Landslide Hazard Mapping of Earthquake Prone Transportation Areas-

Case study: Oat Mountain Area along Route 5 in the State of California

Lauren Lobo

University Transportation Research Center

And

Research Experience for Undergraduates, Disaster Research Center

University of Delaware

August 7, 2009

Abstract

The potential hazard caused by earthquake-triggered landslides is a great threat to the infrastructure of certain areas. These disasters cause million of dollars in damage each year and on average caused somewhere between twenty-five to fifty deaths each year according to USGS. In order to help prevent this from happening, or to help ensure that these areas are better protected, a type of landslide hazard mapping system needs to be developed. This project is designed to evaluate different areas to try and to determine the associated landslide displacement that given earthquake events would cause. By using a combination of GIS and displacement–based dynamic analysis, these areas can be located, assessed, and represented using a series of maps. These maps will depict the different potential threat levels and ultimately show potential earthquake-induced displacements that would occur in the Oat Mountain area along route 5 in California for a single earthquake event. The process will then hopefully be applied to a larger area, and then used to eventually encompass the most of the west coast. This framework can then be later extrapolated to look at the risk posed by different earthquakes over a larger region using a probabilistic approach to hazard analysis.

Introduction

The United States is made of a variety of unique geographic and sociologic conditions that create a challenge of safety in each community. Keefer (1984) observed that earthquakes could cause landslides over an area as large as 500,000-sq km. In earthquake-prone areas, e.g. the west coast of the United States, earthquake triggered

2

landslides are an important threat to the transportation and economic systems. "Landslides are one of the most damaging collateral hazards associated with earthquakes" (Jibson 1998). In some cases, landslide-induced damage can exceed that done by the actual earthquake itself. Earthquake-triggered landslides cause not only millions of dollars in damage, but also cause twenty-five to fifty deaths each year, depending on the magnitude of the earthquake and the stability of slopes in the earthquake-affected areas. Calculating the slope stability can be done by a variety of ways, ranging from rather simple to complex methods. In order to identify the areas that are at the highest risk, a mapping system needs to be used. By using a GIS based approach for mapping tools, it is possible to evaluate, on a more comprehensive level, how safe different areas are in relation to earthquake-triggered landslides. The main goal is to understand the risk caused by earthquake-triggered landslides to infrastructure systems on the west coast of the U.S., and to determine the areas that are the most hazardous.

Modeling Methods: Newmark Method

There are critical components of seismic displacement analysis that must be evaluated. "The critical components of seismic displacement analysis are: (1) earthquake ground motion, (2) dynamic resistance of the structure, (3) dynamic response of the potential sliding mass." (Bray 2007). Of these components, the earthquake-induced ground motion is the most important because it has the strongest effect on the resulting seismic displacement. Earthquake-triggered displacement is also directly related to the static slope-stability of a given slope, for which there is a great range in available techniques for determining the slope-stability of a specific area. The simplest and most commonly

used method for calculating earthquake-induced earthquake deformations is Newmark's Method (Newmark, 1965). Newmark's Method is commonly used in mapping due to its simplicity, which allows the method to be used over a broader area. Initially, the targeted area will be the quadrangle of Oat Mountain California along Route 5. This area has been examined by Jibson (1998) using a different earthquake analysis technique, and will provide a base to compare the calculated results. This step will be performed to ensure accuracy before expanding the project to a broader scale. Figure 1 is a diagram that depicts the sliding block model idealized by Newmark's Method.
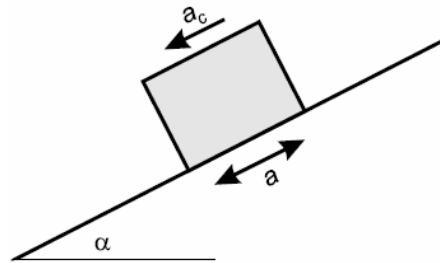

Figure 1. Sliding block model idealized by Newmark (Jibson 1998)

There are different methods that can be used instead of Newmark's Method, but for this approach they are more complex than needed.

Newmark's method makes an analogy between a potential landslide failure mass and a rigid block rested on an inclined base and then "calculates the cumulative permanent displacement of the block relative to its base as it is subjected to the effects of an earthquake acceleration-time history." (Jibson 1998) In an earthquake acceleration-time history, the area of the graph above the yield acceleration line is where the displacement of the rigid body occurs; the greater the area, the greater the overall displacement of the

4

rigid body. Newmark's Method then calculates the yield acceleration using the following

formula: $$a_c = (FS-1)g \ \sin\alpha$$ (Jibson 1998)

The a_c is the yield acceleration, or the critical acceleration. FS is the factor of safety against static slope stability failure, and g is the acceleration of the Earth's gravity. α is the angle from the horizontal, or the slope angle. The yield acceleration is the final point of acceleration before the body begins to move; at applied earthquake accelerations beneath the yield acceleration there is no movement. Based on Newmark's assumptions, the potential failure mass behaves in a rigid-perfectly plastic manner, meaning that the body does not have any displacement until passing the yield acceleration. The body moves as one entity and is rigid. Once the body begins to move, the nature of the yielding is perfectly plastic in behavior. In addition to this formula, there are other variables that must be taken into account. Based on the calculated Newmark displacements using available earthquake acceleration time series, a number of regression equations have been developed. Based on Jibson's model (1998), the resulting Newmark displacements were regressed on the two-predictor variables: critical acceleration and Arias intensity. The resulting regression equation is:

$$\log D_n = 1.521 \log I_a - 1.993 \log a_c - 1.546,$$ (Jibson 1998)

The D_n is the displacement, the I_a is the Arias Intensity, and a_c is the critical acceleration or yield acceleration. By using this equation we are able to find the earthquake-induced deformations.

Methodology and Results

- Some of the information collected will be analyzed using a computer routine written in Matlab. In order to use this approach, it is necessary to first collect a wide variety of available data from existing GIS databases.

The databases that will most likely be used can be found as links off of the main USGS website. The data sets that must be collected include: digital elevation maps, geological data maps, and maps of the different transportation and man-made structures that may be in hazardous areas. Through the USGS Seamless server it is possible to collect the National Elevation Data, in this case in 30m x 30m cells since a smaller size is not available for the desired area. In addition road locations are also available through the server. The Geological map is known as USGS Open-File Report 95-89. Open-File Report 95-89 is a preliminary geological report, which was done by Yerkes and Campbell (1995), and was later used by Jibson (1998). This file comes in a tar.gz format, which is a compressed Unix file. This file must be converted before it is usable in GIS, this conversion will depend on the version on GIS being used. It is important to know what the version is, since certain versions of GIS are more compatible with Unix. For this particular project ArcGIS version 9.2 was used, therefore the data had to be converted into shape files. These shape files can then be used to create the geology map in GIS. The next challenge is assigning the parameters to the geologic map. Figure 2a shows the significant geologic variability that exists in the Oat Mountain area, and Figure 2b shows an elevation map of the Oat Mountain area, which includes existing roadway infrastructure.
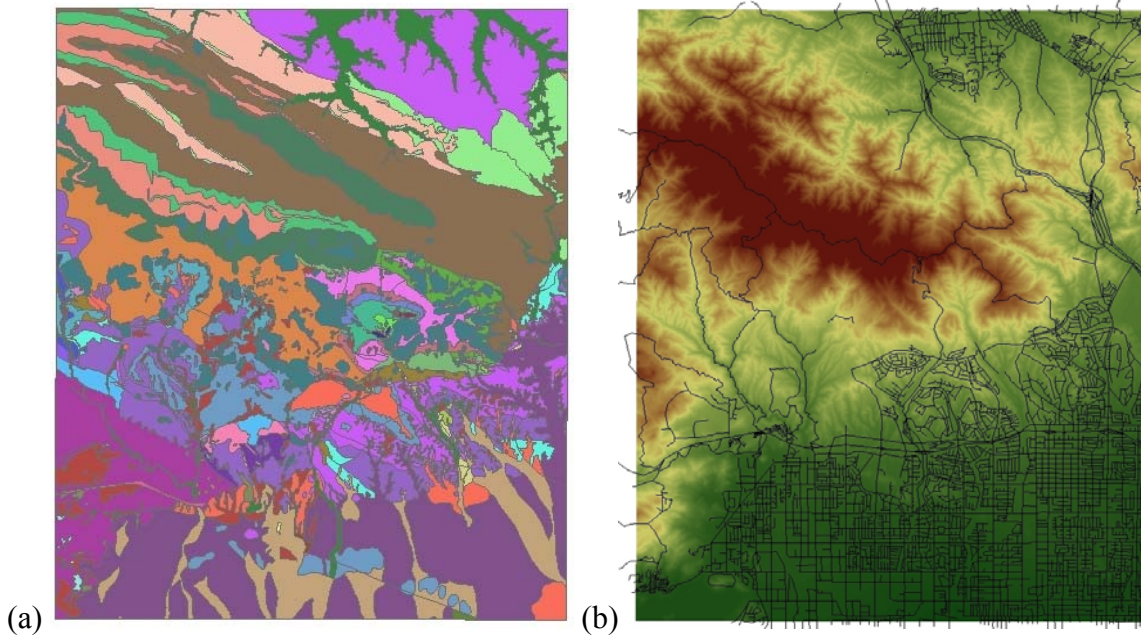
Figure 2: (a) Geologic map of the Oat Mountain area, and (b) Elevation map of the Oat Mountain area that also shows existing road locations

- Computation of the static factor of safety must be performed to assess the risk of dynamic slope failure during an earthquake.

The factor of safety determines if the slope will be able to hold or fail, and if it does hold how much leeway is present. The goal is to calculate a factor of safety of one and find the critical acceleration that produces this answer. These calculations will be done in matlab, which will require the strength data, including cohesion and friction angle of the soil, to be exported in a database file, in order to be used in calculations in matlab. The results from matlab will then be converted into a database file to be uploaded as a layer in GIS.

-The geology and strength data can be used to then calculate the friction angle and cohesion. These two factors are assigned on the geology map and are crucial in calculating the displacement, as shown in the previously stated formulas. Below is the table that shows the corresponding cohesion and friction angle values for the geological

7

data. This table needs to be represented in a separate GIS layer that will correlate to the geological map. The table was originally in a pdf form and must be brought into excel, where it can be saved as a database file (dbf). This file can then be joined to the existing GIS dbf file for the geology layer using the ptype field in the geology map and the symbol field in geol_parameters as the common fields. Using the join function and after fixing a few typos, there are around 243 resulting unmatched records, most of which is in the south in the Qao quaternary, where the land is rather flat.

Table 1: Shear strengths assigned to geologic formations in the Oat Mountain area (Jibson 1998)

SYMBOL	FORMATION NAME	ϕ	c' (lbs/ft^2)
Qal…	Quaternary deposits (many units combined)	34°	350
Qsw	Slope wash	34°	400
Qc	Caliche	34°	400
Qls	Landslide deposits	30°	500
QTs	Saugus Formation	34°	400
QTsu	Saugus Formation, Upper Member (silty breccia)	34°	450
QTsm	Saugus Formation, Lower Member/Sunshine Ranch Formation	34°	450
Tp	Pico Formation (undifferentiated)	32°	500
Tps	Pico Formation (silt)	30°	500
Tpc	Pico Formation (ss/cg)	34°	500
Tw	Towsley Formation (ss)	34°	550
Tws	Towsley Formation (shale)	30°	550
Twc	Towsley Formation (ss)	34°	550
Tm	Modelo Formation (shale)	31°	550
Tm1	Modelo Formation (shale/mud)	31°	550
Tm2	Modelo Formation (porcellaneous shale)	31°	600
Tm3	Modelo Formation (ss)	34°	550
Tm4	Modelo Formation (shale)	31°	550
Tmd	Modelo Formation (diatomaceous shale)	31°	550
Tms	Modelo Formation (shale)	31°	550
Tto	Topanga Formation (ss)	34°	550
Ttb	Topanga Formation (basalt)	34°	700
Tt1	Topanga Formation (shale)	31°	600
Tt2	Topanga Formation (ss)	34°	550
Tt3	Topanga Formation (shale)	31°	600
Tt4	Topanga Formation (ss)	34°	550
Tl	Llajas Formation (ss, silt, clay, cg)	34°	600
Tlc	Llajas Formation (calcareous ss)	36°	900
Ts	Santa Susana Formation (clay shale)	30°	700
Tsc1	Simi Conglomerate (cg)	34°	850
Tsc2	Simi Conglomerate (shale)	30°	700
Tsc3	Simi Conglomerate (ss)	34°	800
Kc	Chatsworth Formation (ss)	40°	1000

Conversion: 1 lb/ft^2 = 0.0479 kPa.

- Digital Elevation Maps in GIS can then use a GIS function to calculate the slope. Calculating the slope angle can be performed using a function in GIS in combination with the DEM. The calculated slope will be represented in a separate layer in GIS. This layer shows the range in the slope angles of the designated area. To calculate the slope of the elevation map, the spatial analysis toolbar must be on. The slope tool is there, and the

8

input factor must be the elevation layer. For this project the slope measurement is done in degrees. Since the elevation layer should already have an existing grid, the two maps should overlap and have corresponding. Figure 3 shows the slope graph of Oat Mountain and some of the surrounding area.
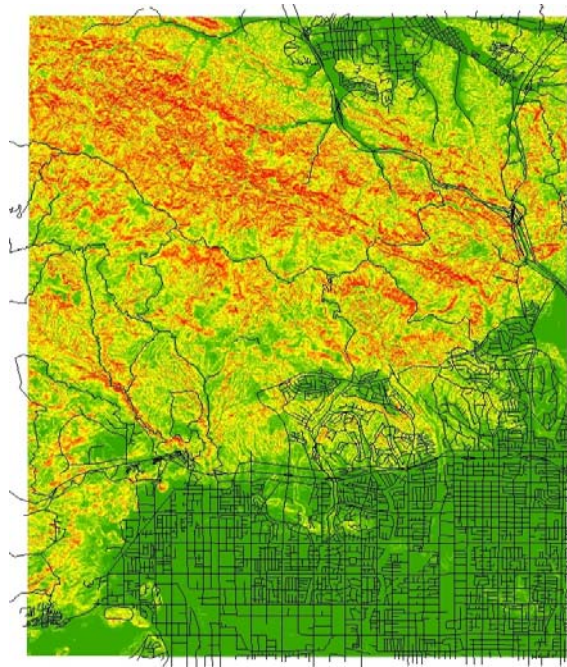

Figure 3: Slope graph of the Oat Mountain area

- The Cohesion, slope, and friction angle will then be used to calculate the factor of safety. These factors will be calculated by using the table, which was previously stated as well as formulas in combination with a code in Matlab.

- The Factor of safety and slope with then is used to calculate the critical acceleration.

For simplicity, the critical acceleration will be calculated based on a shallow sliding failure mechanism. A shallow sliding surface has a planar sliding surface and can be calculated using matlab coding and the cohesion and soil angle, along with the critical acceleration.

- Earthquake data must also be collected and then used in combination with the critical acceleration to find the newmark displacement. The Northridge earthquake will be used in order to compare results to Jibson's (1998) results.

- The Newmark results in combination with the earthquake data will then be used to produce co-seismic displacement maps under possible earthquakes.

- All the data sets that are inputted will be on different layers, including the final displacement map.

- The data will be shown in a series of maps as a final result.

These maps will include a digital elevation map, a geologic map, and a displacement map. The maps will also be explained in the final paper.

Figure 4 shows an example of a similar process that helped to provide the basis for the process for this project.
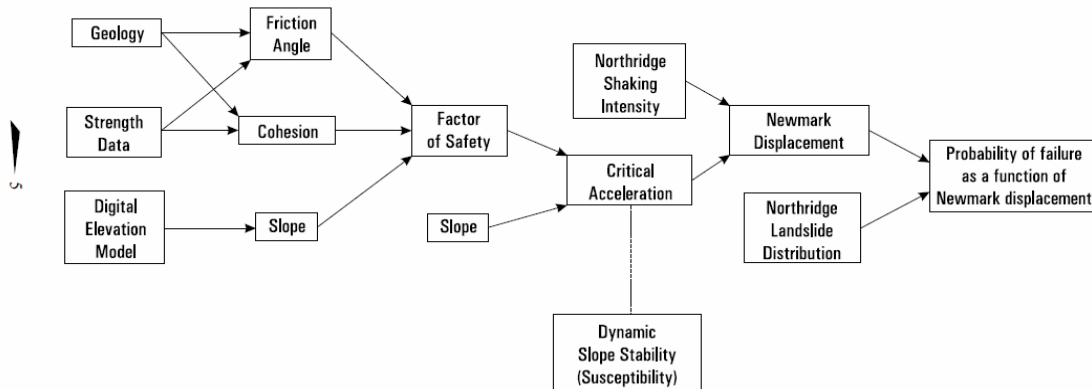

Figure 4: Similar analytical framework as what will be used for the rest of this analysis (Jibson 1998)

There is a major difference between Jibson's (1998) technique and the process that will be used here. Jibson (1998) used a probalistic method, while the process that will be used

is deterministic. Instead of having the final map show the probability of failure, the final map, in this case, will be a landslide displacement map.

Possible Outcomes and Limitations

The end result is to have a general hazard map of at least a part of the US, beginning with Oat Mountain in California. This approach should enable future study of other high-risk areas for earthquake-triggered landslides. A possible implication of this research is to have better preparedness where they may be some change as a result of the research. In addition, it is hoped that an end result would be a different way to help evaluate transportation areas in high risk of earthquake-triggered landslides.

There are a few possible-limiting factors. Time will be a large factor of limitation. There is a large amount of research and work that needs to be accomplished in order to get everything that is proposed herein accomplished. There have been issues in converting the different data types so that they correlate properly. In addition the scaling of the different data sets has made it difficult to compare the maps and results. There has also been the issue of the grid of the elevation map being transferred up through the different layers. This caused a significant issue in relation to having the data imputed into matlab to be manipulated.

Works Cited

Bray, J. D. (2007). "Simplified seismic slope displacement procedures." *4th International Conference on Earthquake Geotechnical Engineering*, Invited Lectures, K.D. Pitilakis (ed.), Springer, 327-353.

Jelinek, Wagner, Robert, Peter. (2007). "Landslide hazard zonation by deterministic analysis." *Landslides*, 4, 339–350.

Jibson, R. W., Harp, E. L., Michael, J. A. (1998). "A method for producing digital probabilistic seismic landslide hazard maps: An example from the Los Angeles, California area." U.S. Geological Survey, *Open-File Report 98-113*.

Miles, S. B. and Keefer, D. K. (2000). "Evaluation of Seismic Slope-Performance Models Using a Regional Case Study." Environmental & Engineering Geoscience, 6(1), 25–39.

Newmark, N. M. 1965. ''Effects of earthquakes on dams and embank- ments.'' Geotechnique, 152, 139 – 160.

"Frequently Asked Questions." *USGS*. September 17,2007. 9 Jul 2009 <http://landslides.usgs.gov/learning/faq/index.php>.

Yerkes, R.F. and Campbell, R.H., 1995, Preliminary geologic map of the Oat Mountain $7\frac{1}{2}'$ quadrangle, southern California—A digital data-base: U.S. Geological Survey Open-File Report 95-89.