Spatial Analysis of Hillslope Failures Using High-Resolution Topographic Datasets, Southern California

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ABSTRACT
A large number of hillslope failures have been observed within a section of the Transverse Ranges north of the city of Los Angeles. The abundance and seemingly random distribution of these landslides poses a threat to infrastructure and utility lines vital to the needs of the Los Angeles area. The types of hillslope failures found in the area include shallow surface landslides and deep-seated failures. The spatial factors controlling the distribution of landslide location and types in this area remains poorly understood. In this study, we attempt to use topographic information derived from high resolution digital elevation models in order to identify key spatial relationships that can be used to explain and predict the distribution of landslide locations within the study area. Landslides were identified and mapped in a GIS using a combination of high-resolution digital elevation models and low altitude aerial photography. The high resolution DEM was then used to derive topographic measurements that include slope, aspect, curvature, landslide area, and hydrologic area for each landslide. Spatial correlations between slide position and possible stability control factors are identified. Results indicate that shallow landslides are more likely to be influenced by topographic variables than deep-seated landslides. In addition, the speed at which these landslides were mapped and key topographic statistics derived suggests that the use of LiDAR is an efficient and effective tool for such regional-scale landslide investigations.

INTRODUCTION
Hillslope stability on a landscape is controlled by various factors that vary over temporal and spatial scales. The temporal triggers of landslides include precipitation, seismic, and hydrologic events and have been extensively studied to determine when landslides in a particular region are likely to occur (Hunt, 2005). Spatially distributed hillslope stability parameters such as soil and geologic conditions, vegetation cover, and topographic setting are more complicated in hillslope stability investigations because they can vary independently over the landscape and contribute to instability in a variety of combinations (McCarthy, 2007).

Current trends in spatially-focused landslide studies have made use of high resolution topographic datasets derived from airborne Light Detection and Ranging (LiDAR) technology (McKean and Roering, 2004; Chadwick et al., 2004; Booth et al, 2008). These datasets are used for identifying and mapping landslides based on typical topographic signatures of hillslope instability (Ardizzone et al, 2007). However, few studies have investigated how these high-resolution topographic datasets can be used to provide statistical measures of topographic variables in landslide investigations. These variables include elevation, slope, aspect, curvature, and roughness.
In this study, we use high-resolution topographic datasets to map landslides and extract characteristic topographic measurements for each landslide to identify relationships between topography and landslide occurrence. These relationships are important for understanding the spatial conditions affecting hillslope stability.

**Field Location and Setting**

The Ridge Basin area of the Transverse Ranges in southern California is an ideal location to study the correlation of the spatial distribution of landslides to causative factors (figure 1). This field area located in the Angeles National Forest is prone to widespread hillslope instability. These failures range from shallow-depth debris slides/flows of colluvial soil (Campbell, 1975) to deep-seated bedrock landslides (Foster, 2003; Fife, 1977). Records also indicate landslides move as both incremental displacements and catastrophic events (Fife, 1977).

The study area is located within the restraining bend of the San Andreas Fault, and experiences high rates of seismic activity as well as high uplift rates (May et al., 1993). Bedrock is composed of weakly-lithified terrigeneous clastic marine and fluvial sediments of the late-Neogene Ridge Route Formation (Crowell, 2003). Typically, these beds consist of interbedded sandstone and clay units that were folded during syn- and post-depositional deformation. Differential erosion has produced a steep, high-relief ridge and valley topography, with slopes running both parallel and opposite to bedding planes. These conditions are not uncommon to other areas experiencing unstable hillslopes.

The factors that influence the timing of slide activity in this region are relatively well understood and are linked to oversaturated soil conditions caused by the frequent and high yield precipitation events in the late winter and early spring (Campbell, 1975). Consideration for spatial factors is generally limited to geotechnical investigations of individual landslides that threaten infrastructure and do not analyze how these factors influence slide activity beyond the affected area (for example, see Kenton, 1996; Soils Engineering, Inc, 1997). A recent study by the California Geological Survey for the California Department of Transportation identified and recorded 200 active and non-active landslides in a section of the Ridge basin (Foster, 2003). This study identified the unique setting and types of landslides in the area and proposed a limited number of spatial controls (primarily geologic structures) on slide activity, but did not identify possible locations for future hillslope failures or deformation. The interpretations made in this...
report were based on observed slides, but were not quantitatively tested.

Datasets

This field location has the benefit of a number of useful datasets available for analysis. In the fall of 2007, a large swath of airborne LiDAR data was collected and made available for this study. From this LiDAR data, a high resolution (5ft posting) Digital Elevation Model (DEM) was constructed. Additional topographic surface maps were produced from this DEM (slope, aspect, curvature, drainage area). At a similar time low altitude black and white stereo air photos were collected for sections of the field site.

Other datasets readily available for the field location include digitized orthoimagery (NAIP 2005), recently published geologic maps (Dribblee, 2002), and a NRCS soil survey of the area.

METHODS

This study utilized two components. A landslide map produced an inventory of slide locations and characteristic attributes. This landslide inventory was then analyzed to identify important relationships between landslide attributes and topographic measurements.

Digital Mapping

This landslide inventory was mapped and stored digitally in ArcGIS 9.3 using the high-resolution topographic datasets to identify characteristic slide morphologies. The surface topography datasets were supplemented with aerial photographs to identify disturbances in vegetation. In addition, a few slides included in the inventory were identified from previous field reconnaissance, ground-based photographs, and geotechnical reports.

Hillslope failures were identified by observing typical landslide features visible in the topography and air photos. The topographic expression of landslides can include irregular or hummocky topography, headscarsps, displaced blocks and depositional deposits or lobes (Hunt, 2005) and are easily expressed in the high-resolution DEM. Disturbances in vegetation or structures (roads) visible in air photos are also indications of landslide activity. Small features, such as tension cracks, are not likely to be visible the resolution of the topographic datasets or air photos.

In general, landslides that showed clear subsurface deformation in the DEM were mapped as deep-seated features. Landslides that were visible in the air photos but not the DEM (did not show significant subsurface deformation) were classified as shallow slides and debris flows.

Besides landslide location and size, additional attribute information will be assigned to each documented landslide in the inventory. During the mapping process, attributes such as landslide type and relative age will be estimated from the topographic data and imagery. Other attribute variables such as aspect, slope, area, roughness, etc., will be quantitatively extracted from the digital elevation model. Geologic maps will be used to determine primary rock type and structure (dip direction and angle) associated with each slide. Characteristic soil properties (soil depth, density, shear strength) for each landslide can be derived from an NRCS soil survey of the area. Additional attributes will be added to the inventory as needed and as available, including spatial precipitation data and hydrologic data.
Figure 2: Locations of landslides in inventory (position of polygon centroids).
RESULTS

Topographic Variables

An abundance of landslides (over 1600) were identified within the entire field area, with varying spatial density and clustering throughout (figure 2). Extracted landslide attributes also have varying distributions. The mean slope for all slide types range from about 18 to 42 degrees, though a small tail exists up to around 55 degrees (figure 3a). Most of the landslides have a negative mean curvature, with an overall concave shape, though a few are slightly positive (figure 3b). Mean elevation has little significance in terms of topographic analysis, however the distribution of mean elevations covers the entire elevation range (figure 3c). The measured relief of landslides occurs most frequently at about 120 ft with a long tail extending to about 450 ft, excluding outliers (figure 3d).

The mean slope for each slide was compared with other topographic variables and attributes to assess stability relationships between variables (figure 4). Figure 4a shows that shallow landslides tend to have a much higher slope than deep-seated slides. The slide absence of data points at low elevation ranges (increasing with higher slope) also indicates that higher slope landslides require higher relief. Shallow slides appear to have a more concave shape than deep-
seated landslides, though deep-seated landslides appear to have an overall planar shape (figure 4b). Figures 4c and 4d indicate that deep-seated landslides have a much larger area (length x width) than do shallow slides.

Figure 4: Relationships between average slope and a) elevation relief, b) mean curvature, c) landslide length and d) landslide width.

Geometric Variables

Landslide dimensions (figures 5a and 5b) are more commonly narrow and long, with a distribution skewing towards wider and longer lengths. Figure 5c indicates that both types of landslide have a positive correlation with relief and length, and shallow slides having a higher relief per length (higher slope). Deep-seated landslides appear to become wider as their length increases, which is also true for shallow landslides, however they remain smaller than deep-seated landslides overall (figure 5d).
DISCUSSION AND CONCLUSIONS

The results of the landslide analysis suggest that shallow landslides and deep-seated failures do not have the same topographic expressions.

Shallow Slides

Shallow slides show a stronger correlation with topographic variables than deep-seated landslides. Shallow slides tend occur on steeper slopes and have a more convex shape. These relationships suggest shallow landslides are either strongly influenced by topography or are influencing topographic variables. It is also possible that the occurrence of landslides on the landscape and topographic form of the landscape are co-contributing to each other’s existence. Including other surficial spatial variables (soil type, hydrology) in the analysis could identify the strength of influence that topography has on shallow landslide occurrence.

Since shallow landslides show a correlation with certain topographic variables, developing a hillslope stability model based on topographic relationships would likely identify other past failures (not identified in the mapping) or predict possible future failure locations.
Deep Slides

When compared to shallow landslides, deep-seated landslides show a wider range of values for all of the topographic variables and do not have a clear relationship between the topographic variables and landslide occurrence, suggesting that the failure mechanisms are likely the result of subsurface conditions rather than surface conditions. Spatial controls of subsurface conditions could include lithology, geologic structure, and groundwater hydrology. Further investigations of these variables could indicate controls on deep-seated landslide positions and topographic expression.

LiDAR for Landslide Investigations

The results and subsequent analysis indicate that high-resolution topographic datasets (derived from airborne LiDAR) are an effective tool for use in landslide hazard mapping and investigations, especially when coupled with low altitude aerial photographs. Depending on the size of the study area, a complete landslide inventory can be created within a matter of weeks to months, with both qualitative (slide morphology, relative age) and quantitative (topographic measurements) attributes. Mapping is made much easier with the LiDAR because of the ability to “strip” away the vegetation to reveal the bare ground landscape. In addition, the investigator can assess difficult or dangerous terrain quickly and safely. While on-site field investigations are capable of producing similar datasets, they require more time and are much costlier when compared to LiDAR methods.

The relationships derived from such investigations can be used to develop simple to complex models of hillslope stability.

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