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Stability analysis of the Weeks Creek landslide, Santa Cruz Mountains, California

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STABILITY ANALYSIS OF THE WEEKS CREEK LANDSLIDE, SANTA CRUZ MOUNTAINS, CALIFORNIA

A Thesis
Presented to
The Faculty of the Department of Geology
San José State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
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ABSTRACT

STABILITY ANALYSIS OF THE WEEKS CREEK LANDSLIDE, SANTA CRUZ MOUNTAINS, CALIFORNIA

by Katerina H. Rousseva

The Weeks Creek landslide is located on the western slope of the northern Santa Cruz Mountains in San Mateo County, California. The active portion of the landslide covers an area of approximately 10 hectares. This study was undertaken to assess the relationship between precipitation, groundwater level, and slope stability. The groundwater level reaches the ground surface in a year of heavy precipitation and rises to about 1 m below ground surface in a year of average precipitation. The landslide becomes unstable if the amount of precipitation exceeds 70 cm per year or if the water table rises above 2 m below ground surface. The active sliding area will increase from about 300 m to about 500 m in length if an earthquake were to occur on the nearby San Andreas fault.

ACKNOWLEDGEMENTS

This study would not have been possible without the cooperation, encouragement, and assistance of many others. First, I would like to thank my advisor, Professor John W. Williams, for getting me started on this project and for his patience, insight, and guidance, for his hands-off approach, his willingness to let me make mistakes but to ensure that I learned from them. I would like to thank Professor June A. Oberdorfer for giving me a better understanding of the groundwater processes and for her patience and enlightenment. I also want to acknowledge the other member of my committee, Mr. Grant Wilcox, who provided me with valuable information about my study area. Thanks are also due to Mr. William Cole and Dr. Gerald Wieczorek. Without their data, this study would have never been possible. Chris Wills, from the California Geological Survey, gave me the first insight into ground acceleration of the Weeks Creek landslide. Special thanks go to Chris Pearson, the owner of the land on which the Weeks Creek landslide occurred, who allowed access to his property and helped me with the installation of my instrumentation. Last, but not least, I would like to thank my beloved husband, Rostislav. Without his encouragement, support, and companionship, especially in the field, I would not have completed this study. Finally, my thanks go to my lovely daughter Kalina, who agreed to watch TV all day long and let me write my thesis.

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INTRODUCTION

The Weeks Creek landslide complex is southwest of the town of Woodside, San Mateo County, California (Fig. 1). It consists of several slumps and is delineated on the north by a gulch. The western margin is Weeks Creek. The southern margin of the landslide follows a west-trending ridge (Fig. 2). The eastern (upper) portion of the slide is gently sloping with a pronounced natural depression (Pearson's Pond), which is accentuated by a man-made berm intended to capture surface runoff (Fig. 3). Besides Pearson's Pond, which probably is a slide depression, there are no other obvious landforms in the eastern portion to suggest landslide activity. The central and western

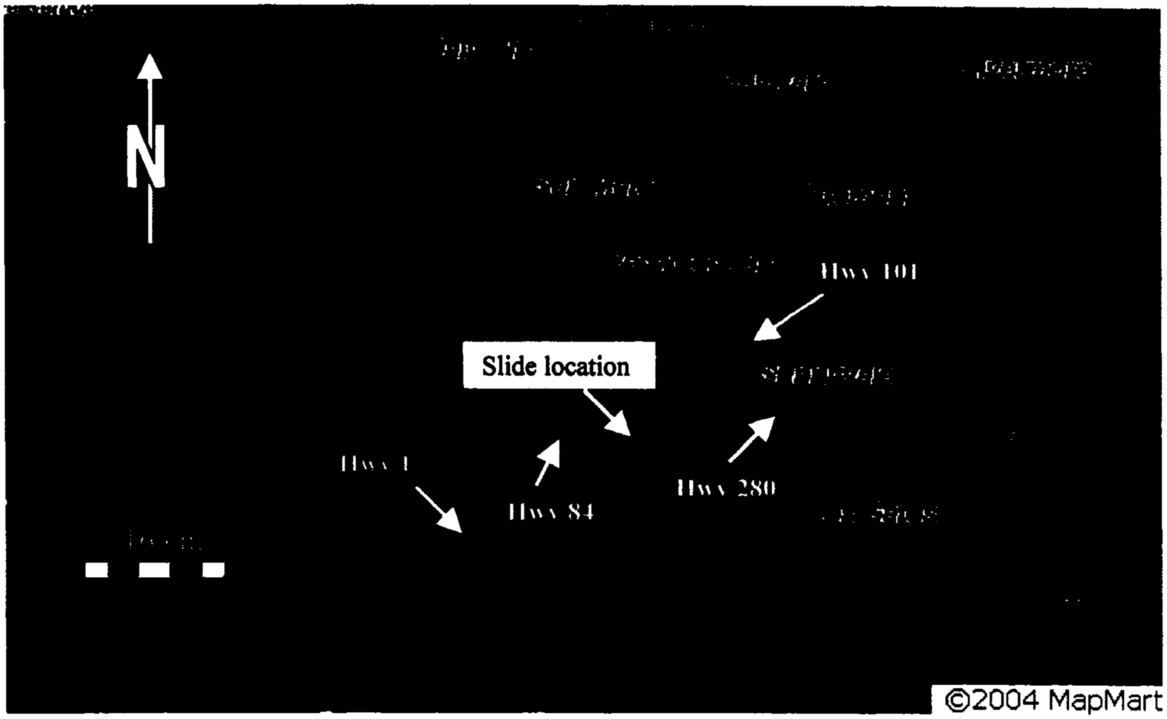


Figure 1. Location of Weeks Creek landslide (modified photo from http://mapmart.com).

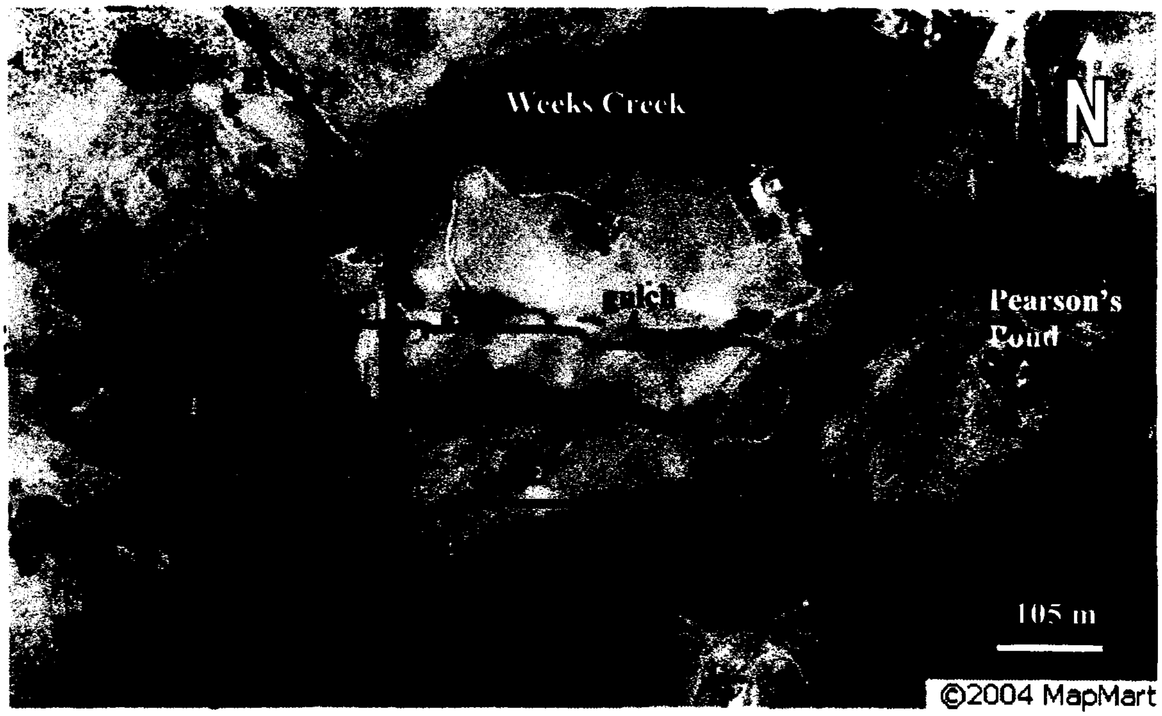


Figure 2. Aerial view of the slide, (modified base photo from http://mapmart.com).

parts of the slide, unlike the eastern portion, contain well-defined ground deformation features such as fissures, uphill-facing scarps (Fig. 4), and open tension cracks indicating that this portion is undergoing movement and is therefore active. This active (central and western) portion of the Weeks Creek landslide complex is approximately 500 m long and 200 m wide, with an area of 10 hectares.

The landslide complex is at least 3,000 years old (Adam, 1975). Triggering mechanisms appear to be seismic shaking and increased pore-water pressure. The landslide moved approximately 1 meter in the 1906 San Francisco earthquake (Lawson, 1908). Seismic shaking from the 1989 Loma Prieta earthquake triggered approximately

Figure 3. Pearson's Pond at the head of the landslide, July 2000.

Figure 4. A major scarp on the active portion of the landslide complex.

3 cm of horizontal displacement (Cotton and Associates, 1994). The landslide moved 2.4 meters and 1.5 meters in the winters of 1966-1967 and 1968-1969, respectively, in response to increased pore-water pressure (Close, 1969). According to the property owners, the active portion of the landslide is in constant motion (Pearson, personal communication, 2002).

As a result of the 1997-1998 wet winters, the Weeks Creek landslide damaged Highway 84 between post mile 11.89 and 11.78 accumulating a displacement of 2.5 cm in 2 weeks (Caltrans, 1998). According to personal observations, during the winter of 2002-03, the landslide moved approximately 5 cm, damaging the pavement (Figs. 5 and 6) of Highway 84, which was later repaired.

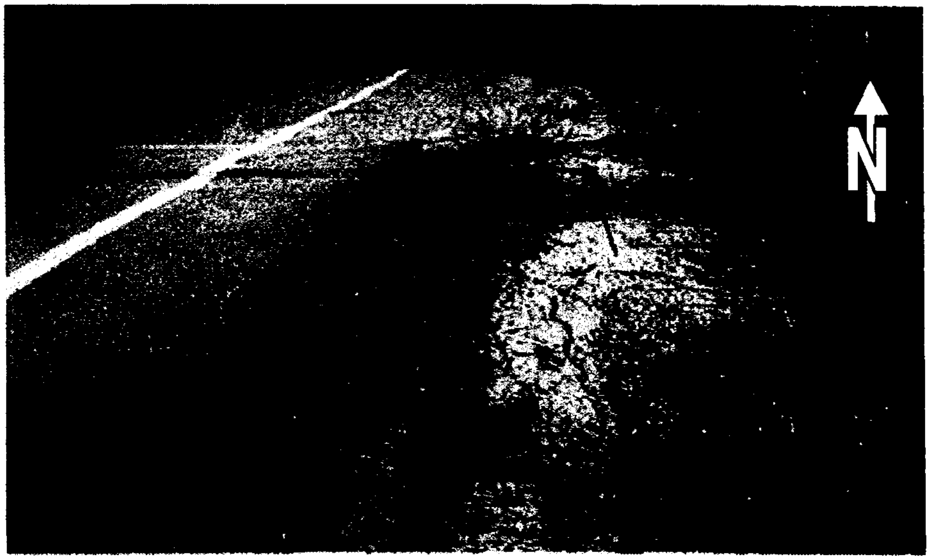


Figure 5. Crack in the road near post mile 12, indicating on-going movement of the slide.

Figure 6. Crack in the road near post mile 11.78, indicating on-going movement of the slide.

The purpose of this study was to analyze the Weeks Creek landslide for the causes and types of failure; to reconstruct the landslide geometry; to locate the water table surface; to identify the hydrologic mass balance; and to interpret the relationship between precipitation, groundwater fluctuations, and slide movement. Some of these aspects have been addressed by previous investigators. The intent of this study was to combine previous information with new data to create a computer model of the slide and to determine the influence of each of the above-mentioned factors on the stability of the landslide.

The study involved the following activities:

1) collection of the available previous data:
    a) geophysical data and engineering geology maps providing information about the landslide material properties,

   b) general geologic map,
   c) seismic data,
   d) topographic maps, and
   e) rainfall data in the vicinity of the landslide,
2) collection and analysis of new data:
   a) hydraulic conductivity measurements in the active landslide area,
   b) mass balance factors that influence the water levels in the study area, and
   c) boundaries of the groundwater flow model,
3) creation of a computer model using groundwater simulation code MODFLOW, and
4) performing a factor of safety (FS) analysis using the STEDWIN computer program.

REGIONAL SETTINGS

Physical Setting

The Weeks Creek landslide complex is on the western slope of the northern Santa Cruz Mountains in the Coast Range Province on the San Francisco Peninsula. The northern Santa Cruz Mountains is a northwest/southeast-trending, rugged, steep mountain range uplifted during the last 4 million years as a result of the onset of transpressional tectonic forces acting across the San Andreas fault (Cotton and Associates, 1994). The major structures in the vicinity of the landslide include the Sky Londa anticline, San Andreas fault, San Gregorio fault, and Pilarcitos fault situated respectively 2 km to the north, 4 km to the northeast, 12 km to the southwest, and 2 km to the northeast of the landslide. The slide topography varies in elevation from 117 meters to 218 meters above sea level. The landslide lies on the axial trace of the Weeks Creek syncline, which is on the south flank of the Sky Londa anticline (Figs. 7 and 8).

The climate in the area is mild, influenced by the Pacific Ocean. Most of the rainfall occurs between November and April. Summer fog is common. The annual precipitation data for the landslide area is 90 cm (Davis et al., 2000).

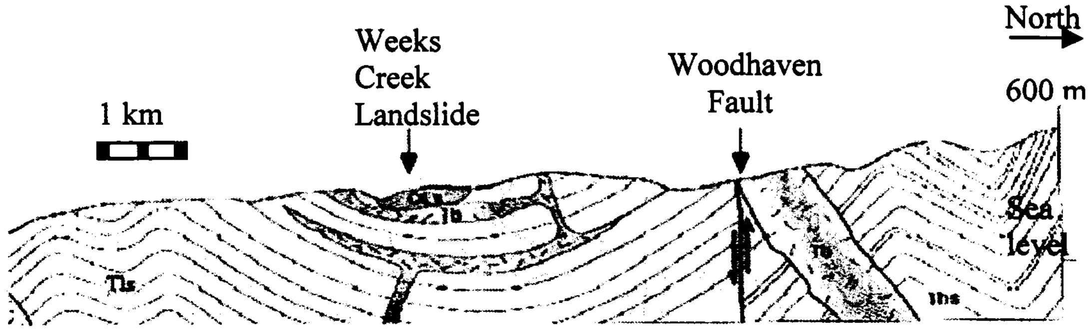


Figure 7. Regional geologic cross-section (modified from Cotton and Associates, 1994).

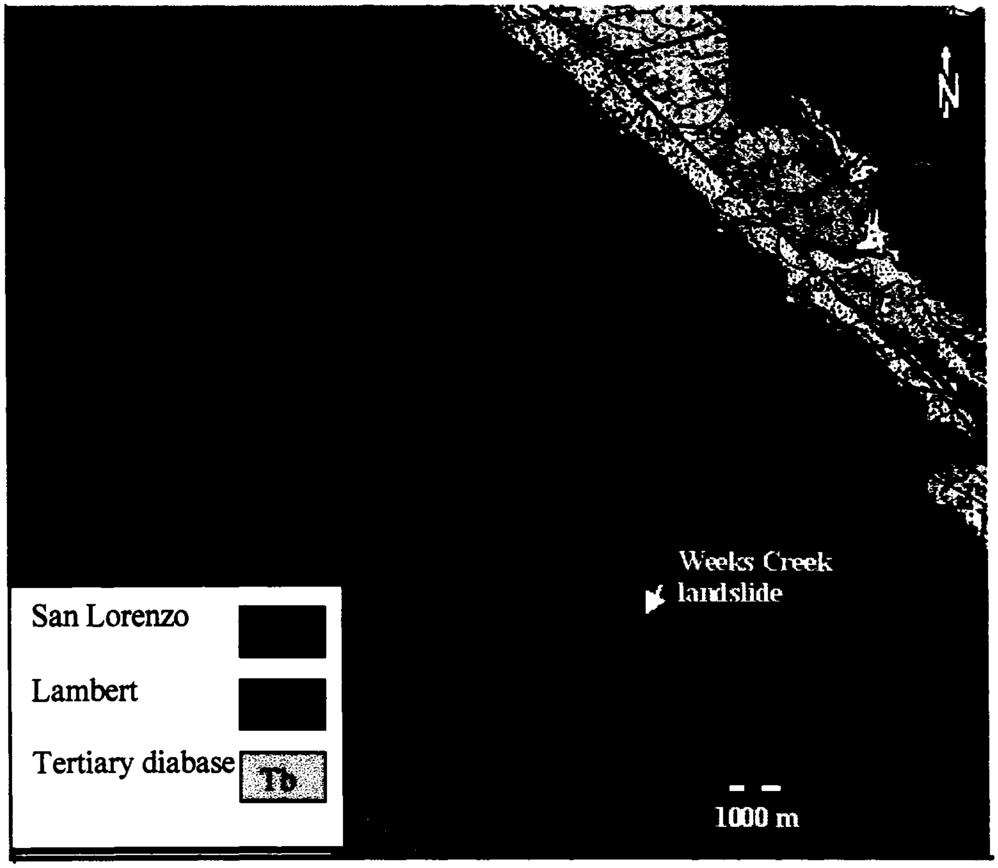


Figure 8. Geologic map of the landslide location, (modified from Brabb and Pampeyan, 1986).

Geologic Setting

The geologic map of San Mateo County (Fig. 8) by Brabb and Pampeyan (1986) indicates that the stratigraphy of the region consists of Lambert shale and San Lorenzo formations of lower Miocene, Oligocene, and middle and upper Eocene age. The San Lorenzo formation consists of dark-gray, brown and red mudstone, siltstone and shale, and beds of fine to coarse-grained sandstone. The formation has been intruded by diabase dikes and sills (Touring, 1959). The mudstones are brown and massive, interlaminated with organic material. Gray-black micaceous siltstones occur locally, particularly towards the base of the formation. Mineralogically, the San Lorenzo sandstone consists of about 50 % quartz; 35 % plagioclase, microcline, orthoclase, sedimentary rock fragments and 15 % clay matrix. Biotite is frequently present, and sandstones are glauconitic. Muscovite, apatite, zircon, and iron sulphides and their weathering products, have been noted. The clay matrix is usually prominent, and most of the sandstones are wackes (Touring, 1959).

The Lambert formation consists of dark-gray to pinkish-brown, moderately-to-well cemented mudstone, siltstone, and claystone. Chert crops out in a few places in the upper part of the cross-section. Sandstone bodies up to 30 m thick, glauconitic sandstone beds, and microcrystalline dolomite are present locally. The Lambert formation is generally more siliceous than the San Lorenzo formation (Brabb and Pampeyan, 1986).

The Tertiary diabase intrusion underlies the San Lorenzo formation. It is dark-greenish gray to orange brown and medium to coarsely crystalline. It commonly weathers spheriodally and occurs as roughly tabular bodies up to 180 m thick (Brabb and Pampeyan, 1986). The intrusion has resulted in an altered and weakened unit at the base of the sedimentary rocks overlying it. The diabase intrusion pre-dates the folding of the area. It is probable that the diabase intruded along or subparallel to bedding planes within the San Lorenzo strata and was folded into the west-plunging Weeks Creek syncline (Cotton and Associates, 1994).

Seismic Setting

The two major active fault systems located close to the Weeks Creek landslide are the San Andreas and the San Gregorio faults (Fig. 9).

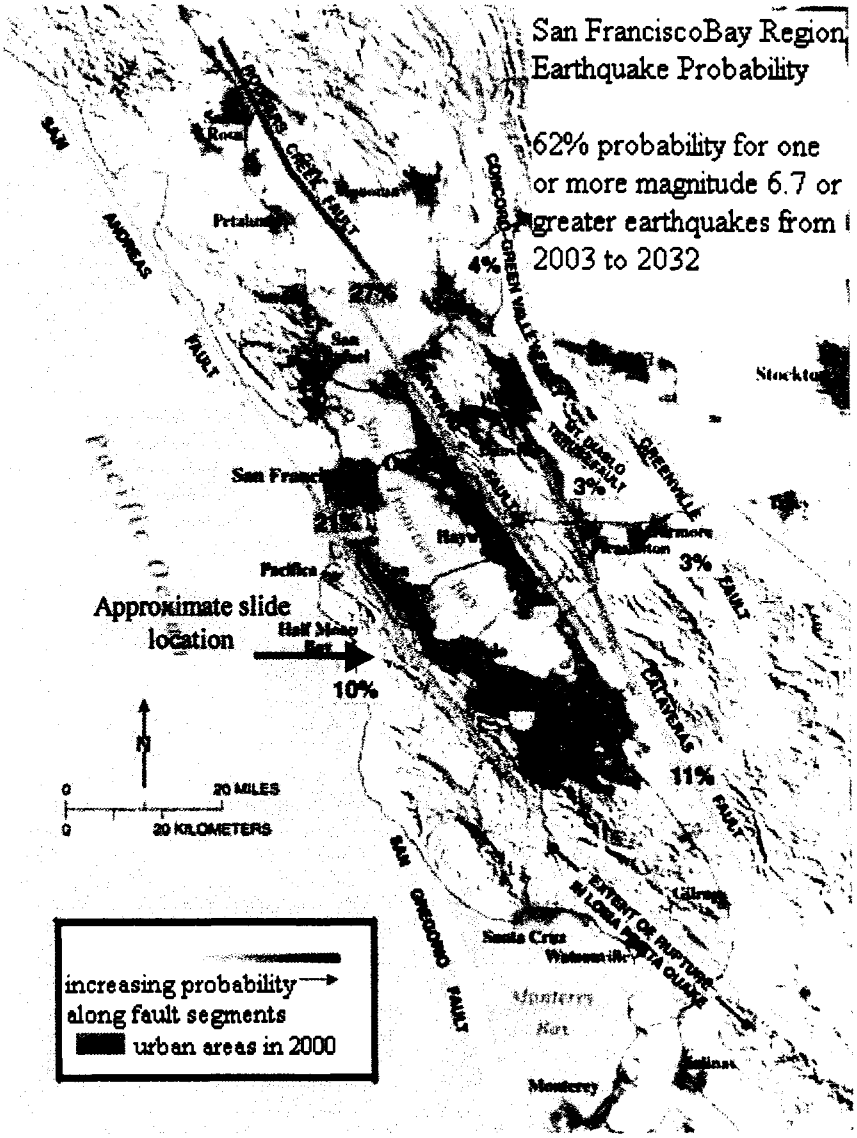


Figure 9. Earthquake probability along the San Andreas fault system, http://geopubs.wr.usgs.gov /open-file/of99-517/figure1.html.

The USGS Working Group on California Earthquakes determined that the probability of one or more large earthquakes ($M \geq 6.7$) in the San Francisco Bay region in the next 30 years is 62% (Working Group on California Earthquakes, USGS, 1999). Therefore, there is high probability that the Weeks Creek landslide will experience strong ground shaking within the next 30 years.

Vegetation

The vegetation around Pearson's Pond at the head of the landslide is largely grass. The crown of the landslide is vegetated by chaparral and redwood trees. Mixed evergreen occur along the stream that flows through the middle of the landslide as well as along the boundaries. The landslide is on private cultivated property, subject to plowing and mowing. The natural vegetation has been replaced by crops that change yearly. On the toe of the landslide is a Christmas tree farm.

Slope Stability

Landslides are common along the portion of La Honda Creek adjacent to this section of Highway 84 in the Santa Cruz Mountains. Most are described as dormant, but an alteration of the hydrologic regime or topography could lead to their reactivation (Wieczorek, 1978). The landslides in the area have been dated using radiocarbon techniques, and all of them are determined to be old, some reaching 4,000 years in age (Wieczorek, 1978). Some of the landslides contain materials of the San Lorenzo formation, while others contain materials of the Purisima formation. The landslides from the San Lorenzo formation, including the Weeks Creek landslide, are influenced by folds in the underlying bedrock. The Weeks Creek syncline underlies the Weeks Creek landslide. The syncline axis parallels the long axis of the landslide. Folding creates preferential directions for slip along fold limbs. These conditions increase the potential for landsliding (Wieczorek, 1978). Laboratory tests of the landslide material obtained from the San Lorenzo formation (Table 1) reveal a low friction angle, low cohesion, low permeability, and low dry unit weight as well as a high percentage of montmorillonitic clays (Wieczorek, 1978).

Table 1. Soil and rock landslide material (Wieczorek, 1978).

Physical Properties	Landslide Samples (San Lorenzo formation)
Peak Shear Strength	$\phi = 15.6°$ $c = 1.0\text{-}4.7$ kPa
Residual Shear Strength	$\phi = 14.6°$ $c = 0$
Dry Unit Weight average	$\gamma_d = 14.23$ kN/m^3 (90.6 lb/ft^3)
Saturated Unit Weight average	$\gamma_t = 18.11$ kN/m^3 (115.3 lb/ft^3)
Natural Moisture Content	$W_n = 28.6\%$
Hydraulic Conductivity	$K = 1.3 \times 10^{-5} - 8.0 \times 10^{-10}$ cm/sec

QUANTITATIVE INVESTIGATION

The Weeks Creek landslide is underlain by the San Lorenzo and Lambert Shale formation sedimentary rocks. Logs of borings drilled at the site by Cotton and Associates in 1994 (WCA-1 and WCA-2) and Caltrans in 1998 (SI-1) indicate the presence of San Lorenzo and Lambert Shale formations from the ground surface to the failure surface. Outcrops near the head of the eastern inactive portion of the landslide consist primarily of brown, very fine-grained siltstone with no discernable bedding or lamination. This is in contrast with sedimentary rock exposures of the Butano formation located approximately 1.5 km north of the landslide that exhibit well-defined bedding (Fig. 10).

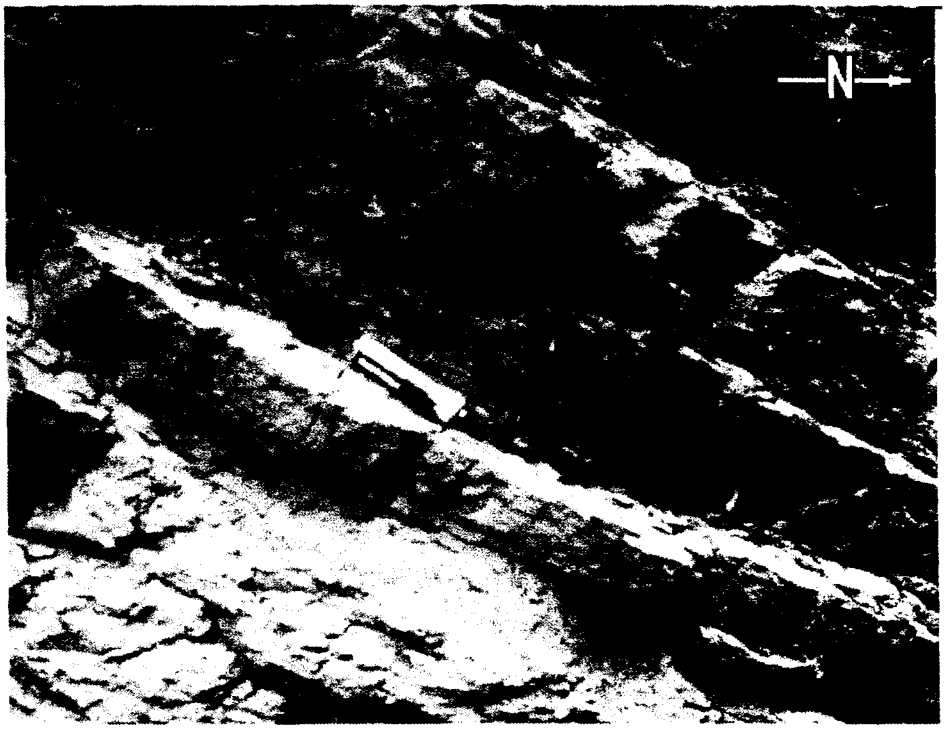


Figure 10. Butano sedimentary rock, 1.5 km north of the Weeks Creek Landslide, (an AA battery is used for scale).

Previous Studies

There are records indicating that over at least the past 100 years the active portion of the Weeks Creek landslide moved during earthquakes or periods of heavy precipitation.

Weeks Creek landslide activity is first recorded by Lawson in 1908 (Lawson, 1908). According to Lawson, the landslide moved 1 meter in response to the 1906 San Francisco earthquake.

The second study of the landslide started in 1967 after extensive earth movement occurred between post mile 11.78 and post mile 11.89 and damaged Highway 84 (HW 84) in the vicinity of Weeks Creek. The study was performed by a team led by Lew Wulff employed by Caltrans (Grant Wilcox, personal communication, 2001). The team made three power borings. A two-inch diameter well was installed in each of the borings for water table observations. No deflection of boreholes was observed over a period of several months, and the team concluded that the thickness of the slide must have been greater than 18 m, the depth of the boreholes. Logs of the power borings are kept in the Oakland Caltrans District Material Department files.

The team concluded that there would be no sudden movement of such magnitude as to cause a road closure and recommended a "wait and see" strategy. Their analysis apparently excludes the possibility of another earthquake of the magnitude of the 1906 San Francisco earthquake with the associated movement of the landslide of 1 meter.

The third study of the landslide was performed by Philip Henry Close III (Stanford University graduate student) in 1969. He monitored the water table of the landslide using the three wells drilled by Caltrans. The water table was at or very near the surface after a period of heavy rain (Spring of 1969). By the beginning of August, near the end of the dry season of 1969, the water level had subsided to 6 meters below ground surface in well #1, 1.5 meters in well #2 and 4.5 meters in well #3 (Fig. 11).

The fourth study of the slide started in 1973 when significant erosion of the downhill portion of the slide narrowed the road. The study was performed by J.F. O'Shea, a Caltrans engineer (Grant Wilcox, personal communication, 2001). O'Shea proposed three approaches to deal with the slide:

1. Repair the slide,
2. Bypass the slide, and
3. Live with the slide.

The first approach was rejected because of the size of the slide and the large financial investment that would be involved. The second approach was rejected because of the rugged terrain conditions. The rejection of the first two approaches led by default to the acceptance of the third solution, to live with the slide.

The fifth study of the slide was performed in 1975 by David P. Adam (Adam, 1975). Using radiocarbon dating, he dated the pollen record in a 2.10- meter long core extracted from Pearson's Pond at the head of the inactive eastern landslide section. The pollen record was used to determine which plants inhabited the area through the years. The method was based on the reasonable assumption that only species that were present within a small radius (e.g., a few meters) of the point of investigation during a particular period of time would have high pollen counts within the layer of the core corresponding

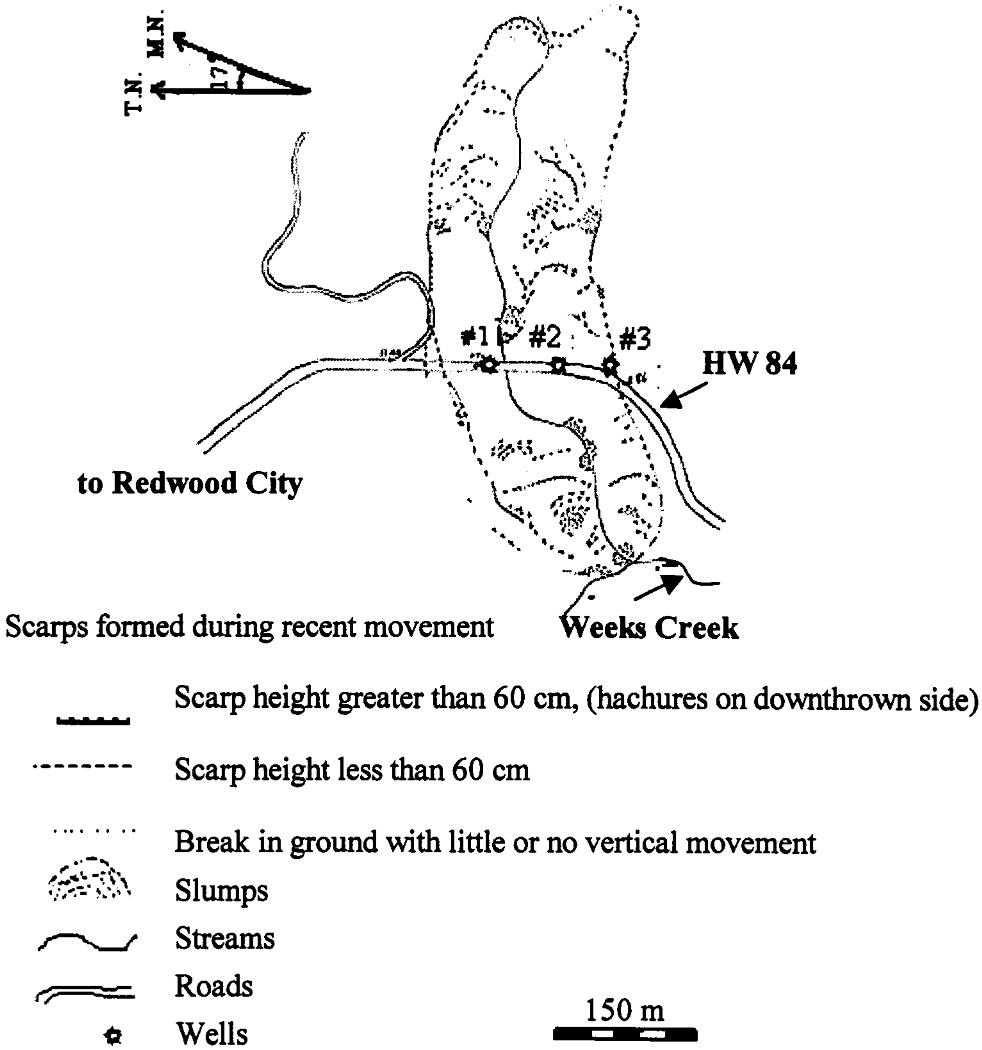


Figure 11. Position of wells in the active portion of the landslide complex (modified from Close, 1969).

to that period. Over the years, different species gradually invaded the area leading to gradual changes in the pollen counts. A landslide event could disrupt the layered structure of the soil and expose older layers. Thus, pollen counts of species that inhabit the area shortly after a landslide event could appear high in older layers, exposed during the landslide, and corresponding to periods when the same species were not there. This disrupts the gradual pattern of pollen counts with depth. In the core extracted from Pearson's Pond, the deepest disruption in the pollen count pattern corresponds to a major sliding event about 3,000 years ago. This first sliding event marked the creation of Pearson's Pond and set the initial conditions for further landsliding.

In 1978 Gerald Wieczorek mapped landslides along La Honda Creek in the central Santa Cruz Mountains of San Mateo County, California. He gave a detailed description of several landslides, one of which was the Weeks Creek landslide (Cole, Cotton and Associates, personal communications, 2001).

In 1981 the U.S.G.S. drilled five shallow exploratory boreholes. Three samples were obtained and tested for grain size distribution and direct shear strength. These data provided a preliminary characterization of the landslide materials. Wieczorek mapped surface features and monitored piezometers, inclinometers and extensometers (Wieczorek, 2003).

In the summer of 1992, Ed Harp and Randy Jibson of the U.S.G.S. installed surface and subsurface instrumentation, which included surface extensometers, ground surface accelerometers, and piezometers to measure slope movement, strong ground motion and groundwater fluctuations (Harp and Jibson, 1995).

In 1994 Cotton and Associates completed detailed geologic and geomorphic mapping of the landslide, a seismic refraction survey, subsurface exploration of the active landslide, hand-sampling of subsurface materials and basal rupture surface, as well as *in situ* and laboratory testing to determine the geotechnical properties of the landslide materials (Appendix A). Patrick Shires performed the seismic refraction survey of the Weeks Creek landslide, which suggested the groundwater level was 3 m below the ground surface and the diabase intrusion was about 30 m below the ground surface (Cotton and Associates, 1994).

Caltrans performed subsurface exploration and logging of a borehole in the winter of 1998. A borehole was drilled and sampled, and laboratory testing was performed to determine the geotechnical properties of the landslide material (Appendix A). They installed an inclinometer near post mile 11.84 to locate the rupture surface of the landslide (Appendix B).

Grant Wilcox from Caltrans performed detailed GPS mapping of the dormant and active portion of the landslide in the winter of 2002 to record the newest surface features of the Weeks Creek landslide (Wilcox, personal communication, 2002).

Subsurface Stratigraphy

Boring Logs

Boring logs prepared by Cotton and Associates and by Caltrans (Figs. 12, 13 and 14) record the subsurface stratigraphy of the Weeks Creek landslide. The borings of Cotton and Associates are located at the middle of the landslide on either side of the stream that flows along the axis of the slide (Fig. 15). The boring by Caltrans is located on Highway 84. The thickness of the landslide was determined from exposures of the basal rupture surface in the boreholes, from velocity differences measured in the refraction survey, and from inclinometer readings.

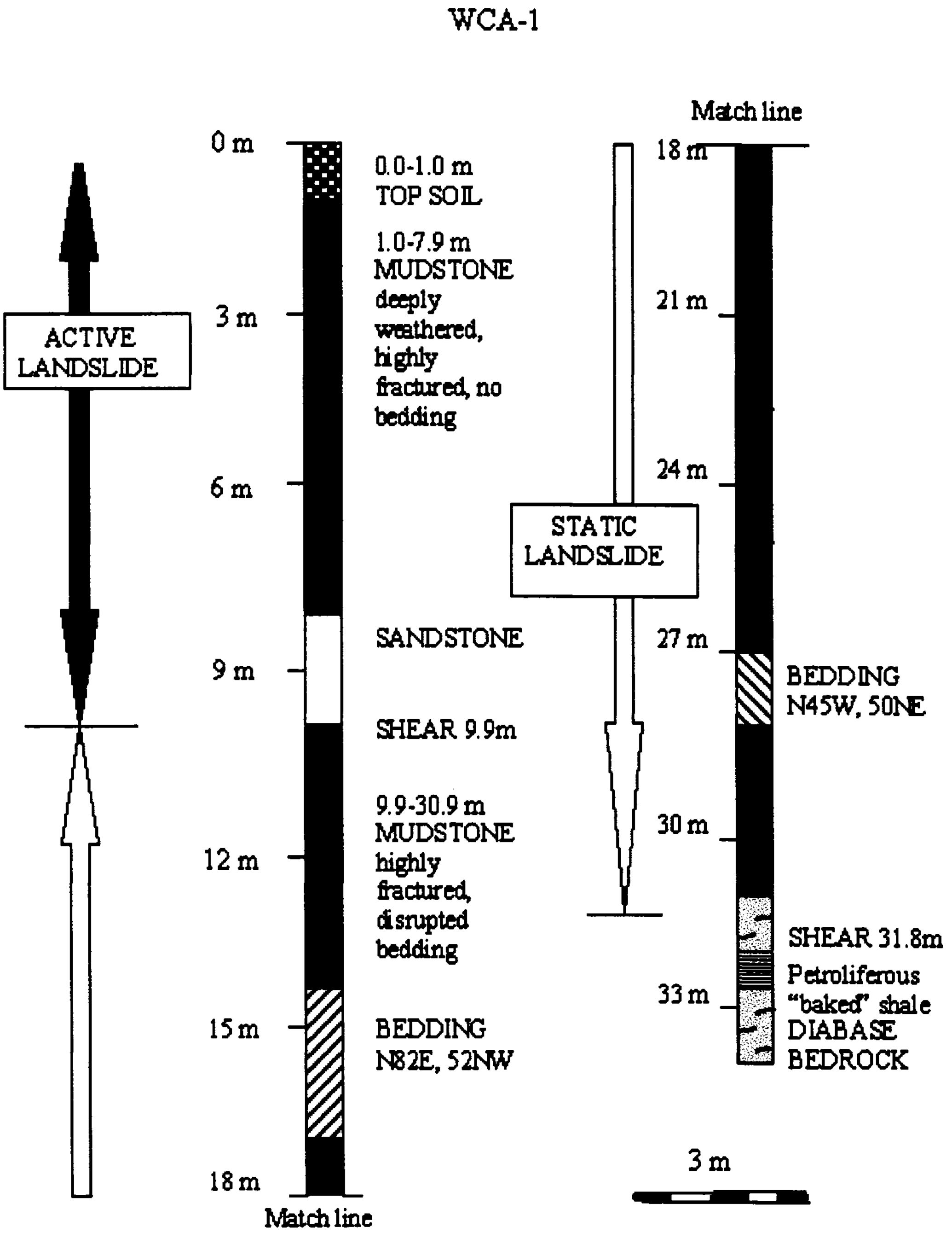


Figure 12. Downhole log of exploratory boring WCA-1 (modified from Cotton and Associates, 1994).

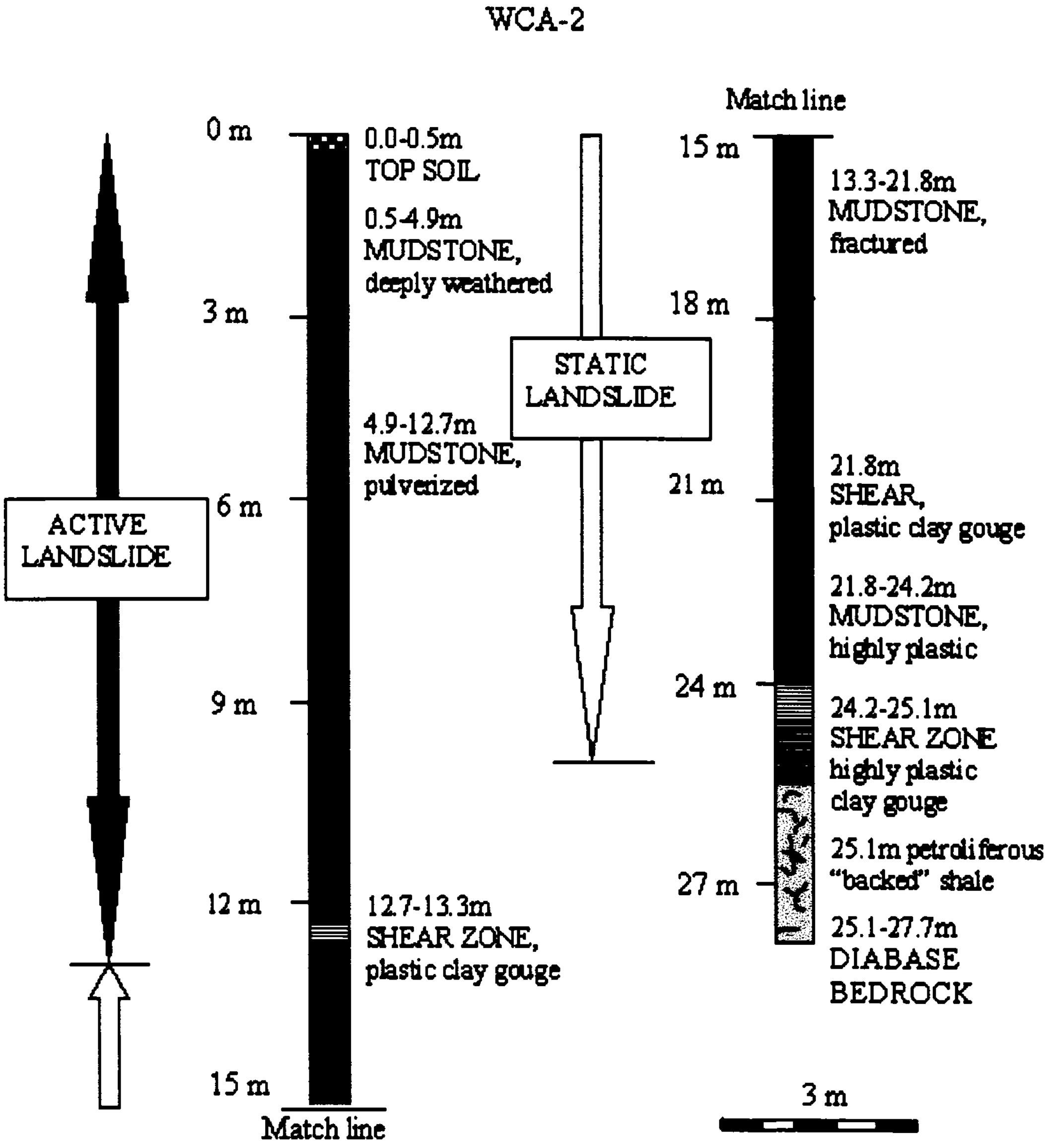


Figure 13. Downhole log of exploratory boring WCA-2 (modified from Cotton and Associates, 1994).

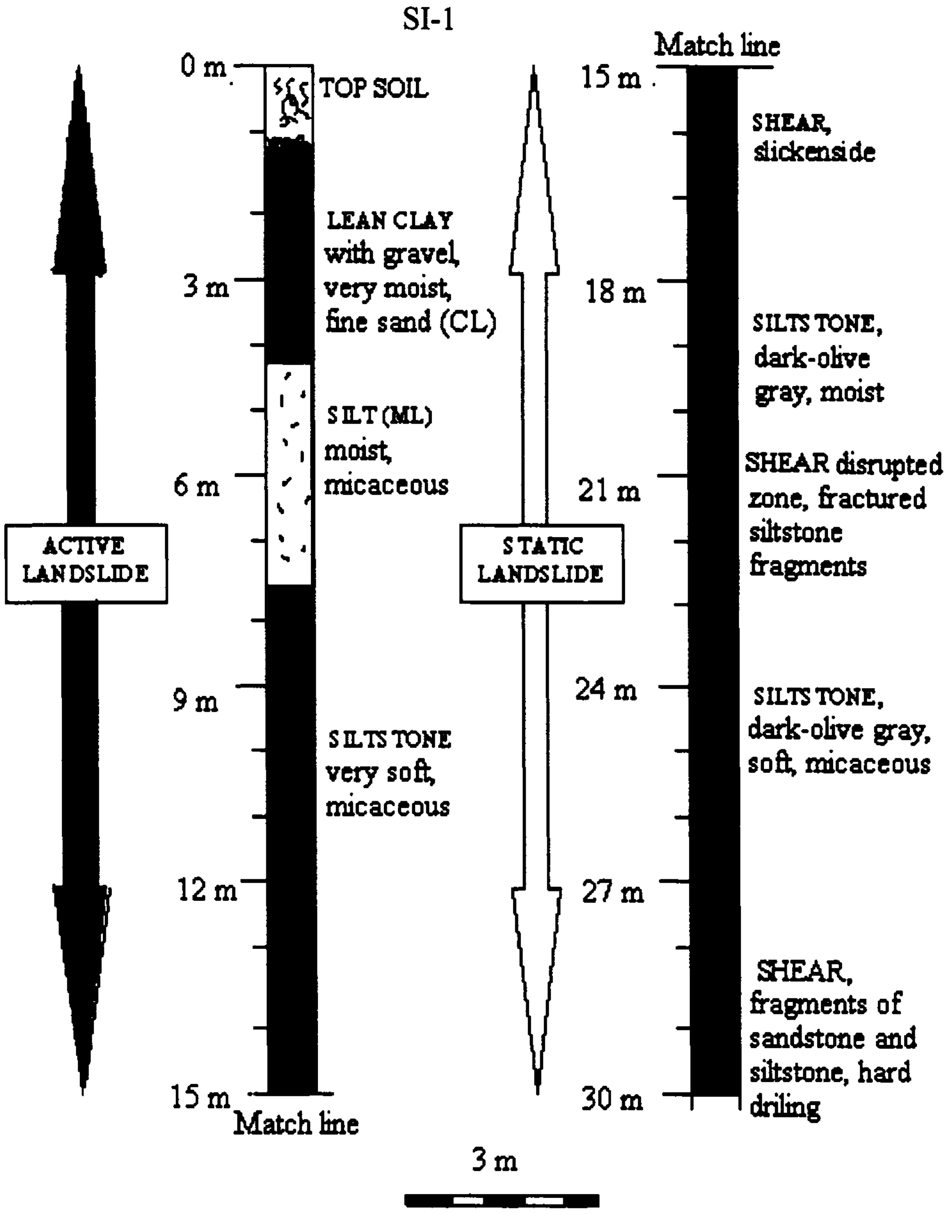
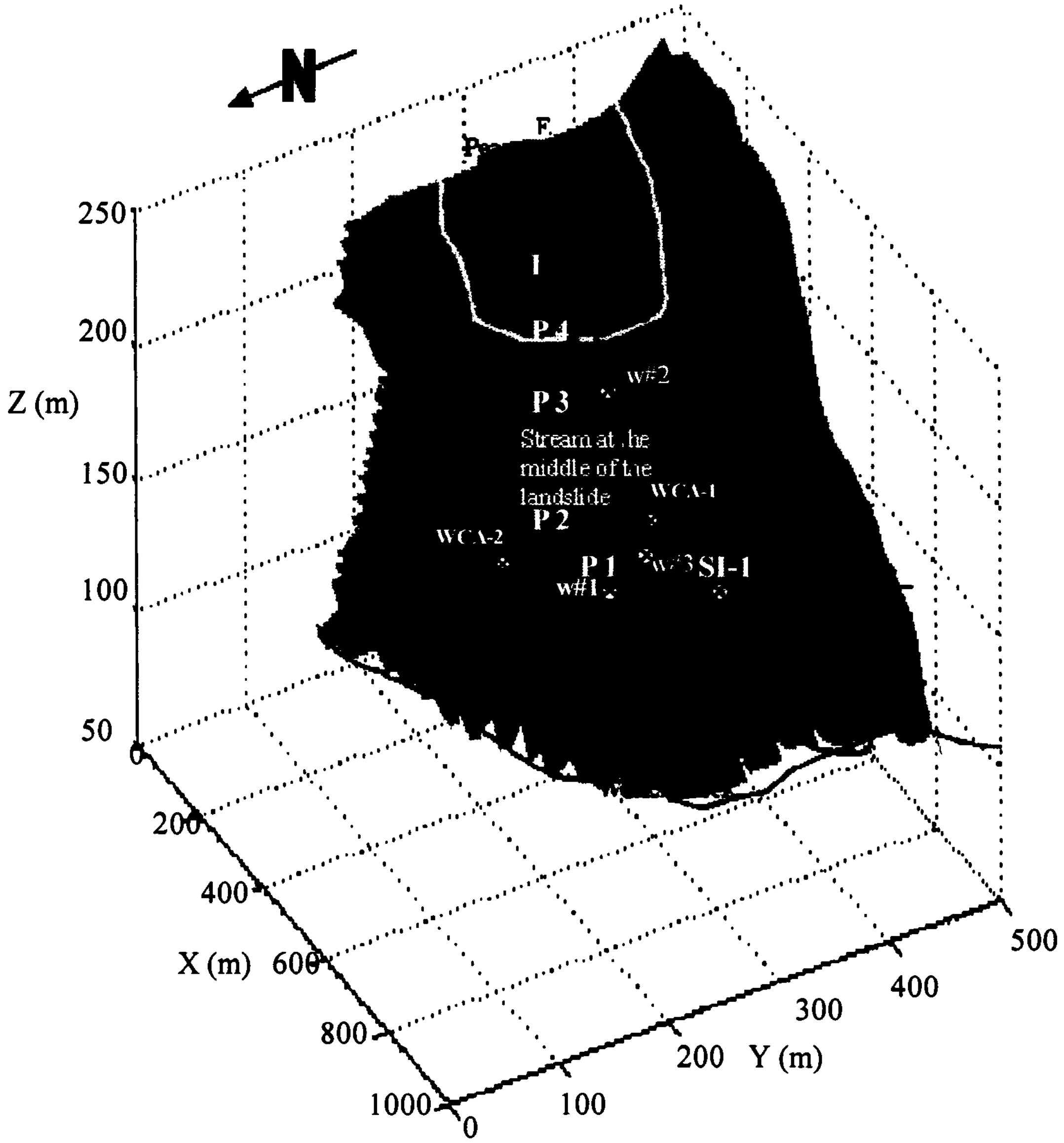


Figure 14. Graphic representation of geologic boring SI-1 (based on data by McIlroy, Caltrans, 1998).



Legend:

E-W Slope Stability X-Section (this study) ————

	Static portion of the landslide complex
——	Active portion of the landslide complex
············	Private Road
⊗	Monitoring Wells 2003 (this study)
⊗	Exploratory Borings 1994 (Cotton and Associates)
⊗	Slope Indicator 1998 (Caltrans)
▲	Piezometers 2003 (Wieczorek)
●	Inclinometer 2003 (Wieczorek)

Figure 15. Boreholes and wells location (based on Cotton and Associates, 1994).

The two 30-inch-diameter exploratory borings (WCA-1 and WCA-2) were drilled in the summer of 1994. BoringWCA-1 (Fig. 12) reached a depth of 34.2 meters. WCA-2 (Fig. 13) reached 27.7 meters beneath the ground surface (Cotton and Associates, 1994). Another 30 meter-deep boring, SI-1 (Fig. 14), was done in the winter of 1998 by Caltrans. The landslide materials observed in the boreholes were a chaotic assemblage of broken rock. The top of the landslide mass consisted of a thin, organic layer of topsoil 0.5 to 1.0 m thick that was disrupted and loose due to periodic plowing. This organic layer covered a highly disrupted, pulverized, and sheared mudstone of the San Lorenzo formation in borings WCA-1 and WCA-2 with little discernible bedding, while in boring SI-1 it covered disrupted lean clay. Isolated, irregular blocks of sandstone bounded by sheared contacts occurred locally within the mudstone in boring WCA-1. In 1994, Cotton and Associates located what they believed to be the basal rupture surface of an active landslide at a depth of 9.9 m in borehole WCA-1 and 13.3 m in borehole WCA-2. Their interpretation was based on the premise of a very pronounced shear surface, characterized by highly plastic clay gouge with striations. The interpretation is shown on Figures 16 and 17. In the borehole SI-1drilled by Caltrans, at a depth of 15 meters below the ground surface, a shear-disrupted zone characterized by siltstone breccia with slickensided surfaces was encountered. The process of drilling below the shear zone was described as very slow because the material was stiff.

Below the basal surface of the active portion, the landslide deposit was composed of more competent mudstone and siltstone. Blocks of disrupted but less pulverized mudstone were encountered in borings WCA-1 and WCA-2 suggesting that, below a

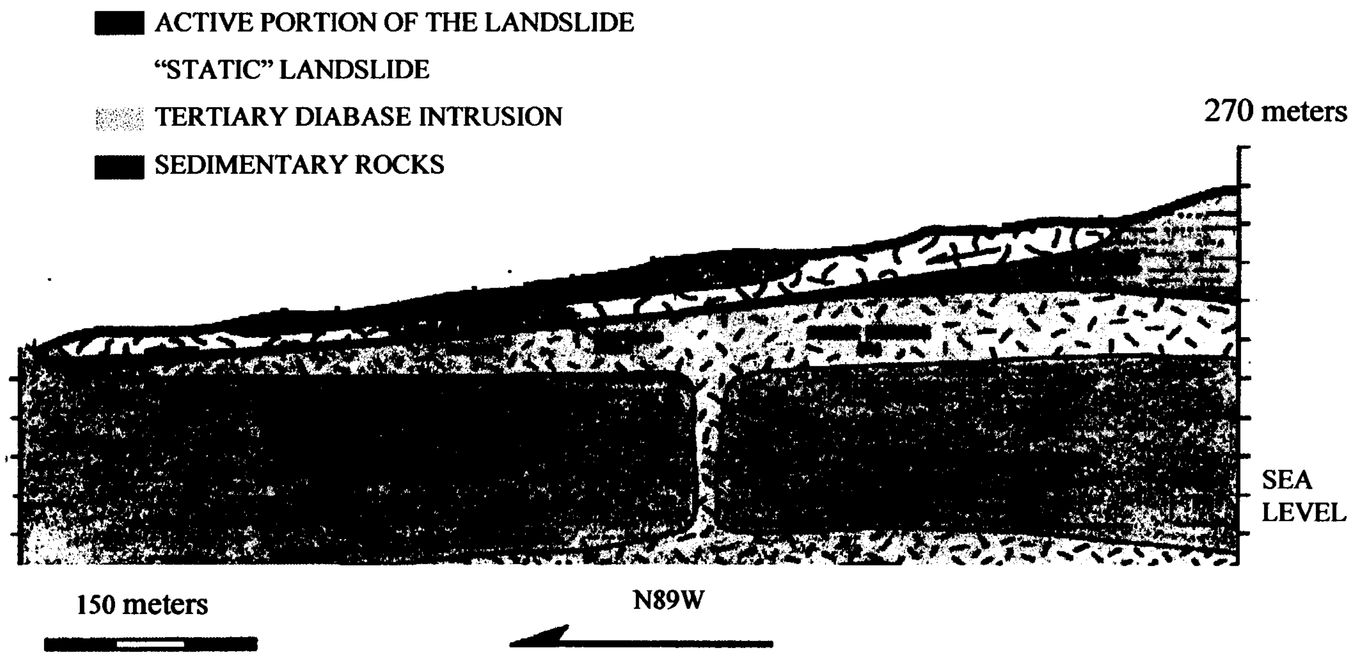


Figure 16. Engineering geologic cross-section (E-W) (modified from Cotton and Associates, 1994).

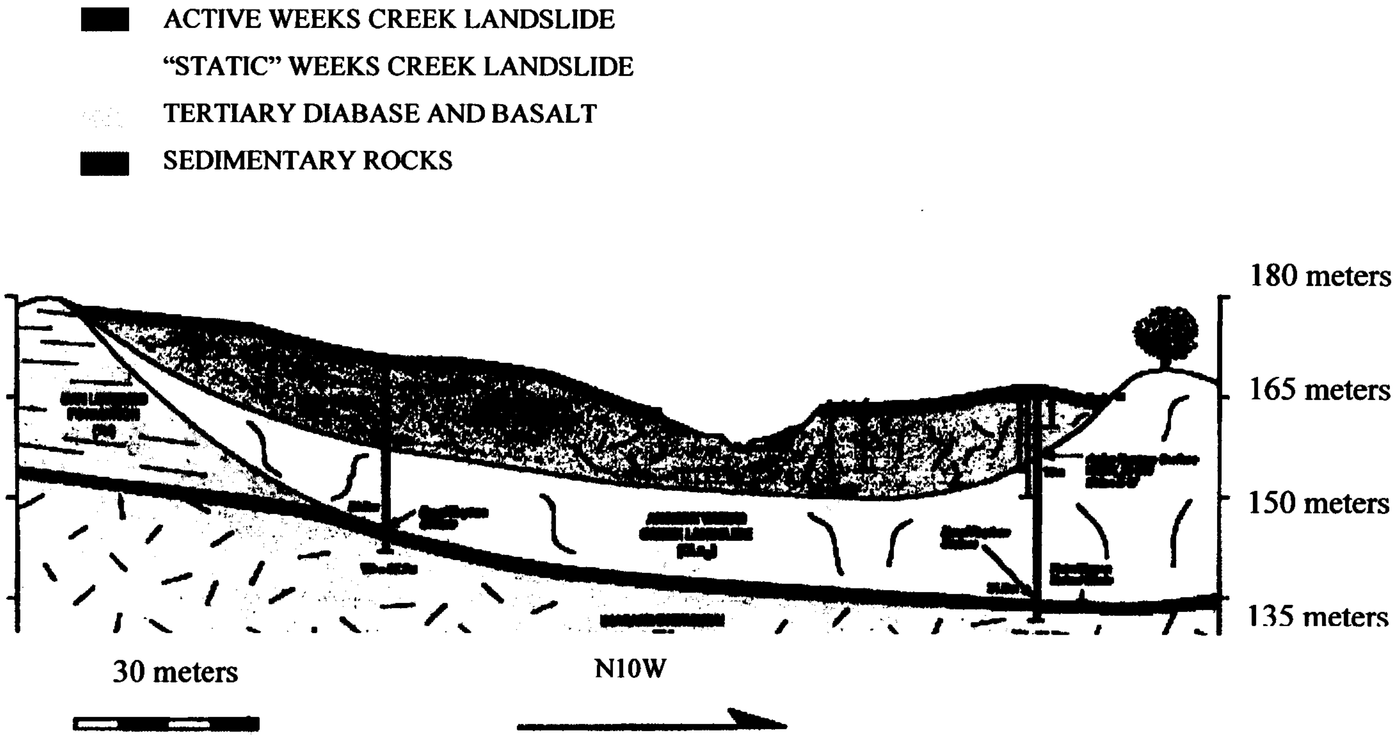


Figure 17. Engineering geologic cross-section (N-S) (modified from Cotton and Associates, 1994).

depth of 15 m, the landslide mass may be “static” (Cotton and Associates, 1994). Below the interpreted active landslide slip-surface, several more "slip-surface zones" containing siltstone were encountered in boring SI-1 (Caltrans, 1998). Those slip-surface zones were very-soft to soft, but they lacked any slickensides. For this reason, the interpretation of those zones was that they were zones of weakness, but not necessarily slip-surface zones. A zone of weakness may be favorable for future sliding.

The basal rupture surface of the “static” landslide was a highly-plastic, clay-gouge shear encountered at depths of 31.8 m and 25.1 m in boreholes WCA-1 and WCA-2, respectively. The rupture surface in borehole SI-1 was encountered at a depth of 30 m where the dominant material was black sandstone. In boreholes WCA-1 and WCA-2, underlying the landslide mass was a 1-meter-thick "baked" shale bedrock unit. This shale was grayish black, dry, fractured, and petroliferous. Very strong, hard diabase was located beneath the shale. This diabase appears to be responsible for the thermal alteration of the overlying San Lorenzo formation mudstone and might have contributed to the landslide development by causing an altered and weakened unit at the base of the overlying sedimentary rocks (Cotton and Associates, 1994).

Inclinometer readings (Appendix B) were taken so that the active slip surface could be confirmed. The readings were taken by Cotton and Associates between November 1995 and December 1996 and by Caltrans in March 1998 and revealed active slip surfaces at depths of 28 m (94 ft) and 26 m (88 ft), respectively, below the ground surface. This coincides with the full thickness overlying the bedrock. The discrepancy between the estimated location of the active slip surface as interpreted from the boreholes and that shown by the inclinometer readings suggests that there may be more than one active slip surface.

Seismic Survey

Patrick Shires (Cotton and Associates, 1994) conducted a seismic refraction survey in 1993. The survey recorded an abrupt velocity change across the contact between the overlying landslide mass and the underlying diabase. Three units characterized by different seismic wave velocities were established. In the uppermost unit to a depth of 3m (10 ft), the velocity ranged from 312 to 339 m/sec (1040 to 1130 ft/sec). The plane along which the first velocity change occurred was interpreted as the water table. Beneath the water table was a unit reaching a depth of approximately 27m (86 ft) where the velocity ranged from 1584 to 1635 m/sec (5280 to 5450 ft/sec). This unit was interpreted as the landslide itself. Beneath the landslide was a unit, believed to be the diabase intrusion, characterized by a velocity of 2643 m/sec (8810 ft/sec).

Exact determination of lithologic units based on a seismic refraction survey is a very difficult task because a single material may exhibit a range of velocities. There is a good correlation between the interpreted seismic data and the logs of the borings obtained by both Cotton and Associates in 1994 and Caltrans in 1998. Unfortunately, a seismic refraction survey cannot always indicate the location of slip surfaces. This is because, if the surface occurs within the same unit, there may be no velocity change across the surface. Also, the seismic refraction study cannot determine whether a surface of changing velocity is a slip surface or not.

GROUNDWATER INVESTIGATION AND MODELING

The purpose of the groundwater modeling of the Weeks Creek landslide was to determine the relationship of the groundwater level to precipitation. Simulated groundwater levels were then used in evaluating the factor of safety (FS) of the landslide and determining the amount of precipitation likely to cause landslide activation.

Historic Rainfall

Over the years, a variety of field data has been generated about groundwater levels at several points in the landslide area. In addition, rainfall and discharge data have been collected. The modeling integrates the data to predict the groundwater level through the landslide area during different seasons. The varying levels allow an estimation of the landslide FS as a function of seasonal precipitation.

The approximate average yearly precipitation for the Weeks Creek landslide region is 90 cm (35 inch) per year (Davis et al., 2000). The precipitation and the groundwater levels in the area of the Weeks Creek landslide vary significantly in different seasons (rainy season versus summer season) (Wieczorek, 2003). Therefore, proper modeling requires data on average historic precipitation for each month of the year. Average historic monthly precipitation data exist for the nearby region of San Gregorio. The average historic yearly precipitation for San Gregorio is about 75 cm (29.52 inch) (U.S. Department of Commerce, 1971-2000), 15 cm less than in the landslide location, which is high on the mountain. Wieczorek (2003) collected precipitation data and examined groundwater level fluctuations from November 1981 to April 1984 for Weeks Creek landslide area. The precipitation data (Figs. 18 and 19) showed that for the months June, July, August and September there is no rainfall. This is in contrast with the average monthly precipitation data for San Gregorio, which is much closer to the ocean. A reasonable approximation for the monthly precipitation in the landslide region can be obtained by starting with the San Gregorio monthly precipitation data (Table 2), equally distributing the June-through-September precipitation over the other eight months (Table 3), and then multiplying the resulting numbers by the ratio 90:75 of yearly precipitations in the two regions (Table 4).

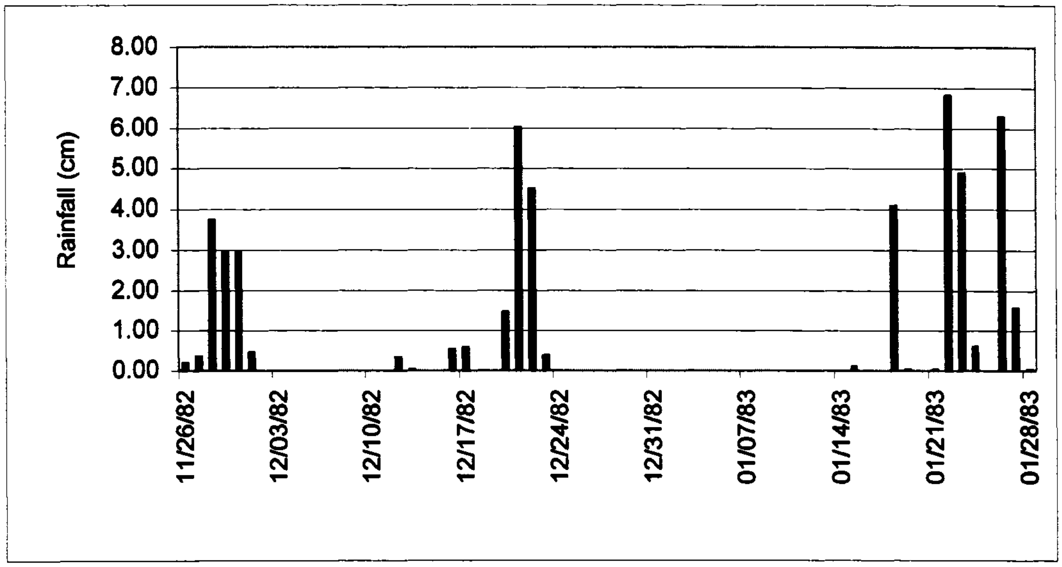


Figure 18. Daily rainfall data at Weeks Creek (Wieczorek, 2003).

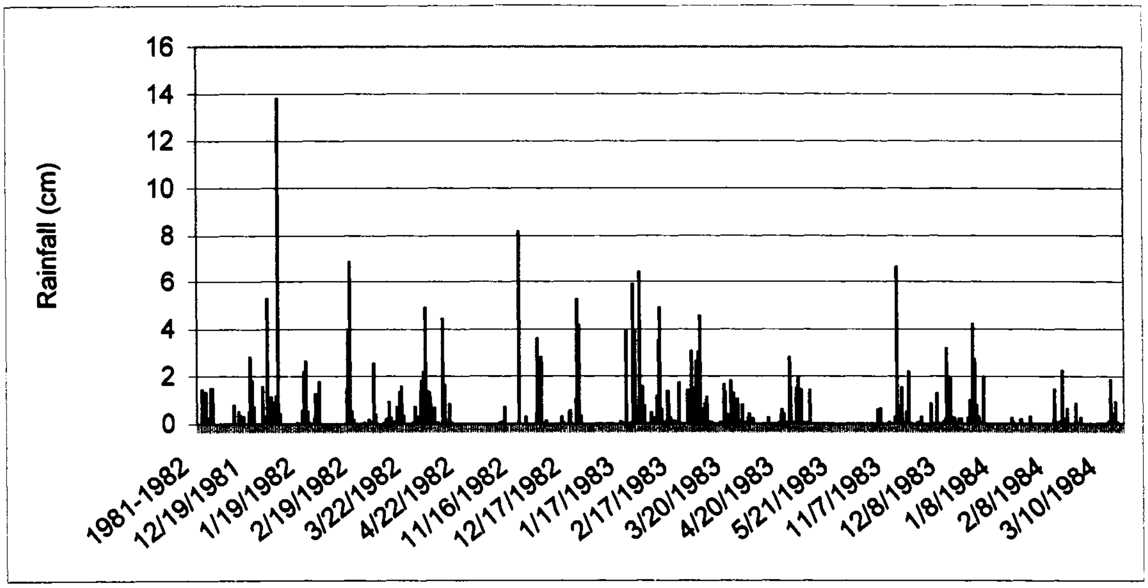


Figure 19. Daily rainfall data at Harrington Creek (Wieczorek, 2003).

Table 2. Historic average monthly precipitation for San Gregorio region, in centimeters (U.S. Department of Commerce, 1971-2000).

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
14.5	13.64	11.68	5.08	2.16	0.74	0.33	0.51	1.04	4.24	9.98	11.07

Table 3. Modified average monthly precipitation for San Gregorio region, in centimeters.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
14.82	13.96	12	5.4	2.48	0	0	0	0	4.56	10.3	11.39

Table 4. Resulting estimated average monthly precipitation for the Weeks Creek landslide region, in centimeters.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
17.78	16.75	14.4	6.48	2.97	0	0	0	0	5.47	12.36	13.67

Comparison of the average historic data (Davis et al., 2000) with the precipitation data collected by Wieczorek (2003) for the landslide area reveals that the raining season of 1982/83 was a heavy season (precipitation above average) with a total precipitation of 114 cm (44.82 inch).

The groundwater level fluctuations measured by Wieczorek (2003) from1981 to 1984 (Fig. 20) showed groundwater levels reaching the ground surface during the wet seasons of heavy precipitation and then subsiding to about 3.5 meters below ground surface during the dry season. The seismic-refraction survey performed in 1993 (Cotton and Associates, 1994) showed a groundwater level 3 m below the ground surface. During the present investigation, in January 2001, a marshy area developed in the region closest to Highway 84, indicating groundwater reaching the surface.

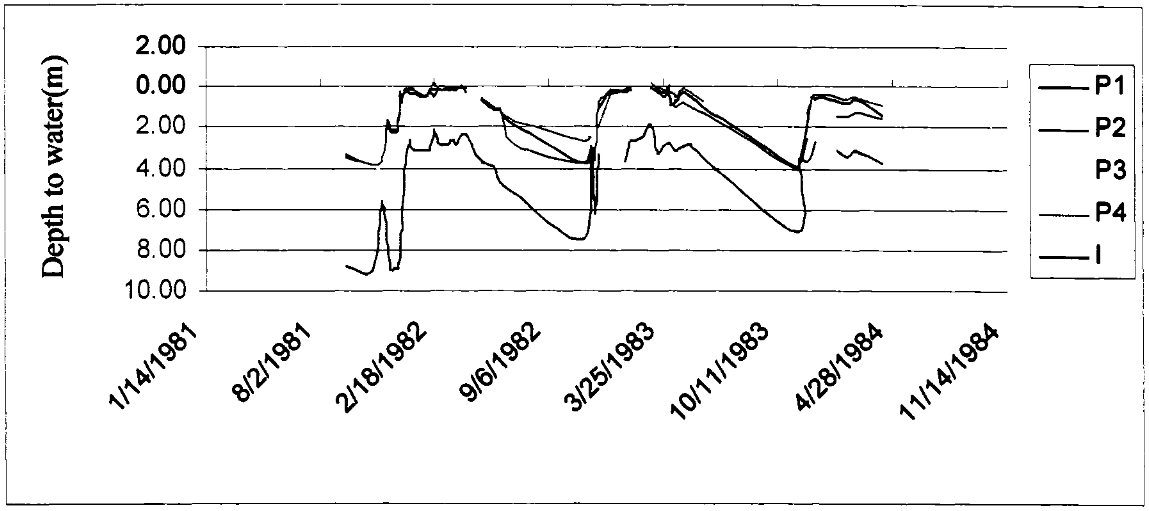
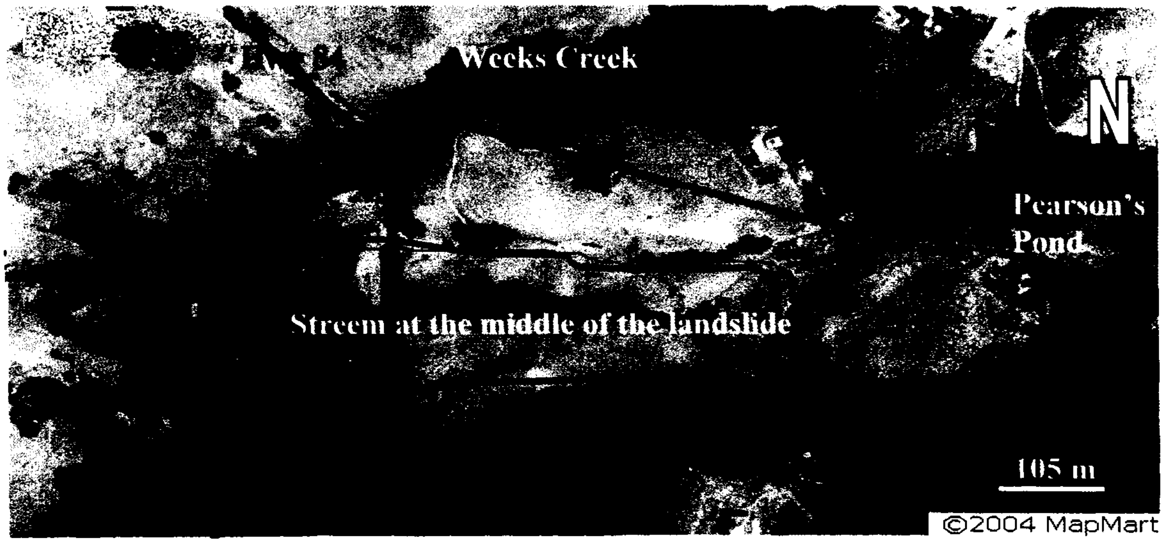


Figure 20. Hydrograph for four piezometers and an inclinometer (Wieczorek, 2003).

Conceptual Hydrologic Model of the Weeks Creek Landslide

To simulate the groundwater levels within the landslide, a conceptual model of the site was developed. The landslide area consists of a single, unconfined aquifer. The geologic units of the study site exhibit similar hydrogeologic properties and form a single continuous water-bearing zone. The aquifer is represented as one hydrostratigraphic unit, the bottom of which coincides with the top of the impermeable diabase intrusion. The ridges on the south and on the northeast side of the landslide serve as hydraulic no-flow boundaries because they are natural groundwater divides. The pond at the head of the landslide represents a known-head boundary. The region is bounded on the west and northwest by Weeks Creek, which is represented in the model by a hydraulic, constant-head boundary (Fig. 21). Because the creek to the west is the lowest part of the landslide region, outflow occurs at that boundary. The un-named stream originating near the head of the active landslide represents a location of additional discharge. Rainfall contributes recharge.



constant-head boundary　　no-flow boundary　　active landslide

Figure 21. Boundary conditions in the groundwater flow model, (modified from http://mapmart.com).

Recharge and Discharge of Weeks Creek Landslide

The fluid mass balance of the hydrogeologic system of the Weeks Creek landslide is determined by the recharge to and the discharge from the aquifer. The recharge is comprised of the infiltration of water from rainfall and the inflow of water from upgradient into the landslide. The discharge occurs to the stream flowing through the middle of the landslide and to the Weeks Creek constant-head boundary at the western edge of the landslide.

Information about the recharge due to rainfall on the Weeks Creek landslide was contained in the study performed by Wieczorek (2003) from 1981 to 1984 and in this study. The measured rainfall occurred predominantly during moderate to heavy storm events, generally between November and May.

To measure the groundwater level, one inclinometer and four Casagrande porous stone piezometers were installed at specific depths by Wieczorek (Fig. 15, page 22). The piezometers' depths were: 3.8 m (12.5 ft) for P1, 7.3 m (24 ft) for P2, 12.8 m (42 ft) for P3, and 3 m (10 ft) for P4. The inclinometer was installed to a depth of 11.6 m (38 ft). Analysis of the field data shows direct correspondence between rainfall and groundwater level change in the piezometers. The shallow piezometer P4 was unable to measure the groundwater level during a portion of the second dry season (1983-1984) when the water level dropped below the bottom of the piezometer. The readings of P1, P2, and P3 indicate that, at depths greater than 3.5 m the landslide was always saturated and that rainfall produced rapid recharge. As shown on Figure 20, once the groundwater level rises in the beginning of the raining season, further fluctuations become minor (on the order of 30 cm for piezometers P1, P2 and P4; the data for piezometer P3 are incomplete and for that reason not taken into account). This is because, once the groundwater level reaches the surface, the excess water flows downhill as surface runoff. According to the readings of P1, P2 and P4, the groundwater level reaches and, at some locations, exceeds the ground surface during the wet season of heavy precipitation. At that point, the groundwater level mimics the topography.

Information about the fluctuation of the groundwater level in the pond at the head of the landslide was obtained by regular personal observations between the summer of 2000 and the winter of 2003-2004. The water level in the pond declines approximately 1.4 m. between late winter and late summer. It is assumed that the fluctuation of the groundwater level in the vicinity of the pond is similar. Information about the discharge to the stream that flows through the middle of the landslide was reported in a study performed by Cotton and Associates (1994). They measured a typical flow rate of 35 to 70 liters per minute. According to Cotton and Associates (1994) and observations made during this study, the pond, the stream in the middle of the landslide, and Weeks Creek do not dry out completely at any time during the year.

Hydraulic Conductivity Estimation

In the summer of 2002, well points 2.54 cm in diameter were installed at three locations (Fig. 15, p. 22), and a slug test conducted at each location. The purpose of the test was to assess the *in situ* hydraulic conductivity of the surrounding soil. The perforated tip was hammered below the water table. In each test, water was introduced into the well, and the rate of water level decline was recorded. The radius of the well casing was equal to the radius of the well screen. The well screen was 30.48 cm in length. The slug test data were analyzed using the Hvorslev (1951) method, as the piezometer did not fully penetrate the aquifer.

Well #1 was installed 7.01 m below the ground surface. Because the length of the screen in the well point was more than eight times the radius of the well screen, the following equation is applicable for determining the hydraulic conductivity:

$$K = \frac{r^2 \ln(L/R)}{2L_e T_0} \qquad (1)$$

where

K is the hydraulic conductivity (m/day),

r is the radius of the well casing (m),

R is the radius of the well screen (m),

L_e is the length of the well screen (m),

L is the length of a gravel pack (m), and

T_0 is the time it takes for the groundwater level to rise or fall to 37 percent of the initial change, in hours or minutes.

In this experiment, no gravel pack was used and L was assumed equal to the length of the well screen L_e (m). A semi-logarithmic plot of the normalized head (h/h_0) versus time is shown in figure 22. The normalized head dropped to 0.37 after 230 hours. Using $T_0 = 230$ h in Eq.1 leads to $K = 8.54 \times 10^{-5}$m/day or 9.8×10^{-8}cm/sec. The field data for well #1 are summarized in Table 5.

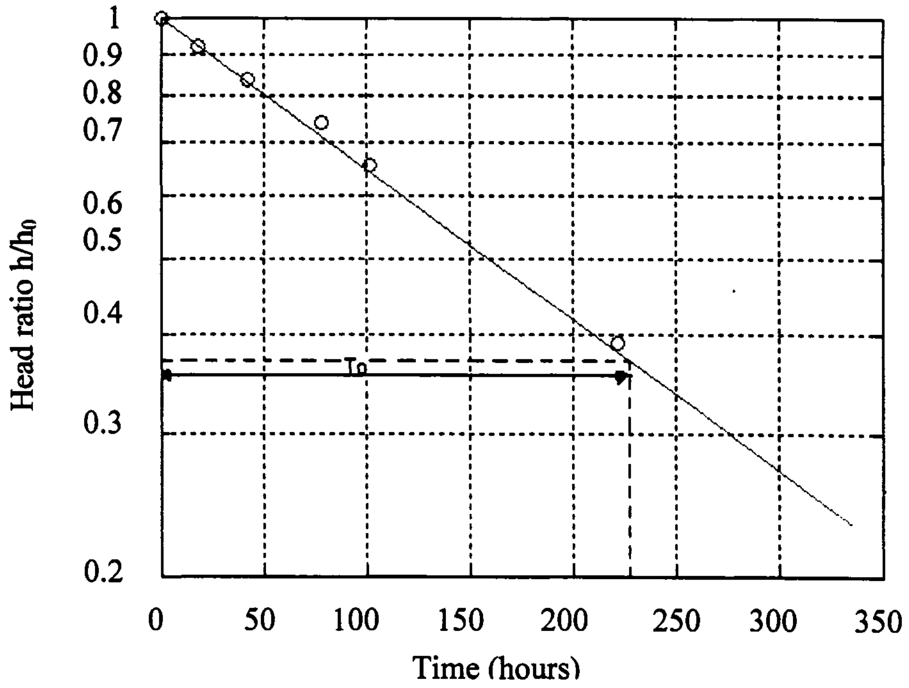


Figure 22. Plot of normalized head, h/h_0, versus time for well #1.

Table 5. Slug test data for well #1.

Elapsed time (hr)	Level to water from bottom of well (m)	Change in water level, h (m)	Head ratio, h/h_0
	3.03 (static)		
0	4.44	1.41 (h_0)	1.000
18.5	4.34	1.31	0.928
42.5	4.20	1.16	0.827
78.5	4.08	1.05	0.748
102.5	3.96	0.93	0.680
222.5	3.58	0.55	0.389
318.5	3.30	0.27	0.192
438.5	3.03	0.00	0.000

Well #2 was installed at a depth of 4.57 m. Shortly (1.0833 minutes) after the beginning of the experiment, an additional quantity of water was poured into the well to ensure adequate water quantity. This made the data recorded until that time invalid. The moment t = 0 on Figure 23 corresponds to 1.0833 minutes after the beginning of the experiment and is considered the beginning of valid data. The field data for well #2 are summarized in Table 6.

The data for well #2 fit two distinct straight lines. In cases like this, the later data are more indicative of the hydraulic conductivity of the soil (Bouwer, 1976, 1989). These data were renormalized so that the later straight-line portion had $h/h_0 = 1$ at $t = 0$. The T_0 for the later straight-line data on figure 23 is 5.4 min. Applying Eq.1 yields a hydraulic conductivity of $K = 2.2 \times 10^{-1}$m/day or 2.54×10^{-4}cm/sec.

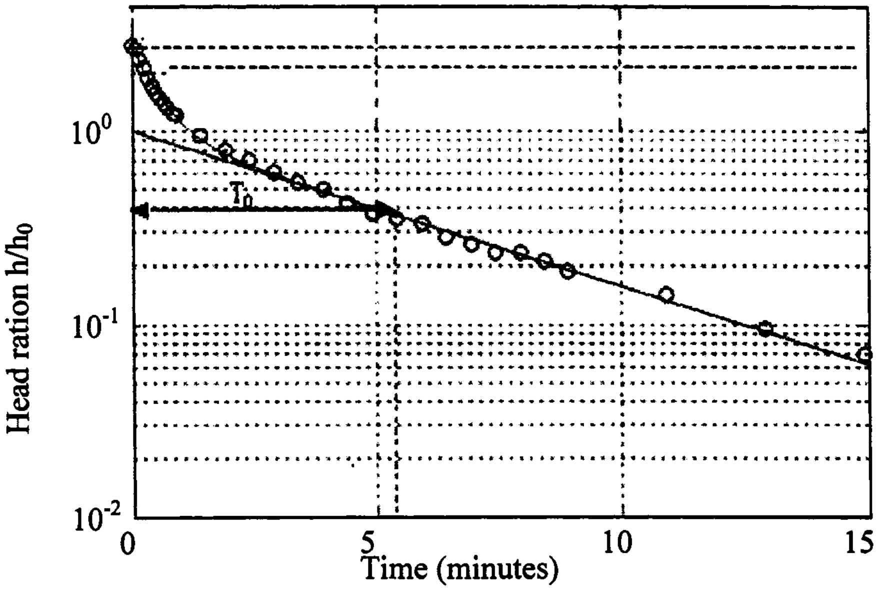


Figure 23. Plot of normalized head, h/h_0, versus time for well #2.

Table 6. Slug test data for well #2.

Elapsed time (min)	Level to water from bottom of well (m)	Change in water level, h (m)	Head ratio, h/h_0
	2.64 (static)		
0	3.82	1.18 (h_0)	1.000
0.0834	3.78	1.14	0.966
0.1667	3.64	1.00	0.847
0.25	3.54	0.90	0.763
0.3333	3.45	0.81	0.686
0.4167	3.37	0.73	0.619
0.5	3.31	0.67	0.568
0.5834	3.27	0.63	0.534
0.6667	3.23	0.59	0.500
0.75	3.20	0.56	0.474
0.8334	3.17	0.53	0.449
0.9167	3.15	0.51	0.432
1.4167	3.04	0.40	0.339
1.9167	2.98	0.34	0.288
2.4167	2.94	0.30	0.254
2.9167	2.90	0.26	0.220
3.4167	2.87	0.23	0.195
3.9167	2.85	0.21	0.178
4.4167	2.82	0.18	0.153
4.9167	2.80	0.16	0.135
5.4167	2.79	0.15	0.127
5.9167	2.78	0.14	0.119
6.4167	2.76	0.12	0.102
6.9167	2.75	0.11	0.093
7.4167	2.74	0.10	0.085
7.9167	2.74	0.10	0.085
8.4167	2.73	0.09	0.076
8.9167	2.72	0.08	0.068
10.9167	2.70	0.06	0.051
12.9167	2.68	0.04	0.034
14.9167	2.67	0.03	0.025
16.9167	2.67	0.03	0.025
18.9167	2.66	0.02	0.017

Well #3 was installed 5.79 m deep. Based on the collected data from the well point, the decay time T_0 equals 230 h (Fig. 24). The resulting hydraulic conductivity is K= 8.5 x 10^{-5} m/day or 9.8 x 10^{-8} cm/sec. The field data for well #3 are summarized in Table 7.

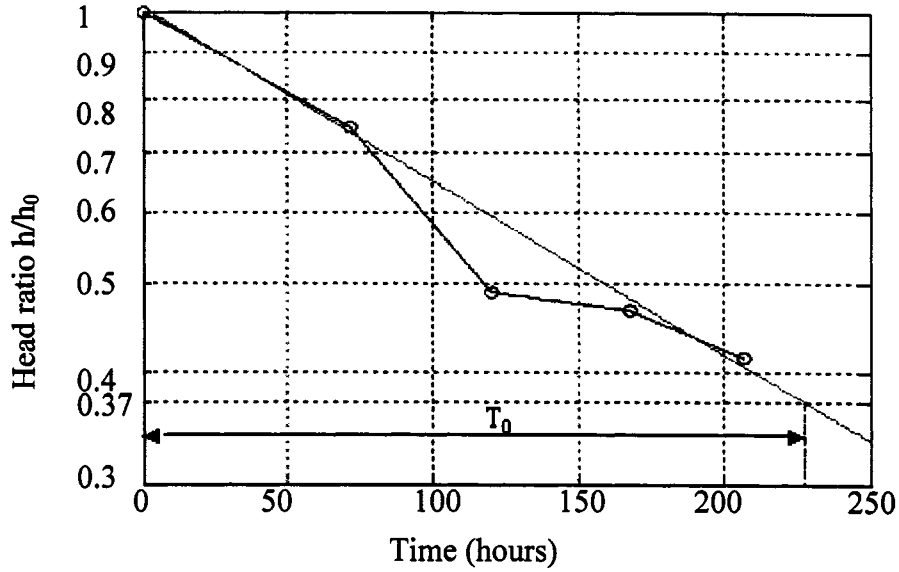


Figure 24. Plot of normalized head, h/h_0, versus time for well #3.

Table 7. Slug test data for well #3.

Elapsed time (hr)	Level to water from bottom of well (m)	Change in water level, h(m)	Head ratio, h/h_0
	2.91 (static)		
0	5.18	2.27(h_0)	1
72	4.57	1.66	0.730
120	3.96	1.05	0.461
168	3.91	1.00	0.438
207	3.78	0.86	0.382

The values of the hydraulic conductivity determined for wells #1 and #3 are identical and more than 3 orders of magnitude smaller than the value for well #2. The discrepancy between the hydraulic conductivity values may be due to either smearing of clay on the well screens or heterogeneity of the geologic material.

Groundwater Modeling with MODFLOW

The groundwater modeling software MODFLOW (McDonald and Harbaugh, 1988) was used to evaluate the processes of the hydrogeologic system of the Weeks Creek landslide. MODFLOW, developed by the U.S.G.S, simulates the flow of groundwater in the saturated zone. MODFLOW was selected for this simulation because it has been used satisfactorily in solving many similar problems and has proven its accuracy and reliability. MODFLOW is a finite-difference, groundwater-flow modeling program that simulates both the steady and transient states of flow in an anisotropic, heterogeneous, layered aquifer system. The program allows the analysis of the spatial distribution of the transfer of fluid mass within the hydrologic system. In addition, it permits time-dependent boundary conditions, allowing the simulation of processes that occur on a long timescale. The heterogeneity of the geologic materials can be represented by creating separate zones with different hydraulic properties.

Grid Design

The Weeks Creek landslide complex is apparently 1 km long and 0.5 km wide. A finite-difference grid was developed with 49 rows and 39 columns (Fig. 25). The grid spacings were set at $\Delta x = 25$ m and $\Delta y = 10$ m. The selected spacings allowed for adequate discretization of the dimensions of the landslide.

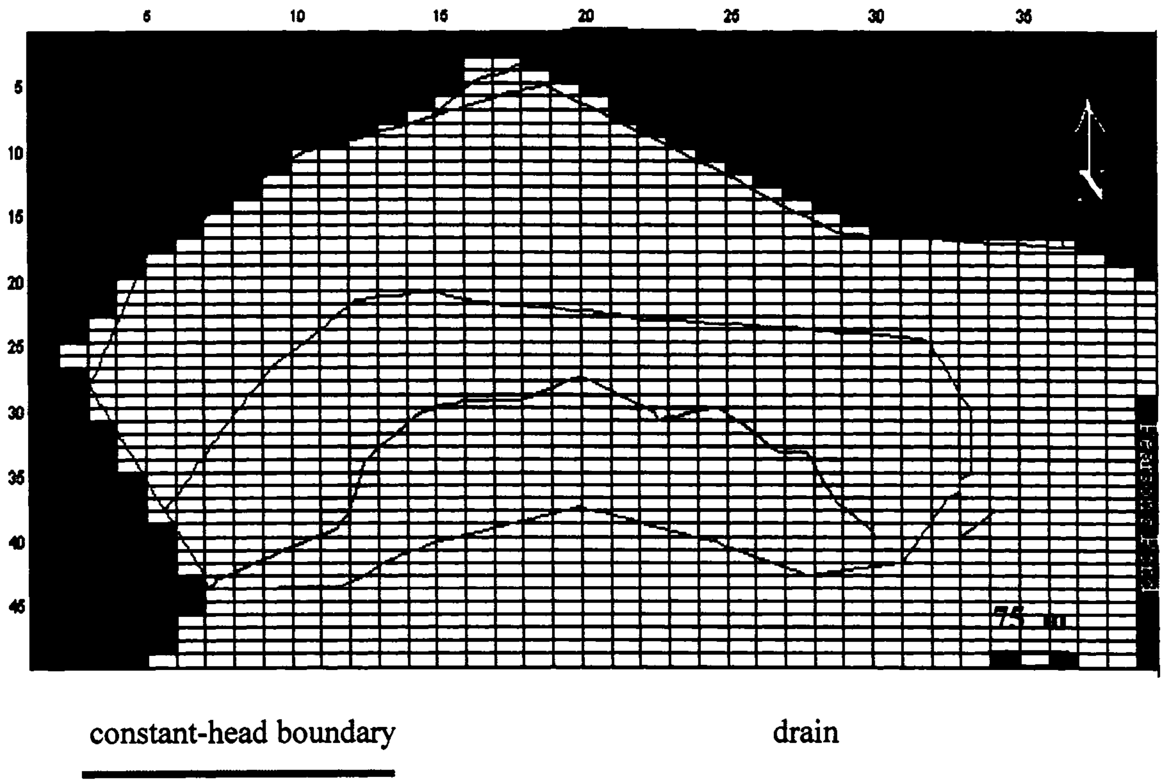


Figure 25. Finite-difference grid design.

Model Input Parameters

Quantifying the Boundary Conditions

To model the landslide, the boundaries of the model must be quantified. The upper surface is represented by the topography of the region (Fig. 26). Recharge provides infiltration through this upper boundary. The amount of water that is going to recharge the modeled region depends on: 1) the amount of precipitation available for recharge; 2) the hydraulic conductivity of the landslide material, which determines the volume of recharge water capable of moving downward (Fetter, 1994). The amount of water

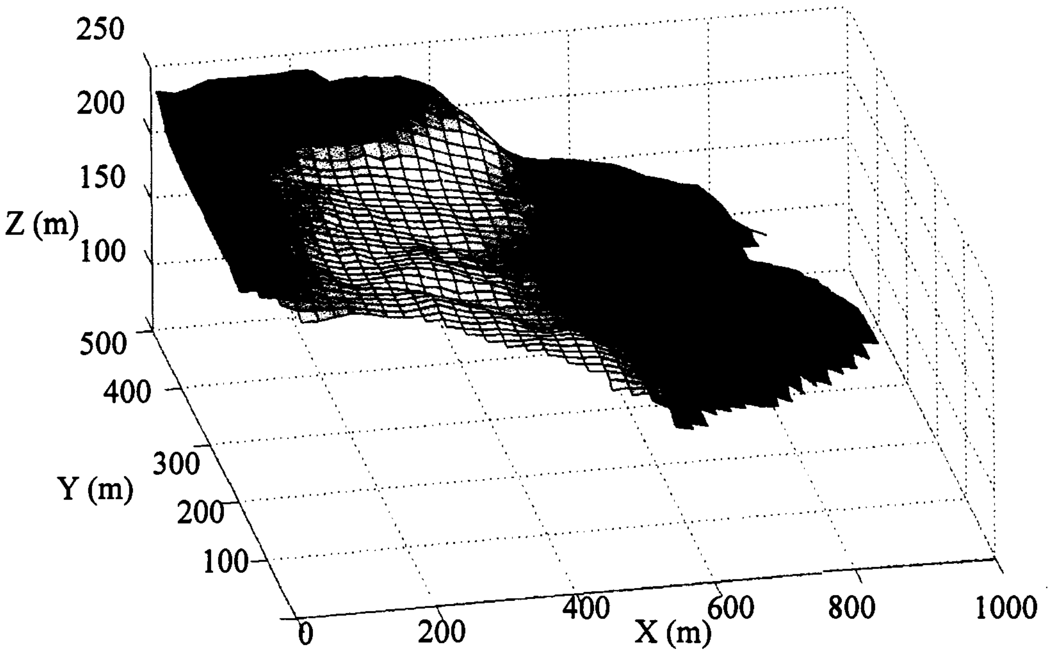


Figure 26. Topography of the study region viewed from the North (based on Cotton and Associates, 1994).

available for recharge is uncertain because it is unclear how much of it is being intercepted by vegetation, and what is the infiltration capacity of the soils which varies from dry to wet season. The recharge was assumed to be 20% of the historic precipitation because the high rainfall (90 cm/year) will contribute a significant fraction to recharge. This value of recharge produced groundwater level response in the monitoring wells and stream outflow matching the field observed data. The average historic precipitation data for the region is 90 cm/yr (Davis et al., 2000). The value of 20% of precipitation going to recharge amounts to a recharge rate of 2.5 x $10^{-3}m^3$/day per square meter or 164 m^3/day for the entire landslide for the steady-state model.

The lateral boundaries are represented by features of the landscape (e.g., ridges, rivers, etc.), that influence the flow into and out of the landslide. The ridges on the northeast and south were set as no-flow boundaries because they are natural groundwater divides. Pearson's Pond at the head of the landslide was set as a constant head boundary, which contributes inflow to the landslide. The head value was set to 216 m for the steady-state simulation. Weeks Creek, which bounds the landslide from the northwest and the west (at the toe of the landslide) was set as a constant-head-boundary, varying from 165 m on the northwest side to 91 m on the west side. The bottom of the model was a no-flow boundary representing the impermeable diabase intrusion, which marks the bottom of the aquifer at a depth of 30 meters. The stream in the middle of the landslide with head values ranging from 205 m at the eastern end to 99 m at the western end represented a head-dependent flux boundary, simulated in MODFLOW as a drain boundary.

Specific Yield Estimation

The typical specific yield of clay and sandy clay, which are the predominant materials of the Weeks Creek landslide, as indicated from borehole WCA-1, WCA-2 and SI-1, varies between 0% and 12% (Johnson, 1967). A way to estimate the specific yield at the study site is to divide a known quantity of recharge by the measured groundwater level response. According to Wieczorek, rainfall between 11/19/1981 and 12/4/1981 resulted in accumulated precipitation of 6.12 cm (2.41 inches). The previously assumed recharge 20% of the precipitation is used in the specific yield estimation. The estimated recharge of 1.22 cm caused the groundwater level in piezometers P1 and P2 to change 305.4 cm (7.62 ft). The following equation for specific yield estimation applies:

Sy = Recharge / Groundwater level change (2)

or Sy = 1.22 cm/ 305.4 cm = 0.4%.

Rainfall between 11/5/1982 and 11/26/1982 resulted in accumulated precipitation of 9.32 cm (3.67 inches). The estimated 20% recharge of 9.32 cm precipitation caused the groundwater level in piezometer P2 to change 396 cm (13 ft). Applying equation (2):

Sy = 1.86 cm/ 396 cm = 0.5%

Rainfall between 12/1/1983 and 12/15/1983 resulted in accumulated precipitation of 7.8 cm (3.06 inches). The estimated 20% recharge of 7.8 cm precipitation caused the groundwater level in piezometer P1 to change 290 cm (9.5 ft). Applying equation (2):

Sy = 1.56 cm/ 290 cm = 0.5%

The average of the three-years-calculated value for the specific yield was later used as an initial value in the calibration of the model. The assumed recharge and specific yield values were applied to the entire landslide area and were adjusted to reproduce the groundwater level response.

The estimated specific yield is uncertain due to uncertainty in the percentage value for the recharge as part of the precipitation. There are many factors that influence the relationship between precipitation and recharge. The more important are: 1) interception by vegetation; and 2) the infiltration capacity of the soil, which varies from dry season to wet season (Fetter, 1994).

Hydraulic Conductivity Value

The slug test measurements indicate a hydraulic conductivity for the landslide area varying from 9.8×10^{-8}cm/sec to 2.54×10^{-4}cm/sec. The value of 2.54×10^{-4}cm/sec was used as an initial value for hydraulic conductivity. The value of the hydraulic conductivity was consecutively adjusted so that an adequate groundwater level response was achieved.

Model Calibration

Steady-State Calibration

The assumed surface recharge was set at 20% of the average historic precipitation data (90 cm/yr) for the region (Davis et al., 2000), amounting to a recharge rate of 2.5×10^{-3} m^3/day per square meter or 164 m^3/day for the entire landslide. To calibrate the model under steady-state conditions, the assumed value for the hydraulic conductivity was adjusted (within its allowable range determined by the field testing) so that the stream discharge measured by Cotton and Associates in 1994 and the groundwater level elevation measured in the summer of 2002 as part of this study match those simulated by the model. The hydraulic conductivity was varied within the range established by the field data to calibrate the model. The value of 1×10^{-1} m/day or 1.16×10^{-4} cm/sec for the hydraulic conductivity matched the steady-state model predictions for the stream discharge and groundwater level in the well points. This calibrated hydraulic conductivity was acceptable because it is within the range of experimentally measured values from wells #1, #2 and #3.

To check for the discrepancy between the measured and the simulated groundwater levels, the residuals for each well were calculated (Table 8). The observed values in the fourth column were obtained at the end of the slug tests, described in the previous section, performed in June, July and August of 2002. The calculated residuals in the sixth column are well within the precision (1 m) of the observed groundwater levels. The stream discharge measured by Cotton and Associates in 1994 was 35 to 70 liters per minute. The calibrated steady-state model generated stream outflow of 100 liters per minute (146 m^3/day), rainfall recharge of 114 liters per minute (164 m^3/day) for the entire landslide and inflow from upgradient of 112 liters per minute (162 m^3/day). The model results indicate that inflow occurs from the upgradient region at the head of the landslide and from rainfall, and that outflow occurs to the stream at the middle of the landslide and to Weeks Creek (Fig. 27). Figure 28 presents the steady-state hydraulic head distribution.

Table 8. Residuals for calibrated steady-state.

Name	X	Y	Observed	Computed	Residual
well #1	416	236	158 m	158.16 m	0.16 m
well #2	626	163	183 m	182.49 m	-0.51 m
well #3	403	175	157 m	156.77 m	-0.23 m

Transient Calibration

Following the steady-state calibration, a transient calibration was performed. The transient simulation began with the head distribution from the calibrated steady-state solution. The transient model was calibrated by fitting of the simulated results to the field data on time dependent water-level changes caused by variations in rainfall recharge.

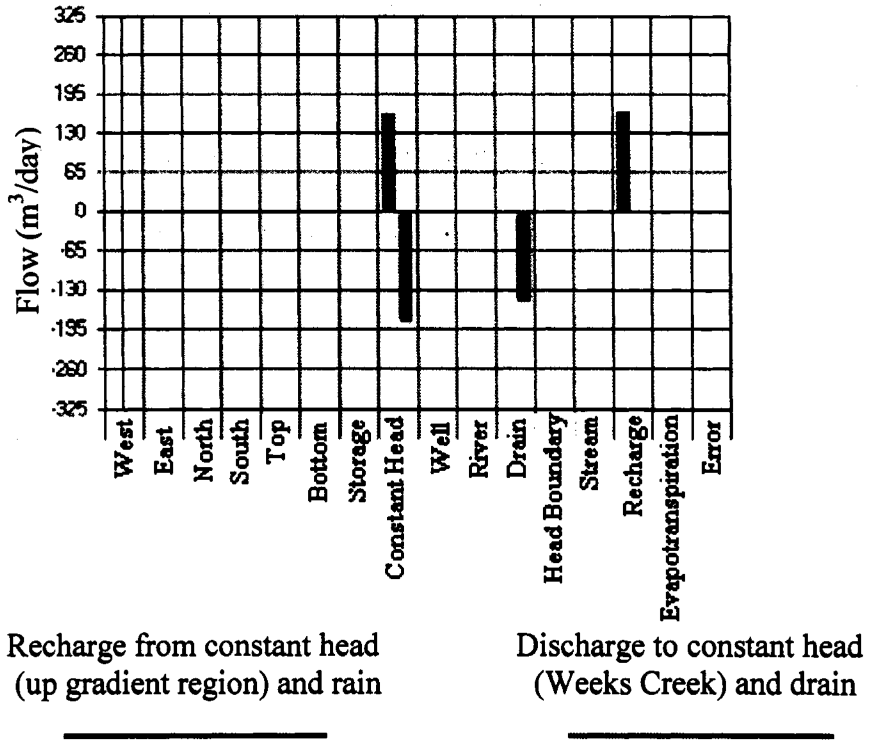


Figure 27. Mass balance summary for the calibrated steady-state model.

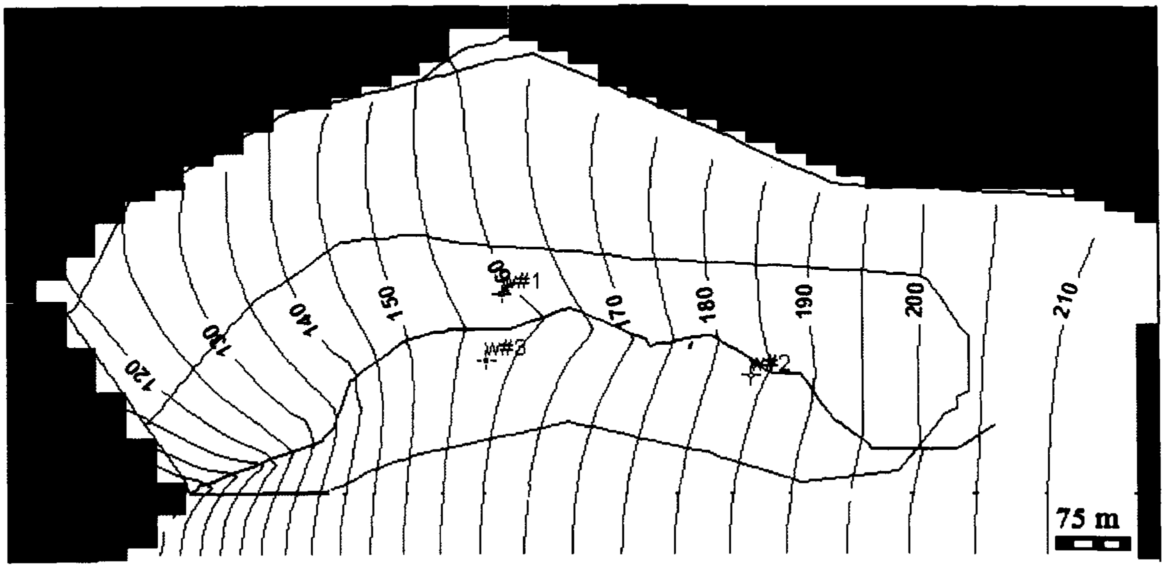


Figure 28. Steady-state hydraulic head distribution.

During the rainfall-free period between the end of the wet season and the end of the dry season of 2002, the water level in the pond at the head of the landslide dropped about 1.4 meters. In the transient simulation, the water level in the pond was adjusted for different stress periods in accordance with the observed water level during the different seasons, rising from 216 m in the beginning of the wet season to 217.4 m and gradually subsiding from 217.4 m in the beginning of the dry season to 216 m (Table 9).

Table 9. Water level fluctuation modeled in Pearson's Pond for a year of average precipitation.

Month	Pond elevation, (m)		Month	Pond elevation, (m)
November	216		May	217.4
December	216.28		June	217.12
January	216.56		July	216.84
February	216.84		August	216.56
March	217.12		September	216.28
April	217.4		October	216

The transient simulation had 36 stress periods, each representing a month between November 1981 and October 1984. Each one-month stress period was discretized into four equal time steps. The recharge value for each month is given in Table 10.

In order for the predicted head to agree with the historic data (Fig. 20, p. 31), the specific yield value had to be adjusted to 2% instead of the above-estimated 0.5%.

The transient output of the model reveals a good correlation between historic and simulated data. A recharge that is 20% of a heavy rainfall year (114 cm per year) leads to a solution (Figs. 29, 30 and 31) that fits well the pattern of corresponding water level data of Wieczorek (2003, Fig. 20, p. 31). The transient solution of the model reflects the relationship between recharge from rainfall and groundwater level. The groundwater

Table 10. Monthly recharge value for year of heavy precipitation.

Month /Year	Recharge (m^3/day)		Month/Year	Recharge (m^3/day)
11 / 81	0.000408		5 / 83	0.00009
12 / 81	0.00109		6 / 83	0
1 / 82	0.0017		7 / 83	0
2 / 82	0.000866		8 / 83	0
3 / 82	0.0013		9 / 83	0
4 / 82	0		10 / 83	0.00006
5 / 82	0		11 / 83	0.000936
6 / 82	0		12 / 83	0.00129
7 / 82	0		1 / 84	0.0000457
8 / 82	0		2 / 84	0.0004284
9 / 82	0		3 / 84	0.0002421
10 / 82	0		4 / 84	0
11 / 82	0.00116		5 / 84	0
12 / 82	0.0008144		6 / 84	0
1 / 83	0.0016		7 / 84	0
2 / 83	0.0016		8 / 84	0
3 / 82	0.0013		9 / 84	0
4 / 82	0.000833		10 / 84	0

level at the piezometer locations fluctuated approximately 3.5 meters between the dry and the wet season in a year with heavy precipitation, reaching the ground surface during the wet season. The model results indicate groundwater fluctuations of approximately 3.4 m in well #1, 3.6 m in well #2 and 3.7 m in well #3 for the transient simulation of a period of heavy precipitation (114 cm per year). There is variation between the modeled and the field data within +/- 20 cm. Therefore, the accuracy of the simulated groundwater levels was assumed to be +/- 20 cm.

The successful transient calibration of the model for the years with heavy precipitation allows for simulation of the groundwater level fluctuations during an average rainfall year (90 cm precipitation). The calculated relationship between recharge from rainfall and groundwater fluctuation is shown in Figures 32, 33 and 34. The model results indicate a groundwater level fluctuation of approximately 2.7 m in well #1, 2.9 m in well #2 and 2.9 m in well #3. The average recharge value for each month is given in Table 11.

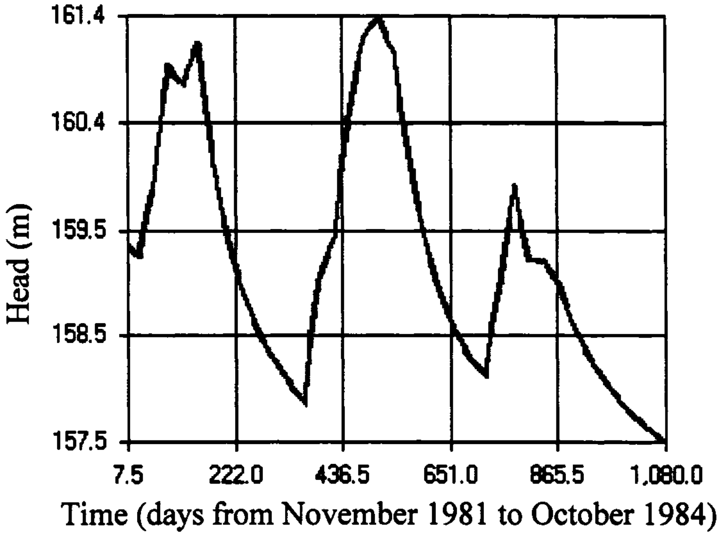


Figure 29. Simulated groundwater fluctuation in well #1 for years of heavy precipitation. The ground surface is at 162 m.

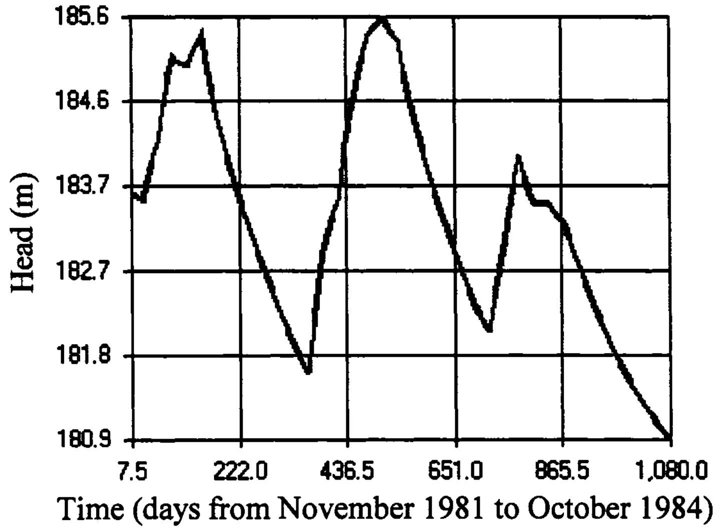


Figure 30. Simulated groundwater fluctuation in well #2 for years of heavy precipitation. The ground surface is at 185.5 m.

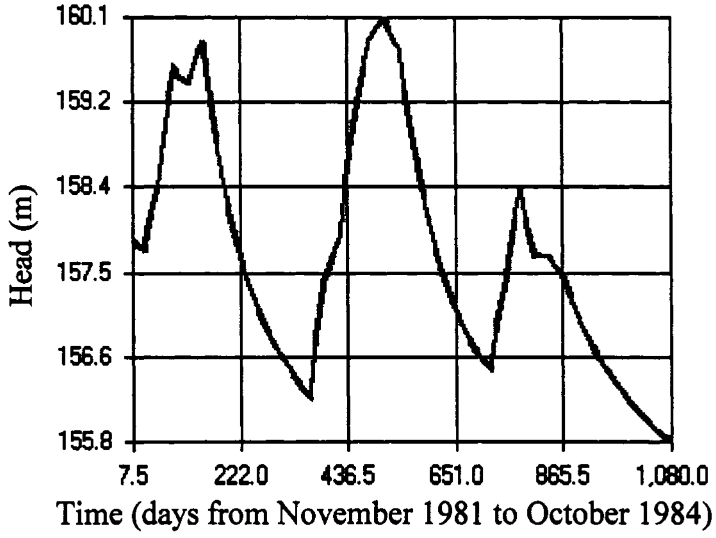


Figure 31. Simulated groundwater fluctuation in well #3 for years of heavy precipitation. The ground surface is at 160 m.

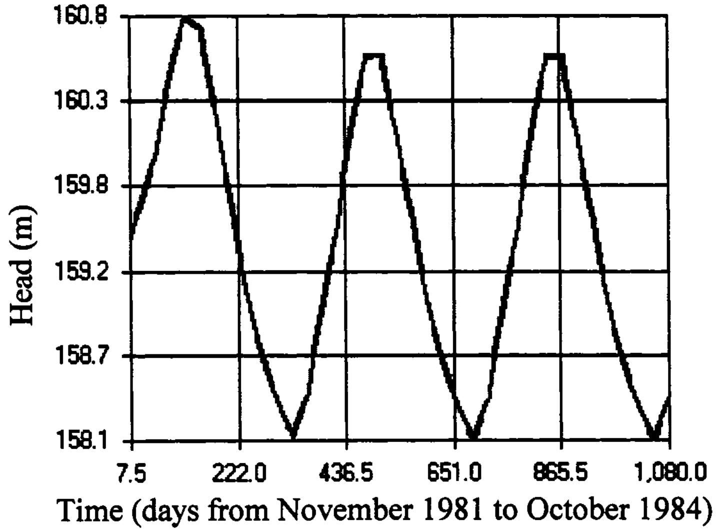


Figure 32. Simulated groundwater fluctuation in well #1 for years of average precipitation. The ground surface is at 162 m.

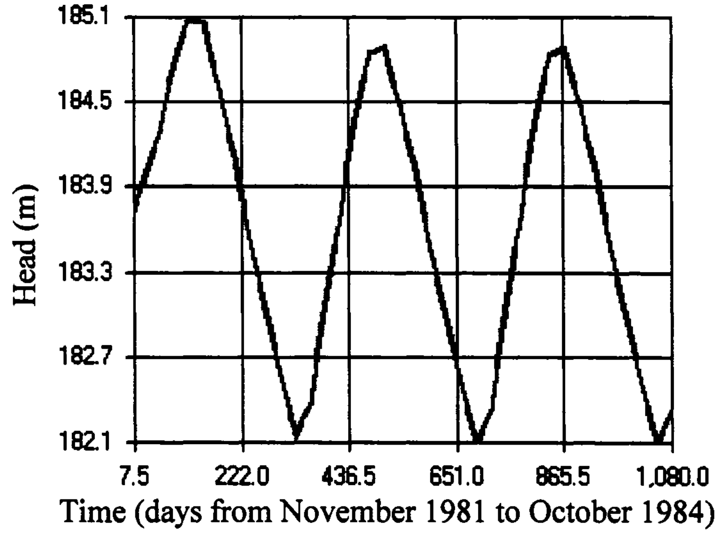


Figure 33. Simulate groundwater fluctuation in well #2 for years of average precipitation. The ground surface is at 185.5 m.

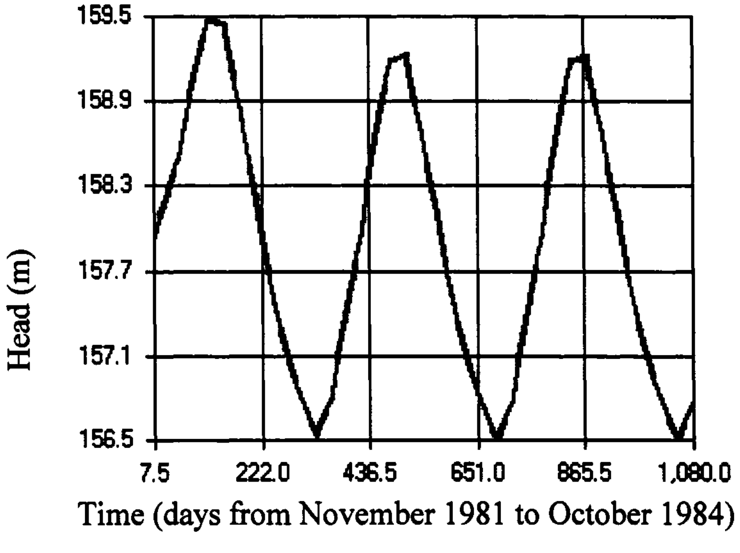


Figure 34. Simulated groundwater fluctuation in well #3 for years of average precipitation. The ground surface is at 160 m.

Table 11. Monthly recharge value for simulated average rainy season.

Month	Recharge (m^3/day)		Month	Recharge (m^3/day)
November	0.0008		May	0.0002
December	0.0009		June	0
January	0.0012		July	0
February	0.0012		August	0
March	0.0009		September	0
April	0.0004		October	0.0004
May	0.0002		November	0.0008
June	0		December	0.0009
July	0		January	0.0012
August	0		February	0.0012
September	0		March	0.0009
October	0.0004		April	0.0004
November	0.0008		May	0.0002
December	0.0009		June	0
January	0.0012		July	0
February	0.0012		August	0
March	0.0009		September	0
April	0.0004		October	0.0004

Results of the Modeling

The groundwater levels throughout the simulated region, calculated for the different seasons, are used for computing the FS of the landslide. The model generated reasonable groundwater level fluctuations for the different seasons and different precipitation rates. The model mass balance analysis indicated that the maximum stream flow for the unnamed creek in the wet season reached 132 liters per minute in March 1983 (191 m^3/day) and a minimum stream outflow of 78 liters per minute (113 m^3/day) in October 1984 or the end of the dry season.

Figures 35 and 36 present a summary of the model-generated inflows and outflows for the period from November 1981 to October 1984. Consistent with the steady-state model, the inflow to the study site is generated by the constant head boundary located at the head of the landslide and by the rainfall. The outflow from the study site occurs at the constant head boundary located at the toe of the landslide and at the drain (the stream) in the middle of the landslide.

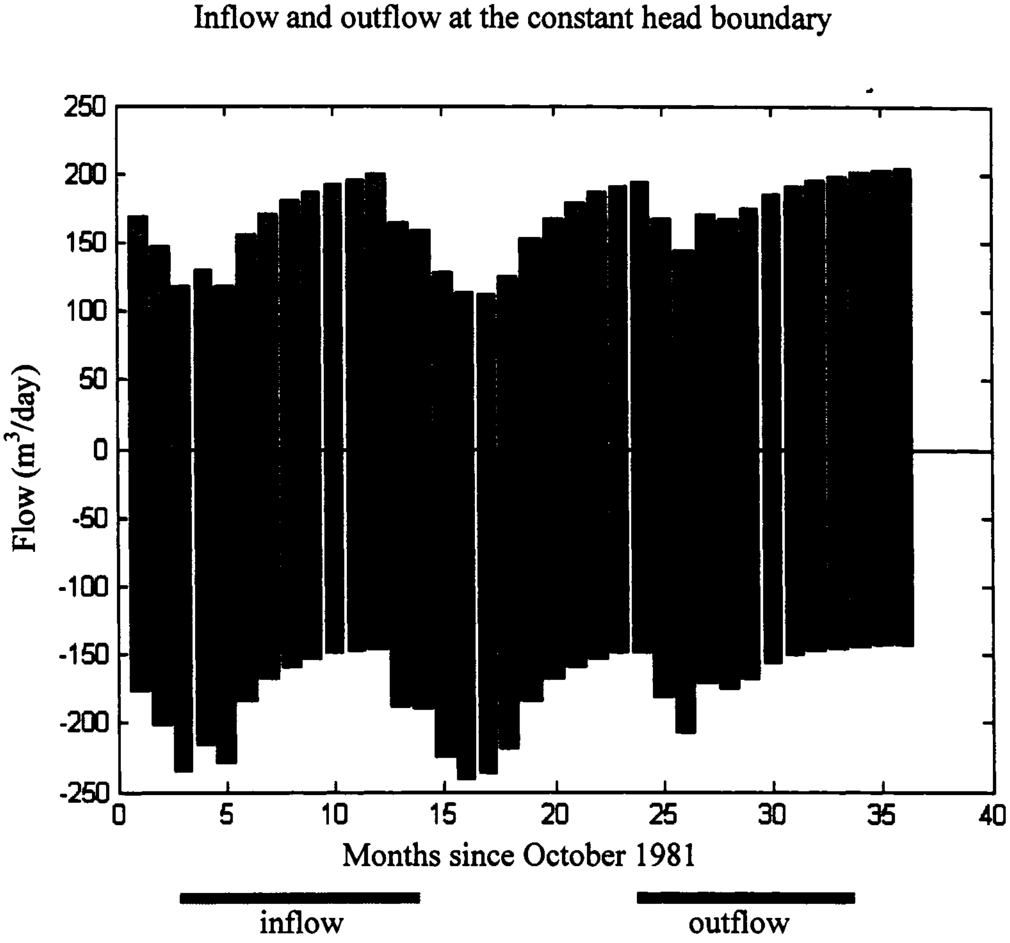


Figure 35. Total landslide inflow contributed by the upgradient region and outflow to Weeks Creek for years with heavy precipitation.

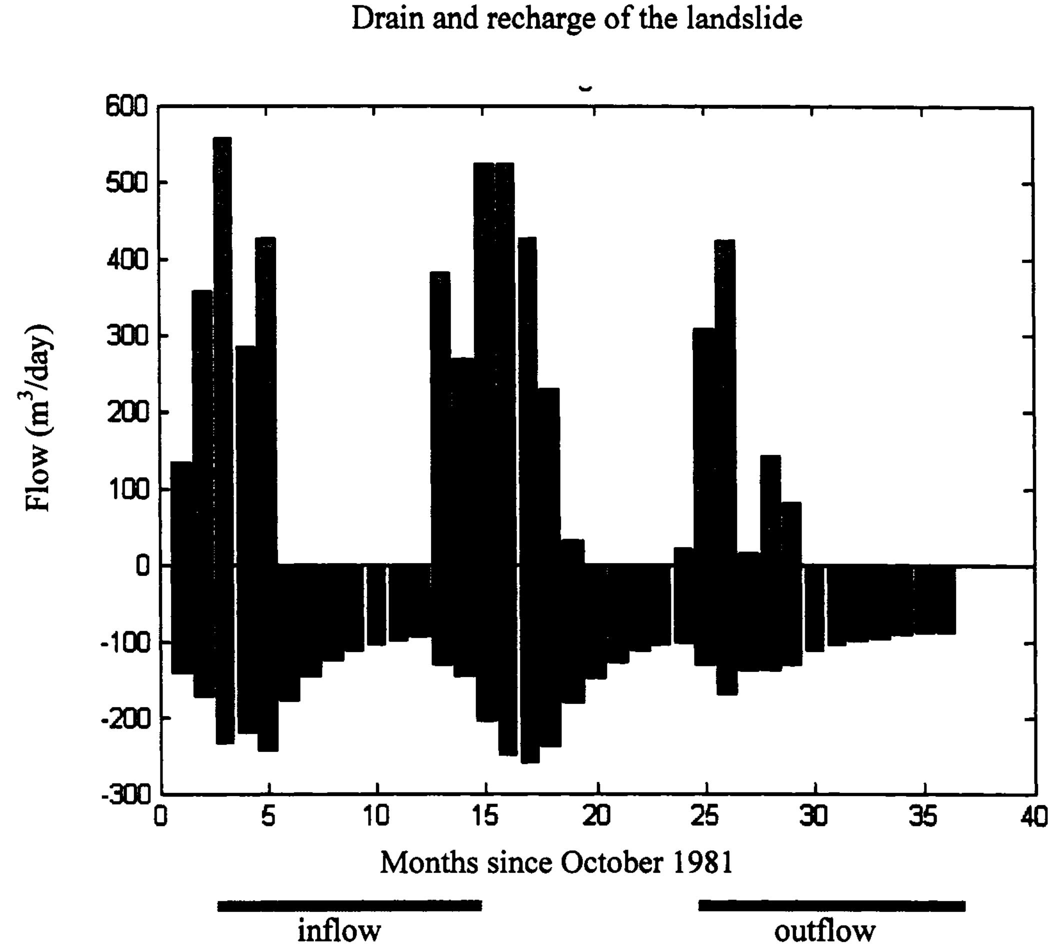


Figure 36. Total landslide inflow contributed for years with heavy precipitation. by rainfall and outflow to the stream at the middle of the landslide.

Uncertainties of Groundwater Modeling

The accuracy with which the groundwater level fluctuation was modeled depended on several factors, the most important are:

1) the accuracy of the estimated hydraulic conductivity,
2) the accuracy of the estimated specific yield,
3) the accuracy of the rainfall recharge,
4) the numerical accuracy of the MODFLOW program,

The slug test measurements, described in the section entitled Hydraulic Conductivity Estimation, indicate a hydraulic conductivity for the landslide area varying from 9.8 x 10^{-8}cm/sec to 2.54 x 10^{-4}cm/sec. Because of the limited ability to collect field data, a single value of the hydraulic conductivity (K = 1.16 x 10^{-4}cm/sec) was used for the entire landslide area. Due to the soil heterogeneity, the hydraulic conductivity may vary over the landslide area. For more accurate groundwater modeling, more field data on the hydraulic conductivity would be needed.

The accuracy of the estimated specific yield is uncertain because the specific yield calculation depends on the amount of recharge from precipitation. The estimated specific yield was Sy = 0.5%. A higher specific yield (S = 2%) had to be assumed in the modeling to match the measured groundwater levels. The amount of recharge from precipitation is uncertain because it depends on a variety of factors such as soil condition (dry or wet) and the types and density of vegetation.

The accuracy with which MODFLOW simulates the groundwater level in a particular location with respect to the ground surface depends on the size of the applied grid. For improvement of the accuracy, smaller grid cells should be used in the regions with steeper slopes and steeper hydraulic gradient.

FACTOR OF SAFETY ANALYSIS

The stability of a slope can be quantified by the factor of safety (FS), defined as the ratio of the forces resisting sliding movement to the forces promoting movement (driving forces). At the moment of failure, the forces resisting movement are equal to or slightly less than the forces promoting movement and the FS is less than one. Thus, if the FS is larger than one, the slope is theoretically stable.

A FS analysis of the Weeks Creek landslide was calculated to determine the conditions under which the landslide becomes active. In particular, the relationship between precipitation on the groundwater levels and the FS of the landslide were determined.

Methods

The computer program used for the FS calculation is STEDWIN, developed by Harold Van Aller in 1999. It utilizes the slope stability analysis program PCSTABLE developed at Purdue University in 1988. STEDWIN is used for inputting the geotechnical and hydrological data and slope geometry of the Weeks Creek landslide, and for generating the numerical calculations and the graphical output of the stability analysis. It offers three methods for calculating the factor of safety. The first method is the Bishop method (Bishop, 1955). In the Bishop method, the program generates slip surfaces of circular shape. The borehole analysis of the Weeks Creek landslide reveals a disrupted and irregular landslide mass in more than one location, as well as significant weakness of the soils. The Weeks Creek landslide is characterized by significant disruption of the failed mass and irregular geometry. These facts suggest that the shape of the failure surface cross-section may not be circular. Therefore the Bishop method was not used in this FS analysis. A second method offered in STEDWIN is the simplified Janbu method (Janbu, 1973). In this method, the slide is divided into vertical slices. The method generates slip surfaces for every slice. This method employs the assumption that the interslice forces are horizontal which can lead to an underestimation of the FS of the slope if the interslice forces have a non-horizontal component. Because of the complicated slip surfaces, it is improper to assume that the interslice forces in the Weeks Creek landslide are strictly horizontal, and therefore the simplified Janbu method was not used. For the mixed characteristics of this landslide (slumps and mudflows), the most appropriate method of calculating the FS was the method of random search. The FS was calculated using the third methodology, which is basically a modified Janbu method. The Janbu method is used to propose potential failure surfaces for each vertical slice. A random search algorithm finds an optimum solution to the complex problem (e. g., finding the failure surfaces with the smallest FS) starting from a population of possible solutions. At each iterative step, an improved solution is proposed by applying mathematical genetic operators: selection, crossover and mutation, to a current population (Goldberg, 1989). After that, the proposed solution is tested to see if it fulfills the model equations better than the previous solutions. If it does, one of the poorer previous solutions is discarded from the population and replaced by the new solution. The whole process is repeated until convergence is reached, i.e., until the new solution does not improve in terms of satisfying the model equations.

The stability analysis used for this investigation involves the following steps:

1) Applying the elevation of the surface of the landslide based on a topographic map,
2) Applying the failure surface of the landslide based on the inclinometer readings,
3) Applying the ground water level for the dry and wet season based on the computer model generated by MODFLOW for both heavy (114 cm per year) and average (90 cm per year) precipitation,
4) Applying the soil parameters:
    a) Saturated Unit Weight = 18 +/- 0.56 kN/m^3 (114.48 +/- 3.18 pcf), (Cotton and Associates, 1994),
    b) Dry Unit Weight = 14.3 +/- 0.97 kN/m^3 (91.05 +/- 6.15 pcf) (Cotton and Associates, 1994),
    c) Cohesion c = 2.62 kPa (54.72 psf), from laboratory test results (Cotton and Associates, 1994), and
    d) Friction angle $\phi = 14.9°$, from laboratory test results (Cotton and Associates, 1994),
5) Calculating the FS using the STEDWIN computer program (using the modified Janbu method with random search).

The topographic surface used in the process of estimating the FS of the Weeks Creek landslide was mapped by Cotton and Associates in 1994. Figure 37 shows a 3-D version of the map.

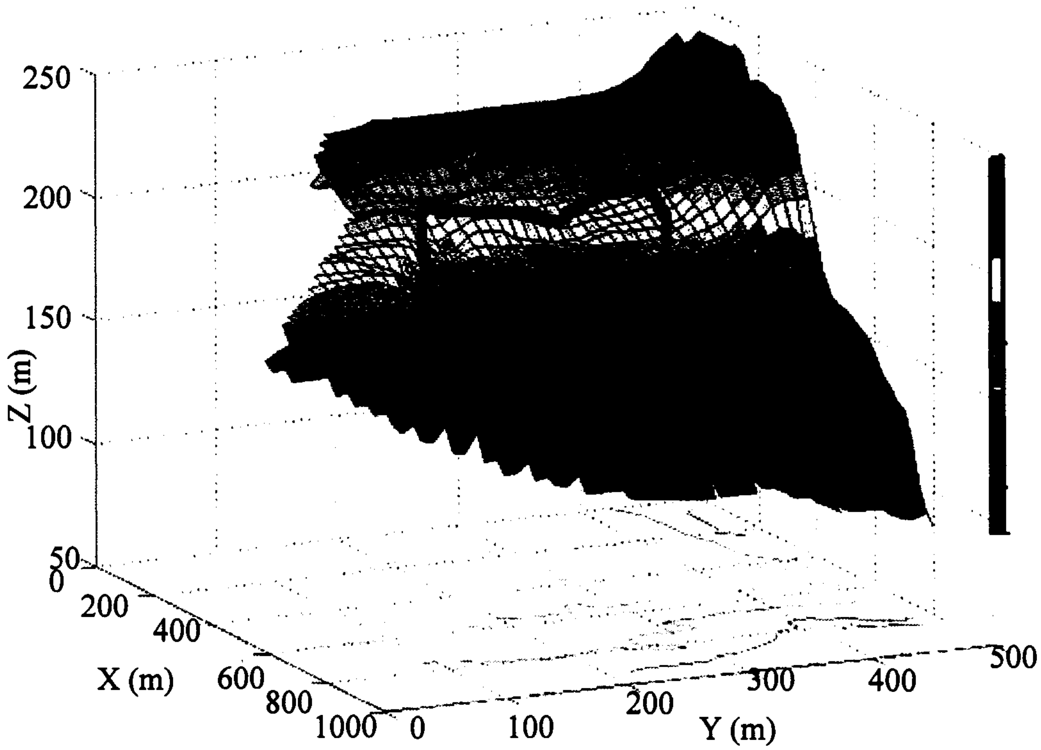


Figure 37. Landslide topography (based on Cotton and Associates, 1994).

Factor of Safety Estimation

The slope-stability computer model described above was used to determine the variation of the FS with changing groundwater level. The computer model generated many potential failure surfaces for each groundwater level. The FS for the landslide is the minimum of the FS for all the potential failure surfaces for a particular groundwater level. Figures 38 and 39 show the potential failure surfaces and their FS as calculated by STEDWIN for the historic average precipitation of 90 cm (Davis et al., 2000). Figure 38 displays the results of the simulation representing the end of the dry season (no precipitation) when the landslide is expected to be at its most stable condition (lowest groundwater level). Figure 39 displays the results representing the end of the rainy

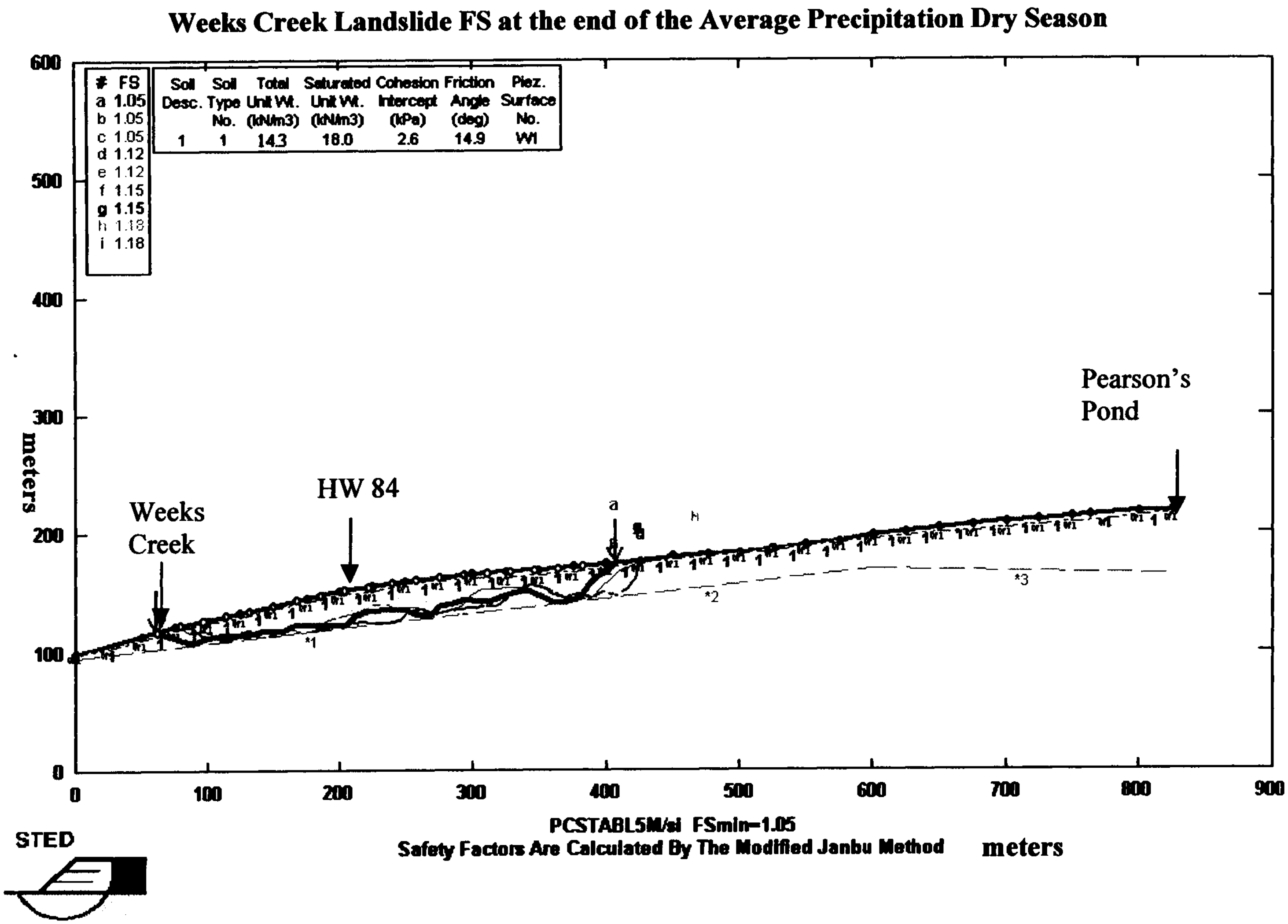


Figure 38. STEDWIN model output for the end of the dry season after an average precipitation season FS=1.05.

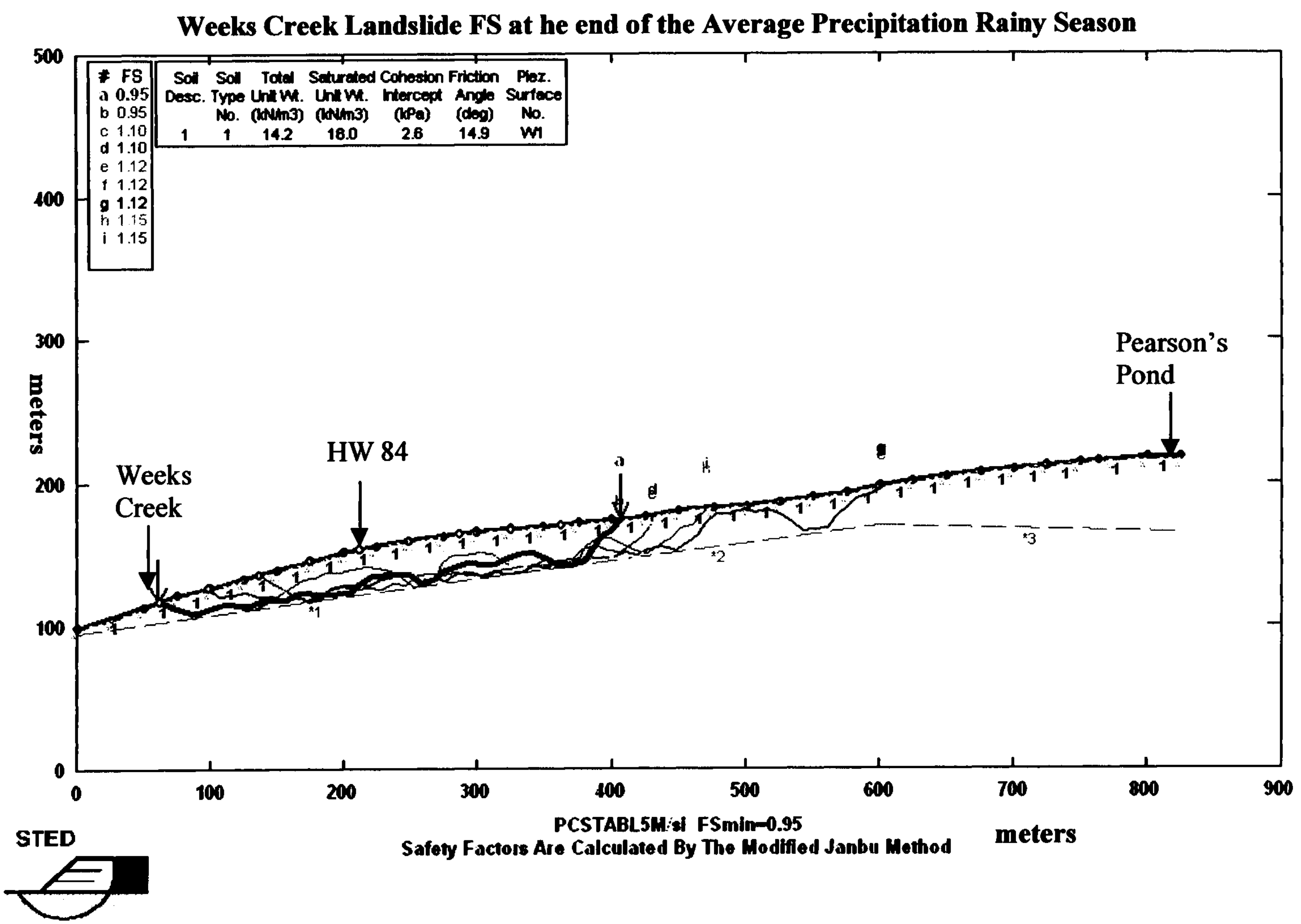


Figure 39. STEDWIN model output for the end of the wet season after an average precipitation season. FS = 0.95

season. Details about the accuracy of the estimated FS are presented in the section of this report entitled: Accuracy of the factor of safety estimate, page 77.

The FS for the Weeks Creek landslide for a season of average precipitation (90 cm per year) at the end of the dry season (Fig. 38), when the water table is about 3.5 m below ground surface, is 1.05 +/- 0.03 (in theory the landslide is stable when FS > 1). For a season of average precipitation at the end of the rainy season, when the water table is about 1 m below ground surface (Fig. 39), the FS is 0.95 +/- 0.03.

Figures 40 and 41 show the potential failure surfaces and their FS for a year with heavy precipitation (114 cm), at the end of the dry season and the end of the rainy season, respectively. The FS for the Weeks Creek landslide for a year of heavy precipitation at the end of the dry season, when the water level is about 3.5 m below ground surface, is 1.05 +/- 0.03. At the end of the rainy season for a year of heavy precipitation, when the water level reaches the ground surface, the FS is 0.91 +/- 0.03.

Several simulations using the computer program STEDWIN, with changing groundwater levels, revealed that if the groundwater level were about 2 m below ground surface the landslide would be potentially stable (FS = 1) at all times. Figure 42 shows the FS for the Weeks Creek landslide for an assumed groundwater level 2 m below ground surface. Several simulations with MODFLOW showed that precipitation of no more than about 70 cm per year would keep the water level more than 2 m below ground surface. This critical precipitation is smaller than the average annual precipitation of 90 cm in the region, suggesting that the landslide will remain active until the climate conditions or the landslide topography or both change significantly.

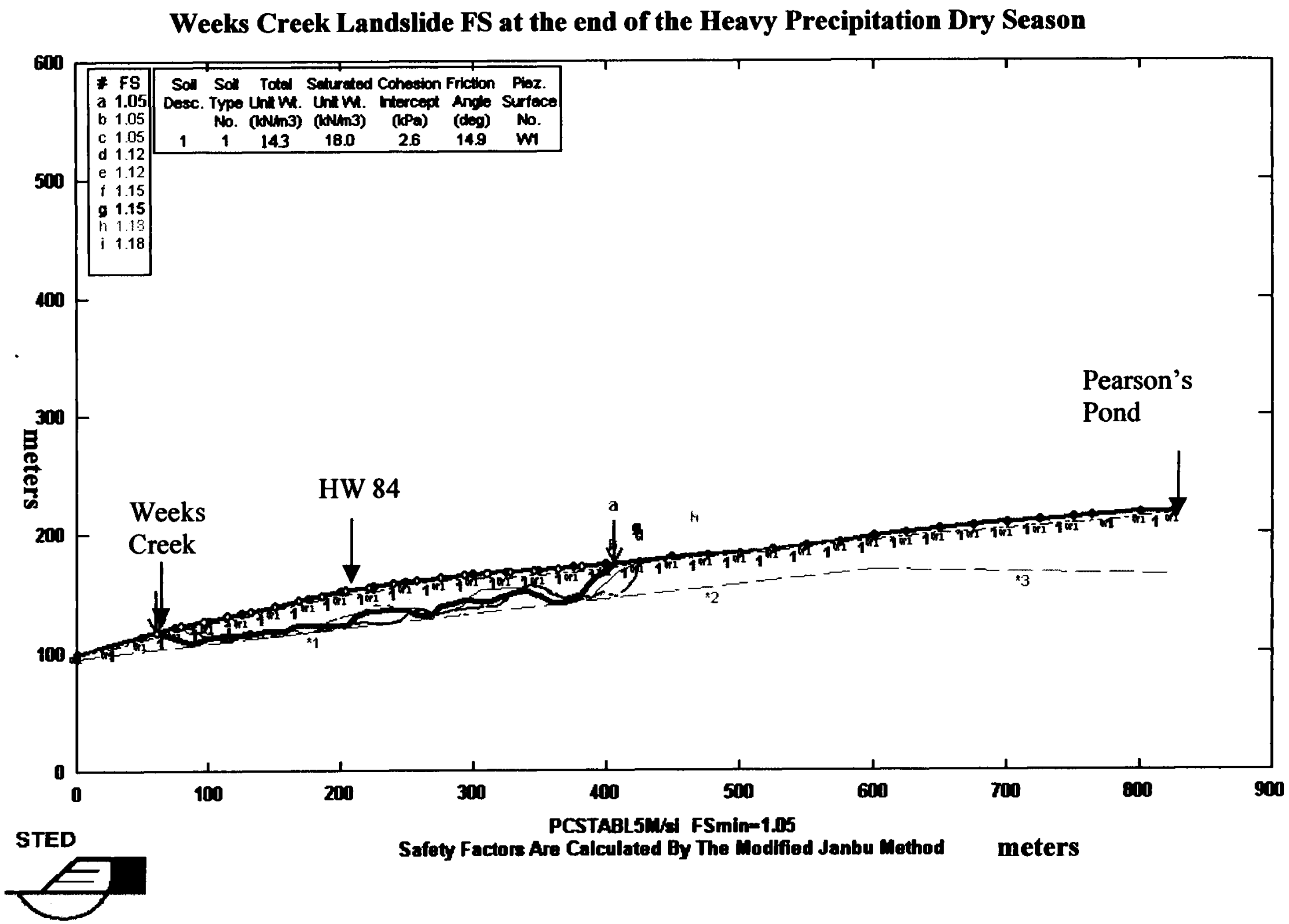


Figure 40. STEDWIN model output for the end of the dry season after a heavy precipitation season FS=1.05.

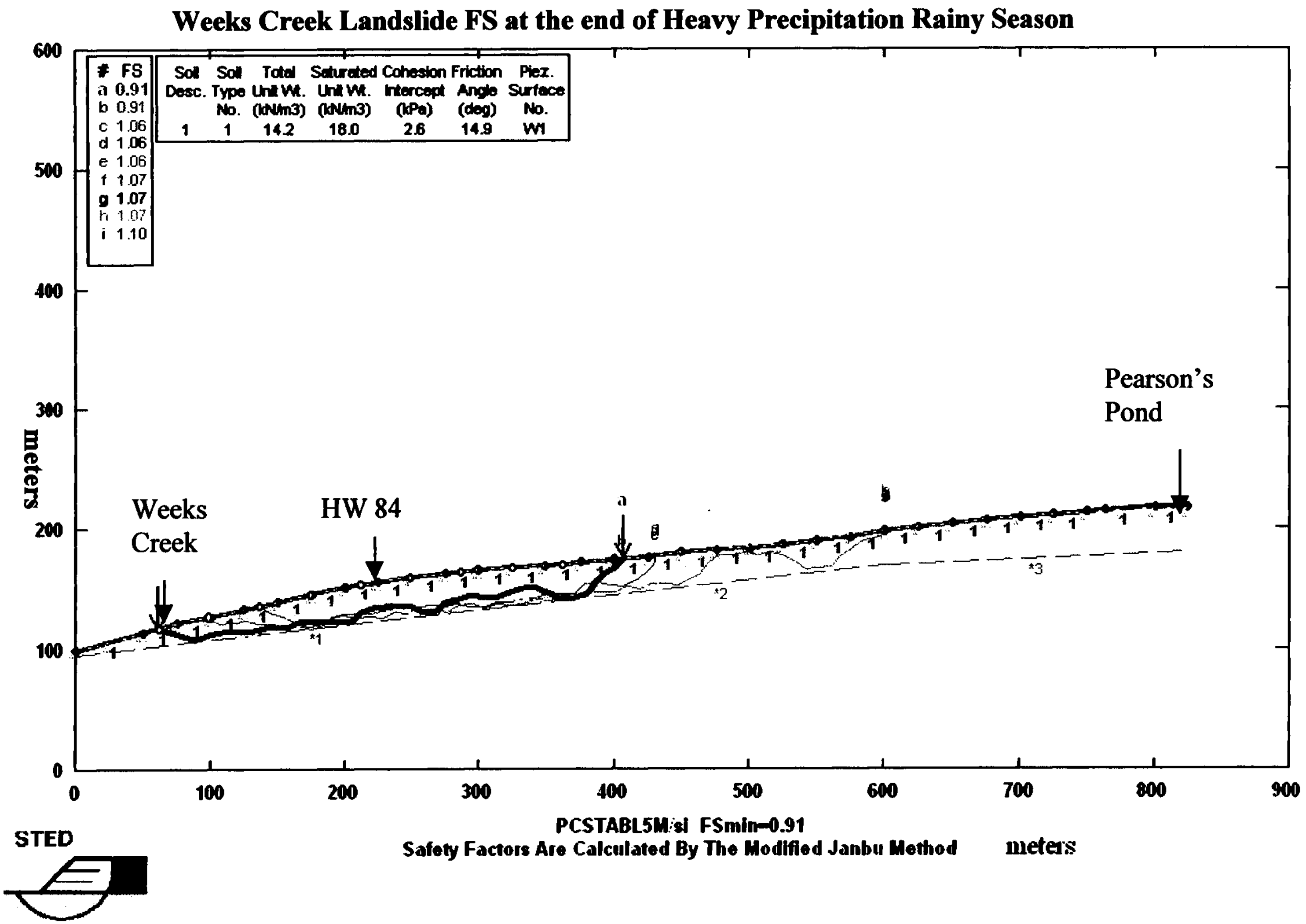


Figure 41. STEDWIN model output for the end of the wet season after a heavy precipitation season. FS = 0.91.

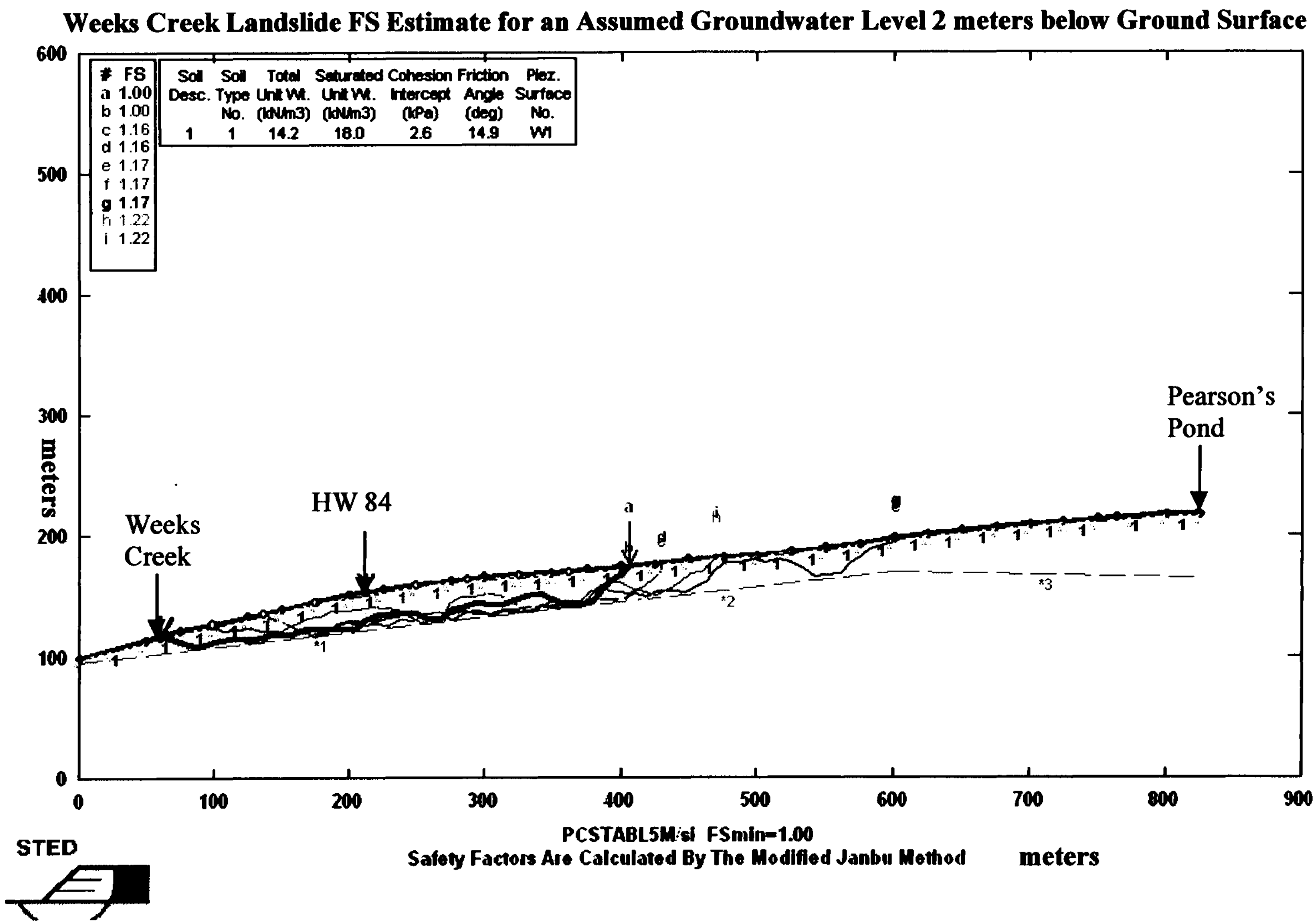


Figure 42. STEDWIN model output for simulated groundwater level 2 m below ground surface. FS = 1.

MODFLOW-simulated-water level for a year of average precipitation (90 cm) demonstrates that the landslide becomes active (groundwater rises above 2 m below ground surface) within 60 days of the beginning of the wet season. The water level then remains above that level throughout the rainy season, which means that during the rainy season the slide is active and becomes temporarily stable (groundwater drops lower than 2 m below ground surface) about 40 days after the beginning of the dry season. For a year of heavy precipitation (114 cm), the landslide becomes active within 45 days of beginning of the wet season and stabilizes about 60 days after the beginning of the dry season.

Seismic Response

Potential Earthquake Response

The Weeks Creek landslide moved approximately 1 meter during the San Francisco earthquake in 1906 and 3 cm during the 1989 Loma Prieta earthquake. Therefore, the slope is prone to sliding not only due to high groundwater levels but also due to seismic shaking.

To estimate the sensitivity of the Weeks Creek landslide to earthquakes originating on the nearby active San Andreas fault (4 km east of the slide), a slope stability analysis was performed and the FS of the landslide was estimated for cases of moderate (5.5 on the Richter scale) and high (>6.5 on the Richter scale) magnitude earthquakes. The STEDWIN computer program allows the estimation of the FS during an earthquake by using as input estimates the peak horizontal acceleration of the ground surface due to the earthquake. The dependence of ground acceleration on the earthquake magnitude was determined from relationships established by Joyner et al. (1981) and Campbell et al. (1980). The material properties of the soils in the Weeks Creek landslide are similar to those described in Joyner's open-file report. The distance-ground acceleration curves from the report (Fig. 43) were used to determine the appropriate ground acceleration at the Weeks Creek landslide.

A potential earthquake with an epicenter 4 km from the landslide and a magnitude of 6.5 on the Richter scale was considered initially (at the end of a dry season or FS>1 if no earthquake is present) and the corresponding FS was calculated (Fig. 44). An earthquake with a magnitude of 6.7 or larger has been predicted to occur in the San Francisco Bay Region in the next 30 years with a probability of 62 percent by The Working Group on California Earthquakes (1999). The FS of the landslide during such an event was reduced to 0.46 +/- 0.03. For an earthquake with a magnitude of 5.5, the FS was 0.53 +/- 0.03 (Fig. 45). Earthquakes with significant variations in magnitude (moderate to strong) produced similar and significant reductions in the FS. Therefore, the possible inaccuracy in the assumed values of the ground acceleration was of limited consequence for the prediction of the earthquake activation of the landslide.

The FS analysis indicates that moderate-to-high magnitude earthquakes centered on the nearby San Andreas fault can cause significant reduction of the FS as well as a significant increase in the size of the sliding mass. Comparison of the sliding area (FS of the potential slip surfaces) on Figures 38, 39, 40 and 41, when no earthquake occurs, with Figures 44 and 45, when an earthquake occurs, reveals an increase in the length of the potential sliding area (all potential slip surfaces having FS<1) by 200 m. The topographically lower section of the landslide serves as a buttress to the upper section.

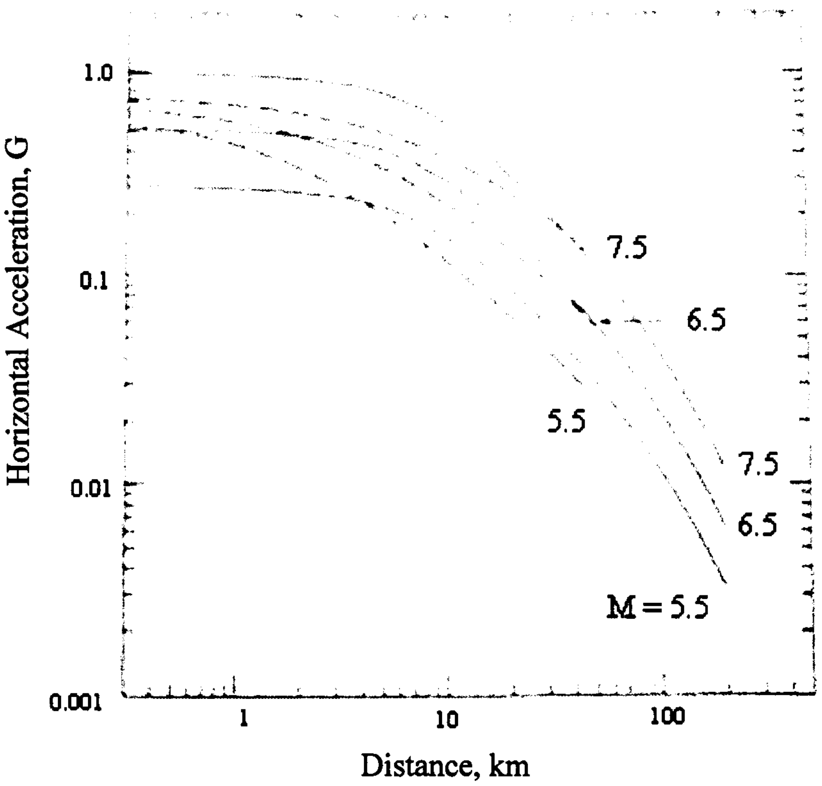


Figure 43. Comparison of predicted values of peak horizontal acceleration by Campbell et al. (1980) (dashed lines) with the curves by Joyner et al. (1981) (solid lines), (Joyner et al, 1981).

As the lower section becomes active during an earthquake, its movement permits movement of the normally stable upper section of the landslide. Thus the length of the landslide mass increases from 300 m to 500 m in length when earthquake occurs. This larger length during earthquakes coincides with the length estimate of the active landslide based on visible topographic features. A map comparison between the active portions of the landslide in conditions with and without an earthquake is shown in Figure 46.

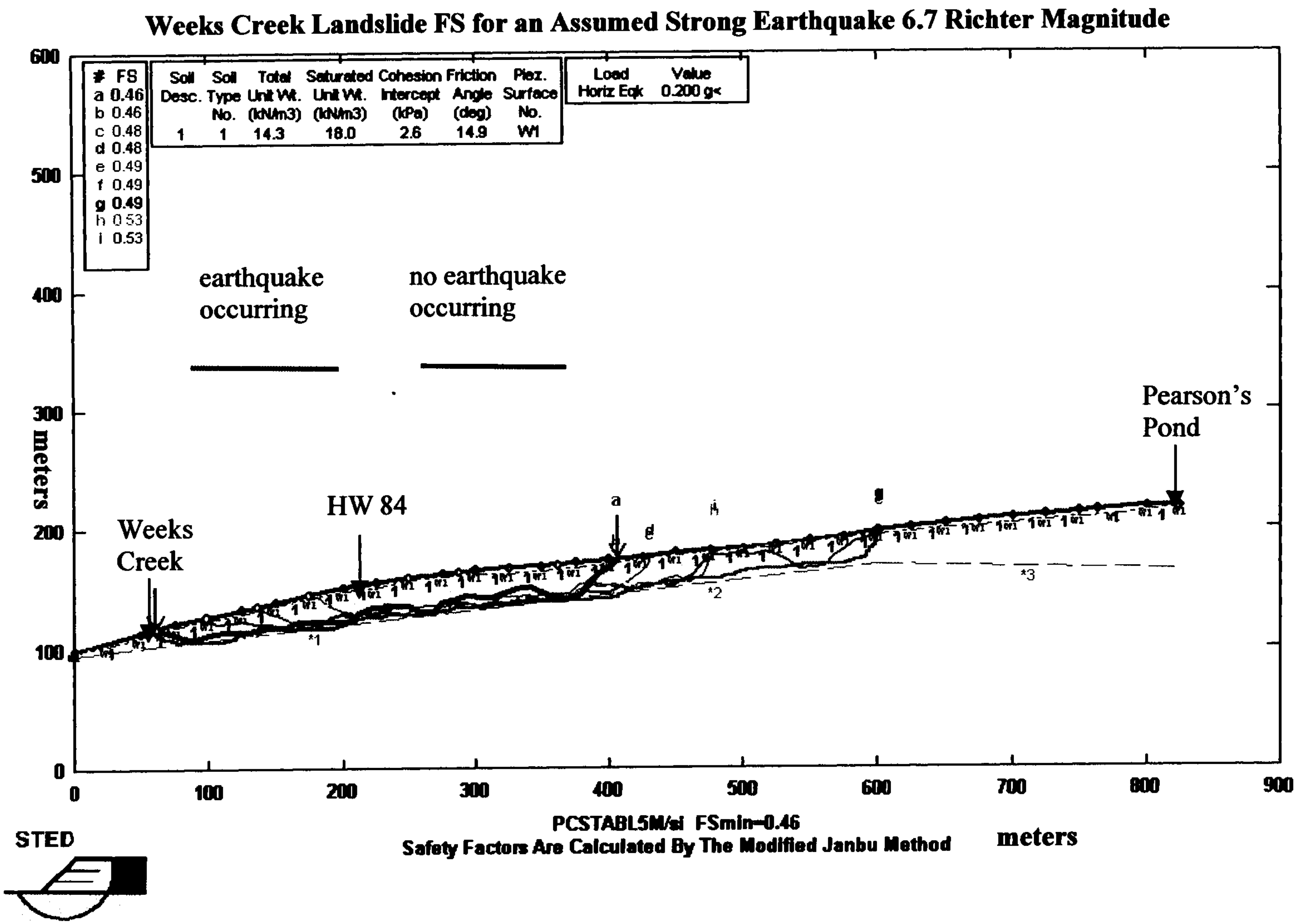


Figure 44. STEDWIN model output for an assumed groundwater level 3.5 m below ground surface and an earthquake of 6.5 Richter magnitude. FS = 0.46.

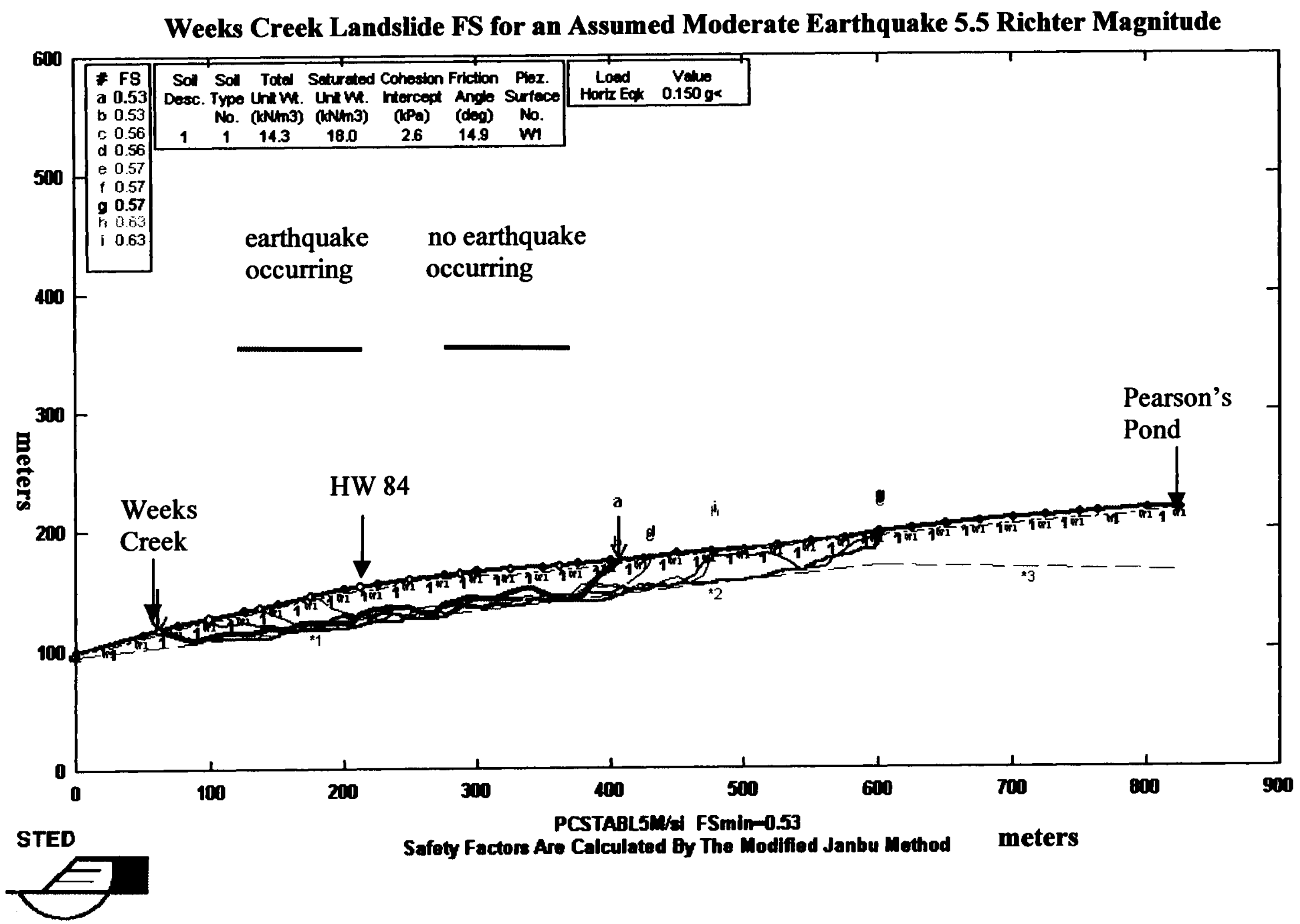
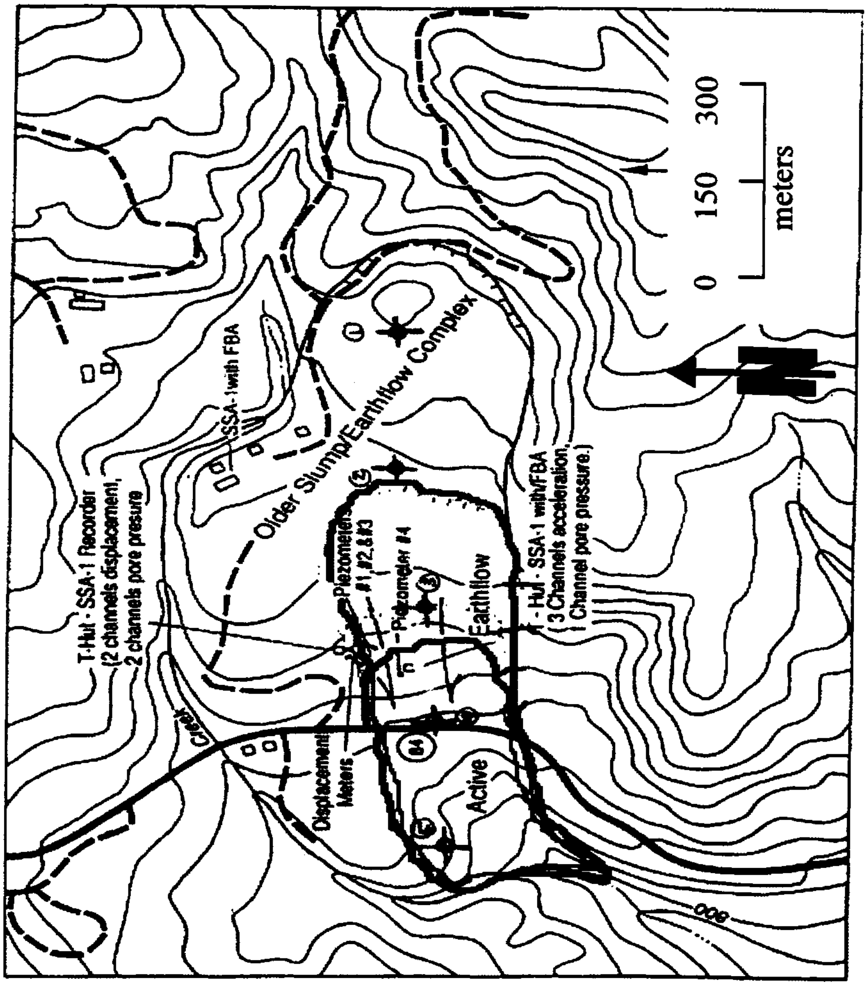


Figure 45. STEDWIN model output for an assumed groundwater level 3.5 m below ground surface and an earthquake of 5.5 Richter magnitude. FS = 0.53.



approximate slide location if earthquake occurs ▬▬

approximate slide location if earthquake does not occur ▬▬

Figure 46. Approximate slide location with and without earthquake occurring, (base map modified from Harp and Jibson, 1995).

Actual Earthquake Response

A simulation of the 1989 Loma Prieta earthquake and the 1906 San Francisco earthquake impact on landsliding was performed using STEDWIN. The Loma Prieta earthquake with a Richter magnitude of 7.1 (Kenner and Segall, 2000) originated 45 km southeast of the Weeks Creek landslide. The estimated horizontal ground acceleration at the location of the landslide is 0.2 g. According to the computer simulation, this leads to a reduction of the FS to 0.46 (Fig. 47). The epicenter of the 1906 San Francisco earthquake was 50 km north of the Weeks Creek landslide with a Richter magnitude of 8.3 (Kenner and Segall, 2000). The estimated horizontal acceleration at the location of the landslide is 0.3 g. The earthquake would have reduced the FS to 0.36 (Fig. 48).

Known Slip Surface Factor of Safety Estimate

The computer program STEDWIN provides an option to input a known slip surface in a study area and to calculate the FS for that particular slip surface. The borehole data by Cotton and Associates in 1994 and Caltrans in 1998 suggest that there is more than one active slip surface in the Weeks Creek landslide. The data suggest an active slip surface at a depth of about 15 meters below ground surface in addition to the slip surface at the surface of the bedrock. The FS analysis using STEDWIN with the slip surface at a depth of 15 meters indicates that, even in a year of average precipitation of 90 cm (groundwater about 3.5 m below ground surface), the top 15 meters of the landslide are likely to remain active at the end of the dry season or all the time. The calculated FS for the known (15 meters below ground surface) slip surface is 0.97 +/- 0.03 (Fig. 49).

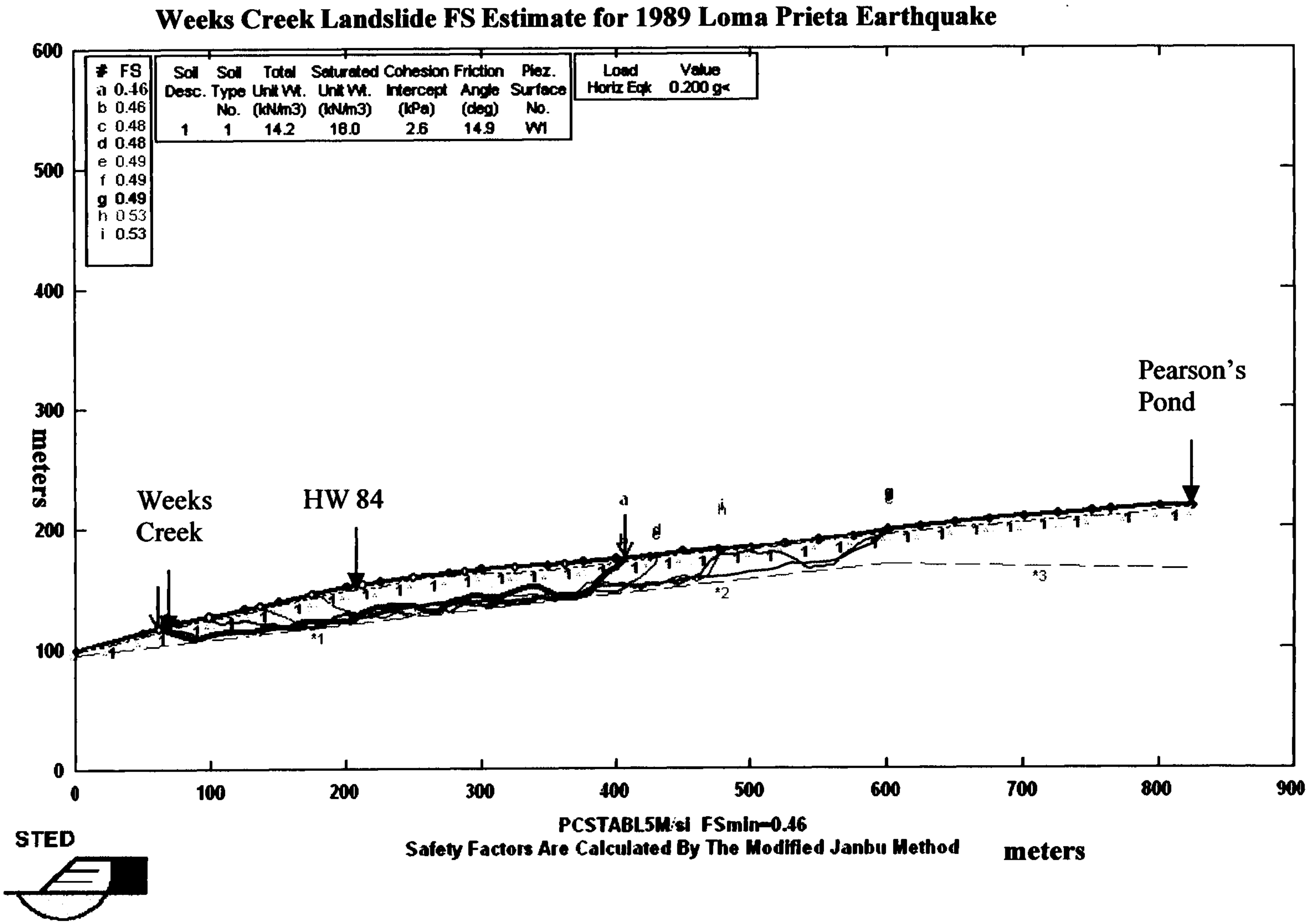


Figure 47. STEDWIN model output estimation of the FS of the Weeks Creek landslide during the 1989 Loma Prieta earthquake. FS = 0.46

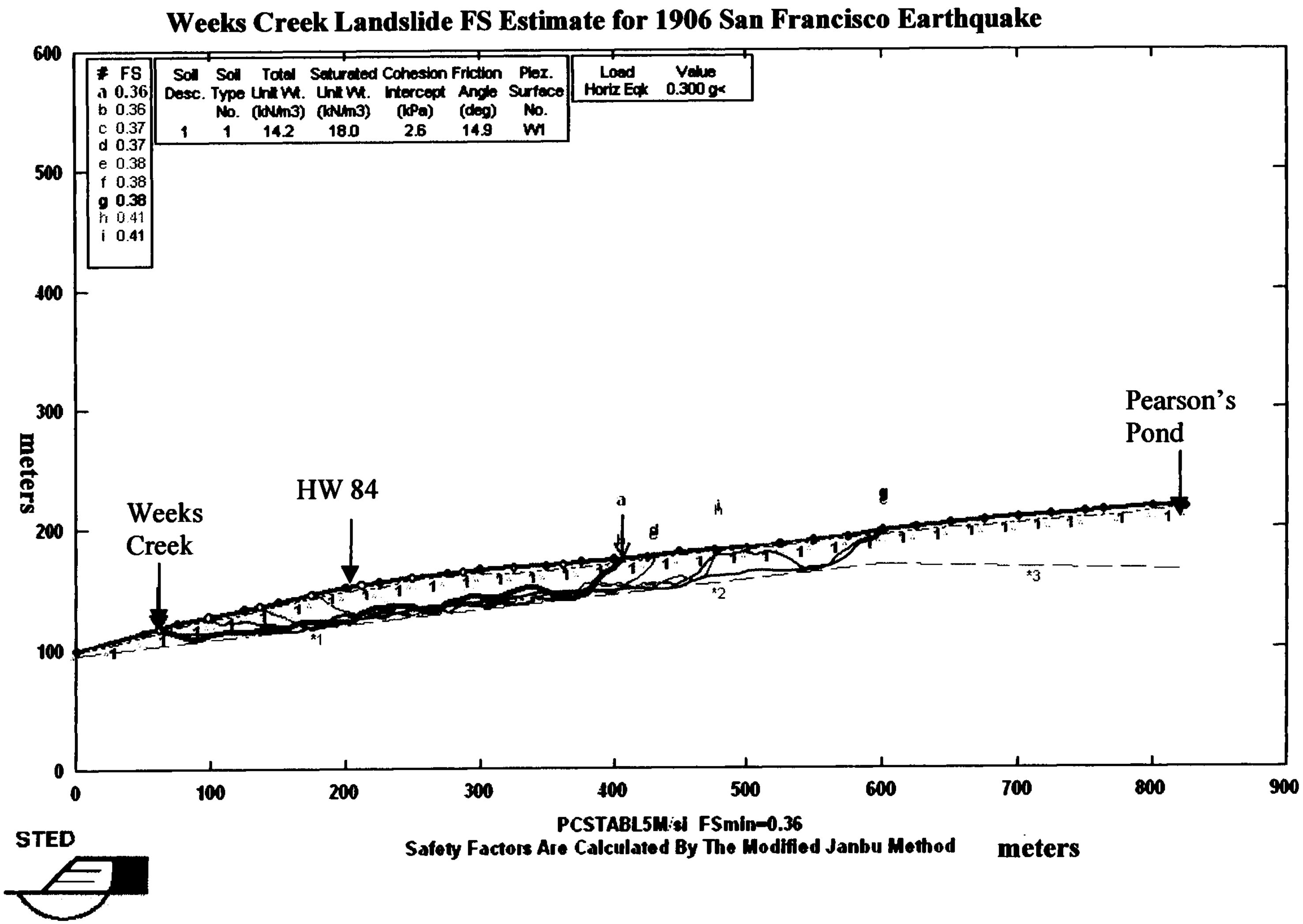


Figure 48. STEDWIN model output estimation of the FS of the Weeks Creek landslide during the 1906 San Francisco earthquake. FS = 0.36.

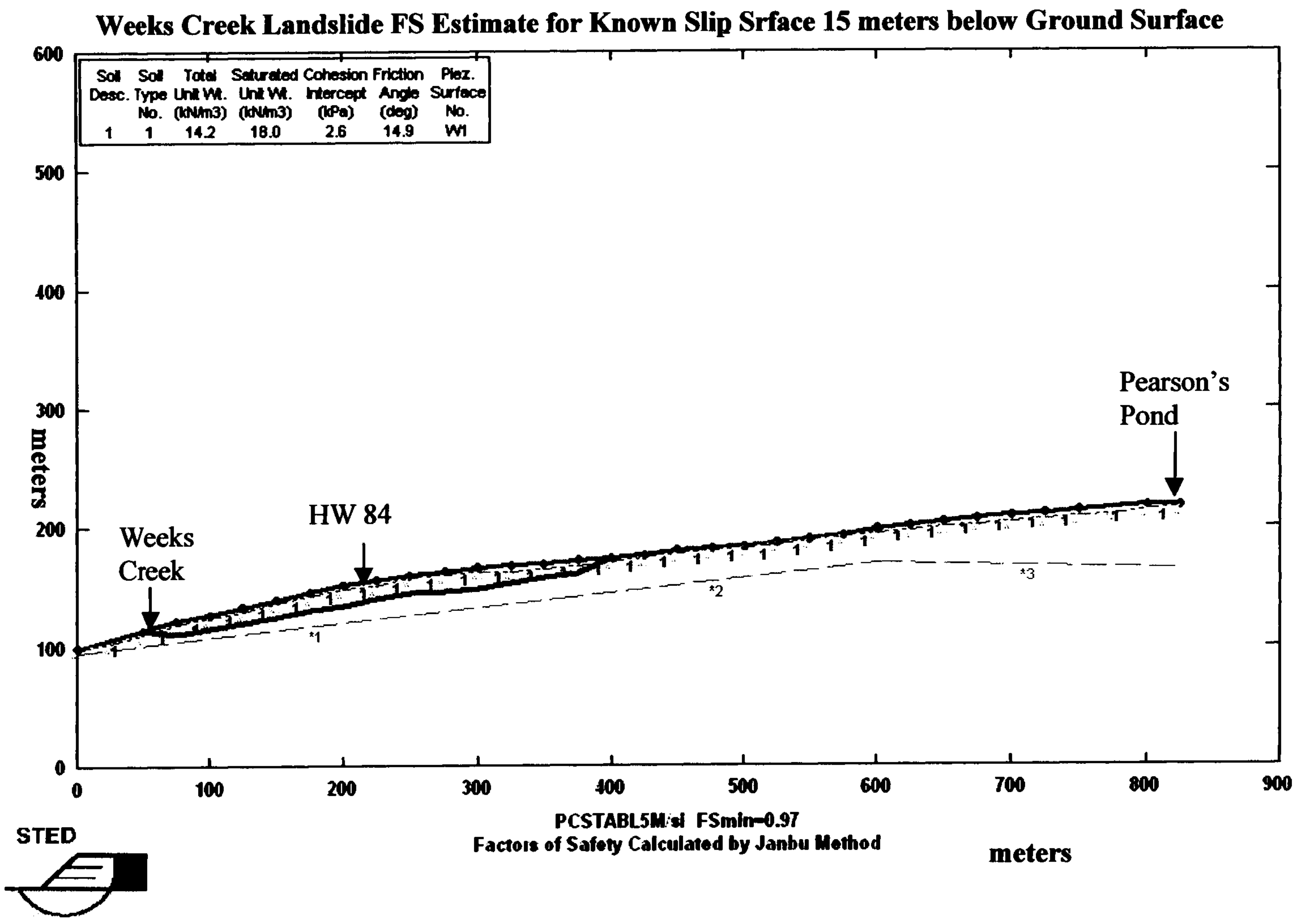


Figure 49. STEDWIN model output for known slip surface 15 m below ground surface. FS = 0.97.

Accuracy of the Factor of Safety Estimate

This investigation of the FS of Weeks Creek landslide was based on the topography of the landslide area, as mapped by Cotton and Associates in 1994. Assumption made prior to evaluating the FS of the landslide was that the soil properties are similar throughout the entire landslide. Although the soils forming the landslide vary across the area, their properties related to the modeling (groundwater as well as slope stability) do not vary significantly based on the borehole analysis and geologic mapping of the region. Thus the model results are qualitatively accurate, although the use of additional data (e.g. more monitoring wells to establish a more accurate hydraulic conductivity value) would allow for more accurate modeling (groundwater and slope stability) and a better FS estimate.

The accuracy with which the FS is determined depends on several variables, the more important of which are the accuracy of:

1) groundwater levels simulated by MODFLOW,
2) estimated soil parameters,
3) STEDWIN program, and
4) mapped landslide topography.

A straightforward way to estimate the accuracy of the FS is to vary each of the parameters that are used in the STEDWIN simulation within the range of accuracy with which that parameter is known. The groundwater level was not varied in this sensibility analysis because it was the only solution of the groundwater modeling that was found to satisfy all the boundary conditions, and it did match the historic levels.

The soil parameter values for γ_{sat}, γ_{dry}, and φ were varied individually from a minimum to a maximum value to test the sensitivity of the FS analysis to that parameter. The average value, used in the earlier analyses, is also given in table 12. Based on samples taken at a shear surface at a depth of 15 m, Cotton and Associates (1994) measured saturated unit weights for Weeks Creek landslide ranging from 17.43 kN/m^3 to 18.5 kN/m^3 (111 pcf to 118.5 pcf) and dry unit weights ranging from 13.33 kN/m^3 to 15.27 kN/m^3 (84.9 pcf to 97.2 pcf). The sensitivity analysis indicates that the FS was not sensitive to changes in the γ_{dry}. The FS was sensitive to changes in the γ_{sat} within a range of +/- 0.03.

Cotton and Associates (1994) performed direct shear strength analysis for that active shear surface of Weeks Creek landslide and reported an angle of internal friction equal to 14.9°. Wieczorek (1978) reported a typical average internal frictional angle for landslide masses occurring in San Lorenzo formation of 15.6°. For the typical average value of the angle of internal friction, the FS increases with 0.03.

Table 12. Summary of the factors influencing the accuracy of the FS estimate.

Parameter	Value	FS
γ_{sat} minimum	17.43 kN/m^3	1.03
γ_{sat} average	18.00 kN/m^3	1.05
γ_{sat} maximum	18.50 kN/m^3	1.08
γ_{dry} minimum	13.33 kN/m^3	1.05
γ_{dry} average	14.30 kN/m^3	1.05
γ_{dry} maximum	15.27 kN/m^3	1.05
φ actual measured	14.9°	1.05
φ typical for material	15.6°	1.08

CONCLUSIONS

The Weeks Creek landslide will remain active due to high pore water pressure along the failure surfaces. During a year of heavy precipitation (114 cm) the active sliding mass extends in depth all the way to the bedrock contact (30 m in depth). The slide becomes active about 45 days after the beginning of the rainy season and remains active throughout the rainy season. At that depth it probably becomes stable about 60 days after the beginning of the dry season. The landslide mass involved during the rainy season in a year of average precipitation (90 cm) also reaches the bedrock contact but becomes stable about 45 days after the beginning of the dry season. During the dry seasons, only the top 15 m of the landslide are likely to remain active. Moderate-to-strong earthquakes originating on the nearby San Andreas fault will cause significant reduction in the FS and an increase in the length of the sliding area from 300 m to 500 m.

The modeling results show a strong correlation between precipitation, groundwater fluctuation, and stability of the landslide. Groundwater fluctuates 3.5 meters between the dry and wet seasons. In a year of heavy precipitation, during the rainy season the water level reaches and remains at the ground surface. In a year of average precipitation, the groundwater rises to 1 meter below the ground surface.

The variations in time of the activity of the landslide area follow the following pattern:

1) With the onset of the rainy season, the water table begins to rise. The water table in the Weeks Creek landslide is always above the slip surface. The rise

in the water table during the rainy season leads to an increase in the mass of the material above the slip surface, leading to a higher gravitational force on that material (the driving force for the slide). In addition, the pore water pressure at the depth of the slip surfaces increases, reducing the resisting friction forces. The combination of these two effects results in a decrease in the FS.

2) With the beginning of the dry season, the groundwater level gradually subsides. The FS increases and the slide becomes temporarily stable at depths greater than 15 meters during the dry seasons.

The slide can be stabilized if the groundwater level is kept deeper than about 2 meters below ground surface. This is unlikely under normal rainfall conditions.

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APPENDIX A

Laboratory Determination of Soil Properties

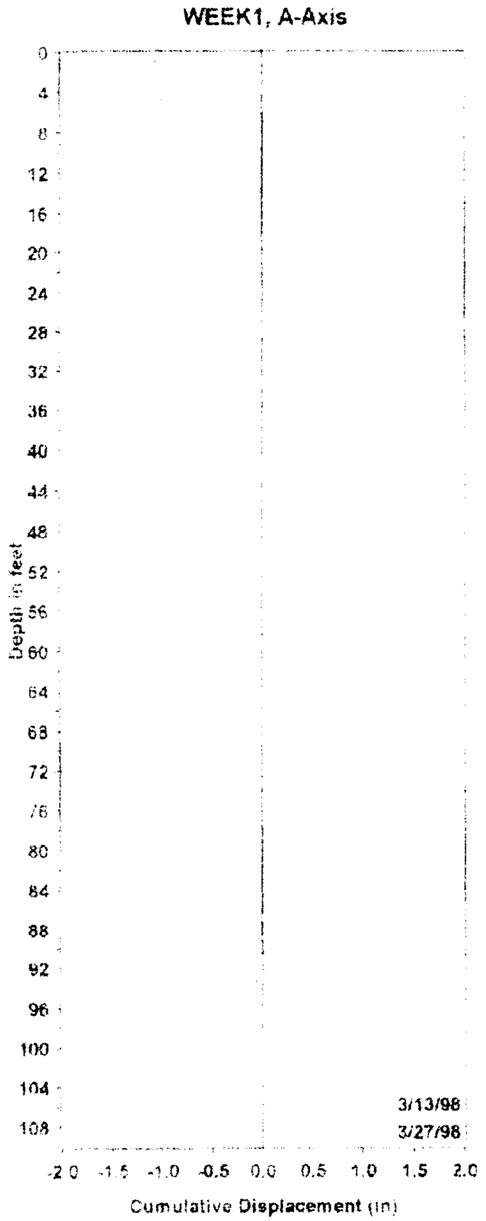
Boring	Sample,N_0	Depth, ft	Material	LL/PI	Natural Moisture content,%	Moist Dtensity pcf	Dry Dencity pcf	Direct Shear σ/τ, psf
WCA-1	T-1	33	Shear		30.2	111	85.2	2.03/0.63
	T-2	33	Shear		30.7	112.1	85.7	4.09/1.08
	T-3	33	Shear		35.9	115.4	84.9	6.03/1.7
	T-4	31.6	Shear		25.2	117.1	93.5	
	T-5	31.8	Shear		24.1	118.5	95.4	
	T-6	31	Sandstone		24.4	120.9	97.2	
	T-7	16	Mudstone		22.7	115	93.7	
	B-1	24	Mudstone		28.6			
	B-2	34.5	Mudstone		30			
	B-3	33.5	Shear	84/59	38.6			
	B-4	27	Sandstone	76/46	16.6			
	B-5	62	Shear		35.1			
	B-6	82	Mudstone		30.9			
	B-7	94	Mudstone		30.1			
	B-7a	97	Mudstone		35.2			
	B-8	104	Shear		18.6			
Cotton and Associates, 1994	B-9	106	Shear		15.9			

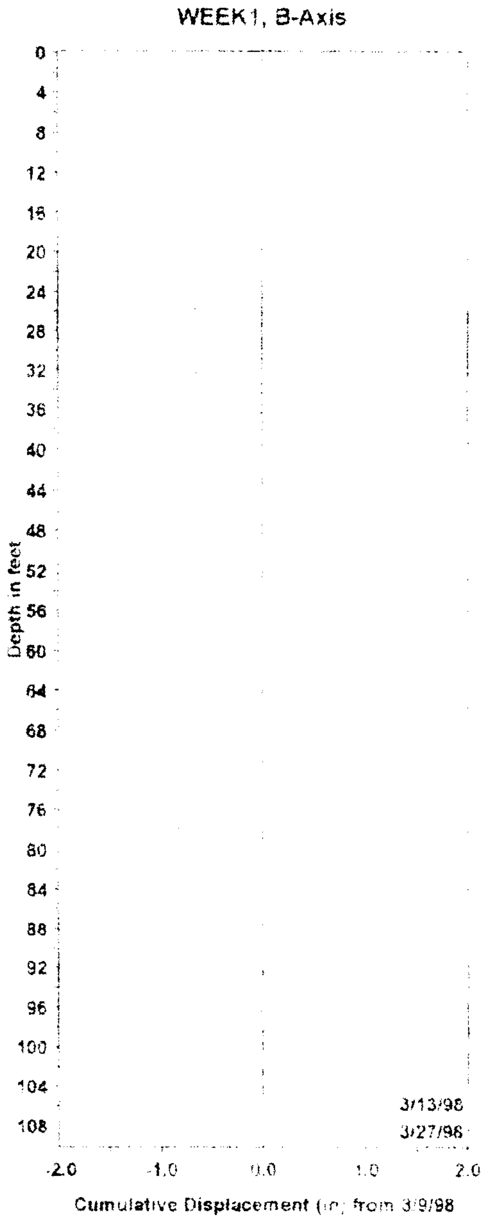
Hole	Sample	Depth, ft	Material	Natural Moisture Content, %
SI-1	1A	5	Clay (CL)	19.1
	2A	10	Clay (CL)	31.7
	3A	15	Silt (ML)	28.7
	4A	20	Silt (ML)	26.3
	5A	25	Silt (ML)	22.6
	6A	30	Siltstone	22.8
	7A	35	Siltstone	20.1
	8A	40	Siltstone	15.1
	9A	45	Siltstone	22.7
	10A	50	Shear	27.0
	11A	55	Shear	27.9
	12A	60	Siltstone	21.9
	13A	65	Siltstone	20.7
	14A	70	Shear	22.2
	15A	75	Shear	26.3
	16A	80	Siltstone	24.0
	17A	85	Siltstone	25.8
	18A	90	Shear	17.1
	19A	95	Shear	14.0

Caltrans, 1998

APPENDIX B

Inclinometer Readings



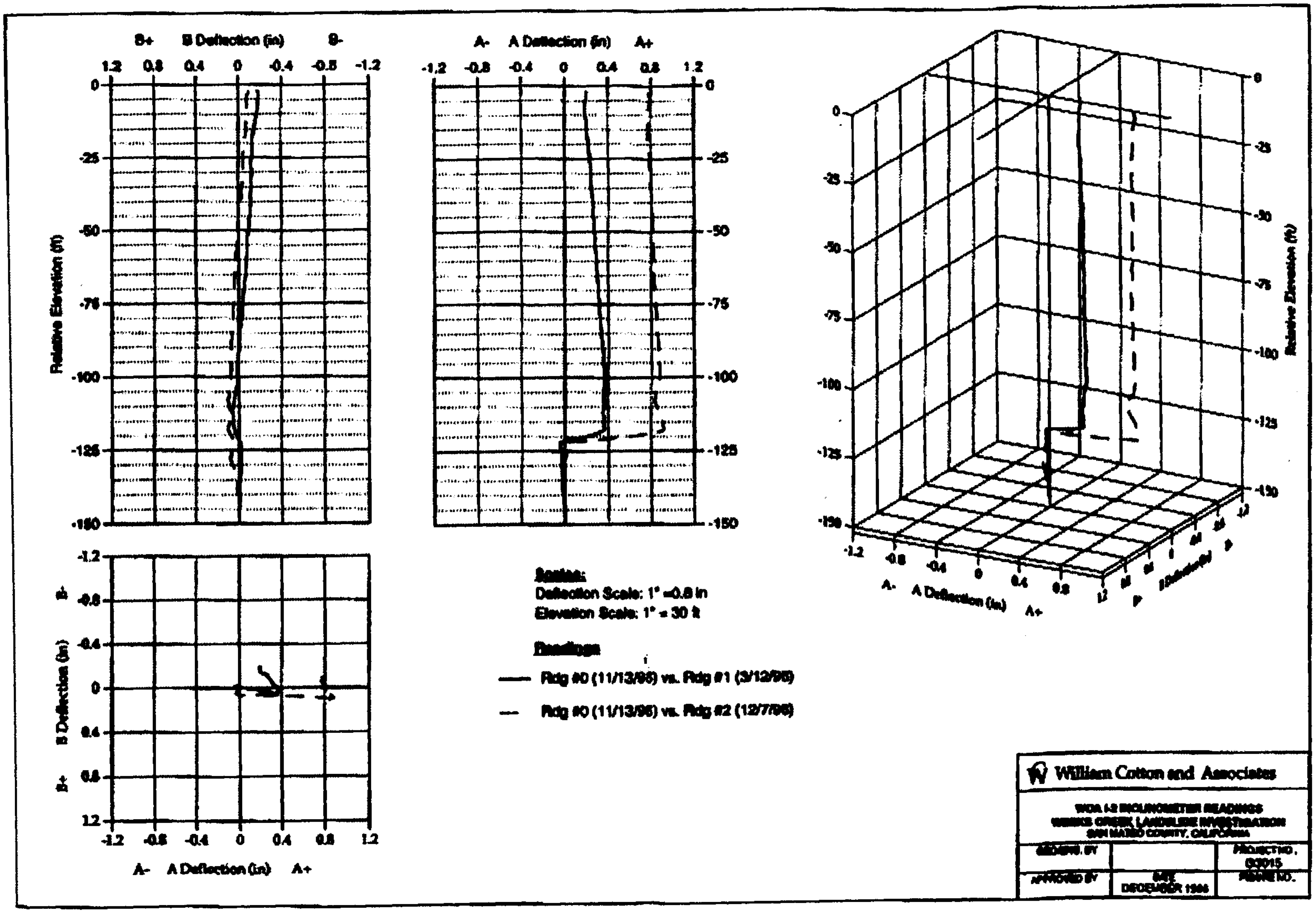


WEEKS CREEK SI-1 (No Adjustment Made)
04-SM-84-12.0

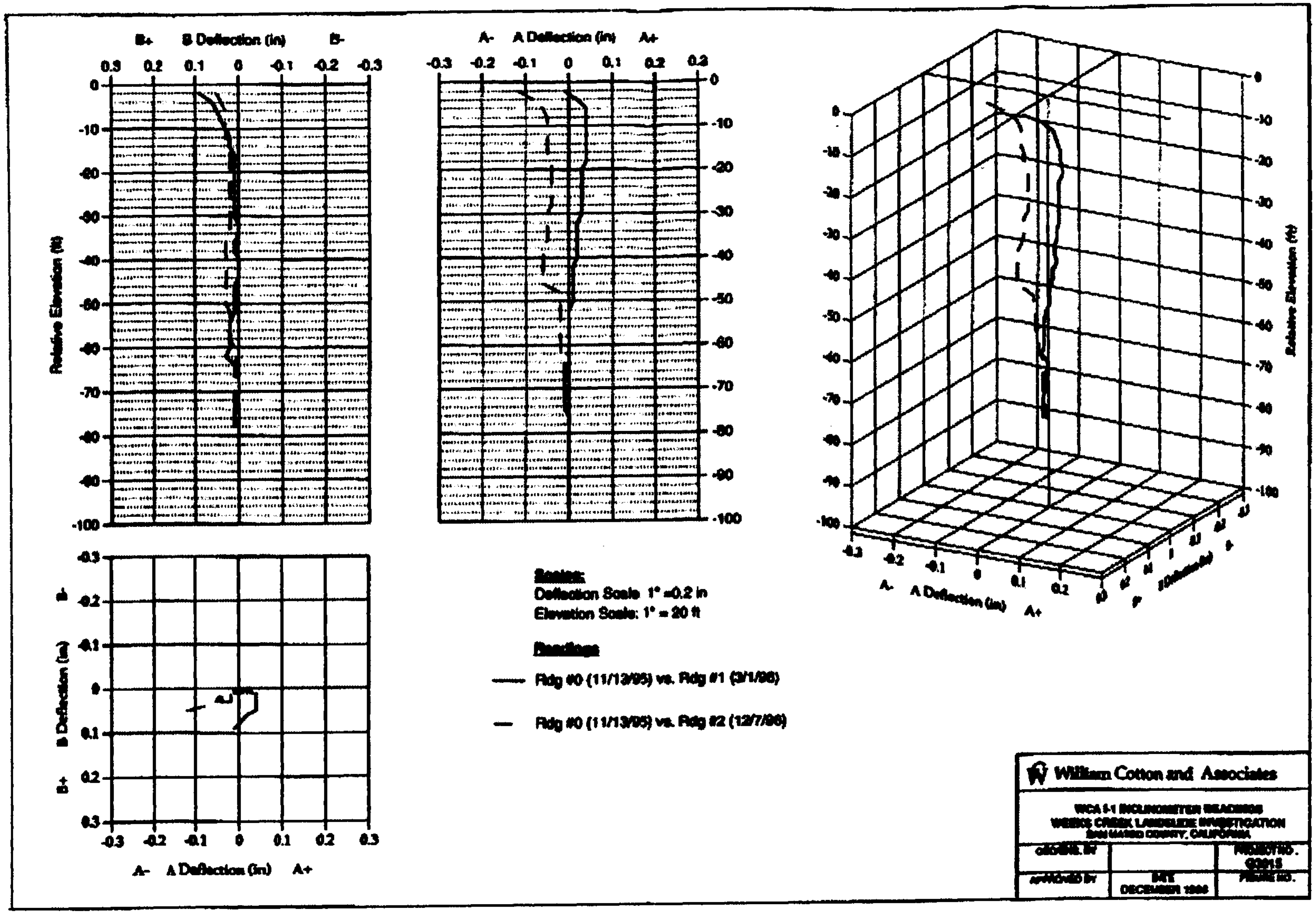
Initialed 3/9/98

CA-Dept. of Transportation
District 4 Engineering Services
Materials Field Support

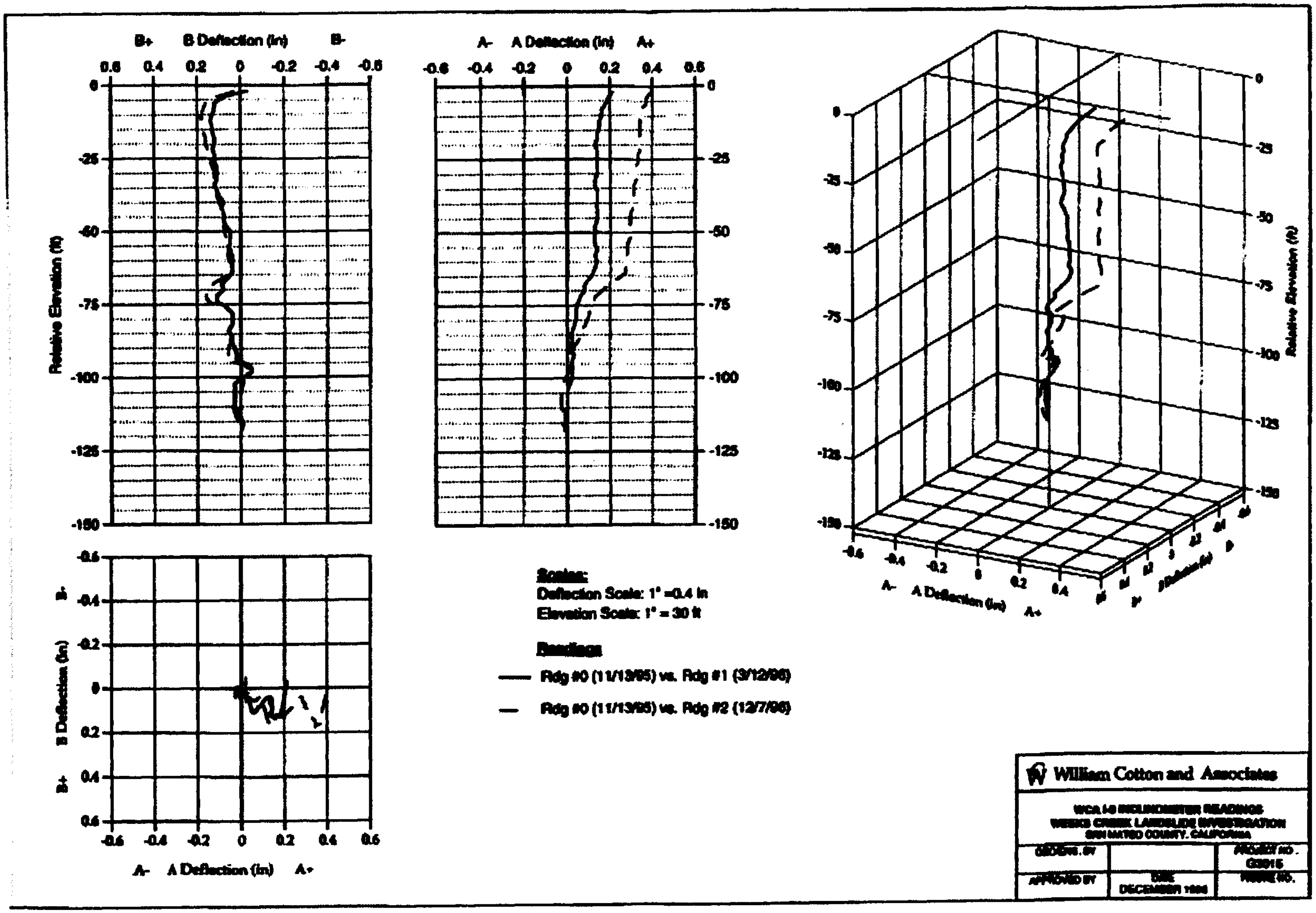
Caltrans,1998.



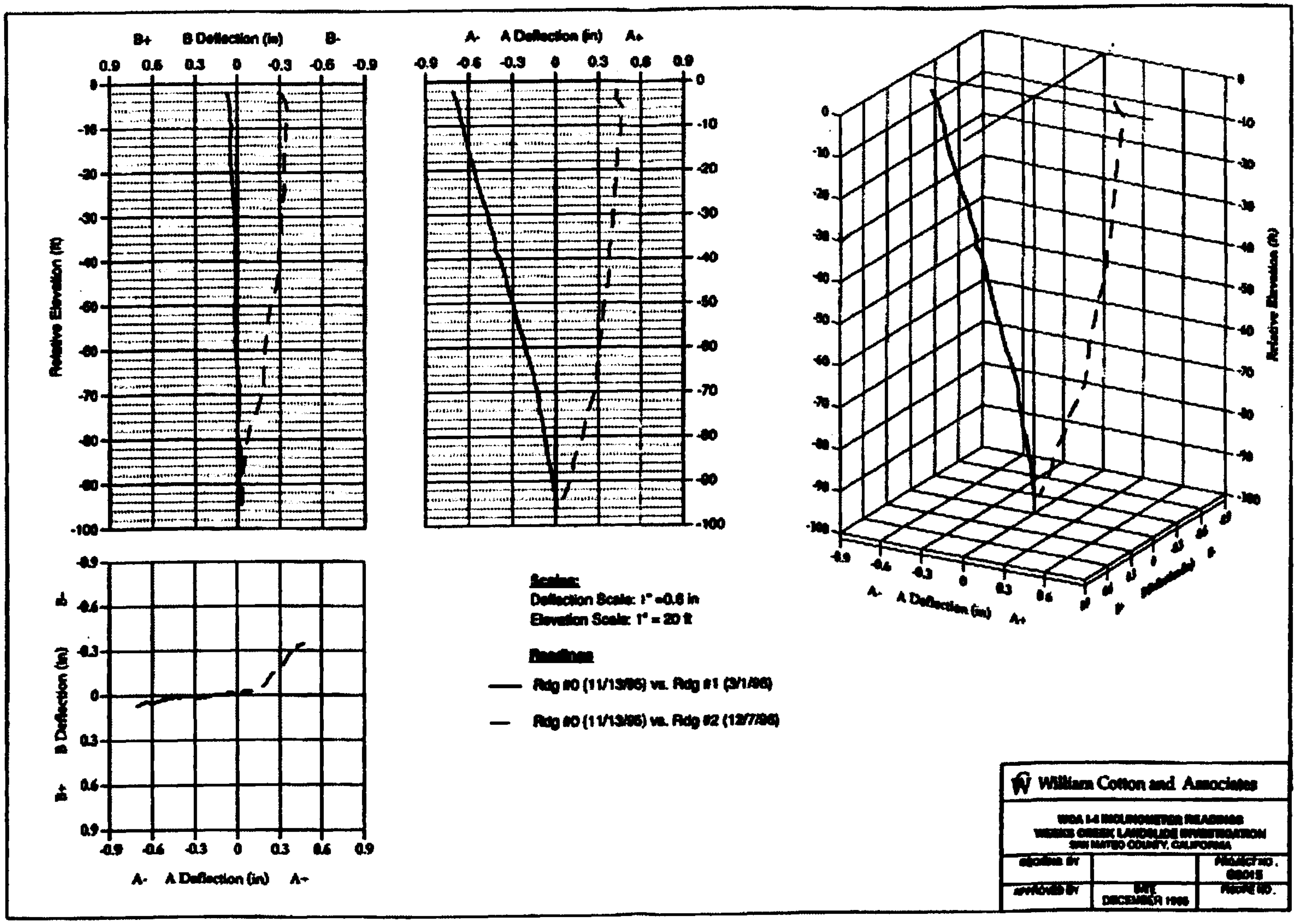
Written communication, Cotton and Associates, 1996.



Written communication, Cotton and Associates, 1996.



Written communication, Cotton and Associates, 1996.



Written communication, Cotton and Associates, 1996.

Dear Mr./Ms., Figure 1, 2 and 21 in my thesis are modified from an aerial view of my study area widely provided on interned by several distributors such as: Microsoft Virtual Earth, Google Maps, Mapquest Maps, MapMart, Yahoo Maps, Globe Explorer and many others. The data for those map images is provided ether by NAVTEQ, which permission letter I include, or USGS - a government organization, which publications are public.

The following figures are also obtained through USGS publications: figure 9 (modified by me), 8 (modified by me), 18 (the data for the figure is from USGS publication, the figure itself is created by me), 19 (the data for the figure is from USGS publication, the figure itself is created by me), 20 (the data for the figure is from USGS publication, the figure itself is created by me), 43 (modified by me) and 46 (modified by me).

Figure 14 is interpretation of the data provided to me by Mr. Grant Wilcox from CALTRANS (California Department of Transportation), which is a public government organization. Mr. Wilcox also provided me the inclinometer reading of inclinometer SI-1 included in Appendix B.

Figures 7, 12, 13, 15, 16, 17, 26 and 37 are ether modified by me from the originals of Cotton and Associates or created by me using their data. I include their letter of permission to do so. Their letter also indicates that I have their permission to include in my thesis their unmodified inclinometer readings (Appendix B).

Figure 11 is modified by me (unpublished report). I obtained it through the Department of Housing San Mateo County- a public source.

The rest of the figures are created from my own data and modeling.

Ted Sayre <tsayre@cottonshires.com> wrote:

> ----- Forwarded Message
> From: Ted Sayre
> Date: Wed, 15 Nov 2006 09:58:07 -0800
> To:
> Subject: Weeks Creek
>
> Hi Katerina-
>
> I am an Associate Engineering Geologist at Cotton, Shires & Associates and you are welcome to use our previous Weeks Creek information as you have described. You are allowed to use modified figures from our previous report about Weeks Creek landslide and the inclinometer readings. If an unbound copy of your thesis is not a great expense, then we would very muck like to receive a copy.
>
> Thanks,
>
> Ted Sayre
> 330 Village Lane
> Los Gatos, CA 55030
>
> ------ End of Forwarded Message

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"Tierney, Tom" <tom.tierney@navteq.com> wrote:

> Kate:
>
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> may use up to 10 maps in the thesis without incurring a license fee.
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> Please note that NAVTEQ provides the map data. If you are requesting
> permission for the aerial image that overlays the map, (Hybrid view), or
> just the aerial image, you may need to contact Globexplorer for similar
> permission. (www.globexplorer.com)
>
> Best Regards,
> Tom Tierney
> Developer Alliance Manager
> NAVTEQ
>
> -----Original Message-----
> From: kate_roussev@yahoo.com [mailto:kate_roussev@yahoo.com]
> Sent: Thursday, November 30, 2006 8:12 PM
> To: NABC_English@navteq.com
> Subject: Contact Us
>
> Role: Journalist/ Researcher
> Question: Other
> Name: Katerina Rousseva
> Email: kate_roussev@yahoo.com
> Phone: 650 497 6777
> Business: San Jose State University
> Address: 112 Jenkins Court, apt. 109
> City: Stanford
> State / Province: California
> ZIP / Postal Code: 94305
>
> Preferred Contact Method: email
> Device: printed copy of a map
> Comments:
> I am a geology graduate student at San Jose State University. I would
> like to ask for your permission to use a map, provided on internet as a
> product copyright of which is held by you, and includ it in my thesis.
> The map shows an aerial view of the location of my study area. It is
> along Hwy 84 near La Honda.
> Please let me know if I need permission and if so how can I obtain one.
> Tank you very much for your attention!
> Sincerely, Katerina Rousseva

Jevaun Licciardo <jlicciardo@globexplorer.com> wrote:

Katerina,

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Jevaun Licciardo
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GlobeXplorer, LLC.
3021 Citrus Circle, Suite 150
Walnut Creek, CA 94598
Direct: (925) 280-5279
Web: www.globexplorer.com

-----Original Message-----
From: kate_roussev@yahoo.com [mailto:kate_roussev@yahoo.com]
Sent: Friday, December 01, 2006 9:51 AM
To: inquire
Subject: inquire

Name: Katerina Rousseva
Title: student
Company: San Jose State University
Phone: 650 497 6777

Dear Mr./Mrs.,
I am a geology graduate student at San Jose State University.
I would like to ask for your permission to use an aerial view of a map that shows the location of my study area. I was referred to you by Mr. Tom Tierney from NAVTEQ who I contacted with the same request. His answer was that for an academic thesis I have their permission to use the map if it does not exceeds 250 copies. But NAVTEQ provides the map data only and not the actual aerial image. For permission to use the image of the map I was asked to contact you.
The map for which permission to use I ask, shows the location of my study area. It is along Hwy 84, near La Honda, California. I would like also to indicate the boundary of my study area.
Please let me know how I can obtain permission to use your map,
Thank you very much for your attention.
Sincerely,
Katerina Rousseva

Chad Mickelson <cmickelson@mapmart.com> wrote:

> I wouldn't worry about it as long as you provide a credit for the imagery.
>
> Good luck!
>
> Chad Mickelson
> Account Executive
> IntraSearch, Inc. D/B/A MapMart
> 5340 South Quebec Street
> Suite 300 South
> Greenwood Village, CO 80111
> Phone: 303-759-5050 X177
> Fax: 303-759-0400
> cmickelson@mapmart.com
> www.mapmart.com
>
> ---
>
> **From:** Katerina Rousseva [mailto:kate_roussev@yahoo.com]
> **Sent:** Monday, December 04, 2006 1:51 PM
> **To:** Chad Mickelson
> **Subject:** RE: Mapmart Project Request No.21480
>
> Thank you very much for your reply.
> It is not very clear to me if I am in violation of the rights because I already have the image and I would like to use it for academic purposes.
> Please let me know whether (even if I already have it) I steel need to by it from you directly in order to included in my thesis.
> Thank you very much for your attention,
> Sincerely,
> Katerina Rousseva
>
> ***Chad Mickelson <cmickelson@mapmart.com>*** wrote:
>
> > I am not sure if you received my email, but you can get that imagery for $35. It was collected in 1991. Does that interest you?
> >
> > Thanks,
> >
> > Chad Mickelson
> > Account Executive
> > IntraSearch, Inc. D/B/A MapMart
> > 5340 South Quebec Street
> > Suite 300 South
> > Greenwood Village, CO 80111
> > Phone: 303-759-5050 X177
> > Fax: 303-759-0400
> > cmickelson@mapmart.com
> > www.mapmart.com

From: Katerina Rousseva [mailto:kate_roussev@yahoo.com]
Sent: Friday, December 01, 2006 2:47 PM
To: Chad Mickelson
Subject: Re: Mapmart Project Request No.21480

I am sending you an attachment at the exact aerial view of the landslide.
I would like to use this image to indicate the boundaries of the landslide.
Thank you very much for your attention,
Sincerely,
Katerina Rousseva

> ***Chad Mickelson <cmickelson@mapmart.com>*** wrote:
> Katerina,
>
> I received your inquiry about the aerial imagery. Can you provide more detail of what you are looking at?
>
> Is there a specific area of interest? If you could provide two sets of coordinates in decimal format that define your area, I could tell you what we have available. I would need one set of lat/long for the NW corner and one set for the SE corner.
>
> It all depends on what imagery it is. Let's start by figuring out what it is that you need and go from there.
>
> Thanks,
>
> Chad Mickelson
> Account Executive
> IntraSearch, Inc. D/B/A MapMart
> 5340 South Quebec Street
> Suite 300 South
> Greenwood Village, CO 80111
> Phone: 303-759-5050 X177
> Fax: 303-759-0400
> cmickelson@mapmart.com
> www.mapmart.com

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