Landslides and Engineered Slopes: Protecting Society through Improved Understanding – Eberhardt et al. (eds)

Monitoring the subsurface hydrologic response for precipitation-induced shallow landsliding in the San Francisco Bay area, California, USA

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ABSTRACT: Intense winter storms in the San Francisco Bay area (SFBA) of California, USA often trigger shallow landslides. Some of these landslides mobilize into potentially hazardous debris flows. A growing body of research indicates that rainfall intensity-duration thresholds are insufficient for accurate prediction of landslide occurrence. In response, we have begun long-term monitoring of the hydrologic response of landslide-prone hillslopes to rainfall in several areas of the SFBA. Each monitoring site is equipped with sensors for measuring soil moisture content and piezometric pressure at several soil depths along with a rain gauge connected to a cell phone or satellite telemetered data logger. The data are transmitted in near-real-time, providing the ability to monitor hydrologic conditions before, during, and after storms. Results are guiding the establishment of both antecedent and storm-specific rainfall and moisture content thresholds which must be achieved before landslide-causative positive pore water pressures are generated. Although widespread shallow landsliding has not yet occurred since the deployment of the monitoring sites, several isolated landslides have been observed in the area of monitoring. The landslides occurred during a period when positive pore water pressures were measured as a result of intense rainfall that followed higher-than-average season precipitation totals. Continued monitoring and analysis will further guide the establishment of more generalized thresholds for different regions of the SFBA and contribute to the development and calibration of physically-based predictive models.

1 INTRODUCTION

Landslides cause millions of dollars of damage in the San Francisco Bay area (SFBA) when large winter storms impact the region (Crovelli & Coe, 2009). Rainfall during 1955–1956, 1968–69, 1972–73, 1982, 1997–98, and 2005 triggered numerous landslides across the Bay area (Fig. 1). These failures cause property and infrastructure damage (Fig. 2) and in a few cases like the 1982 storms, fatalities.

Research on regional landslide initiation in the San Francisco Bay area has focused on mapping steep areas susceptible to landslides (e.g., Nilsen & Turner 1975, Nilsen et al. 1976, 1979), developing precipitation-based thresholds for landsliding (e.g., Wieczorek 1987, Cannon 1988, Wilson & Jayko 1997) and depicting regional landslide susceptibility using topographically-driven slope stability models (e.g., Pike & Sobieszczyk 2007, Schmidt & Sobieszczyk 2007). Several studies have also investigated the geomechanics and hydrogeology that contribute to failure (e.g., Reid et al. 1988, Johnson & Sitar 1990, Collins & Znidarcic 2004). These efforts have largely focused on shallow (<3 m depth) landslides which tend to pose threats to life because they can mobilize rapidly into debris flows. Deep-seated landslides also pose significant hazards, but generally move at rates that allow timely evacuation.

Figure 1. Debris flows triggered during 1998 storms in the East Bay region. Landslide concentrations here reached 32 landslides/km^2 (Coe & Godt 2001). Photo by Mark Reid, USGS.

Whereas landslide hazards are generally widespread throughout the SFBA, geology and topography tend to concentrate shallow landsliding and associated debris flows within specific areas of the region. For example, in the January 3–5, 1982 storm, over 18,000 shallow

Figure 2. Landslide damage from 1998 storms in the Marin County region. Homes built on stilts (upper right corner) attest to both the steepness and dense development of many SF Bay area hillslopes. Photo by Mark Reid, USGS.

landslides mobilized into debris flows, resulting in millions of dollars of damage and 14 fatalities (Ellen et al. 1988a). Whereas landsliding occurred in each of the 10 counties in the region (including Santa Cruz County), detailed mapping revealed that several locations (northern San Francisco Peninsula mountains, Santa Cruz Mountains, northern East Bay Hills, southwest Solano County hills, and Marin Hills) had particularly high landslide concentrations (number of landslides per unit area) of 40 to 60 landslides/km^2 (Wieczorek et al. 1988, Ellen et al. 1988b). Similarly, during the 1997–1998 El Niño winter season, landsliding also affected the entire region but with landslide concentrations near 30 landslides/km^2 in the East Bay Hills (Coe & Godt 2001, Coe et al. 2004). In each of these cases, extreme precipitation (i.e., with storm totals between 50 and 400 mm) could generally be linked to the high landslide concentrations, guiding in some respects, future expectations of the sub-regional landslide hazard. This type of direct correlation between precipitation and landsliding, and particularly debris flow initiation, was instituted as an operational program in the SFBA from 1986 to 1995. Several warnings in 1986 and 1993 coincided with observed debris flows that caused minor damage in the SFBA (Keefer et al. 1987, Wilson 1997, Wilson 2004).

Since the time of the warning system, it has become clear that precipitation alone is not a sufficient guide for landslide susceptibility because of the role of site-specific antecedent soil moisture conditions. However, strides have been made with regard to the general understanding and ability to analyze and measure subsurface hydrologic response. Sophisticated numerical models can be set up and run efficiently for a number of different subsurface hydrologic configurations and boundary conditions, and instrumentation to measure subsurface antecedent conditions is relatively inexpensive and reliable. However, thresholds based on soil moisture conditions and the fundamental research that goes into developing them are somewhat lacking. That is, a baseline knowledge of what specific type of subsurface response can be expected from major precipitation events is not well constrained. This need was highlighted by Keefer et al. (1987) in response to their initial efforts that relied primarily upon antecedent and short-term precipitation forecasts.

In response, and as a part of the U.S. Geological Survey's (USGS) mission to research and provide information about landslide hazards, a soil-moisture and pore-pressure-based landslide monitoring network has been installed throughout the San Francisco Bay area. The project provides baseline data and assessments of soil saturation levels at typical shallow landslides in regions where potentially life threatening debris flows could mobilize. This paper presents a generalized background on this monitoring net-work, describes the instrumentation, and presents preliminary results based on one year of data. It concludes with a discussion on where this information can lead landslide initiation research given a sufficiently long data record.

2 METHODS

2.1 *The San Francisco Bay Area landslide monitoring network*

We set up the SFBA landslide monitoring network to measure soil moisture, pore water pressure, and rainfall. We hypothesized that by understanding conditions at a few monitoring sites, we could infer when landslide susceptibility might increase regionally during the storm season. In selecting monitoring sites, we targeted landslide-prone locations that were representative of general regional topographic, geologic, hydrologic, and vegetative characteristics. In addition, the sites were selected to be germane to conditions in densely populated regions of the region and therefore of societal relevance (Fig. 3).

We chose four sites (one each in Alameda County and Marin County, and two installed at different locations of San Mateo County; Fig. 4) using the following criteria:

1. Evidence of shallow landsliding in at least two previous storm events (e.g., 1982 and 1997–98 winters). This ensured that monitoring sites were not simply representative of special conditions that might have occurred from one particular storm event.

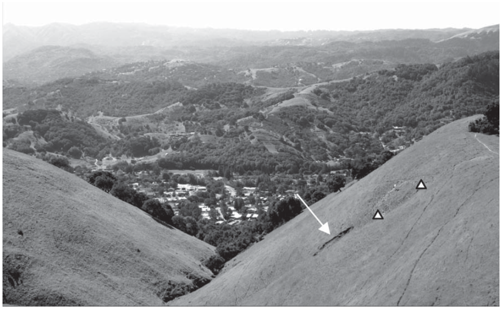

Figure 3. Typical landslide-prone slopes and monitoring site located above existing development (Marin County). The instrumentation (triangles) are located along the axis of the approximately 35° hillslope, just upslope from an existing shallow landslide scar (arrow) from 2005.

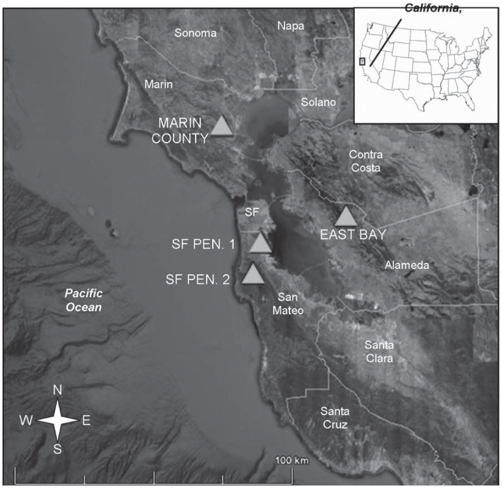

Figure 4. Locations of SFBA landslide monitoring sites (triangles) and county names.

2. Colluvial-filled hollows with slopes of at least 30° and contributing drainage areas between 500 to 1000 m^2. This serves to normalize the topography among sites, and steep hollows are preferential sites of landslide initiation in much of the SFBA (e.g., Dietrich et al. 1986, Montgomery & Dietrich 1994).
3. Sandstone bedrock where coarse-grain overlying soils tend to mobilize into debris flows (e.g., Ellen & Fleming 1987).
4. Shallow soil profiles of approximately 1 m depth. In addition to being representative of typical shallow landslide-prone hillslopes, this allowed manual installation of all equipment so that site disturbance could be minimized.
5. Grassland vegetative cover. Whereas shallow landslides also occur in heavily vegetated areas of the SF Bay area, selecting only grasslands with minimal chaparral simplifies the monitored and modeled precipitation conditions by being able to neglect canopy and transpiration effects on rainfall and soil moisture.
6. Absence of obvious anthropogenic disturbances.

2.2 *Instrumentation*

The instrumentation layout was designed to sample subsurface moisture and piezometric response at multiple locations and multiple soil depths along the axis of each landslide-prone hillslope (Fig. 5). Each site consists of two nests of sensors placed at the upslope ("upper") and downslope ("lower") portions of the hollow axis. Each nest contains a shallow (~20 cm depth) and deep (~80 cm depth) volumetric soil moisture content sensor (Decagon EC-5) along with a pore pressure sensor (Stevens Greenspan PS7000) located just above the soil/bedrock interface. In instances where the bedrock interface is relatively deep (>1 m), we installed a third moisture content sensor midway between the shallow and deep sensors.

All cables are routed below ground in PVC-metallic conduit to a data logger (Onset Hobo U30) located in an above-ground enclosure which also houses piezometer batteries. An Onset 0.2 mm tipping bucket rain gauge is located above and adjacent to the data logger enclosure. All sensors are logged at 1 minute intervals and in one-case (East Bay), the data is averaged at 10 minute intervals to sync with, and not exceed, telemetry uplink limits.

Figure 5. Landslide monitoring site located in the East Bay. Two instrumentation nests (triangles) are located along the axis of the colluvium-filled hollow. Cables run underground to a protective enclosure that contains the rain gauge, datalogger, batteries, and telemetry uplink.

2.3 *Telemetry*

Data from three of the sites are telemetered to allow remote access. This serves three purposes:

1. Instrumentation can be checked to ensure that systems are functioning properly, especially. prior to large storms;
2. Data can be downloaded remotely, eliminating the need to physically travel to each site on a regular basis;
3. When large storm events do occur, data can be monitored to guide additional field reconnaissance that might be warranted to verify if landsliding has occurred.

The monitoring system has not been designed to serve as a warning system. Insufficient data is yet available to draw conclusions on relationships between monitored signals and the likelihood for landsliding. More importantly, operational support is not available to ensure 100% functionality during all times of the year.

Telemetry is currently provided by commercial networks on 10 to 60 minute intervals via either cell-phone or satellite uplinks and serves as a relatively trouble-free, low maintenance telemetry solution.

3 RESULTS AND ANALYSIS

3.1 *Water years*

The monitoring sites were installed in May 2009, February 2010, June 2011, and February 2012 at the East Bay, Marin County, San Francisco Peninsula #1 and #2 sites, respectively. Here, only selected data from water year 2010 (WY2010 = Oct. 1, 2009 to September 30, 2010) and WY2011 for the East Bay site are presented.

3.2 *Precipitation response*

The climatic response of the San Francisco Bay area is extremely varied, with a wide-range of microclimates. These are caused by the dramatic topography and the presence of large bodies of water, among other factors, which lead to significant disparities in regional weather, including precipitation. Comparing precipitation totals for a particular storm requires a thorough understanding of the location being investigated and a careful comparison of storm totals (for example, using multiple locations to describe storm response over the region).

In WY2010, the SFBA as a whole received above average precipitation. At the Oakland Museum weather station (NWS#046336, 17 km from the East Bay monitoring site), the annual total (63 cm) was 123% of normal. This is substantially more

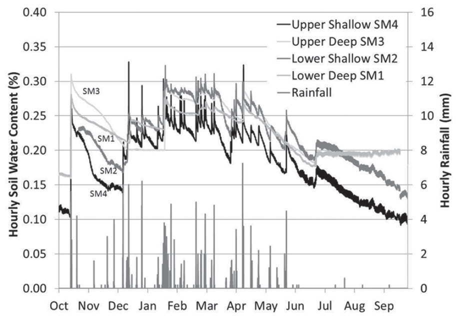

Figure 6. Precipitation and soil moisture data from the East Bay monitoring site for WY2010 (10/1/2009–9/30/2010). Instrument depths are provided in Table 1.

than the data from the East Bay site (44 cm, Fig. 6) which is located approximately 320 m higher in elevation than the Oakland Museum station. This comparison reinforces the importance of how local microclimates have a strong influence on the spatial distribution of rainfall.

In WY2011, the SFBA received substantially above-average precipitation in some areas and average amounts in others At the San Rafael Civic Center weather station near the Marin County monitoring site, WY precipitation was 99% of normal, whereas in the East Bay, rainfall at the Oakland Museum weather station (80 cm) was 156% of normal. Although our East Bay monitoring site precipitation total was again substantially less (45 cm), the precipitation during this year led to significant hydrologic and landsliding effects, as detailed in the next sections.

3.3 *Soil moisture saturation response*

By examining the soil moisture response records, baseline values of saturation can be extracted. We found that soil moisture values reached consistent upper limits (i.e., "peaks") throughout the season, and interpreted these limits as a value at or near saturation. Mean peak values were determined by averaging each of the peak values that generally coincided with individual storm events separated in time by one or more days. The total number of individual peaks at saturation were also tallied. From this, we derive the number of days in which our sensors indicate that the site soils approached saturation. This is useful to assess the relative hazard in a particular region—with increasing time at saturation, the hazard is greater that additional precipitation could generate landslide-inducing positive pore water pressures.

At the East Bay site in WY2010, the peak soil moisture at saturation was approximately 30% (Table 1). The data (Fig. 6) indicate that shallow

Table 1. Soil moisture response at East Bay site in WY2010.

Sensor (location[1]-depth)	Mean peak soil moisture (%)	Total # of saturation peaks	Total time at saturation (days)
SM1 (lower-140 cm)	27.7	5	14.9
SM2 (lower-20 cm)	30.6	16	6.6
SM3 (upper-60 cm)	29.5	3	28.1
SM4 (upper-20 cm)	29.7	24	1.7

[1]Location refers to upper or lower position along the slope axis.

depths were above 95% saturation for between 2 and 7 days of the year compared to between 14 and 28 days for the deeper sensors (Table 1). In addition, the data show that the deeper soil profile underwent fewer peaks compared to shallow soils, indicating that the deep soils remained saturated for much longer periods of time once this threshold was reached.

These analyses agree with expectations that deeper soils tend to be wetter for longer periods of time and do not respond as rapidly to precipitation fluxes compared to shallow depths. Interestingly, the upper deep soil (sensor SM3) was saturated for a longer period of time compared to its downslope, and deeper, counterpart (SM1). Whereas it would be expected that the deeper soils stay saturated longer, this may indicate that the deeper soils (i.e., those below 1 m) drain more rapidly (Fig. 6) at this location.

3.4 *Piezometric response and observed landsliding*

Despite the short length of time in which monitoring has occurred, the piezometric response has been informative and in one case, coincided with nearby shallow landsliding. Since installation, positive pore pressures have been recorded at the Marin County and East Bay sites. During a storm on March 24, 2011 which caused remobilization of deep-seated landslides and substantial damage at several SFBA locations, positive pressure heads of up to 18 cm were generated at the East Bay site, peaking over a period of approximately 5 hours and remaining elevated for several days (Fig. 7). Daily precipitation reached 4.2 cm at the Oakland Museum weather station and 1.8 cm at the East Bay monitoring site. The timing of the storm coincided with nearby shallow landsliding (Fig. 8); subsequent ground, overflight, and satellite imagery analysis identified 31 failures within a radius of 5 km from the East Bay site, including several that mobilized into debris flows. Previous positive pore pressures at the same site in October 2010 were much lower (less than 6 cm), and were not accompanied by any regional landsliding. March 2011 pore pressures at the Marin site were also less than 10 cm, and there were no observed landslides in the area. We interpret the coincidence of positive pore pressures development at the East Bay site with nearby shallow landsliding as an indication that this style of monitoring holds some promise for estimating conditions needed to generate regional shallow landslide events.

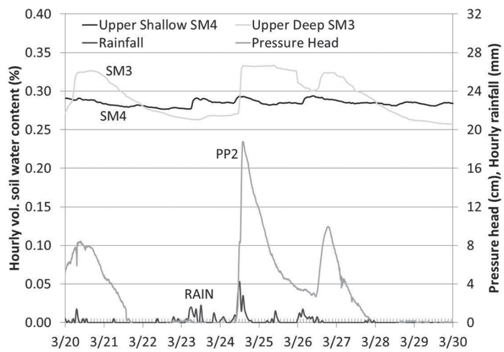

Figure 7. Piezometric data from March 2011 at the East Bay monitoring site. Positive pressures coincide with the general timing of landsliding in Figure 8.

Figure 8. Shallow landslides (arrows) from March 24, 2011 storm near the East Bay monitoring site (*). Scarps are approximately 3 to 5 m wide, 2 to 6 m long, and 50 to 75 cm deep.

4 DISCUSSION AND CONCLUSIONS

The general effects of soil moisture and piezometric conditions on shallow landsliding are well understood, but the exact relationships for particular sites and from varying storm influences are less easily interpreted. The effect that any one particular storm has on a region may vary widely and is dependent on more than just antecedent precipitation conditions. The USGS' San Francisco Bay area landslide monitoring network should provide new information to address these issues through data analysis from a network of subsurface hydrology instrumentation.

Data thus far highlights a number of key findings that relate directly to the assessment of landslide hazards. First, the length of time that the subsurface is near saturation can be calculated from the data and used as a basis for determining the frequency and length of time that landslide-prone conditions typically occur. Knowing the relative frequency of hazard can assist land developers, community planners, and emergency personnel in planning for various scenarios. Second, the timing of soil saturation, also available from the data but not highlighted here, can be related to established antecedent precipitation thresholds. This type of analysis could then be used to bracket the expected effects from particular types of storms. For example, knowing that soils saturate slowly in a particular area would allow timing the expected response should a large storm be predicted. Finally, the data can be used to guide empirical, deterministic, and probabilistic landslide analyses. The relationship between recorded pore water pressure and documented landsliding highlighted here for the March 2011 storm event in the East Bay is a simple example of this type of analysis and will be used to direct future research.

ACKNOWLEDGEMENTS

This project is funded through the Landslide Hazard Program of the USGS. We thank Kevin Schmidt and Mark Reid for field assistance in selecting and installing the monitoring sites, Stephen Ellen and Ray Wilson for discussions and field visits during the planning stages of this project, and Kevin Schmidt and Jonathan Godt for providing comments on a draft of this paper. Partnerships with the East Bay Municipal Utility District, Lucas Valley Homeowners Association of Marin County, San Mateo County Division of Parks, and San Francisco Public Utilities Commission are gratefully acknowledged.

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