GIS-BASED KINEMATIC SLOPE STABILITY ANALYSIS

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ABSTRACT

Kinematic slope stability analysis can be used to evaluate the potential for plane or dip-slope failure, which is sliding along a bedrock discontinuity plane (such as bedding), and wedge failure, which is sliding along an intersection line of two intersecting discontinuity planes (such as bedding and a fault). The geometric relationship between the orientation of the discontinuity planes and the orientation of the overlying topography determine the kinematic stability of a slope. We apply a GIS-based kinematic model to address slope stability for a canyon landfill in southern California. Geologic data is compiled into the GIS to create a representative model of the geologic structure across the study area. Spatial analysis of the geologic model and the topographic model determine kinematic slope stability and identify areas of potential plane failure or wedge failure. This study demonstrates the feasibility and usefulness of performing kinematic slope stability analysis within the GIS framework. The study also demonstrates that GIS-based kinematic analysis is superior to traditional application of kinematic analysis in that GIS-based analysis provides: (1) greater accuracy of results, (2) increased efficiency of analysis, and (3) better communication of findings.

INTRODUCTION

The stability of natural and man-made slopes is an important concern for numerous types of site uses and objectives, including the development or protection of infrastructure, homes, and natural resources. Slope stability is often the most critical safety issue or feasibility component for dams and hydroelectric facilities, canyon landfills, quarries and borrow pits, water storage tanks, bridge abutments, and residential developments in hillslope environments.

Slope stability depends in large part upon the geologic and geotechnical characteristics of the bedrock and soil that compose the slopes. Not surprisingly, the strength of these materials plays an important role in slope stability. For slopes composed predominantly of bedrock, however, often the most important factor is the geologic structure of the rock. Geologic structure refers to the location, orientation, and spacing of discontinuities within the bedrock mass. Such discontinuities include those along bedrock bedding, bedrock joints, faults, and shears.

Geologic structure, in particular the orientation of bedding, was thought to be a key factor for slope stability at the subject study site – a canyon landfill in southern California. Investigators observed that most landslides which had occurred at the site appeared to have slid along bedding. Additionally, slope stability analyses representing several locations at the site indicated that the stability of the slopes was sensitive to bedding orientation.

A study was commissioned to further evaluate the stability of these slopes and to develop preliminary plans for stabilizing slopes found to be unstable. As part of that study, and in an effort to facilitate preparation of slope-grading plans, we developed a GIS-based kinematic analysis model to characterize geologic structural controls on slope stability. The following section of this paper describes how kinematic analysis is used to evaluate slope stability. While this paper presents results from an actual study of a southern California canyon landfill, the emphasis of the paper is on the methodology and application of the GIS-based kinematic analysis, rather than the details of the site geology or model results.

KINEMATIC SLOPE STABILITY ANALYSIS

As discussed above, the stability of a bedrock-composed slope is often controlled by the geologic structure within the bedrock. In such cases, the geometrical relationships between the geologic structures and the orientation of the overlying slope determine the kinematic stability of a slope. Kinematic refers to the geometrically-possible motion of a body without consideration of the forces involved. Kinematic analysis is concerned with the direction of movement, which movement is allowable and which is constrained. With respect to slope stability, kinematic analysis generally is used to evaluate whether blocks or masses of rock may move along geologic structures and slide out of the face of a slope.

Kinematic analysis commonly is used, and was used in this study, to evaluate two principal modes of potential sliding: plane failure and wedge failure. Plane failure is sliding along a single, planar, geologic structure that tilts downward (dips) at an inclination flatter than that of the overlying slope face. Wedge failure is sliding along a line of intersection between two intersecting geologic structures where the line of intersection points downward (plunges) at an inclination flatter than that of the overlying slope face. These two modes of sliding – plane failure and wedge failure – are described in more detail below. Evaluation of two other modes of bedrock sliding – toppling and rock-slumping – is less common and was not applicable to the subject site.

Plane Failure

As indicated above, plane failure occurs along a single geologic structure, typically along a bedding plane (also referred to as dip-slope failure). For plane failure to occur, the plane must dip downward in roughly the same direction as the overlying slope face, but less steeply. Kinematically, the plane must intersect the slope face to allow movement of the sliding mass. Where the plane is exposed in the slope face, the plane is said to "daylight".

Hoek and Bray (1981) propose that the following conditions must be satisfied in order for sliding to occur on a single plane:

- STRIKE COMPONENT – The plane on which sliding occurs must strike parallel or nearly parallel (within approximately +/- 20 degrees) to the slope face. The strike of a plane (or slope) is the compass bearing of a horizontal line within the plane; the strike is perpendicular to the dip direction.

- DIP COMPONENT – The failure plane must "daylight" in the slope face. This means that the dip of the slope face must be steeper than the apparent dip of the failure plane (apparent dip of the failure plane is the downward tilt along the plane in the direction of the dip of the slope).

- ANGLE of FRICTION – The dip of the failure plane must be greater than the angle of friction of this plane. *For a strictly kinematic analysis, strength (angle of friction) is not considered; angle of friction is assumed to be zero in this analysis.*

- LATERAL RELEASE – Release surfaces which provide negligible resistance to the sliding must be present in the rock mass to define the lateral boundaries of the slide. *Lateral resistance is assumed to be negligible in this analysis.*

As indicated by the strike component criterion, plane failure can not occur where the strike of a structural plane differs from the strike of the slope by more than approximately

20 degrees. Although plane-sliding can not occur, movement of bedrock blocks may be kinematically allowable if an additional structural plane intersects the first at an angle that creates a wedge failure condition.

Wedge Failure

Wedge failure involves sliding along an intersection plunge between two geologic structures, typically a bedding plane and a joint, fault, or shear. For wedge failure to occur the line of intersection must plunge downward toward and "daylight" out of the slope face. The two geologic structures upon which this mode of sliding occurs define the two underside surfaces of a wedge-shaped mass of rock; the slope face defines the upper side of the wedge.

Where a structural intersection line "daylights" out of the slope, it creates an area of potential wedge failure. Geometrically, this can be represented by the following conditions:

- TREND COMPONENT – The trend (compass bearing) of the intersection line must be orientated within 90 degrees of the dip direction of the slope face.

- PLUNGE COMPONENT – The plunge of the intersection line must "daylight" in the slope face. That is, the apparent dip of the slope face (the downward tilt along the trend of the intersection line) must be greater than the plunge of the intersection line.

Angle of friction (which controls release of the wedge) does not, in the case of wedge failure, lend itself to a simply stated criterion. However, as was the case for plane failure, strength (angle of friction) is not considered in strictly kinematic analysis. Accordingly, angle of friction is assumed to be zero in this analysis. In addition, both models do not consider the forces that cause sliding.

TRADITIONAL APPLICATION OF KINEMATIC ANALYSIS

Kinematic slope stability analysis traditionally has been performed using either one of two methods – a graphical method or calculations using trigonometry-based equations.

The graphical method involves the use of a stereonet, which is a two-dimensional representation of a three-dimensional sphere. The three-dimensional orientation of lines (such as structural intersections) and planes (such as bedding planes or planar slope faces) are projected onto the two-dimensional stereonet as points and arcs (portions of “great circles”), respectively. The relative positions of the points and arcs representing the various wedge intersections, bedding planes, and slope faces can be compared visually to identify which slopes have plane or wedge failure conditions.

The trigonometry-based equations are mathematical formulations which describe the geometric relationships between wedge intersections, dip-slope planes, and slope faces. The three-dimensional orientations of these features are represented by variables in the equations, which are defined for the particular features being analyzed. Solving the equations identifies whether a slope has plane or wedge failure conditions.

Either method may be performed by hand or with the use of computer software applications. For both the graphical method and the equations, either by hand or using a computer, each geometric relationship of interest must be analyzed separately. For example, suppose it has been determined that the intersection of planes A and B does not pose a wedge failure threat for a specified slope of interest. To determine if there is wedge failure potential caused by the intersection of plane A with plane C, which is oriented 5 degrees differently from plane B, the analysis must be re-performed. For the graphical method, this would involve plotting another arc, visually identifying the point that represents the intersection line, and comparing that point to the arc that represents the slope face. For the mathematical method, the equations would be re-solved, inputting the revised parameters for the appropriate variables.

To perform a single analysis, by either method, is a relatively quick process, especially using computer software. However, the performance of numerous analyses can be very time-consuming, even with the use of a computer.

As a consequence, traditional application of kinematic analysis typically incorporates simplifying assumptions and techniques to minimize the number of analyses that must be performed. Traditional applications of kinematic analysis divide the study area into independent generalized structural regimes. The various slope and structural orientation parameters – slope strike and dip, bedding strike and dip, etc. – are averaged or otherwise homogenized over a large area (e.g., several hundred feet), although hillslope orientation and geologic structure orientations may change significantly across that area. Also, parameter sensitivity studies (the variation of different parameters to evaluate the effect on the results) are not commonly performed during traditional application of kinematic analysis, and are limited when they are performed.

GIS-BASED KINEMATIC ANALYSIS

For this study, we performed kinematic slope stability analysis within a GIS framework. The kinematic analysis is executed within ESRI's ArcGIS platform using tools from the Spatial Analyst and 3D Analyst Extensions. To utilize the spatial analysis functions of the GIS, the hillslope and geologic model are discretized into appropriately sized cells in this case at 10 foot spacing. To increase model efficiency, all cell parameters are linked into a Microsoft Access Database where model calculations (apparent dip, plane intersections, and geometric relationships) are executed in an automated environment.

Site Characterization

Kinematic analysis is based on the geometrical relationships between geologic structures and the orientation of overlying slopes. Therefore, to perform the analysis, both the topography and the geologic structure must be characterized across the area to be analyzed.

Topography

The initial topographic model is based on a digital elevation model of the study area. Figure 1 is a three-dimensional (3D) perspective view looking south at the study area. The model is created with 10 foot grid cell spacing. Characteristic slope variables including, slope facing direction (aspect) and slope dip (angle), are derived from the 3D topographic model and assigned to the model cells using the 3D Analyst Extension (Figure 2). The slope facing direction or slope bearing is the outward normal or aspect to the slope face and perpendicular to the strike of the slope face.

Geologic Structure

A geologic model is created to characterize the geologic structural conditions. Structural data orientations from field mapping and borehole logging are compiled into a GIS and interpolated to a grid representing the subsurface geology. Commonly, observations of structural orientations need to be converted from Strike-and-Dip notation into Right-Hand-Rule notation for subsequent calculations. Care must be taken also in interpolation of structural domains. The local and regional geologic conditions must be addressed. For example, if a terrain consists of rotated fault-bounded blocks, orientations for each block should be interpolated independently.

To characterize the geologic structure orientations from bedding, joint, fault, and shear planes are incorporated into the GIS. In the example presented, approximately 1500 attitudes from surface mapping and borehole logging were compiled into the geologic model/database.

Characterization of bedding was based on approximately 900 bedding observations. Figure 3 shows the variation of bedding within the study area on a lower-hemisphere stereonet, with each orientation represented by the plot of its pole (a line normal to the plane). Bedding orientations observed within slide debris were excluded from the model. The characterization of bedding calculates bedding strike and bedding dip for every model cell.

Joints, faults, and shears (including clay bed shears and slip planes) are geologic structures that may intersect bedding and allow wedge sliding movement. The analysis used approximately 500 joint orientations and over 200 fault and shear orientations to assess the dominant orientations of these structures. Figure 4 presents two lower-hemisphere stereonets with the orientation of each joint, fault, or shear represented by a plot of its pole (a line normal to the plane). Average planes for the prominent bedrock discontinuities derived from these stereonets are (as Strike-and-Dip): N40W, 68NE; N11W, Vertical; N24E, 70SE; and N-S, 65E. Preliminary evaluation indicated that stability was more sensitive to bedding orientation than to the orientation of these other discontinuities. Therefore, for this example, these other discontinuities are represented by their dominant structures, which are assumed to be ubiquitous in the subsurface geology. If it was so desired, however, these discontinuities could be characterized contiguously and variably across the site within the model, as was done for bedding. Individual structures (i.e., a mapped fault) can also be isolated and evaluated based on its spatial extents.

Application of Kinematic Analysis

The aforementioned characterization of hillslope orientation and geologic structures calculates four parameters for every model cell: Slope Aspect, Slope Dip, Bedding Strike, and Bedding Dip. The parameters are linked to a Microsoft Access Database to facilitate calculations of plane intersection, apparent dip, plane failure, and wedge failure.

Geologic structure intersection lines – identified by the parameters Trend and Plunge – are calculated between bedding and the dominant structures. In this example, we calculate an intersection between each of the dominant structures and bedding for every model cell. Since every cell has a unique bedding orientation, it follows that every cell will have a unique intersection line for each of the dominant structures. Intersections between structures for each cell are calculated with an intersection algorithm implemented within Microsoft Access' development environment. In this example, the four dominant structures produce four intersections, each with a trend and plunge: Structure 1 - Bedding Intersection Trend, Structure 1 - Bedding Intersection Plunge; Structure 2 - Bedding Intersection Trend, Structure 2 - Bedding Intersection Plunge; Structure 3 - Bedding Intersection Trend, Structure 3 - Bedding Intersection Plunge; and Structure 4 - Bedding Intersection Trend, Structure 4 - Bedding Intersection Plunge.

The complete characterization produces a database with 12 parameters for every cell (Slope Aspect, Slope Dip, Bedding Strike, Bedding Dip, and the eight parameters listed above).

<u>Plane Failure</u>

For plane failure to occur, a cell must have both a *strike component* and a *dip component* that are consistent with the definitions provided in a previous section of this paper. To analyze the *strike component* of plane failure, we compare the strike of the slope to the strike of the bedding. If the strikes are within 20 degrees of each other, then the cell is identified as *strike critical*. To analyze the *dip component*, we compare the slope dip to the apparent dip of the bedding. If the apparent dip is less than the slope dip, the cell is identified as *dip critical*. Where a cell is both *strike critical* and *dip critical*, it is an area of potential plane failure, and the cell is marked appropriately in the database. Iteration of these two calculations on every cell in the model produces the spatial distribution of potential plane failure across the model (Figure 5, red areas).

Wedge Failure

To calculate the potential wedge failures, we check to see if the derived intersection between bedding and dominant structures "daylights" out of the slope. If the intersection bearing is within 90 degrees of the slope facing direction, the cell is *bearing critical* (out of slope). To compare the slope dip to the intersection plunge, we must use the apparent dip of the slope in the direction (bearing) of the intersection. Where the intersection plunge is less than the slope's apparent dip, the cell is *plunge critical*. Where a cell is both *bearing critical* and *plunge critical*, it is an area of potential wedge failure, and the cell is marked appropriately in the database. Calculation of the wedge failure parameters on a cell by cell basis produces a spatial distribution of potential wedge failure for a given structure. By iterating this approach with all of the dominant structures, we can define the total potential wedge failure area (Figure 5, blue areas).

Results of Analysis

Figure 5 is a 3D perspective of the kinematic analysis results for both plane and wedge failure based on the current topography. Colored areas are defined by the model as area of potential plane (red) and wedge (blue) failure.

The results of the kinematic analysis identified areas of potential slope instability within the current topography. Interpreting these results within the context of the historic record of landslides can resolve the mechanisms causing slope failures. Such interpretation also can be used to help guide and develop plans for future slope-grading.

Inputting a digital elevation model of a proposed grading plan into the GIS and iterating the kinematic analysis detailed above will evaluate the kinematic stability of the proposed plan. This iteration assumes that the subsurface geologic model is applicable to the proposed grading plan. Figure 6 is a 3D perspective of the kinematic analysis results for both plane and wedge failure for a grading plan that has been proposed for the study site. As for the previous topographic model analyzed, colored areas are defined by the model as area of potential plane (red) and wedge (blue) failure.

ADVANTAGES OF GIS-BASED KINEMATIC ANALYSIS

Comparison of the GIS-based method of kinematic analysis to the traditional application of kinematic analysis reveals several advantages the GIS-based method has over the traditional application.

Accuracy of Results

In traditional applications of kinematic analysis, the various slope and structural orientation parameters – slope strike and dip, bedding strike and dip, etc. – are averaged or otherwise homogenized over a large area, although hillslope orientation and geologic structure orientations may change significantly across that area. The analysis results, which are considered to apply to the entire region of interest, are based on single averaged values for slope strike and dip and bedding strike and dip. The GIS-based method, however, uses location-specific data a much more local scale (in this example, 10 feet, compared to several hundred feet for traditional application). Consequently, results for each incremental area across a region more accurately reflect the variability of the factors affecting slope stability.

Consider the 3D perspective of the kinematic analysis results for the proposed grading plan presented in Figure 6. Just to the left of the middle of the figure, the results for the proposed excavation slope indicate that there is wedge failure potential and some plane failure potential near the bottom of the slope and to the side, while the remainder is generally free from these hazards. A traditional application of kinematic analysis would not have provided this information. In that case, averaged values would have been used for input parameters, and only one condition would have been deduced to exist across this entire slope. Traditional application may have indicated that there is no failure potential for this slope (the entire slope). Such a conclusion would be unconservatively inaccurate, which could lead to dangerous conditions during subsequent site uses. Alternatively, traditional application with more conservative selection of input parameters may have indicated that there is wedge failure potential for this slope (the entire slope). Such a conclusion would be overly conservatively inaccurate, which could lead to large expenditures (to stabilize areas that are already stable) or to abandonment of the project altogether. Note that this excavation slope has constant orientation (strike and dip) across the entire slope; the differing results across the slope (shown in Figure 6) are caused solely by the fluctuation in bedding orientation.

By leveraging the spatial analysis power within a GIS, a site no longer has to be generalized, but can be analyzed at a scale reflecting the actual density of structural data. In essence, the GIS will analyze the kinematic stability for thousands of miniature slopes that form the larger hillslope. Thus, application of GIS-based kinematic analysis is superior to traditional kinematic analysis in that it produces a more detailed evaluation and eliminates the generalization of the hillslope and structure into a few key sections. Its usefulness increases with the increase in bends and turns of the hillslope.

Regardless of the analytical power of the GIS, the development of a representative geologic model based on adequate field mapping is critical. Care must be taken when interpolating field observations across structural domains. Sufficient data must be collected to create a reliable model of areal distribution of geologic parameters. GIS-based kinematic analysis requires explicit consideration and analysis of the data in order to prepare input for the analysis. The professional judgment that would be applied to input data for traditional analysis can be (and was) applied to the data used in the GIS-based analysis.

Efficiency of Analysis

As discussed previously, it is a relatively quick process to perform a single kinematic analysis (for a single set of input parameters). However, the performance of numerous analyses can be very time-consuming, even with the use of a computer. Consequently, it is time-consuming to analyze multiple regions, or to consider multiple geologic structures within a region, or to perform parameter sensitivity studies.

The GIS-based analysis takes more time to set up than a single traditional kinematic analysis. However, once the model is prepared, numerous analyses across the entire study area are performed simultaneously. Subsequent analyses are also performed quickly. Consequently, updates or modifications to the geologic data set can be analyzed much more quickly than for traditional analysis. Multiple or iterative versions of grading plans (or other topographic models) can be analyzed easily and rapidly; to attempt to do so using traditional analysis would be very time-consuming. Also, parameter sensitivity studies may be performed easily using the GIS-based model by importing modified data sets.

Communication of Findings

Kinematic slope stability analysis traditionally has been performed using either one of two methods – a graphical method or calculations using trigonometry-based equations. Use of the trigonometry-based equations provides numerical output indicating whether there is failure potential, or in the case of some computer software may also provide a graphic representation of a bedrock wedge. Each analysis provides one such output. When using the graphical method, slope-failure potential is discerned by visually comparing the relative positions of points and arcs on a stereonet, such as those shown in Figure 4. Although streonets are used commonly among geologists, information presented on stereonets is not generally understood by others and requires a great deal of explanation. Multiple analyses may be shown on one stereonet, but this tends to clutter the presentation and require more explanation.

Results of the GIS-based kinematic analysis are presented on a map and/or rendering of the study site. These results can be intuitively understood or easily explained to virtually any audience. In this format, the results for every portion of the site are presented simultaneously on one figure, as opposed to multiple figures or data sets to represent each region. The GIS-based presentation allows for quick understanding of how conditions vary across the site. Side-by-side comparisons of grading plans or sensitivity studies are easy to perform and understand with the GIS-based presentation.

Results of the GIS-based kinematic analysis are more transferable than those from traditional applications. The GIS-based kinematic analysis results can be incorporated into other GIS applications to be used by others. The GIS-based results can be transferred directly into the CAD environment. The results may overlay or be overlain by other graphical or non-graphical information in the form of printed maps.

CONCLUSIONS

This study has demonstrated the feasibility and usefulness of performing kinematic slope stability analysis within the GIS environment. The GIS-based analysis is a rigorous method that incorporates the same scientific approach to kinematic analysis as used in traditional applications. The GIS-based analysis provides greater output than does the traditional application using the same geologic data. The results of the GIS-based analysis are broadly applicable and useful to end-users, without increased effort on the part of site investigators, project owners, or regulators.

GIS-based kinematic slope stability analysis represents a clear advancement in engineering practice as applied to the study of slope stability. GIS-based kinematic analysis is superior to traditional application of kinematic analysis in three key ways:

- Greater accuracy of results
- Increased efficiency of analysis
- Better communication of findings

The GIS-based kinematic slope stability model prepared for this project can be used to guide site development by identifying areas of existing potential hazard and analyzing proposed grading plans within the local structural geologic framework.

While this analysis only looks at the geometric relationship between hillslope and geologic structures, the hillslope and geologic models developed within can be used in conjunction with more sophisticated slope stability models to integrate material strengths, hydrostatic pressures, seepage forces, active forces, passive forces, and other properties.

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