Assessment of Seismic Slope Stability Using GIS Modeling

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Abstract

In recent years there has been a growing interest in developing GIS based models for mapping and identification of seismically-induced landslide hazards. A review of assumptions in the relationships and the data typically used in GIS seismic slope stability models, shows that there are three components which are commonly used together: pseudo-static slope stability analysis, attenuation of ground shaking models, and Newmark's displacement method (Newmark 1965). These relationships are typically combined in a raster or vector data model to produce a map of seismically-induced landslide displacements. To produce a map of ground displacement, a digital coverage of the geology and a high resolution DEM are needed at the very least. Additional data layers such as shear strength parameters and soil depth can be estimated from the geology and they can add to the sophistication and accuracy of the model. A case study was developed which combines the components of site and slope response in a vector data model and the results show that qualitatively acceptable results can be readily obtained. However, the model falls short of capturing the overall performance of any particular slope and at best it only provides a mean estimate of the potential seismically induced slope displacement. Thus, more sophisticated methods of slope and site response will have to be implemented in this platform to increase the robustness of the model. In particular, the resolution and quality of input data sets will have to be improved and rigorous probabilistic procedures will have to be implemented, so that the error bounds and the magnitude and the source of errors can be fully quantified.

I.INTRODUCTION

Landslides are a common phenomenon associated with most earthquakes. Earthquakes as small as magnitude 4.0 may trigger landslides in susceptible slopes and very large earthquakes can generate tens of thousands of landslides affecting areas as great as 500,000 km^2 (Keefer 1999). For example, thousands of landslides of various types occurred in the mountains of Central Taiwan during the most recent devastating earthquake of Sept. 21, 1999, and caused substantial widespread damage and loss of life (http:/ /www.eerc.berkeley.edu/taiwan/geotech/). In the 1964 Alaska earthquake earthquake-induced landslides caused about 56% of the total cost of damage (Youd 1978; Wilson and Keefer 1985). Although landslides are generated by many processes, including precipitation, snowmelt, frost action, erosion, changes in the ground-water surface, and human-activities (Terzaghi 1950), in some seismically active regions earthquake shaking may dominate (Simonet 1967; Adams 1980; Pain and Bowler 1973; Keefer 1994; Wieczorek and Jager 1996). Given the importance of earthquake-induced landslides in their contribution to natural hazards in seismically active regions, there is a need to quantitatively assess their potential hazard on a regional scale.

The advent of geographic information systems (GIS) has provided a tool for effectively managing data interpretation and analysis required for regional seismic slope stability modeling. The development of techniques for using GIS for regional seismic slope stability analyses offers tremendous advantages over the traditional techniques data management and modeling techniques because of the large amount of data and the complexity of the analyses. More importantly, once a GIS based approach is adopted, the hazard analysis can be extended to multiple scenarios, the input variables can be updated and adjusted, and the model can be automated in a expert systems methodology so that it can be used on a routine basis without direct expert input.

Currently, there are several approaches for using GIS in mapping of seismically induced landslide hazards. Most approaches use a deterministic model to compute the ground displacements for a given scenario of input soil-strength parameters, design earthquakes, and faults to rupture. The GIS platform allows the user to modify and update input parameters to obtain a deterministic assessment of seismic landslide susceptibility based on subjective input, as appropriate. Another approach is to use a probabilistic model in which all the variables, including the earthquake characteristics: magnitude, distance, acceleration, and duration and the material characteristics, such as strength parameters and pore pressures, are treated as random variables. In addition the models, whether they are deterministic or probabilistic, differ in their

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equations of slope and site response and their raster or vector based data integration methodologies. The purpose of this paper is to provide a brief overview of the different approaches and to review the data needs, including data quality as they relate to our ability to successfully apply these models in a predictive fashion. A case study of a seismic slope stability model in the Southern San Francisco bay area is used to illustrate these issues.

II. SEISMIC SLOPE STABILITY MODELS

In analyzing seismic slope stability there are three components, which need to be evaluated: the level of shaking at the site, the stability of the slope under pseudo-static loading equivalent to the earthquake loading, and the magnitude of deformation along the potential slip surface during shaking. The level of shaking is obtained from attenuation relationships, the pseudo-static slope stability is evaluated using traditional slope stability models, and the magnitude of displacement is determined using Newmark's displacement method (Newmark 1965). The union of pseudo-static slope stability analysis, a ground shaking attenuations model and Newmark 's displacement method in a GIS framework is the approach employed by several deterministic models for earthquake-induced landsliding assessment. These approaches are based on the Wieczorek et al. (1985) model for evaluation of seismically induced landslide hazards, which uses the infinite slope model for both static and seismic slope stability calculations and a simplified Newmark's method to provide estimates of permanent displacements/deformations.

Pseudo-Static Slope Stability Analysis

The pseudo-static slope stability analysis is based on the evaluation of the limit equilibrium in which the inertial effects of the earthquake are represented as horizontal and vertical forces. These are the so-called pseudo-static forces, which are assumed to be proportional to the weight of the slope multiplied by a seismic coefficient in the horizontal and vertical direction. The result of the pseudo-static analysis is a factor of safety against failure, which is 1.0 or greater for stable slopes. Earthquake-induced sliding occurs when the pseudo-static forces within the slide mass cause the factor of safety to temporarily drop below 1. 0. The value of the peak ground acceleration within the slide mass required to cause the factor of safety to drop to 1.0 is denoted as the critical or yield acceleration, a_c.

While the pseudo-static analysis is commonly used because of the relative ease with which this analysis can be preformed, it has some serious limitations. The overall slope performance is not captured by the pseudo-static analysis. A slope may remain intact in an earthquake, but in the analysis any exceedance of the critical acceleration, no matter how brief, will assume that this slope has failed. Another limitation inherent to the pseudo-static analysis is the difficulty associated with obtaining appropriate seismic coefficients (Sharma 1996). Most GIS models use the limit-equilibrium infinite slope analysis, which is the simplest pseudo-static slope stability analysis, mainly because it does not require an external computer code and because the geometry of the slope is simplified by the assumption of a constant depth of soil. Even though these analyses make a crude assumption and represent the transient and complex effects of earthquake shaking by a single constant unidirectional pseudo-static acceleration, they are used because they at least provide an index of relative, if not absolute, stability.

Ground Motion Attenuation Model

The natural attenuation of ground shaking with distance from the source is represented by attenuation relationships, which are specific to the type of faulting. These relationships define ground shaking for rock conditions based on earthquake magnitude, distance away from the fault rupture, site conditions and other parameters. The attenuation relationships are used to estimate the peak ground acceleration (PGA). There are several attenuation relationships listed below, which are specific to the types of earthquakes (shallow crustal earthquakes, deep and subduction zone earthquakes) and associated fault movement for the Western and Eastern United States.

Since the attenuation relationships are derived from a suite of strong motion generally recorded between 5 and 100 km, they tend to overestimate the ground acceleration at distances very close to the fault. An alternative to using empirical attenuation relationships is to estimate the average motion through the soil using an external program such as SHAKE (Schnabel et al. 1972; Idriss and Sun 1992) that can approximate the soil response at a site given a representative input accelerogram. The selection of a representative input rock motion may be difficult and the shear wave velocity profile at the site has to be known or inferable.

Newmark's Displacement Method

The seismically induced deformations are calculated using the approach originally developed by Newmark (1965). Using a sliding block analogy, Newmark was able to model the cumulative displacement of a slope as a result of dynamic earthquake loading. Newmark's analysis assumes that the slope is rigid and perfectly elastic, a well-defined planar slip surface exists, there is negligible loss of shear strength during shearing and that displacements only occur if dynamic stresses exceed shear resistance. Since Newmark's method depends on critical acceleration, it will tend to overestimate landslide displacements in viscoplastic materials such as some fine-grained, highly plastic soils, that have a very low critical acceleration. These soils can significantly dampen the seismic response and they tend to experience negligible inertial displacements even at very large earthquakes (Jibson et al. 1991). Overall, however, Newmark's method has been applied successfully to predict movement of slope and permanent ground deformation on a regional basis on a GIS platform (Carlton et al. 1997; and Jibson 1995).

Newmark's method can be implemented in a GIS in two ways. The first approach uses an algorithm which calculates cumulative displacement for each slope by double integrating the area under the accelerogram that exceeds the critical acceleration. This requires an external program and the selection of a representative input motion. Another alternative is to use a simplified approach to Newmark's method that uses a closed form solution for displacement, which is obtained by performing regression on displacements computed from as suite of actual ground motions. The latter empirical approach is easier to implement in GIS and it eliminates the necessity to select a single representative ground motion. However, there are additional limitations: the displacement at a particular site may not be captured by the mean displacement curves and in most cases the analyses do not account for local site response.

III. DATA DEMANDS

Regional seismically-induced landslide hazard models require a database, which includes at the very least geologic and topographic information. Other data layers, which add to the sophistication of the model, include soils, hydrology, surficial geology, existing landslide inventory maps, rainfall intensity maps, and vegetation, among others. Otherwise, the model is self-sufficient after the pseudo-static stability analysis. To compute the Factor of Safety in the pseudo-static stability analysis, information is needed about the slope, soil shear strength parameters (friction angle and cohesion), soil depth, as well as water saturation/ pore pressures. If the rigorous Newmark analysis is used, ground motion and other information have to be integrated into the model at a later stage.

Surface and Slope Models

Digital Elevation Models (DEMs) at the largest scale of 7.5 minute quadrangles with a grid spacing of 30 meters are commonly used to characterize the slopes. For some areas high-resolution 10 meter DEMs can also be found. In our study we have developed a more accurate surface model by correlating 1:24,000 DEMs with 1:24,000 hypsography DLGs, and then refining the resulting model with 1:24,000 hydrography DLGs to account for surface variations along stream banks (http://www2.ced.berkeley.edu:8002/).

Shear Strength Parameters

Soil strength parameters such as cohesion and friction angle are material properties that are typically not included on geologic maps or soil maps. Thus, this information, which is a very crucial ingredient to the analysis, often has to be inferred from available databases of soils and geology. A good rule of thumb is, the better the resolution of these maps, the better the inference that can be made on soil strength parameters. The landsliding mechanism should also be considered when choosing these databases. For example, a bedrock geology map is more appropriate to use for deep-seated landslides, whereas hillside material maps or surficial geology maps tend to be better suited for shallow landslides. Geologic maps describing the units based on composition and properties of bedrock, texture of the surficial material (soil cover) and detailed description of material types, bedding thickness and fracture spacing allow the expert to assign strength parameter values to these units. Likewise, soil databases conveying information about the units based on a USCS (Universal Soil Classification System), swelling potential, liquid limit, and particle size among others allows for an intelligent assignment of strength parameters. If at all possible, assigned values should be verified against tested samples from engineering projects in the area. Unfortunately, soil strength test data is usually proprietary information and difficult to obtain and even when it is available it is highly localized and not easily generalized. Thus, in this context, it is important not to overestimate the predictive capabilities of a GIS model by combining data layers which are not consistent in their level of detail. The goal in assigning strength parameters to geologic units is to aim for a conservative estimate of cohesion value and friction angle, but also integrate as much information as possible to obtain a level of accuracy consistent with other layers.

Soil Depth

Most GIS based slope stability models assume a constant soil depth. However, the soil depth typically varies as a function of slope angle, as a function of the local climatic conditions, and as a function of the weathering characteristics of the source bedrock. The choice of the characteristic value of the depth of surficial material has a strong influence on the calculated factor of safety, i.e. changing the soil depth by 1 foot can change the critical acceleration by an order of magnitude. As with the strength parameters, soil depth is often a difficult parameter to ascertain, since is not routinely recorded in geologic mapping on regional scale.

Pore Pressures/Water Table Elevation

Most regional studies of slope stability tend to consider the most extreme situations, i.e. totally dry and totally saturated. For totally saturated conditions it is assumed that the water table is at the surface. However, this is an extreme condition that may occur very rarely even in highly landslide susceptible slopes. Thus, good understanding of the typical sliding mechanisms and typical saturation conditions which lead to slope failures in the different geologic units is essential to this step of the analysis. Rainfall intensity maps can also be utilized to determine the amount potential for saturation to occur based on the precipitation magnitude and intensity.

IV. DATA MODELS

Raster Data Model

The most compelling reason for using raster based data is that digital elevation models (DEMs) are stored as grids and their vertical integration into other layers is trivial in a raster-based analysis, but requires manipulation in a vector-based model. However, since most of the other data layers such as geology, soils, hydrology and others used in an earthquake-induced landslide model are vector-based, the raster-based data model may not adequately represent these units and may reduce the spatial accuracy of the polygon and line boundaries. On the other hand, the raster data model has an inherent advantage when the information of interest is spatial variability. For example, Jibson et al. (1998) estimate probability of failure by comparing the digital inventory of landslides triggered by the Northridge earthquake against the modeled displacements from their model. Even though a vector-based analysis allows for these type of comparisons as well, a raster representation is generally better suited.

Vector Data Model

The vector approach permits a better representation of morphology and provides a convenient means for storing attribute data. All of the essential elements required in the database for a landslide hazard analysis with the exception of DEMs are vector-based datasets. To allow overlay analysis for DEMs with other vector-based data a conversion to TIN (Triangulated Irregular Network, Peucker et al. 1980) has to be performed. The advantage of TIN compared with a gridded representation is that the TIN can use fewer points, capture the critical points that define discontinuities like ridge crests, and can be topologically encoded so that adjacency analyses are more easily done (Arnoff 1989). Within a vector-based data model further refinements to the surface model can be achieved by accurately defining locations of abrupt surface change. Elevation data from very detailed regular grid 10-meter DEMs can be combined with 1:24,000-scale digital line graphs (DLG's) of hypsography to interpolate a new surface. This surface can then be further densified by using break lines to define sharp breaks in the terrain such as the top and toe of slopes, stream banks, ridges, road cuts, and other locations of abrupt surface change.

V. CASE STUDY

The San Francisco Bay Area was used as a study region to implement an earthquake-induced landslide hazard model. Available digital data sets for this region include (1) detailed (1:24,000) DLG's of hydrography and hypsography as well as high-resolution (10 meter grid) DEMs of the topography, (2) 1:24,000-scale soil map and 1:125,000 digital coverage of hillside materials for the San Francisco Bay Region, (3) 1:275, 000 scale detailed USGS maps of landslide inventory and summary of distribution of slides and earth flows in the San Francisco Bay Region. A program written to automate the analyses, combines these datasets in a dynamic model based on pseudo-static analysis and Newmark's displacement model. The program allows for user interaction to update the input datasets and modify the input parameters as well as the flexibility to change models of slope and site response. The program generates landslide displacement maps for specific input scenarios and allows the user to obtain an assessment of seismic landslide susceptibility based on subjective input as appropriate.

Figure 1 is a flowchart showing the sequential steps involved in the hazard-mapping procedure. The sequence consists of:

a) *Create a Surface Model:* Construct a slope map by combining 10 meter DEM's with 1:24,000-scale Hypsography DLGs. Further refinement of the surface model is obtained by accounting for surface

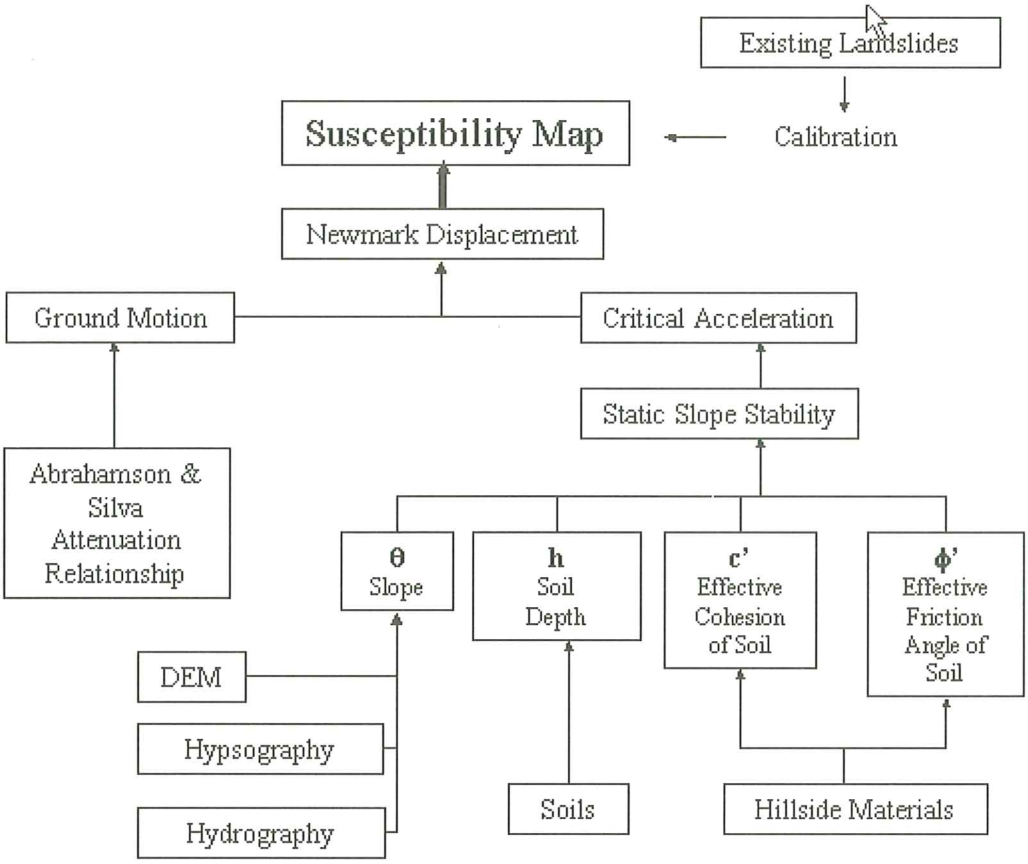

Figure 1. Flowchart of Hazard Mapping Procedure.

variations along streams, roads, landslide scarps and ridges by using a break-line algorithm within Arc/Info to interpolate a surface.
b) *Compute Static Factor of Safety*: Combine slope-data, shear-strength parameters and a model for soil depth variations in an infinite slope stability analysis to estimate static factors of safety.
c) *Compute the Yield Acceleration*: A yield acceleration is calculated by combining the slope coverage with the coverage obtained for static factor of safety and setting the Factor of Safety equal to unity:
d) *Estimate Ground Motions*: Calculate PGA for the centroid of each slope polygon using an attenuation relationship for a design earthquake and distance away from fault rupture.
e) *Compute Newmark Displacements*: Combine the coverage containing yield acceleration and the coverage for peak ground acceleration in a regression relationship to estimate Newmark displacements.
f) *Calibration*: Use the landslide inventory maps as a training set for the model as they are cross validated by comparing them with predicted landslides. When the database falls short of providing sufficient support for the predictions, the model allows the introduction of the expert knowledge to modify the GIS-based multi-layer spatial data attributes. The additional information should improve the prediction results.

An Arc Macro Language (AML) program was written to generate all intermediate coverages and to create a landslide susceptibility map for user specified input values. This takes full advantage of functionality and ability of GIS to manipulate spatial data. The dynamic maps which are created can be modified and regenerated using different sets of input parameters for any site which exists in the southern San Francisco Bay Area for which there is currently a hillside material map available in Arc/Info format by the USGS (Ellen and Wentworth 1995). The USGS has plans of producing hillside materials maps for the entire bay area in digital format in the near future. Once the base coverages are imported into a directory, the user must specify an earthquake moment magnitude for which a landslide susceptibility map is being generated. As an alternative, the user can input a starting and ending moment magnitude and an interval so that a range of simulations can be done for the site. Then the user can enter up to five faults on which the earthquake may rupture. The user has the option to enter four UTM coordinates site within the Southern San Francisco Bay Area for which

Figure 2. Magnitude5, dry conditions

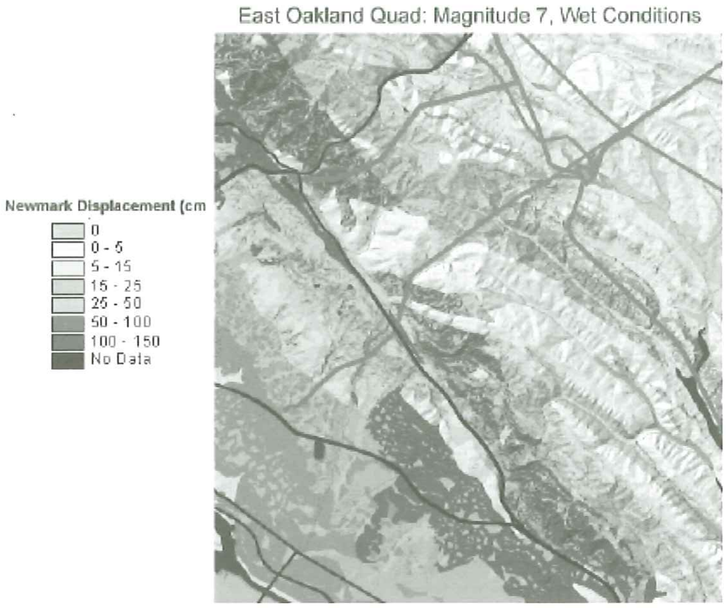

Figure 3. Magnitude7, wet conditions

landslide susceptibility model is being generated. Default strength parameters can be accepted or new parameters can be specified by the user. Since the strength parameters are a crucial factor in the output susceptibility map and the default values are not based on laboratory tests, these values should be replaced whenever actual site data is available. Once all the input parameters are specified, the user can execute the program and generate a landslide susceptibility map for the area of interest. The output consists of Newmark displacement for wet and dry conditions for each earthquake and seismic source. A cumulative displacement value, which is the sum of all events is also calculated.

In order to produce the example results shown in Figures 2 nad 3, various earthquakes were simulated on the Hayward fault to assess the seismic landslide potential of a prototype site in the North Berkeley Hills of the Oakland East 7.5 minute quadrangle. The analysis was then extended to the entire Oakland East Quadrangle for which a susceptibility analysis was performed for a magnitude 5 and 7 earthquakes on the Hayward fault for both wet and dry conditions. Newmark displacements ranged from 0 to 140 centimeters and the results showed that no movement would be predicted for either dry or wet conditions anywhere in the prototype site for earthquakes with a moment magnitude of less than 4.6.

V. MODEL LIMITATIONS

While predicting Newmark displacements for hypothetical earthquakes of specified magnitude and location it is important to consider the following limitations:

Shear strength parameters: Shear strength typically has large spatial variability in nature even within geologic units, and assigning representative shear strengths to entire units is fraught with uncertainty. In the current model we assigned peak shear strengths in order to render the model statically stable. As can be seen from the generated susceptibility maps, the relative strengths between units have strong control on the predicted displacements. For example, for intact rock units with high cohesion values, zero displacement was predicted regardless of the magnitude of the earthquake. Conversely, for clayey soil with zero cohesion value and low friction angles very high displacements were obtained. Calibration against the existing inventory of landslides should allow us to constrain the relative strengths of the different geologic units. More importantly, a more rational approach is to develop a probabilistic model for regional slope stability so that shear strength can be treated as a random variable and the uncertainty associated with it can be implicitly expressed. For deterministic case scenarios, however, the user should strive to use the most accurate parameters appropriate for the study area.

Slope model: The modeling procedure is heavily slope-driven and the effects of slope angle on the model output far outweigh the effect of modest differences in material strength. Thus the inital focus in our model was therefore to render an accurate surface model rather than obtaining highly accurate

Figure 4. Surface model

characterizations of strength. Elevation data from very detailed regular grid 10-meter DEM's were combined with 1:24,000-scale DLG's of hypsography to interpolate a new surface. This surface (Figure 4) was further densified by using break lines to define sharp breaks in the terrain such as the top and toe of slopes, stream banks, ridges, road cuts, and other locations of abrupt surface change. A significant improvement to the model output is achieved by accurately defining the locations of abrupt surface changes.

Ground motion: The regression relationships for the peak ground acceleration was based on ground motions generally recorded at distances greater than 5 km from the hypocenter. Since the prototype site is located less than 3 km from the Hayward Fault, the regression analysis will not predict representative PGAs. Extremely high PGAs were obtained for sites immediately on the fault and unreasonable values were predicted for sites less than 1 kilometer away from the fault. For this reason all sites that were within 1 kilometer of the fault were given a distance value of 1 kilometer.

Saturation conditions: Since pore water pressures cannot be adequately accounted for in displacement calculations, the model made a total dry and total saturated conditions assumption. For totally saturated conditions it was assumed that the water table was at the surface. This will happen only occasionally during extreme precipitation events and thus displacements predicted for wet conditions are very conservative

VI. CONCLUSION

GIS modeling provides a very convenient platform for the evaluation of seismically induced landslide hazard. The advantage of this approach is that regional geological, geomorphological, and elevation data can be readily combined within the GIS model and then can be analyzed using a pseudo-static seismic slope stability analysis, a ground shaking attenuation model and Newmark's displacement method. Example application of this approach to East Oakland Quadrangle in California shows that qualitatively acceptable results can be readily obtained. However, while the pseudo-static slope stability analysis can be easily integrated into a GIS, it falls short of capturing the overall performance of any particular slope. In addition, ground-shaking attenuation models have to be selected very carefully, since they are specific to the type of earthquake and associated fault movement. Finally, the simplified approach to Newmark's displacement method, while also easy to implement, provides at best only the mean estimate of the potential ground displacement in failing slopes and site specific response is not accounted for. Thus, more sophisticated methods of slope and site response will have to be implemented in this platform to increase the robustness of the model. In particular, the resolution and quality of input data sets will have to be improved and rigorous probabilistic procedures will have to be implemented, so that the error bounds and the magnitude and the source of errors can be fully quantified.

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