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ABSTRACT

The paper presents a slope stability analysis of a proposed embankment contained within an abandoned coal mine reclamation project near Sallisaw, Oklahoma. The project involved the use of computer modeling to analyze the slope stability of the earth-filled embankment. The project plans call for mine spoils and silty-clay borrow materials is used to construct a 74,000 cubic yard embankment, which will be used as a water impoundment for a small lake. The embankment, as designed, consists of a central clay core, mine spoils and a silty-clay material cap. The software program Galena was used as a modeling tool for the slope stability analysis of the proposed embankment. Additionally, seven different variations on the embankment's proposed design were modeled. The ultimate goal was to determine the factor of safety (FS) for each variation. Results show that the Galena program provides a higher factor of safety when compared with conventional methods using the Taylor stability chart. The difference in these values is probably attributed to the general assumptions of the Taylor method.

INTRODUCTION

The purpose of this project is to perform a slope stability analysis of an earth-filled embankment for an actual civil engineering project near Sallisaw, Oklahoma. The project design started in 2010, although no formal slope stability analysis was performed on the embankment prior to this project report. The US Department of the Interior, Office of Surface Mining Reclamation and Enforcement (OSM), intends to grade and cover existing coal mine spoil piles, eliminate exposed high-wall segments, stabilize the slopes of a hazardous water body and vegetate an existing abandon coal mine site in Sequoyah County, Oklahoma. Due to the large amount of excess spoil piles on the site, approximately 500,000 CY (cubic yard), about 80% of the spoil material cannot be graded in place, as this would have resulted in a large plateau in one area of the site that would not have conformed to the contours of the surrounding geographic area. Thus, about 400,000 CY of the spoil material will be transported to the southern end of the project site to create a large impoundment area, which will ultimately fill with water and create a small recreational lake. The lake will be surrounded by a long, earth-filled embankment, which is the subject of this project report. The embankment will be constructed using the mine spoil piles overburden containing mostly shales, with some silts and clays. The embankment will be approximately 1,800 feet long, 17 feet tall and 175 feet wide (toe to toe) at its tallest and widest points and contain about 74,000 CY of material. Borrow soils on the mine site, such as clays and silts, will also be excavated and used in the embankment for the impermeable core and slope blanket materials.

BACKGROUND AND SCOPE OF WORK

The intent of the project is to evaluate the stability of the embankment as currently designed (base-case scenario). The slope geometry and material characteristics will also be altered to study the effect of these changes on slope stability. Such changes include altering the upstream (u/s) and downstream (d/s) slope angles, changing material types, and altering the headwater elevation. Figure 1 shows a cross-section of the embankment and associated dimensions which will be used as the base case scenario. The upstream side of the embankment has a 4:1 slope and the downstream side has a 5:1 slope. A central clay core is flanked by the mine spoils which constitute the main body of the dam and provide a seepage deterrent. Normal water surface (head pressure) on the upstream side is assumed to be 13 feet, which corresponds to the primary spillway level during normal operating conditions. Because of the project limitations, some assumptions have been made using best engineering judgment, including material properties such as density, friction angles, and cohesion.

It must be noted that no stability analysis was originally performed during the actual design of the embankment, thus the content of this report is unique. Furthermore, this study is strictly for academic purposes only and the results should not be used for the actual project's design or construction of Dwight Mission Mine Site Reclamation Project.

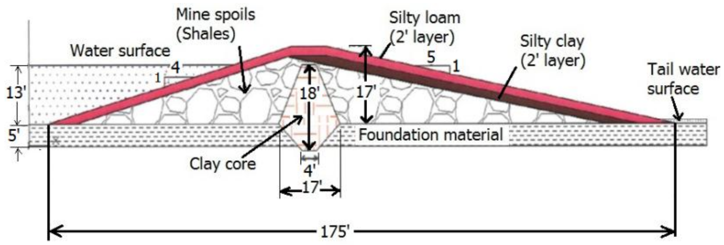

Fig. 1. Cross-section of the embankment base case, as presently designed

Slopes can either occur naturally or are man-made structures, as in the case of this project. The slope stability problems have been encountered throughout history, when slopes have been created or disturbed. The design of a foundation must consider slope movement (Day 2006). The need for engineered structures on construction projects continues to increase, as well as the need for advanced analysis methods such as computer modeling, investigative tools, and stabilization methods to solve slope stability problems (Lou 2007). Stability problems most often occur when an embankment is built upon soft soils, such as clays with low bearing capacity, silts or organic soils (Engineer Manual # 1110-2-1902 1986).
When a ground surface is not horizontal, a component of gravity moves the soil downward. Embankments constructed over relatively deep deposits of soft soils have displayed this type of "circular arc failure". The weight of the embankment soils above the failure surface serve as the driving force of movement. The driving moment is the product of the weight of the embankment acting through its center of gravity times the horizontal distance from the center of gravity to the center of rotation. The resisting force against movement is the total shear strength acting along the failure arc. The resisting moment is the product of the resisting force times the radius of the circle (FHWA 2001). Slope stability is a function of four basic factors: density (or unit weight) of the soil, slope angle, cohesion of the slope material, friction angle. Cohesion (c) can be thought of as the inherent ability of a material to bond itself together. The friction angle (ϕ) of a material measures the amount of friction that keeps the block from moving when a shear force is applied. The four elements listed above can be used to demonstrate a soil blocks tendency for movement when forces are applied. Forces encouraging failure depend on the weight above the plane of weakness (Lou 2007).

Figure 2 shows the four major types of stability issues encountered with embankments over weak foundations soils. The stability problems shown in Figure 2 can be classified as internal or external. Internal stability problems within embankments result from poor quality embankment materials or improper placement or compaction of embankment fills. The infinite slope failure in Figure 4 is an internal stability example, as material sloughs from the surface of the slope. The issues with internal stability can be addressed through project specifications such as compaction specifications (FHWA 2001). The other failure modes shown in Figure 2 (b, c, d) are examples of external stability problems (FHWA 2001). NAVFAC (1986) suggests that failure of embankment fill slopes can be caused by overstressing the foundation soil, drawdown and piping, and vibrations such as earthquakes, blasting, etc.

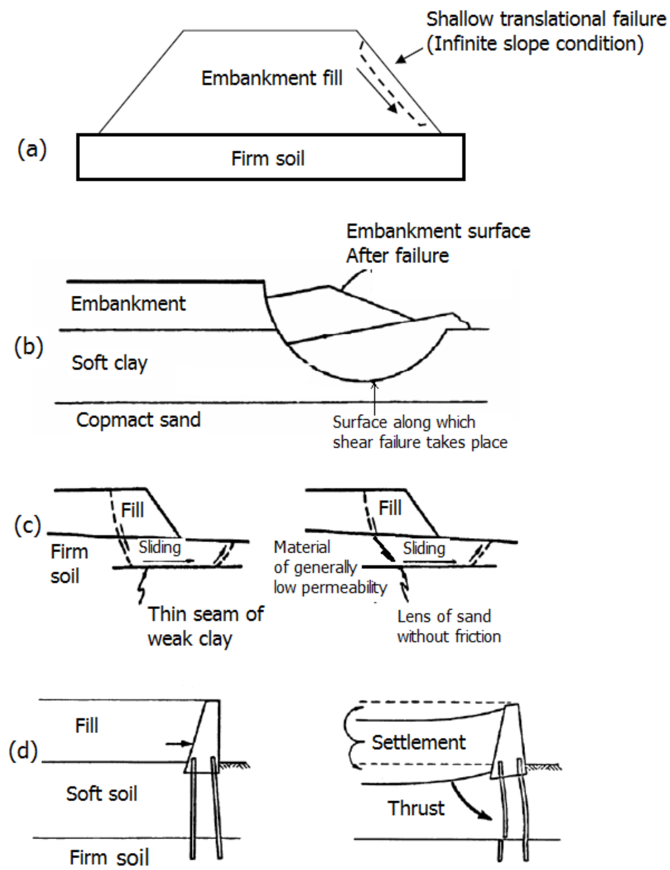

Fig. 2. Embankment Failures: (a) Infinite slope failure in embankment fill, (b) circular arc failure, (c) Sliding block failure, (d) Lateral squeeze of foundation soil (FHWA 2001)

FACTOR OF SAFETY

After finding the soil profile, soil strengths and water table location have been determined by laboratory testing or field exploration, the stability of the embankment can be analyzed and the factor of safety can be determined (FHWA 2001). The shear strength of the soil should be compared against the stresses on the surface most likely to fail (Day 2006). The factor of safety (FS) is the ratio of the forces resisting failure (shear strength of the soil) to the forces causing failure (shear stress developed along the failure surface) (Day 2006).

$$FS = \frac{\text{Resisting strength}}{\text{Forces causing failure}}$$

A factor of safety below one implies the slope will fail, as the resisting forces are less than the forces causing failure. The greater the factor of safety, the greater is the slope's resistance to collapse. Generally, a value of 1.5 is acceptable for the factor of safety of a stable slope (Day 2006), although a minimum factor of safety as low as 1.25 is sometimes used for highway embankment side slopes (FHWA 2001). Table 1 referred from the US Army Corps of Engineers provides a good guide for minimum factors of safety for new earth-fill dams. In general, when selecting an appropriate factor of safety, an engineer should consider what method of stability analysis was used, methods for determining shear strength, degree of confidence in material data, how critical the application and severity of failure if it were to occur (FHWA 2001).

Table 1. Minimum Required Factors of Safety for New Earth and Rock-Fill Dams (Engineer Manual No. 1110-2-1902, 1986)

Analysis Condition[1]	Required Minimum Factor of Safety	Slope
End-of-Construction (including staged construction)[2]	1.3	Upstream and Downstream
Long-term (Steady seepage, maximum storage pool, spillway crest or top of gates)	1.5	Downstream
Maximum surcharge pool[3]	1.4	Downstream
Rapid drawdown	1.1-1.3[4,5]	Upstream

[1]For earthquake loading, see ER 1110-2-1806 for guidance; An Engineer Circular, "Dynamic Analysis of Embankment Dams".
[2]For embankments over 50 feet high on soft foundations and for embankments that will be subjected to pool loading during construction, a higher minimum end-of-construction factor of safety may be appropriate.
[3]Pool thrust from maximum surcharge level. Pore pressures are usually taken as those developed under steady-state seepage at maximum storage pool. However, for pervious foundations with no positive cutoff steady-state seepage may develop under maximum surcharge pool.
[4]Factor of safety (FS) to be used with improved method of analysis.
[5]FS = 1.1 applies to drawdown from maximum surcharge pool; FS = 1.3 applies to drawdown from maximum storage pool.

For dams used in pump storage schemes or similar applications where rapid drawdown is a routine operating condition, higher factors of safety, e.g., 1.4-1.5, are appropriate. If consequences of an upstream failure are great, such as blockage of the outlet works resulting in a potential catastrophic failure, higher factors of safety should be considered.

SLOPE STABILITY ANALYSIS METHODS

There are several methods available for circular arc slope stability analysis for embankments built upon soft ground. These techniques can generally be classified into three broad categories e.g., limit equilibrium methods, limit analysis, and finite element methods (NAVFAC 1986). Many of the methods for stability analysis fall into the limit equilibrium category. The method of slices is commonly used in limit equilibrium solutions. The soil mass within the slip surface is divided into several slices, and the forces acting on each slice is considered. The limit equilibrium method does not account for load deformation characteristics of the materials, whereas the limit analysis method considers yield criteria (NAVFAC 1986). The finite element method is used in more complex problems where earthquake and vibrations are part of the total loading system.

The analysis of slope stability can be performed by using slope stability charts. The stability charts can be used as a graphical tool to check factors of safety before a more detailed computer analysis. They have been designed with the assumptions of two-dimensional limit equilibrium, simple homogeneous slopes and circular slip surfaces. The charts are for ideal, homogeneous soils that are typically not encountered in the field (NAVFAC 1986). The two most common stability charts were developed by Taylor (1948) and Janbu (1968). Janbu established stability charts for slopes in soils with uniform strength for $\phi = 0$ and $\phi > 0$ conditions. Other charts account for surcharge loading at the top of slope, submergence and tension cracks.

Several methods are available for slope stability calculation. These include the Bishop (1955) method, Janbu (1954) method and the Spencer (1967) method. These methods are basically variations on the Method of Slices (FHWA 2001). Software programs, such as Galena which will be used for this project, require the user to select the analysis method. The method used for determining the factor of safety depends on the soil type, source of soil strength parameters, level of confidence in values and type of slope being designed (FHWA 2001). Some general guidelines for recommended methods are shown in Table 2.

Table 2. General Guidelines for Selection of Slope Stability Analysis Method (FHWA 2001)

Foundation Soil Type	Type of Analysis	Source of Strength Parameters	Remarks (see Note 1)
Cohesive	Short-term (embankments on soft clays – immediate end of construction – $\varphi = 0$ analysis).	UU or field vane shear test or CU triaxial test. Use undrained strength parameters at p_o	Use Bishop Method. An angle of internal friction should not be used to represent an increase of shear strength with depth. The clay profile should be divided into convenient layers and the appropriate cohesive shear strength assigned to each layer.
	Stage construction (embankments on soft clays – build embankment in stages with waiting periods to take advantage of clay strength gain due to consolidation).	CU triaxial test. Some samples should be consolidated to higher than existing in-situ stress to determine clay strength gain due to consolidation understaged fill heights. Use undrained strength parameters at appropriate p_o for staged height.	Use Bishop Method at each stage of embankment height. Consider that clay shear strength will increase with consolidation under each stage. Consolidation test data needed to estimate length of waiting periods between embankment stages. Piezometers and settlement devices should be used to monitor pore water pressure dissipation and consolidation during construction.
	Long-term (embankment on soft clays and clay cut slopes).	CU triaxial test with pore water pressure measurements or CD triaxial test. Use effective strength parameters	Use Bishop Method with combination of cohesion and angle of internal friction (effective strength parameters from laboratory test)
	Existing failure planes	Direct shear or direct simple shear test. Slow strain rate and large deflection needed. Use residual strength parameters.	Use Bishop, Janbu or Spencer Method to duplicate previous shear surface.
Granular	All types	Obtain effective friction angle from charts of standard penetration resistance (SPT) versus friction angle or from direct shear tests.	Use Bishop Method with an effective stress analysis.
Note 1: Methods recommended represent minimum requirement. More rigorous methods such as Spencer's method should be used when a computer program has such capabilities.			

DESIGN CONSIDERATIONS FOR EMBANKMENT DAMS

The design of an earthfill dam cross-section is controlled by the material properties of the embankment materials, the foundation characteristics, and the construction methods used and the amount of construction control anticipated (Design of small Dams 1987). Dams are classified by their construction materials used, their ultimate end use, or their hydraulic design. For this project, the dam can be classified by the embankment materials that are being used to construct the structure. The basic principle of design is to produce a functional structure and a minimum total cost.

The selection of proper foundation materials is critical in the design of the dam. Although rock foundations provide the greatest shear strength and bearing capacity, earthfill dams can also be constructed on silt, sand and clay foundations such as in the case of this project. Silt or fine sand foundations have design concerns which include non-uniform settlement, soil collapse upon saturation, piping and protection at the downstream toe portion of the embankment from erosion. Clay foundations can be used, but require relatively flat embankment slopes because of relatively low shear strengths and the tendency for clay soils to consolidate. Proper tests must be done to determine bearing capacities and consolidation characteristics of clay foundations. When the foundation is earth, all organic and other deleterious material should be stripped and removed prior to construction (Engineer Manual No. 1110-2-1902, 1986).

The rolled-filled type of construction is being used almost exclusively for the construction of earth-filled dams. This involves the construction of the dam in successive, mechanically compacted layers. After the foundation of the embankment has been properly prepared, material from borrow areas is transported to the construction site by means of trucks or scrapers. The layers (lifts) are compacted to the required density and moisture contents using compaction equipment such as rollers or the material hauling equipment itself (proof rolling). Standard compaction tests (such as the Proctor compaction test) can be used to determine these values. Rolled-filled dams are categorized into three types: diaphragm, homogeneous and zoned (Design of small dams 1987).

This project design involves the use of a zoned embankment type. This is the most common type of rolled, earthfill dam. Earth-fill dams are constructed with impervious cores when local borrow materials do not provide adequate quantities of impervious material (Engineer Manual No. 1110-2-1902, 1986). A central impervious core is flanked by zones of materials considerably more pervious, called shells. The pervious shells protect and support the impervious core, the upstream section allows for protection against rapid drawdown and the downstream pervious zone acts as a drain to control seepage and lower the phreatic surface.

The design and construction of earth-filled dams is complex because of the nature of the varying foundation conditions and range of properties of the materials available. A detailed geological and subsurface evaluation must first be conducted. This allows for the proper characterization of the foundation, abutment and borrow material. The next step involves a study of the physical and engineering properties of the embankment materials (Engineer Manual 1986).

The foundation of the embankment should provide an adequate bearing surface and provide protection from excessive seepage. If the foundation material is impervious and comparable to the embankment material in structural characteristics, little foundation treatment is required. At a minimum, the foundation area should be stripped of sod, organic topsoil and other deleterious material. The top several feet of soil foundation lacks the density of the underlying material because of frost action, runoff, wind, etc. [12].

When foundations consist of saturated fine grained soils, their ability to resist shear stresses may be determined by their soil group classification and relative consistency. The most practical solution for saturated foundations of fined grained soils is flattening the slopes of the embankment. This requires the critical sliding surface to lengthen, thereby decreasing the average shear stress along its path and increasing the factor of safety against sliding (Design of Small Dams 1987). Table 2 shows some recommended slopes for embankments typical for the groups within the Unified Soil Classification with different consistency.

EMBANKMENT STABILITY IMPROVEMENT TECHNIQUES

If an embankment design stability analysis returns a factor of safety too low for safe operation, there are many available solutions to solve stability issues and increase the factor of safety. The solution method should be economical and consider available materials, quality and cost, and construction time schedules [4].

GALENA PROGRAM DESCRIPTION

Galena is a powerful slope stability analysis program designed for engineers to solve geotechnical problems. The program was selected because of popularity, reliability, ease of use and availability as it relates to this project. Galena offers three different analysis methods: Bishop, Spencer-Wright, and Sarma. These are mathematical iteration methods that the program uses to resolve forces acting on a slope. The method is chosen by the user, and should be determined by slope geometry, material properties and a general understanding of geotechnical engineering. The Bishop method is used to determine the stability of circular failure surfaces, the Spencer-Wright method is used for both circular and on-circular failure surfaces, and the Sarma method is used for more complex stability problems (Lou 2007). Table 1 in this project report can also be used as a general guide for analysis method selection.

The program produces printable results which include cross sections showing the failure surface along with the resulting factor of safety. Galena allows shear strength properties to be defined using traditional c and phi values, the Hoek-Brown (1983) failure criterion (m, s and UCS), or with shear/normal data from lab curves (Clover Technology 2003). Multiple material types and locations within the embankment can be altered and shown in a graphical display. Figure 3 show a screenshot of the Galena user environment with the embankment for this project. The program allows for the input of an assumed failure surface (location of failure curve, radius of circle) and then this failure location can be altered to find most probable failure surface with the minimum factor of safety. The user can use a trial-and-error approach to determine the failure surface with the lowest factor of safety corresponding to the most probably failure surface.

PROJECT FINDINGS

Before any computer analysis could be performed with Galena, information about the embankment needed to be obtained. This information included material properties for the embankment, foundation, clay core and embankment cap such as soil types, depth of foundation, density, cohesion, friction angle, and dimensions of the embankment and all subsequent layers. Because of the remote location of the project site, soil testing such as core drilling was not performed for this project. Thus, many properties had to be assumed based on available literature and project information. The project plans and design specifications were used to obtain embankment dimensions and material types to be used. The project specifications describe the clay core, foundation preparation requirements and embankment compaction requirements. Design sheet D1 and D4 of the project plans provide plan views and cross sections of the embankment, as well as dimensions of the embankment, impermeable clay core and silty-clay material cap (Chris 2012). A cross section of the embankment at its largest point can be seen in Figure 1. This cross section was used for model dimensions of the "base case" scenario. The dimensions of the normal water level, foundation, embankment, clay core and cap can be seen in the figure.

The United States Department of Agriculture, Natural Resources Conservation Service provides a valuable resource of soil types throughout areas of the United States. Their website (USDA 2012) was used as a reference to generate a Custom Soil Resource Report for the project site. The report presents a soils map which displays different soil types in the areas in question. The different soil types are outlined in the report and properties such as USGS (United States Geological Survey) soil name, permeability, density, drainage class, depth to restrictive feature and typical soil profiles are shown. From the soil report, it is seen that the soils making up the foundation of the embankment include SrB (Stigler silt loam), VaC (Vian silt loam), and SnC (Spiro silt loam). Table 3 below shows a summary of the embankment foundation soils and important soil properties obtained using the USGS soil report. The NRCS (Natural Resources Conservation Service) also provides a guide for estimating moist bulk density of soils when laboratory test data is not available. These densities are also reported in Table 3.

Fig. 3: Galena User Environment

Table 3. Embankment Foundation Soil Type

USGS Soil Unit	Description	Portion of Embankment Footprint (%)	Avg. Depth to Bedrock (inches)	Avg. Density (lb/ft^3)
SrB	Stigler Silt Loam	50%	72.0	94.0
VaC	Vian Silt Loam	25%	>80.0	94.0
SnC	Spiro Silt Loam	25%	30.0	97.0
		Weighted Average:	63.5	94.8

Table 4. Other Embankment Materials

Material	Source	Average Density (lb/ft^3)	Friction Angle (ϕ)	Compacted Cohesion (psf)	Saturated Cohesion (psf)
Clay Core	VaC and SnC silty clay loam (compacted)	111.4	32	2,000	300
Embankment Fill	Mine Spoils (shales)	110.0	10	1,044	200
Silty Loam Cap	VaC Silt Loam	97.0	28	1,550	300
Silty Clay Blanket	SnC Silty Clay	97.0	25	1,750	300
Foundation	VaC, SnC, SrB Soils	94.8	30	1,550	300

Because the foundation material appears to vary between these 3 soil types over the entire footprint, a weighted average density, and depth to bedrock was assumed using the footprint percentages of each soil type. This allowed for foundation properties to be used in the cross-section of the Galena computer model. The foundation depth was assumed to be 5 feet with an average density of 94.8 lb/ft^3. It was assumed that below the foundation competent rock exist as reported in USDA soil report. Other embankment material properties can be seen in Table 4. These material properties were also estimated using the available literature mentioned above. Also, a NAVFAC (1986) material properties guide provided a useful table of approximate material properties that helped in determination of friction angle (ϕ) and cohesion (c) values for the embankment materials. A copy of this material table is included in report by Chris (2012). Other sources listed in the references section of this project report were consulted for material classification and assumed properties.

GALENA COMPUTER MODELING RESULTS

In this study embankment slope stability was analyzed by using the Galena program. After defining all material properties, dimensions, failure analysis method (Bishop), phreatic surface, assumed failure surface (circle radius and location) the program outputs a factor of safety for the embankment. The failure surface was first assumed, and then a trial-and-error approach was used to find the failure surface with the lowest factor of safety.

The program allowed for multiple scenarios (analyses) to be modeled. The eight different scenarios or analyses that were considered as follows:

(i) Base Case (as designed). Includes clay core, spoils and select material cap, Figure 1
(ii) Base Case without water behind embankment
(iii) Embankment with 3:1 in-slope
(iv) Embankment with 2:1 in-slope
(v) Embankment with 1:1 in-slope and 1:1 out-slope
(vi) Taller Embankment with 0.5:1 in-slope and 0.5:1 out-slope
(vii) Same as #6 but without water behind embankment
(viii) Embankment with base case dimensions, but fully homogeneous fill

A screenshot of the Galena output file for the base case scenario and the results of all eight analyses have been shown in Figure 4 and Table 5, respectively. The Table 5 displays a description of each scenario along with a corresponding factor of safety for that scenario. Full Galena output files for all eight scenarios can be obtained from the report by Chris [15].
For the current design (base case, analysis # (i)) the factor of safety was found to be 5.11. This high factor of safety was anticipated due to relatively flat slopes of the embankment as well as the low design height of 17′. From Table 2 earlier in this project report, a 20′ embankment built on clays of medium stiffness is recommended to have a slope of at least 3:1. Thus, it is logical to obtain a higher factor of safety with flatter slopes.

Also from Table 2, as the embankment height is increased, the recommendations call for flatter slopes to maintain acceptable factors of safety. The effect of slope height can be observed in analysis # (vi), as the factor of safety was reduced to 2.12 when the embankment height was raised to 35 feet. Further analysis can be done to compare slopes with the same slope angles but varying heights to determine the relationships of the slope heights on the factors of safety. The stress on the failure surface is a direct result of the weight (and density) of the soil above the failure surface, thus as the height is increased, this weight of soil increases and factor of safety is reduced.

In comparing analysis # (viii) with analysis # (i), changing the embankment to a fully heterogeneous fill (as compared with the base case) did not have a significant effect on factor of safety (5.11 vs. 4.88). Because slope geometry did not change between the two analyses, the effect can be attributed to the material properties that influence shear strength such as cohesion (c) and friction angle (ϕ). The difference between the two factors of safety can also be attributed to the estimated location of the failure surface as discussed earlier in this report.

As a general verification of the Galena computer method, Taylor's stability chart was used to check the factor of safety of analysis # (ii). A factor of safety of 1.8 was obtained versus 3.72 with the Galena method. The difference in these values is probably attributed to the general assumptions of the Taylor method as mentioned earlier in this project report. Future research with Galena could involve varying slope angles, slope heights, material types, material properties, foundation characteristics, failure surface type (circular vs. non-circular), water influences, and other factors. These changes could be analyzed to determine their influence on the slope factor of safety. The failure analysis method that the program uses could also be changed (Bishop vs. Spencer-Wright Method). 'Back analysis' is also possible to determine the most appropriate slope angle and height for a desired factor of safety, rather than using these values to output factors of safety.

This study provided valuable experience with the Galena program, as well as offering an increased knowledge of slope stability concepts and the factors that influence stability. It is important to note that variations in material properties can have a significant effect on slope stability (such as cohesion and friction angle). In actual project, soil sampling from the project site should have been conducted to obtain more defensible input data for the Galena model. In the case of this project report, the assumptions and methods used to obtain material properties were necessary and acceptable to satisfy the academic exercise.

Table 5. GALENA Program Results

Case No.	Description of the Case	Embankment Height (ft)	Slope angle In slope	Slope angle Out slope	FOS
1	Base Case - Clay core and select material cap (Fig. 1)	17	4:1	5:1	5.11
2	Base Case without Water behind embankment	17	4:1	5:1	3.72
3	Embankment with steeper in-slope	17	3:1	5:1	4.60
4	Embankment with steeper in-slope	17	2:1	5:1	3.66
5	Embankment with steeper in-slope and out-slope	17	1:1	1:1	3.54
6	Embankment Height Increased with steep slopes	35	0.5:1	0.5:1	2.12
7	Embankment Height Increased with steep slopes (no water)	35	0.5:1	0.5:1	1.34
8	Fully Homogeneous Embankment (all spoils)	17	4:1	5:1	4.88

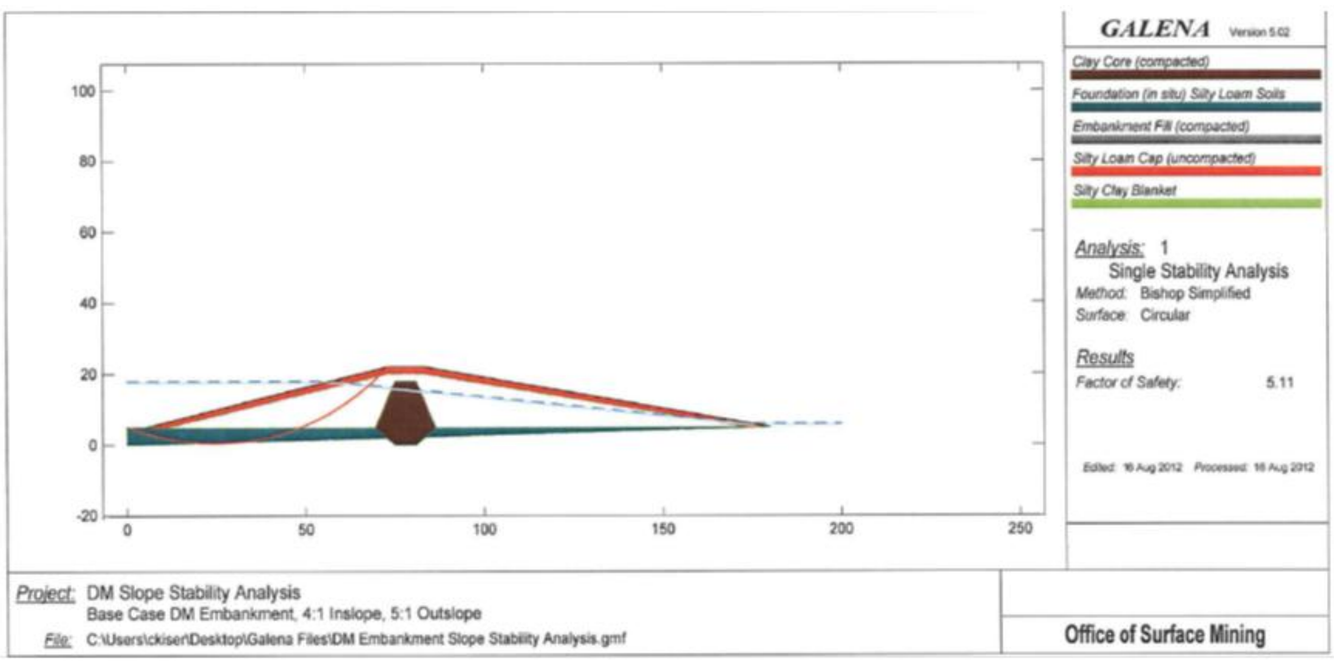

Fig. 4: GALENA Output for Base Case Scenario

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