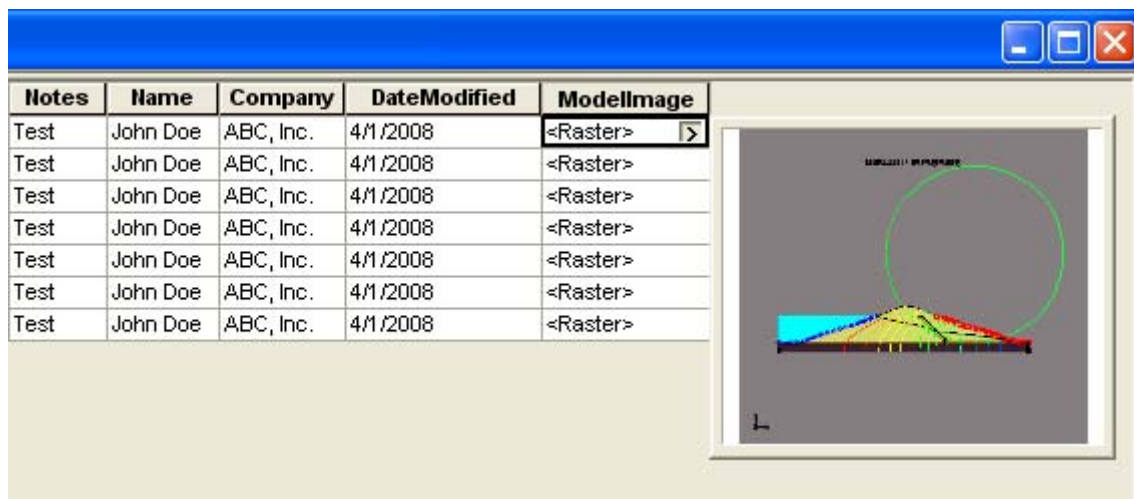


Figure 3-10 *ModellImage* raster field in the *Simulation* table

The last field included in the *Simulation* table is the *Orientation* field which stores a coded-value representing the orientation of the levee cross section. The *Orientation* coded-value domain was created to document the direction of the levee in regards to the water body it is designed to hold back. Figure 3-11 shows the *Orientation* coded-value domain. The two available values in the *Orientation* domain are +X and -X. As is seen in Figure 3-12, +X orientation implies that moving from the landside of the levee towards the water body is in the positive X-direction. Conversely, the -X orientation implies that

moving along the levee from the landside towards the water body is in the negative X-direction (Figure 3-12).

Coded value domain	
Orientation	
Description	Orientation of levee
Field type	String
Split policy	Default value
Merge policy	Default value
Code	Description
0	+X
1	-X

Figure 3-11 Orientation coded-value domain

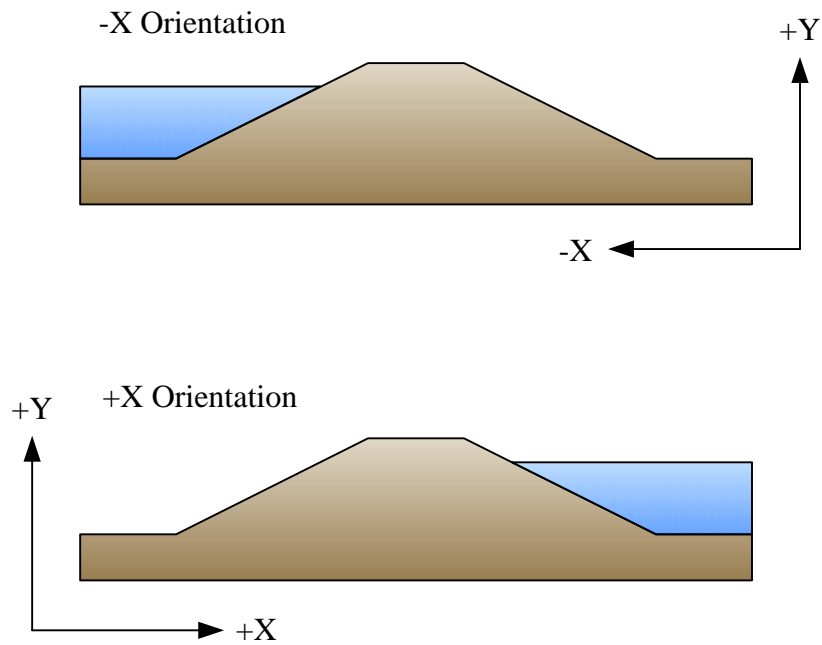


Figure 3-12 -X and +X levee orientations

3.5 Seepage Table

The *Seepage* table stores information relating to seepage analyses, including the flow rate, the river stage, and the related units used in the analysis. The *Seepage* table also contains a *CrossSectionLineID* field which is used to store the HydroID of the cross section to which the seepage analysis is related. A *SimID* field is included in the *Seepage* table to relate each seepage analysis record in the table to a record in the *Simulation* table. The *SeepageID* field is used to store unique record identifiers for each seepage record in the table. An additional *Notes* field allows the user to include any notes relating to the seepage simulation. The structure of the *Seepage* table is summarized in Figure 3-13.

Table Seepage						
Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale Length
OBJECTID	Object ID					
SeepageID	Long integer	Yes			0	
SimID	Long integer	Yes			0	
CrossSectionLineID	Long integer	Yes			0	
FlowRate	Double	Yes			0	0
FlowRateUnits	String	Yes				255
RiverStage	Double	Yes			0	0
RiverStageUnits	String	Yes				
Notes	String	Yes				255

Table containing information relating to the levee seepage solutions.

Unique record identifier in the table

Defines the simulation record the seepage solutions is related to

HydroID of the reference CrossSectionLine feature

Unit flow rate through the levee for the seepage solution

Units of the flow rate

River stage for the seepage simulation

Units of the river stage

Any additional notes relating to the seepage solution

Figure 3-13 Fields in the *Seepage* table

3.6 Slope Stability Table

The *Slope Stability* table stores summary information relating to slope stability simulations, including the factor of safety, the river stage and river stage units, and the type of slope stability simulation. As with the *Seepage* table, the *Slope Stability* table contains a *CrossSectionLineID* field to store the HydroID of the related cross section. The

SimID field is used to relate each slope stability simulation to a record in the *Simulation* table. *The Slope Stability* table structure is seen below in Figure 3-14.

Table SlopeStability						
Field name	Data type	Allow nulls	Default value	Domain	Precision	ScaleLength
OBJECTID	Object ID					
SlopeStabilityID	Long integer	Yes			0	
SimID	Long integer	Yes			0	
SeepageID	Long integer	Yes			0	
CrossSectionLineID	Long integer	Yes			0	
FactorOfSafety	Double	Yes			0	0
RiverStage	Double	Yes			0	0
RiverStageUnits	Double	Yes			0	0
SimulationType	String	Yes		SlopeStabilityType		255
Notes	String	Yes				255

Table containing information relating to the levee slope stability solutions.

Unique record identifier in the table
 Defines the simulation record the slope stability solutions is related to
 Defines the seepage record the slope stability solution may be related to
 HydroID of the referenced CrossSectionLine feature
 Factor of safety for the slope stability solution
 Unit flow rate through the levee for the seepage solution
 Units of the flow rate
 Coded value domain representing whether the simulation is for the upstream or downstream slope
 Any additional notes relating to the seepage solution

Figure 3-14 Fields in the *Slope Stability* table

In GMS, it is possible to use a SEEP2D seepage simulation to compute the pore pressures that are required for a UTEXAS slope stability simulation. In order to show the relationship that can exist between a seepage simulation and possibly multiple slope stability simulations, an additional field, the *SeepageID* field, was added to the *Slope Stability* table. The *SeepageID* field can have a null value if there is not an associated seepage simulation; however, it is possible to have multiple slope stability simulations related to a single seepage simulations, as is seen in Figure 3-15.

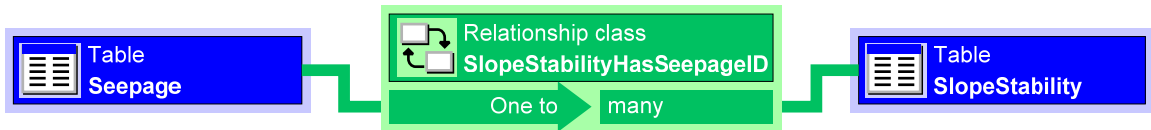


Figure 3-15 Relationship between the *Seepage* and *SlopeStability* table

Slope stability analyses can exist for the landside or the riverside embankments of a levee. The *SimulationType* field was created to store a coded-value representing the different types of orientation possible for a slope stability simulation. The values in the *SlopeStabilityType* coded-value domain are seen in Figure 3-16 and include *Riverside* and *Landside*. A *Riverside* slope stability type indicates the slope stability analysis was performed on the riverside of the levee as seen in Figure 3-17. On the other hand, a *Landside* slope stability orientation indicates the slope stability analysis was performed on the landside of the levee (Figure 3-17).

Coded value domain	
SlopeStabilityType	
Description	<i>Slope stability classification</i>
Field type	<i>String</i>
Split policy	<i>Default value</i>
Merge policy	<i>Default value</i>
Code	Description
RIV	Riverside
LND	Landside

Figure 3-16 *SlopeStabilityType* coded-value domain

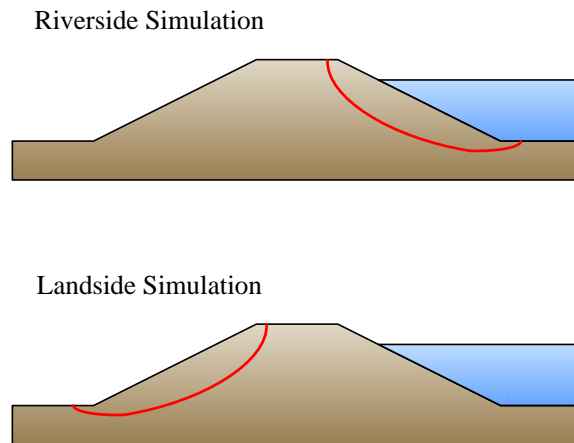


Figure 3-17 Landside and riverside slope stability orientations

3.7 Executables Table

The *Executables* table, seen in Figure 3-18, is the final table included in the LADM. The *Executables* table stores the location of the slope stability and/or seepage software program executable files used to perform the different analyses stored in the database. One of the ArcGIS geoprocessing tools included in the Levee Analyst, the *Export Simulation* tool, allows the user to launch the seepage and/or slope stability simulations in the program in which they were created for review or for further analysis. To facilitate this tool, it is necessary to indicate the location of the program executable files on disk. The *Export Simulation* tool references the *Executables* table to launch the related seepage or slope stability program. The *Executables* table includes two fields, the *FileType* field and the *ExecutablesPath* field. The *FileType* field stores a *FileType* coded-value as seen in Figure 3-9 and the *ExecutablesPath* field contains the full file path of the location of the program executable on disk. It is possible to store several different program executables in the *Executables* table based on the *FileType* coded-values.

Table Executables						
Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale Length
OBJECTID	Object ID					
FileType	String	Yes		FileType		255
ExecutablePath	String	Yes				255

Table containing the program executable paths for the different types of files stored in the geodatabase.

Coded value domain representing the file type

File path for the location on disk for the corresponding program executable

Figure 3-18 Fields in the *Executables* table

4 Levee Analyst ArcGIS Toolkit

The Levee Analyst also includes a toolkit of ArcGIS geoprocessing tools that assist in managing data stored in the Levee Analysis Data Model and that aid the user in analyzing information stored in the database. The Levee Analyst toolbox currently contains five tools, including: *Add Blob to Table*, *Add Current River Stage*, *Export Simulation*, *Query Factor of Safety*, and *Simulations Query*. This initial toolbox could be expanded to add greater analysis functionality. Figure 4-1 show the Levee Analyst toolbox as it appears in the ArcToolbox structure in ArcGIS. Brief summaries of each of the tools are included to describe the functionality and uses of the tools.

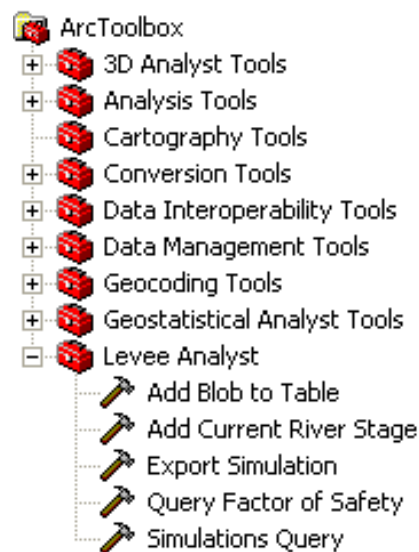
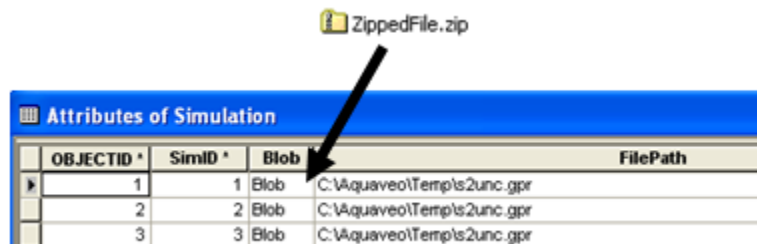


Figure 4-1 Levee Analyst toolbox seen within the ArcToolbox structure in ArcGIS

4.1 Add Blob to Table

The *Add Blob to Table* geoprocessing tool is a general tool that allows a user to select a file and then add that file to a blob field of a table or a feature class. The tool was specifically developed to allow the user to add zipped files to the *Simulation* table as seen in Figure 4-2. The path to the original files is stored for convenience, but all of the files are stored in the *Blob* field so that all simulation data is included in the Arc database. Beyond adding zipped files, the *Add Blob to Table* tool could be used to add any item that is supported in a blob field, such as a PDF, CAD drawing, or document, to a user-created blob field, allowing a user to store information beyond that defined in the LADM.



OBJECTID *	SimID *	Blob	FilePath
1	1	Blob	C:\Aquaveo\Temp\2unc.gpr
2	2	Blob	C:\Aquaveo\Temp\2unc.gpr
3	3	Blob	C:\Aquaveo\Temp\2unc.gpr

Figure 4-2 *Add Blob to Table* functionality

The geoprocessing tool requires the user to specify the location of the zipped file to be added to the table as a blob. The tool also requires the user to specify the table the blob is to be added to, the location of the *Blob* field within the specified table, and a unique Object ID within the table which references the record the blob will be added to. Figure 4-3 shows the *Add Blob to Table* geoprocessing tool and the required input fields.

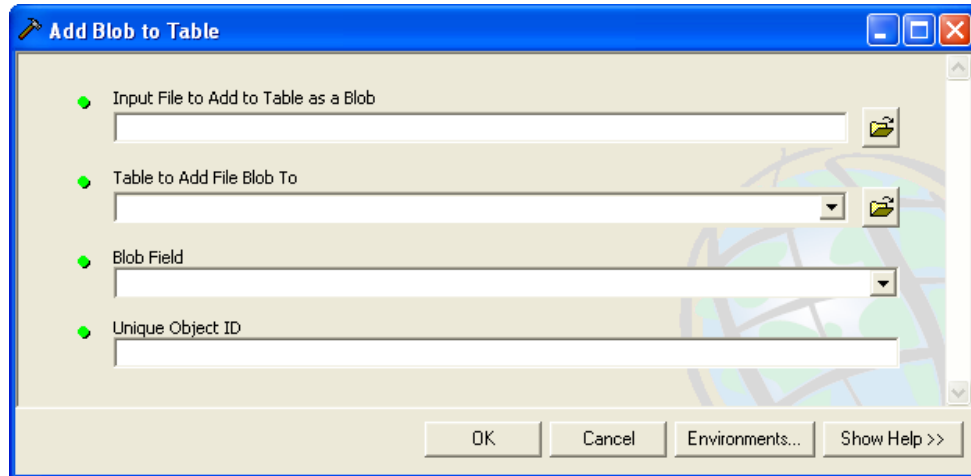


Figure 4-3 *Add Blob to Table* geoprocessing tool

4.2 Add Current River Stage

The *Add Current River Stage* geoprocessing tool allows the user to add the current river stage at a specified cross section location to the cross section feature class. As is seen in Figure 4-4, the tool requires the user to specify the cross section feature class, the location of the *HydroID* field, the unique HydroID of the cross section the river stage is to be added to, the current river stage field within the cross section feature class, and the current river stage value. Although a user could simply use the editing tools available within ArcGIS to edit the cross section feature class and add the current river stage value, the *Add Current River Stage* provides a geoprocessing tool that simplifies the process of adding the river stage. The tool could be modified in order to allow the tool to link to a real-time river stage monitoring system that would automatically add the current river stage.

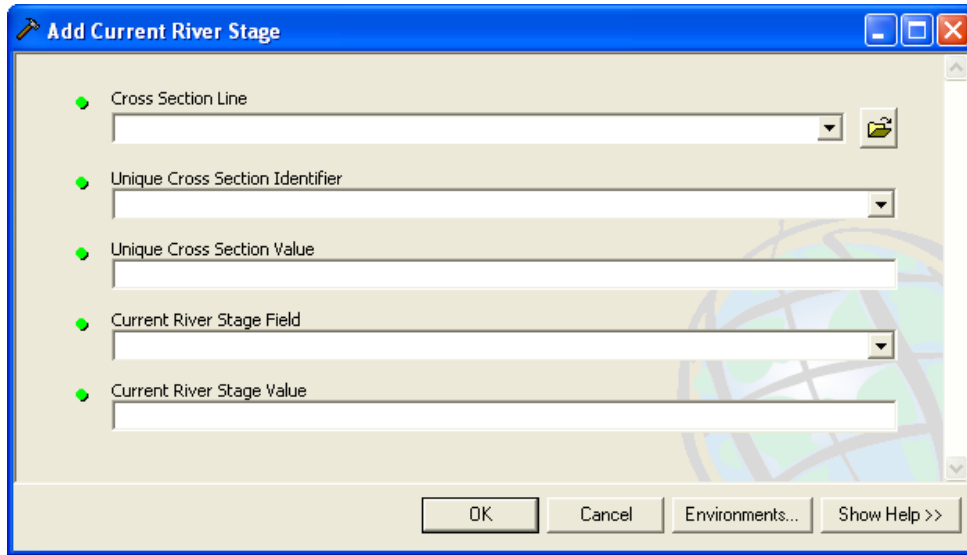


Figure 4-4 Add Current River Stage geoprocessing tool

4.3 Query Factor of Safety

The *Query Factor of Safety* tool allows the user to perform a series of queries to quickly determine an approximate factor of safety for the river stage stored in the *CurrentRiverStage* field in the *CrossSectionLine* feature class. The tool presupposes that a series of stability analyses at small increments of river stage have been pre-computed and archived in the database. The tool requires the user to specify a *CrossSectionLineID* value within the *Slope Stability* table. This *CrossSectionLineID* is then used to query the *Slope Stability* table to determine all of the river stage values and factor of safety values for the specified cross section. The queried river stage values are compared against the current river stage value stored in the *CrossSectionLine* feature class. The factor of safety for the river stage closest to the current river stage value is copied into the factor of safety field at the specified cross section in the cross section feature class. Once the factor of

safety field is populated by the tool, it can be queried or used to generate a map layer indicating factors of safety along a selected river reach. The geoprocessing tool also determines the difference between the current river stage and the nearest river stage and posts this value in the *Difference* field in the *CrossSectionLine* feature class. Posting the difference between the current river stage and the river stage used in approximating the factor of safety allows the user verify the accuracy of the approximated factor of safety.

The *Query Factor of Safety* geoprocessing tool, seen in Figure 4-5, requires the user to specify the slope stability table, the location of the *CrossSectionLineID* field in the slope stability table, a value of the *CrossSectionLineID*, the location of the river stage field in the slope stability table, the cross section feature class, and *CurrentRiverStage*, *FactorOfSafety*, and *Difference* fields in the *CrossSectionLine* feature class.

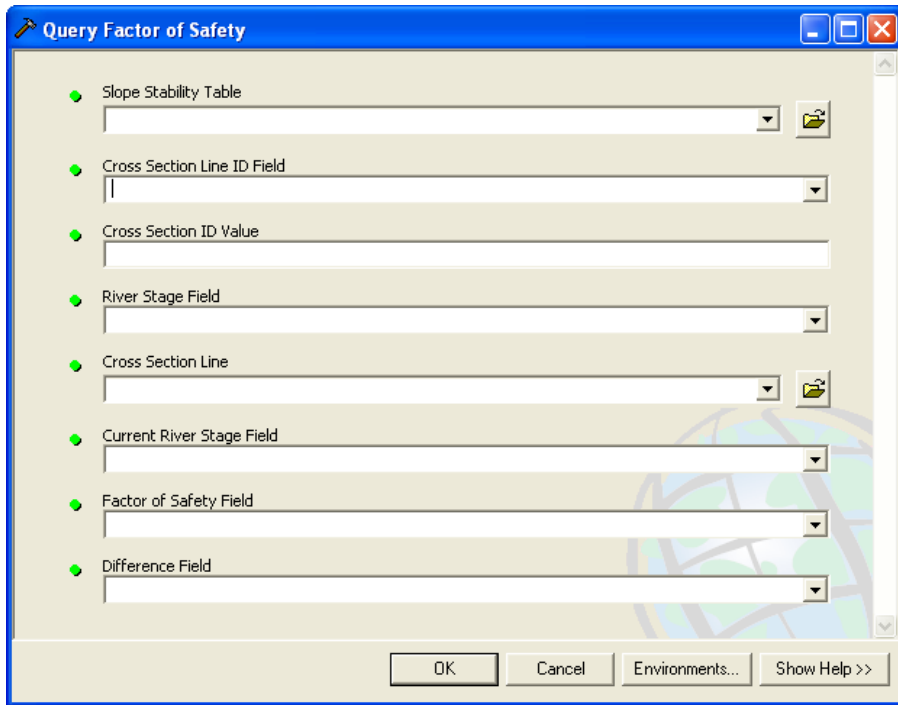


Figure 4-5 *Query Factor of Safety* geoprocessing tool

4.4 Simulations Query

The *Simulations Query* geoprocessing tool is used to query the *Simulation*, *Seepage*, and *Slope Stability* tables to find all of the records in these tables related to a user-specified cross section identifier. The tool has been designed to work in tandem with the *Export Simulation* geoprocessing tool, which allows the user to launch a seepage and/or slope stability analysis within the program in which the analyses were created.

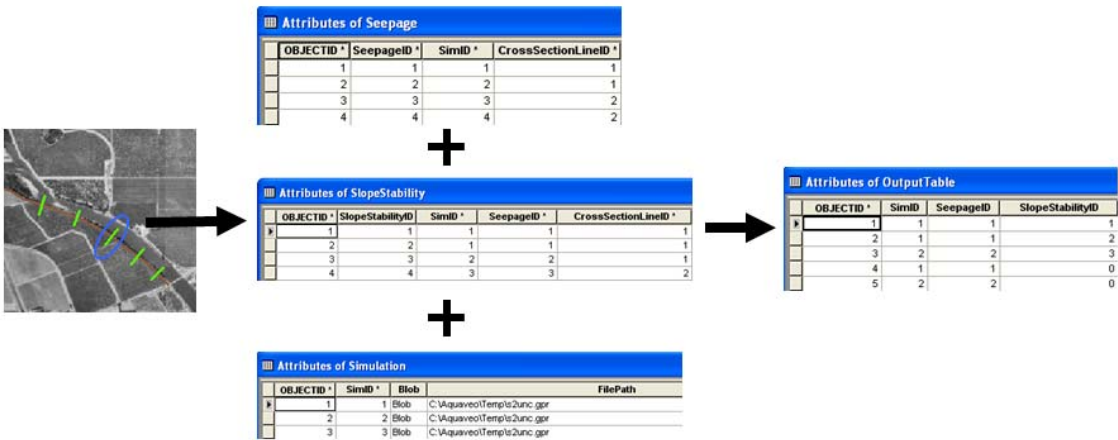


Figure 4-6 Workflow of the *Simulations Query* geoprocessing tool

The geoprocessing tool queries the *Seepage* and *Slope Stability* tables and finds all of the records related to the user-specified CrossSectionLineID and then adds these records to a new user-named table. The *Simulation* table is also queried as part of the geoprocessing tool and the file archive (blob) within the *Simulation* table related to the queried seepage and slope stability analyses is also added to the new table. This process is illustrated in Figure 4-6.

In using the *Simulations Query* tool, the user must first specify the feature class containing the cross section polylines and the field containing the cross section HydroIDs. The user must also specify the unique cross section line HydroID value for the cross section of interest. This HydroID value of the cross section line is then used to query the *Seepage* and *Slope Stability* tables. Summary information from the *Seepage* and *Slope Stability* tables, including the SeepageID, the SlopeStabilityID, the seepage flow rate, and the slope stability factor of safety, is added to a new user-named table. The user also must specify the output geodatabase to which the new table is to be added. Using the SimID of the queried seepage and slope stability simulations, the *Simulation* table is also queried and the file path, file type, file blob, and summary model image are also added to the new table for the seepage and slope stability records. Figure 4-7 shows the *Simulations Query* geoprocessing tool and the required tool inputs.

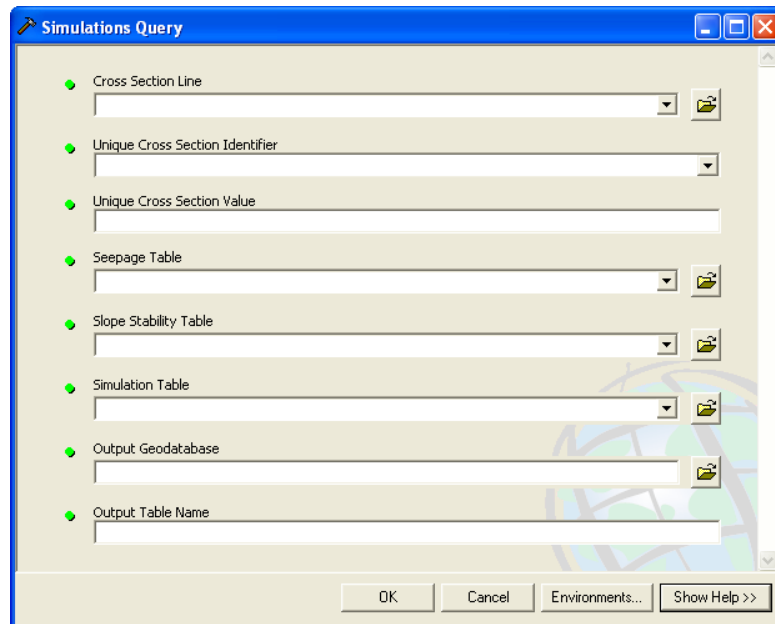


Figure 4-7 *Simulations Query* geoprocessing tool

4.5 Export Simulation

The final tool in the Levee Analyst toolbox is the *Export Simulation* geoprocessing tool which allows a user to select a record from the output table created in the *Simulations Query* tool based on the object identifier of the record. The tool then uses the file type stored in the table to query the *Executables* table to determine the path of the program executable that will launch the associated file stored in the table. The file archive stored in the *Blob* field is then unzipped and the associated program executable is launched as show in Figure 4-8. Once the external program has been launched the user can analyze or adjust the seepage and/or slope stability simulation as necessary.

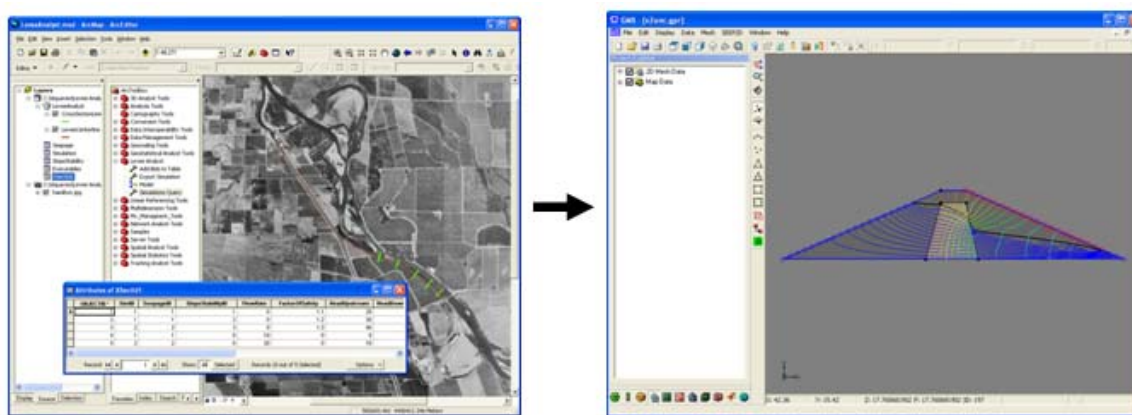


Figure 4-8 Workflow of the *Export Simulation* geoprocessing tool

As part of the *Export Simulation* geoprocessing tool, the user must specify the location of the *Executables* table, the *Simulations Query* output table to be referenced, and the object identifier of the record within the *Simulations Query* output table containing the seepage and/or slope stability file that is to be launched outside of ArcGIS. Figure 4-9 shows the *Export Simulation* geoprocessing tool and the required inputs.

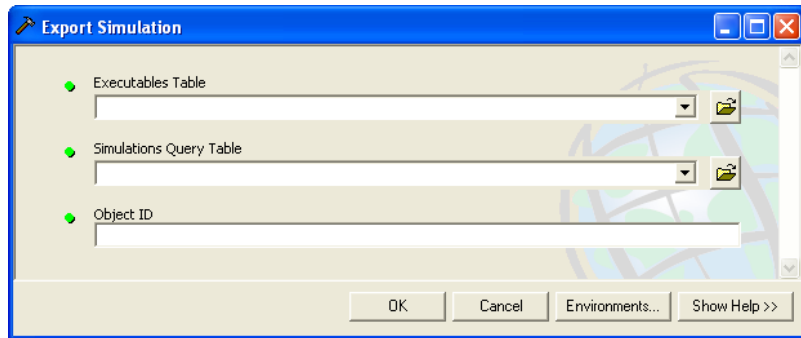


Figure 4-9 *Export Simulation* geoprocessing tool

5 GMS Levee Analyst Database Wizard

Although the Levee Analyst can be used as a central archive for seepage and slope stability simulations generated in most seepage and slope stability programs, the Levee Analyst was tested using SEEP2D seepage and UTEXAS slope stability models generated within GMS. In addition to the Levee Analyst geoprocessing toolkit developed for use in ArcGIS, an additional tool has been developed within GMS that provides for automatic archiving of seepage and slope stability data to a user-specified ArcGIS geodatabase. The tool is entitled the *Export to Levee Analyst Database Wizard* and is accessed through the *SEEP2D* or *UTEXAS* model menus within GMS. The wizard includes a series of four steps that help the user to determine the information to be archived to the geodatabase. This tool is used to archive new seepage and slope stability simulations into the LADM using the ArcObjects software application programming interface (API). It can also be used to update or overwrite simulation data to the LADM for simulations launched in GMS using the *Export Simulation* geoprocessing tool described above. A brief description of each of the steps in the *Export to Levee Analyst Database Wizard* is included to further explain how to use the tool.

5.1 Step 1

The first step in the *Export to Levee Analyst Database Wizard* allows the user to specify the location of the destination geodatabase for the seepage and slope stability simulations, the HydroID of cross section line the simulations are to be associated with, and the orientation of the levee. Figure 5-1 shows the Step 1 dialog as it is seen in GMS.

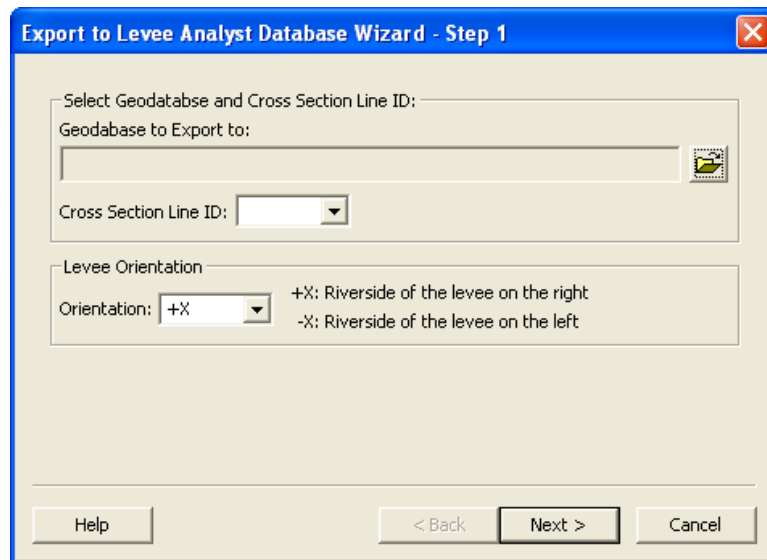


Figure 5-1 *Export to Levee Analyst Database Wizard - Step 1*

Once the user specifies the geodatabase to which the simulations will be exported, the cross section line ID combo box will automatically populate with the available cross section HydroIDs in the geodatabase, forcing the user to associate the seepage and/or slope simulations with an existing cross section feature arc. The user can also specify the orientation of the levee by clicking on the combo box and selecting either +X or -X depending on the alignment of the levee.

5.2 Step 2

The second step in the *Export to Levee Analyst Database Wizard* allows the user to specify the SimID to be used in archiving the seepage and slope stability files to the simulation table in the geodatabase (Figure 5-2). The next available SimID in the simulation table will be automatically populated in the *New SimID* text field. If the simulation has been previously archived to the geodatabase from GMS, the options for overwriting the existing SimID will be available. By selecting the toggle to overwrite an existing SimID, the records within the *Seepage*, *Slope Stability*, and *Simulation* tables will be overwritten with the information exported from GMS; however, if the simulation has not been archived previously to the database or if the user chooses not to overwrite the existing SimID, new records will be created within the *Seepage*, *Slope Stability*, and *Simulation* tables.

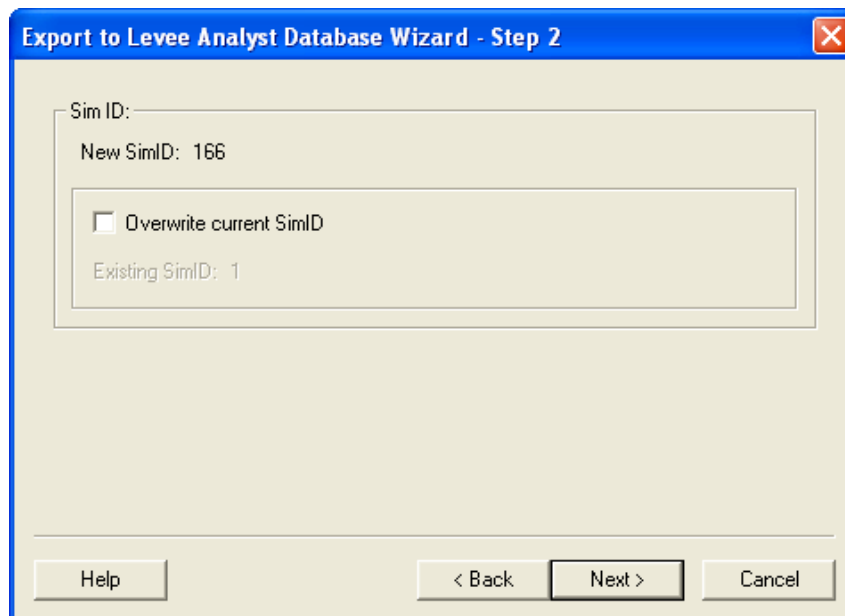


Figure 5-2 *Export to Levee Analyst Database Wizard – Step 2*

5.3 Step 3

The third step in the *Export to Levee Analyst Database Wizard* allows the user to specify the SEEP2D seepage and UTEXAS slope stability simulations to export to the database. After the user clicks “Next” in the Step 2 of the wizard, all of the SEEP2D seepage and UTEXAS slope stability simulations in the current project are automatically added to the two spreadsheets seen in the dialog in Figure 5-3. The user then has the option to select those simulations to export to the geodatabase by clicking the check box to the left of the seepage or slope stability simulation name. For each seepage and/or slope stability simulation selected, a new record will be created in the *Seepage* and *Slope Stability* tables in the geodatabase.

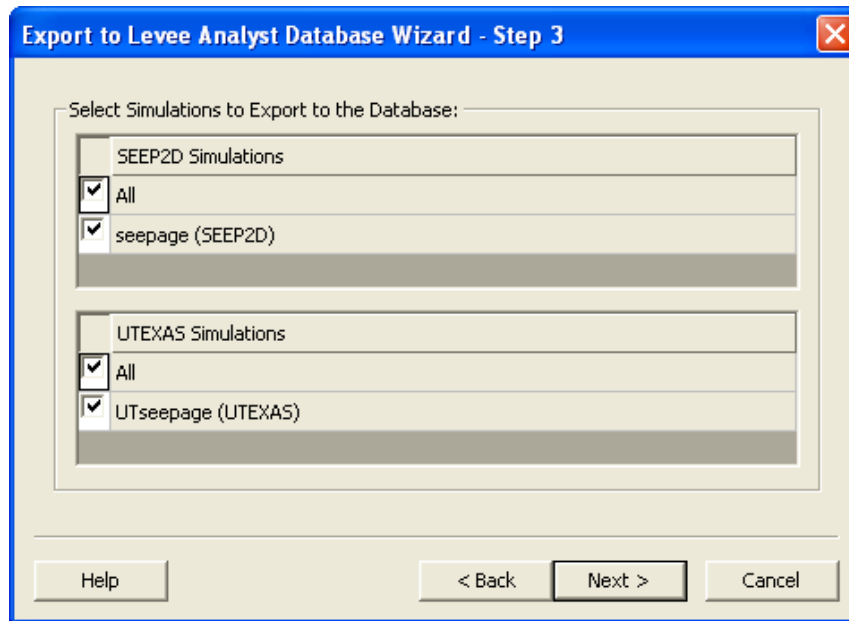


Figure 5-3 *Export to Levee Analyst Database Wizard – Step 3*

5.4 Step 4

The final step in the *Levee Analyst Database Wizard* allows the user to verify the river stage and to enter general metadata (Figure 5-4). GMS will attempt to guess the river stage based on the model boundary conditions established for the SEEP2D or UTEXAS models. However the user should verify that the river stage and river stage units are correct. A river stage value of 0.00 will be displayed if GMS cannot guess the river stage based on the model boundary conditions.

The user also has the option to enter general metadata, including his/her name, the name of the company or agency performing and archiving the simulation, the date the simulation was last modified, and any notes that should be included in the database. The *Data Modified* field will automatically list the current date. The data entered into the field in the metadata section will be entered into the respective fields in the *Seepage*, *Slope Stability*, and *Simulation* tables of the geodatabase.

The screenshot shows a dialog box titled "Export to Levee Analyst Database Wizard - Step 4". It features a blue title bar with a close button (X) in the top right corner. The main content area is divided into two sections. The first section, "River Stage:", contains a text input field with the value "75.000000" and the unit "(ft)" to its right. The second section, "Metadata:", contains four input fields: "Name:" (empty), "Company:" (empty), "Date Modified:" (a dropdown menu showing "4/18/2008"), and "Notes:" (empty). At the bottom of the dialog, there are four buttons: "Help", "< Back", "Finish", and "Cancel".

Figure 5-4 *Export to Levee Analyst Database Wizard – Step 4*

5.5 Understanding the GMS File Structure

In order to fully understand the *Export to Levee Analyst Database Wizard*, a brief note must be made about the structure used to store GMS files. Most of the information relating to a GMS project is stored in a generic Hierarchical Data Format Version 5 (HDF5) file format (Folk, 2008) and the resulting file is entitled the project file. Within the project file are multiple data objects filled with information about the GMS project. After running the *Export to Levee Analyst Database Wizard*, some of the information established in the wizard, including the company, the cross section line ID, the database filename, the name of the engineer or technician working on the simulation, any notes related to the simulations, the levee orientation, the river stage, and the SimID, is written as a data object to the project file. When the project file is launched within GMS and if the *Export to Levee Analyst Database Wizard* is run again, the saved information will be inserted automatically into the appropriate fields in the wizard.

6 Case Study

In order to demonstrate the capabilities of the Levee Analyst and the benefits it offers to users, a simple case study was performed. Initially, real-world data was sought from the USACE and from an engineering consulting firm in the private sector; however, it became unfeasible to obtain data by the required submission deadlines. Therefore a fictitious case study was developed, including a levee centerline, a series of polylines representing levee cross sections, and a series of SEEP2D seepage and UTEXAS slope stability simulations for each cross section. Although the data included in this case study are fictitious, it adequately demonstrates the capabilities of the LADM, the geoprocessing tools included in the Levee Analyst, and the *Export to Levee Analyst Database Wizard* tool included in GMS.

6.1 Creating the Geodatabase

The first step in creating the case study was to create a new personal geodatabase and then import the Levee Analysis Data Model schema into a new geodatabase, thus establishing the feature classes, tables, and relationships necessary to use the Levee Analyst. In ArcCatalog a new personal geodatabase was created using the *New->Personal Geodatabase* command (See Figure 6-1). The structure of the LADM was then imported from an XML document into the geodatabase using the *Import->XML*

Workspace Document... command (Only available with ArcEditor or ArcInfo licenses)
 (See Figure 6-2).

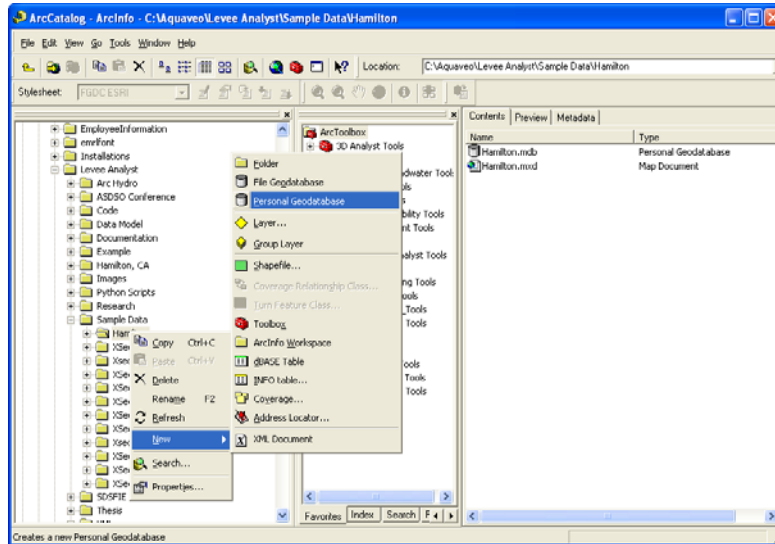


Figure 6-1 Creating a new geodatabase in ArcCatalog

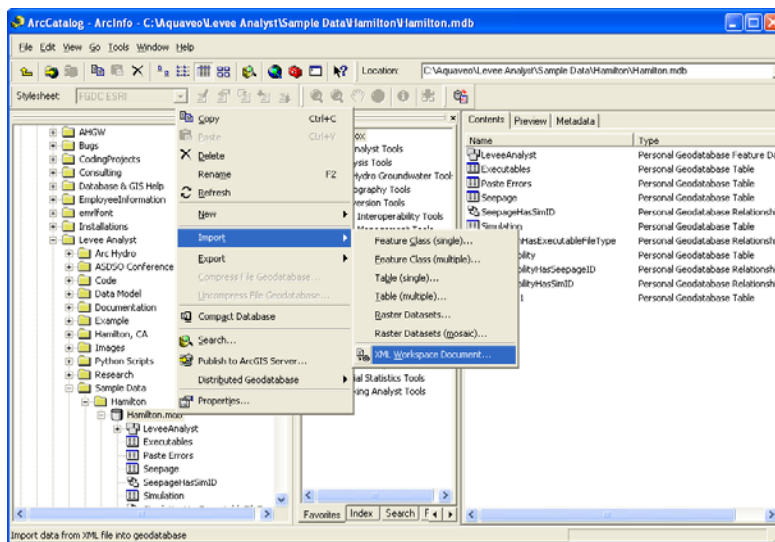


Figure 6-2 Importing an XML document into a geodatabase

6.2 Creating the Levee Centerline and Cross Sections

The next step in the case study was to generate a polyline representing the location of a levee centerline and polylines representing cross sections. For the case study, a levee known as the “J” Levee along the Sacramento River near Hamilton, California was used as an example. While the levee exists, the data used in this example is fictitious.

6.2.1 “J” Levee

The “J” levee is a privately-owned levee that was constructed along the Sacramento River in 1914 to provide flood protection for the city of Hamilton. The “J” levee does not meet current construction standards and portions of Hamilton have flooded in 1983, 1986, 1995, 1997, and 1998 (Cowan and Lemon, 2004). Currently, the USACE and The Reclamation Board of the State of California are investigating ways to improve flood protection and restore the local ecosystem through construction of a new levee (Cowan and Lemon, 2004). The existing and proposed levee locations are seen in Figure 6-3.

6.2.2 Digitizing the Centerline and Cross Sections

The editing capabilities within ArcGIS were used to generate the polyline representing the current location of the “J” Levee for this case study. The polyline was added to the *LeveeCenterline* feature class and a unique HydroID, HydroCode, and Name were assigned in the appropriate fields in the feature class. The polyline representing the “J” Levee is seen in Figure 6-4.

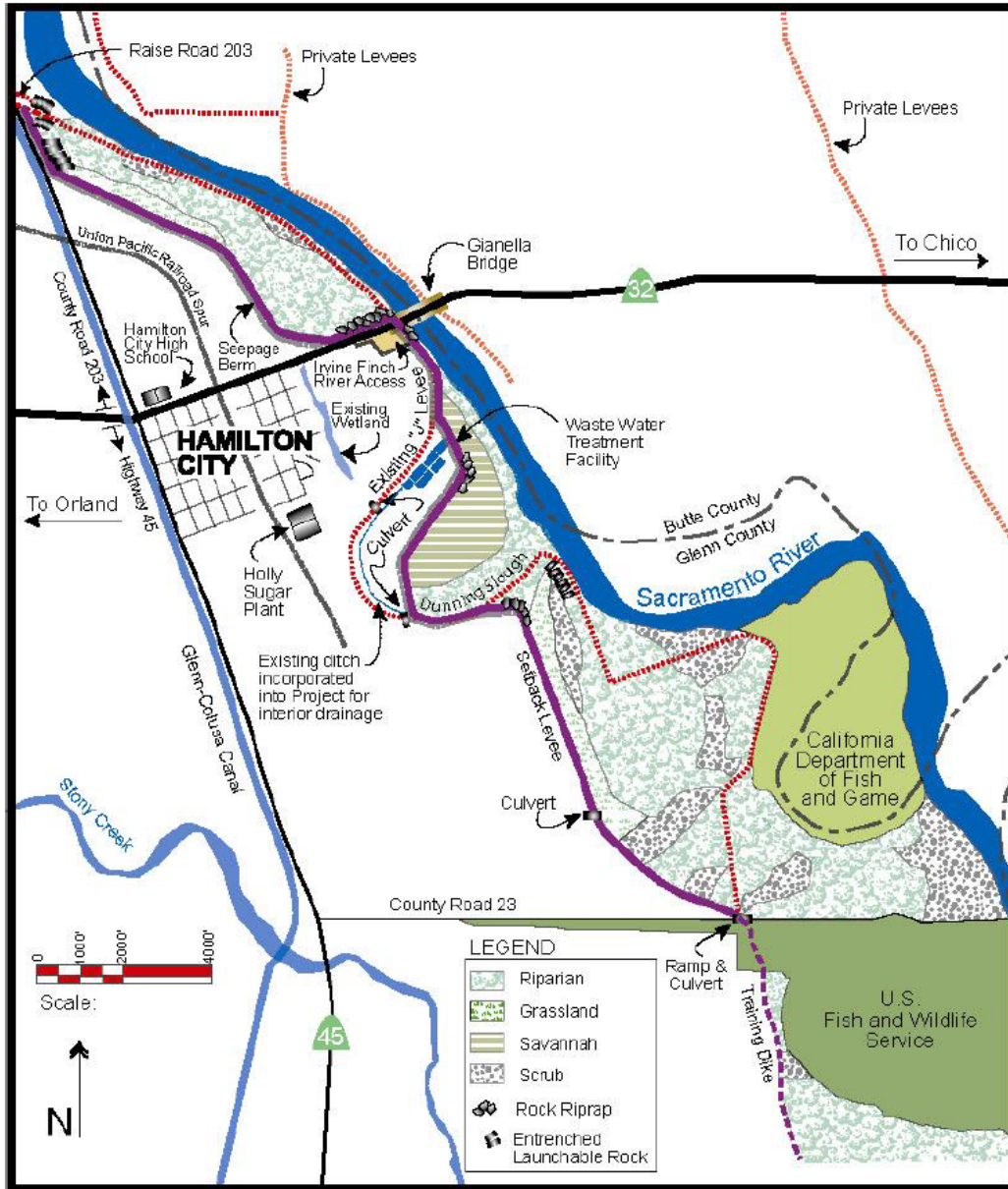


Figure 6-3 Current and proposed locations of the "J" Levee near Hamilton, CA (Adopted from Hamilton City Flood Damage Reduction and Ecosystem Restoration Fact Sheet)



Figure 6-4 "J" Levee polyline as seen in ArcGIS

After digitizing the location of the “J” Levee, eleven cross sections were also digitized at various locations along the length of the levee, as seen in Figure 6-4. These cross sections were again created using the editing capabilities within ArcGIS. Although the locations of the cross sections and the actual size of the cross sections do not truly represent the locations and sizes of actual cross sections along the “J” Levee, the fabricated data provides an adequate example of how such data could be used in the Levee Analyst. HydroIDs, HydroCodes, cross section names, and the corresponding LeveeCenterLineID, were also assigned to the appropriate fields in the *CrossSectionLine* feature class for each cross section feature.



Figure 6-5 Local of cross sections on the “J” Levee

6.3 Formatting the Executables Table

After creating the levee centerline and cross section polylines, it was necessary to store in the *Executables* table the location of the program executable files for the programs to be used to launch the seepage and slopes stability simulations. This is a necessary step in order to allow the user to make use of the *Export Simulation* geoprocessing tool. For this case study, GMS was used to display and edit the SEEP2D seepage and UTEXAS slope stability simulations, and therefore the *GMS Project* coded-

value domain value in conjunction with the path for the GMS executable were stored in the *Executables* table as seen in Figure 6-6.

OBJECTID *	FileType *	ExecutablePath
1	GMS Project	C:\Quick\Dev\GMS\APP\bin\GMSD.exe

Record: 1 Show: All Selected Records (0 out of 1 Selected)

Figure 6-6 *Executables* table with the GMS program executable stored as a record in the table

6.4 Creating SEEP2D and UTEXAS Simulations in GMS

After the levee centerline and cross section polylines were digitized in ArcGIS, a series of SEEP2D and UTEXAS simulations were generated in GMS and then archived to the *Seepage*, *Slope Stability*, and *Simulation* tables in the geodatabase using the *Export to Levee Analyst Database Wizard*. As part of this process, a 15-foot generic levee cross section was first created (See Figure 6-7) and then SEEP2D seepage and UTEXAS slope stability simulations were generated at one foot intervals for every vertical foot along the cross section, creating a set of fifteen seepage and slope stability simulations. These generated SEEP2D and UTEXAS simulations were then copied to new folders for each of the 11 cross sections included in the case study to provide data for each of the cross sections. In reality each cross section would have unique seepage and slope stability simulations; however, for simplification and time-saving purposes, the seepage and slope stability simulations were copied and used for each of the cross section features.

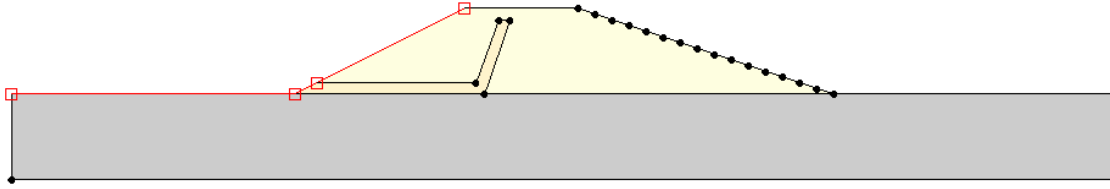


Figure 6-7 Generic cross section developed in GMS

The *Export to Levee Analyst Database Wizard* was then used to export the SEEP2D and UTEXAS simulations for each one-foot interval to the corresponding levee cross section within the geodatabase. For each cross section, 15 seepage simulations and 15 slope stability simulations were exported, creating a total of 165 records in the *Seepage*, *Slope Stability*, and *Simulation* tables.

6.5 Adding the River Stages

After exporting the seepage and slope stability simulations to the geodatabase, the current river stages at each cross section were added to the *CurrentRiverStage* field in the *CrossSectionLine* feature class. The *Add Current River Stage* geoprocessing tool was used to add the current river stage at each cross section. For demonstration in this case study a range of values were added for the cross section river stage values, ranging from 1.2 feet to 11.3 feet.

6.6 Querying the Factor of Safety

After entering the river stages, the *Query Factor of Safety* tool was then used to determine the closest factors of safety for each levee cross section based on the current cross section river stage. The tool was run once for each cross section, populating the

FactorOfSafety and *Difference* fields in the *CrossSectionLine* feature class as seen in Figure 6-8.

OBJECTID	SHAPE	HydroID	HydroCode	Name	LeveeCenterlineID	CurrentRiverStage	FactorOfSafety	Difference	SHAPE_Length
1	Polyline	2001	LevJ1	XSect1	1001	1.2	3.51	0.2	194.924712
2	Polyline	2002	LevJ2	XSect2	1001	2.3	3.43	0.3	209.984868
3	Polyline	2003	LevJ3	XSect3	1001	3.4	3.38	0.4	138.363849
4	Polyline	2004	LevJ4	XSect4	1001	4.5	3.37	0.5	135.30984
5	Polyline	2005	LevJ5	XSect5	1001	5.6	3.42	0.4	184.265668
6	Polyline	2006	LevJ6	XSect6	1001	6.7	3.51	0.3	170.629363
7	Polyline	2007	LevJ7	XSect7	1001	7.8	3.63	0.2	119.89802
8	Polyline	2008	LevJ8	XSect8	1001	8.9	3.78	0.1	110.931304
9	Polyline	2009	LevJ9	XSect9	1001	9.1	3.78	0.1	130.740466
10	Polyline	2010	LevJ10	XSect10	1001	10.2	3.98	0.2	149.860067
11	Polyline	2011	LevJ11	XSect11	1001	11.3	4.21	0.3	159.742664

Figure 6-8 Factors of safety as seen in the *CrossSectionLine* feature class

After running the *Query Factor of Safety* geoprocessing tool, the user can take advantage of the display capabilities in ArcGIS to better visualize the factors of safety using different symbology and labels. For this case study, a graduated color ramp was used to display the color of the cross section lines based on the factor of safety. As is seen in Figure 6-9, the higher factors of safety have a green color indicating those cross sections are areas that the slope stability simulations suggest are of lesser concern, while those cross sections with lower factors of safety are colored yellow or red, showing those areas of greater concern based on the current river stage levels and available slope stability simulations. ArcGIS also allows the user to add labels based on a field in a feature class. In this case study, a label of the factor of safety was added to each cross section, providing a quick survey of the factors of safety (See Figure 6-9).



Figure 6-9 Cross sections displayed with graduated colors based on the factor of safety, labels also added for the factors of safety

6.7 Querying the Simulations

As described previously, the *Simulations Query* allows the user to query the tables included in the geodatabase to find all of the seepage and slope stability simulations associated with a cross section polyline. In this case study, the SimID of the first record in the *CrossSectionLine* feature class was used to query the geodatabase to find all of the related seepage and slope stability. The output table created by running the *Simulations Query* geoprocessing tool is seen in Figure 6-10.

OBJECTID	SimID	SeepageID	SlopeStabilityID	FlowRate	FlowRateUnits	FactorOfSafety	RiverStage	RiverStageUnits	FilePath	Blob	FileType	ModelImage
1	1	1	1	5.352272	(ft ³ /s)(ft)	3.508	1	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run1_Riverside.gpr	Blob	GMS Project	<Raster>
2	2	2	2	12.640926	(ft ³ /s)(ft)	3.43	2	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run2_Riverside.gpr	Blob	GMS Project	<Raster>
3	3	3	3	22.083735	(ft ³ /s)(ft)	3.379	3	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run3_Riverside.gpr	Blob	GMS Project	<Raster>
4	4	4	4	33.915164	(ft ³ /s)(ft)	3.36	4	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run4_Riverside.gpr	Blob	GMS Project	<Raster>
5	5	5	5	48.322514	(ft ³ /s)(ft)	3.373	5	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run5_Riverside.gpr	Blob	GMS Project	<Raster>
6	6	6	6	65.663838	(ft ³ /s)(ft)	3.421	6	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run6_Riverside.gpr	Blob	GMS Project	<Raster>
7	7	7	7	86.296825	(ft ³ /s)(ft)	3.506	7	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run7_Riverside.gpr	Blob	GMS Project	<Raster>
8	8	8	8	110.681867	(ft ³ /s)(ft)	3.625	8	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run8_Riverside.gpr	Blob	GMS Project	<Raster>
9	9	9	9	138.733172	(ft ³ /s)(ft)	3.784	9	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run9_Riverside.gpr	Blob	GMS Project	<Raster>
10	10	10	10	170.900677	(ft ³ /s)(ft)	3.977	10	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run10_Riverside.gpr	Blob	GMS Project	<Raster>
11	11	11	11	207.766522	(ft ³ /s)(ft)	4.21	11	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run11_Riverside.gpr	Blob	GMS Project	<Raster>
12	12	12	12	249.726347	(ft ³ /s)(ft)	4.474	12	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run12_Riverside.gpr	Blob	GMS Project	<Raster>
13	13	13	13	296.188949	(ft ³ /s)(ft)	4.765	13	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run13_Riverside.gpr	Blob	GMS Project	<Raster>
14	14	14	14	351.478544	(ft ³ /s)(ft)	5.073	14	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run14_Riverside.gpr	Blob	GMS Project	<Raster>
15	15	15	15	413.393252	(ft ³ /s)(ft)	5.339	15	(ft)	C:\Aquaveo\Levee_Analyst\Sample Data\X\Sect1\Run15_Riverside.gpr	Blob	GMS Project	<Raster>

Figure 6-10 Simulation Query output table

6.8 Exporting a Simulation

After running the *Simulation Query* tool, the user can then make use of the *Export Simulation* geoprocessing tool export the a seepage or slope stability simulation to the program in which it was created. After running the *Simulation Query* to determine all of the records associated with the cross section stored in the first record in the *CrossSectionLine* feature class, the *Export Simulation* geoprocessing tool was used to export the first record in the output table created by the *Simulation Query* tool. After providing the necessary information in the *Export Simulation* geoprocessing tool, the GMS project file associated with the first record in the output table was launched in GMS as seen in Figure 6-11.

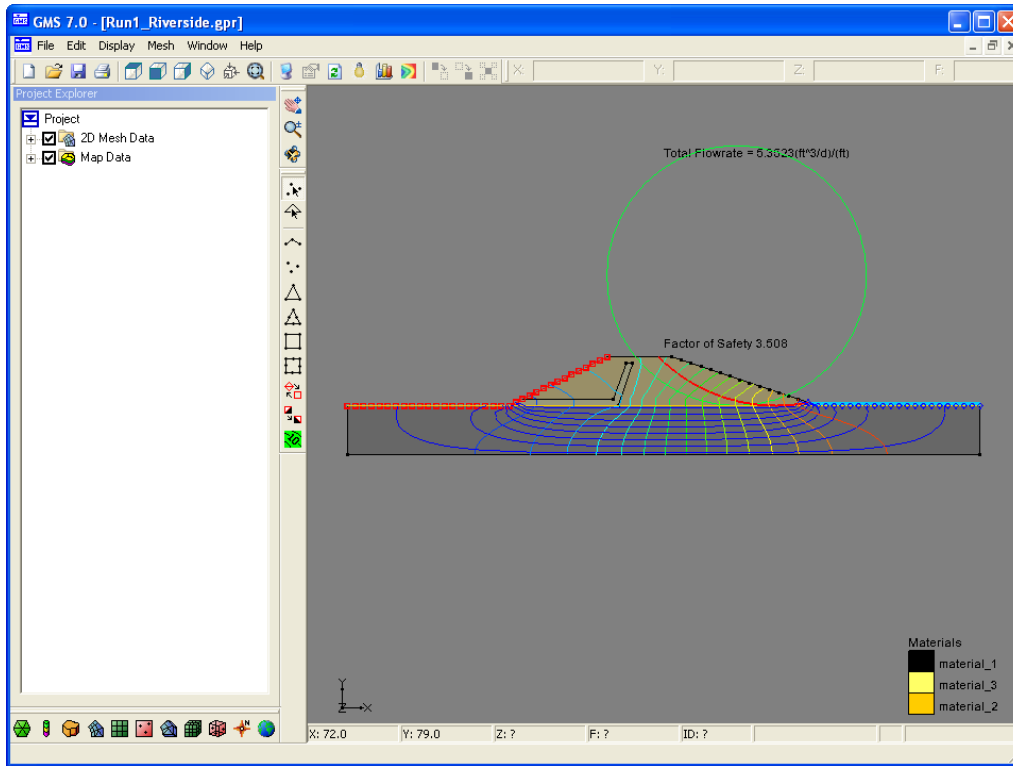


Figure 6-11 Simulation exported from ArcGIS to GMS using the *Export Simulation* geoprocessing tool

6.9 Re-archiving a Simulation

The final part of this case study was to demonstrate the ability to re-archive a simulation to the geodatabase after analyzing the simulation exported to GMS by the *Export Simulation* geoprocessing tool. The simulation was re-archived by using the *Export to Levee Analyst Database Wizard* again. On Step 1 of the Wizard, the defaulted information was assumed while on Step 2, the option to overwrite the existing SimID was selected. On Step 3, the SEEP2D and UTEXAS simulations were selected to be exported and on Step 4 the defaulted information was accepted. After clicking the *Finish* button, the records within the *Seepage* and *Slope Stability* tables, as well as the summary

simulation data contained in the *Simulation* table, including the zipped file containing the necessary GMS files, were all overwritten with the updated information for the SEEP2D and UTEXAS simulations.

In the course of the case study, levee information was added to the geodatabase using the *Export to Levee Analyst Database Wizard*, analyzed using the Levee Analyst geoprocessing tools, exported to GMS using the *Export Simulation* geoprocessing tool, and then re-archived to the geodatabase by again using the *Export to Levee Analyst Database Wizard*, demonstrating the ability to transfer information back and forth between ArcGIS and GMS using the Levee Analyst tools.

7 Conclusions

The Levee Analyst leverages existing software capabilities to provide a data model and suite of tools that assists in analyzing the current state of America's levees. The Levee Analyst toolkit, in combination with the Levee Analysis Data Model, provide a concise and expandable structure for managing, archiving, and analyzing large amounts of levee seepage and slope stability data. New tools can easily be added to the Levee Analyst toolkit, expanding the ability to further analyze and manage the simulations stored in the database.

7.1 Benefits of the Levee Analyst

The Levee Analyst offers many benefits to users, including compatibility with the new NLD, integration with GMS and the supported SEEP2D seepage model and UTEXAS slope stability model, and the ease of organization offered by using a central geodatabase structure for storing levee seepage and slope stability data. The Levee Analyst offers many applications for companies or agencies doing work with levee seepage and slope stability data. First, the Levee Analyst provides a data model structure for storing large amounts of seepage and/or slope stability simulations in a unified and comprehensive GIS geodatabase. Second, the structure of the *Export Simulation* geoprocessing tool within ArcGIS and the *Export to Levee Analyst Database Wizard* in

GMS provide a framework for archiving and retrieving model results in such a way that the model simulations can be edited and reevaluated in a concise and simple manner. Finally, the Levee Analyst also allows a user to take full advantage of the mapping and visualization tools available in ArcGIS. For example, a user could use the *Query Factor of Safety* tool to quickly determine the factor of safety for each cross section stored in the database and then use the visualization capabilities within ArcGIS to visualize the various factors of safety along the length of a levee. This provides a quick way to easily analyze current levee conditions based on current river stage information.

7.2 Future Developments

The Levee Analyst is simple in its design and construction, yet extensible and tools could easily be added in the future. This initial version of the Levee Analyst is primarily to demonstrate the Levee Analysis Data Model and the functionality of the few tools included in the Levee Analyst toolkit. The Levee Analyst is expansible and several new tools could be added in future versions as further resources and time permit. Some of the future capabilities that could be added to the Levee Analyst include real-time updating of current river stage information at the levee cross sections. Currently, the *Add Current River Stage* geoprocessing tool simply allows the user to manually update the current river stage information stored in the cross section line feature class. A future version of the tool could connect to an online server or database that contains real-time river stage information and simply running the tool would populate all of the existing cross sections with the real-time river stage data.

Another possible future development is the addition of real-time updating of factors of safety based on seismic analyses or two-stage (sudden drawdown) analyses. These developments would work in a similar fashion to the existing *Query Factor of Safety* tool, but instead would use seismic and two-stage analyses information.

Future versions of the Levee Analyst could support the automatic extraction of cross section geometry stored in the database to be used for input in the seepage and/or slope stability analyses to be run in GMS. Future tools could also perform risk analyses based on the factors of safety information available in the database, providing an efficient method of analyzing the risks to life and property based on the current levee conditions. A web interface could also be developed that could present modeling results to the general public, increasing the public's awareness of the condition and state of local, state, or federal levees.

7.3 Final Thoughts

As part of my research I have developed an effective, yet simple data model and set of ArcGIS geoprocessing tools that assist in the management, archival, and analysis of levee seepage and slope stability data. The NLD provides a great resource for storing most information relating to the nation's levees, however, the Levee Analyst fills the need for a database to store levee seepage and slope stability data, a need not satisfied by the NLD. Also as part of my research, I have developed a simple ArcGIS toolkit of geoprocessing tools that aid in managing and analyzing the seepage and slope stability data stored in the database.

By combining a simple relational data model and a toolkit of GIS geoprocessing tools, the Levee Analyst provides an effective and expandable platform for archiving and analyzing levee seepage and slope stability data. As continued efforts are made on local, state, and federal levels within the United States to improve the oversight and management of levees, the Levee Analyst provides a database structure and a new set of tools for managing valuable seepage and slope stability analyzes relating to the nation's levees.

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Appendix A. Levee Analysis Data Model Diagram

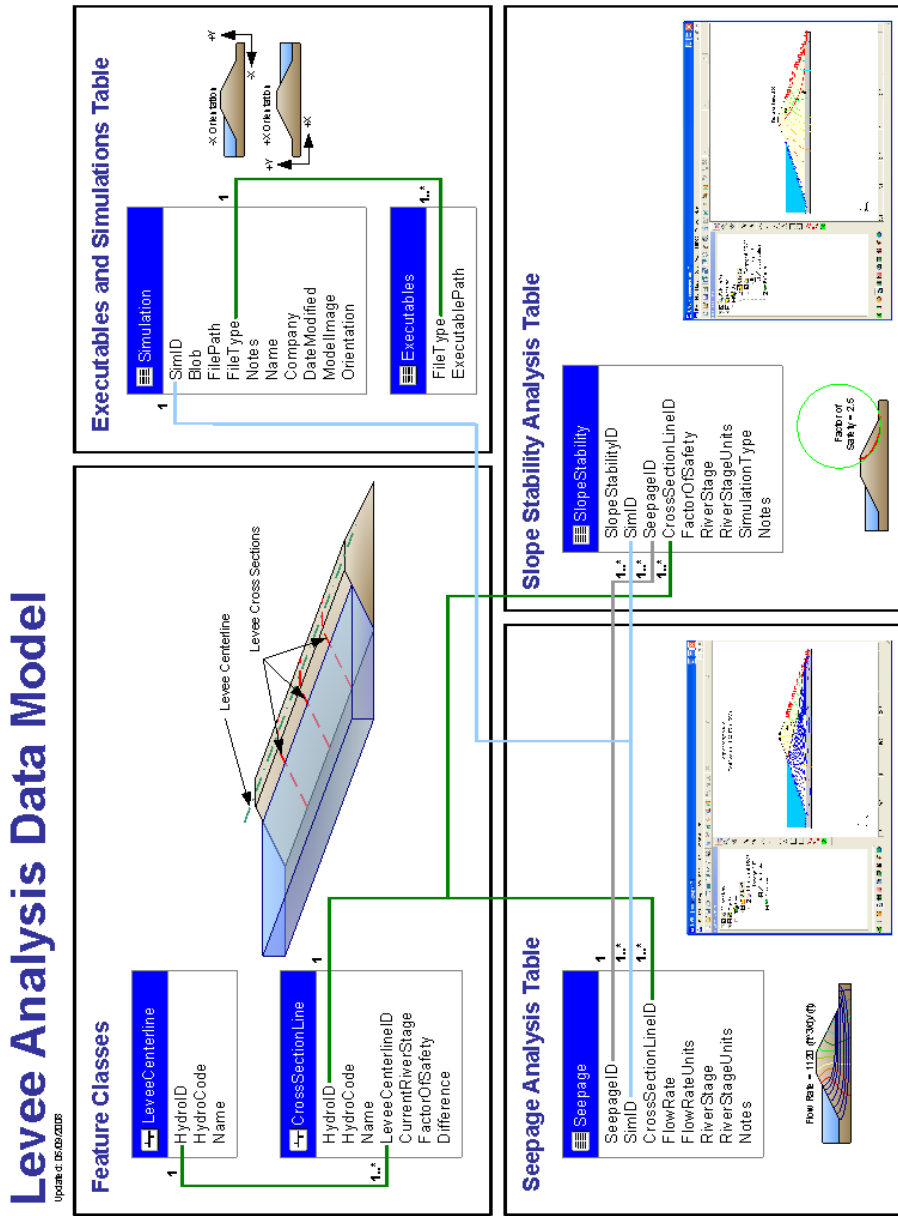


Figure A-1 Summary of the Levee Analysis Data Model

Appendix B. National Levee Database Data Model Features

cross_section_line		levee_centerline	
PK	<u>Cross_Sec_ID</u>	PK	<u>Levee_ID</u>
FK1	FC_Segment_ID Levee_Station_Code River_Mile Survey_Date Coordinate_Method_d Horiz_Accuracy Vert_Accuracy Comments	FK2	FC_Segment_ID Up_River_Mile Down_River_Mile Feature_Name Feature_Length Gage_Code Gage_Owner Slope_Landside Slope_Waterside Bank_d Coordinate_Method_d Cutoff_Type_d Levee_Type_d Primary_Material_d Crest_Width Crest_Access Flood_Source River_Basin Horiz_Accuracy Vert_Accuracy Comments

Figure B-1 Features from the National Levee Database Data Model used in the Levee Analyst (Adopted from the SDSFIE website)