THE NORTHRIDGE BLUFF LANDSLIDE: RAPID BLUFF RETREAT ASSOCIATED WITH A MAJOR COASTAL LANDSLIDE IN DALY CITY, CALIFORNIA

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Abstract: The Northridge Bluff Landslide, located on a 140m high coastal bluff in Daly City, California, failed catastrophically during December 2003 as a large, deep-seated rock landslide that disaggregated into a flow, descended the steep bluff, and subsequently advanced 100 m into the Pacific Ocean. The bluff is composed of poorly indurated fine sandstone, siltstone, and claystone of the Pliocene Merced Formation that dips steeply to the north. Following the initial failure, blocks of bedrock above the headscarp began to creep down slope, locally progressing to rapid rockslide and flow failures and resulting in regression of the headscarp. Failure on the upper portion of the slope is structurally controlled by a steeply dipping bed of sheared claystone that marks one lateral margin of the landslide and two prominent joint sets that acted as “sliding” and “releasing” surfaces. The sheared claystone bed extends eastward from the bluff, defining the region of potential landslide regression. Properties located upslope from the headscarp and north (up section) of the sheared claystone bed have a much higher risk of impact from future landsliding than those located south (down section) of the sheared bed.

The risk posed by this landslide was not recognized or fully evaluated prior to development of the community or fully characterized prior to design of recently completed adjacent municipal storm drain outfall facilities. The catastrophic failure placed a critical city storm drain system and a new community church in jeopardy. Using both qualitative geologic judgment and quantitative engineering analyses, we developed a landslide hazard map that defines a zone of high risk along the margins of the landslide area. The potential for bluff retreat from this type of failure is greater in magnitude but likely less frequent than may be recognized by analysis of historical sea bluff data. Thus, careful geologic characterization and risk analysis are necessary to supplement bluff retreat analysis prior to development near coastal bluffs.

INTRODUCTION

Coastal Bluff Retreat

Coastal bluff retreat occurs where wave energy is sufficient to rapidly erode the cliff face resulting in landward migration of the shoreline. This episodic process tends to occur in California primarily during strong to moderate intensity El Nino events that generate high storm surge (Storlazzi and Griggs, 2000). The retreat rate of coastal bluffs depends upon wave attack, runoff, and bluff lithology (Griggs, 1997). Sea bluff instability presents a significant constraint to coastal development and personal safety (Lajoie and Mathieson, 1985). Some have modeled sea bluff instability as vertical block failure that results from undercutting of sea bluffs by wave erosion during high storm surge events (Sayre, et al., 2001); this model is particularly applicable to bluffs composed of poorly consolidated Quaternary sediments. The California coastal Commission (Johnsson, 2002) has recognized this model as valid for establishment of setback from coastal bluffs and evaluation of bluff retreat rate. An average annual retreat rate is typically established by review of historical aerial photographs and maps to determine bluff locations over a period of at least 40 to 50 years. By extrapolation from this annual rate, a setback allowing for a 100-year project lifespan is typically defined.

However, sea bluffs composed of bedrock are also prone to less frequent, large scale, deep-seated landsliding resulting from wave erosion into weak, fractured and sheared bedrock. Such landslides may result in rapid bluff retreat that is much greater in magnitude than would be predicted based upon analysis of historical shorelines known from mapping and aerial photograph data. Thus, calculated annual retreat rates and setback from coastal bluffs may be insufficient where the site geology is vulnerable to large-scale, deep-seated landsliding. This paper presents the results of a recent study of a spectacular large-scale bluff failure (Figure 1), the Northridge Bluff Landslide (NBL). The NBL is located on the San Francisco peninsula in Daly City, California (Figure 2). This bluff failure resulted in sudden and substantial bluff retreat that placed coastal development and key engineered facilities at risk.

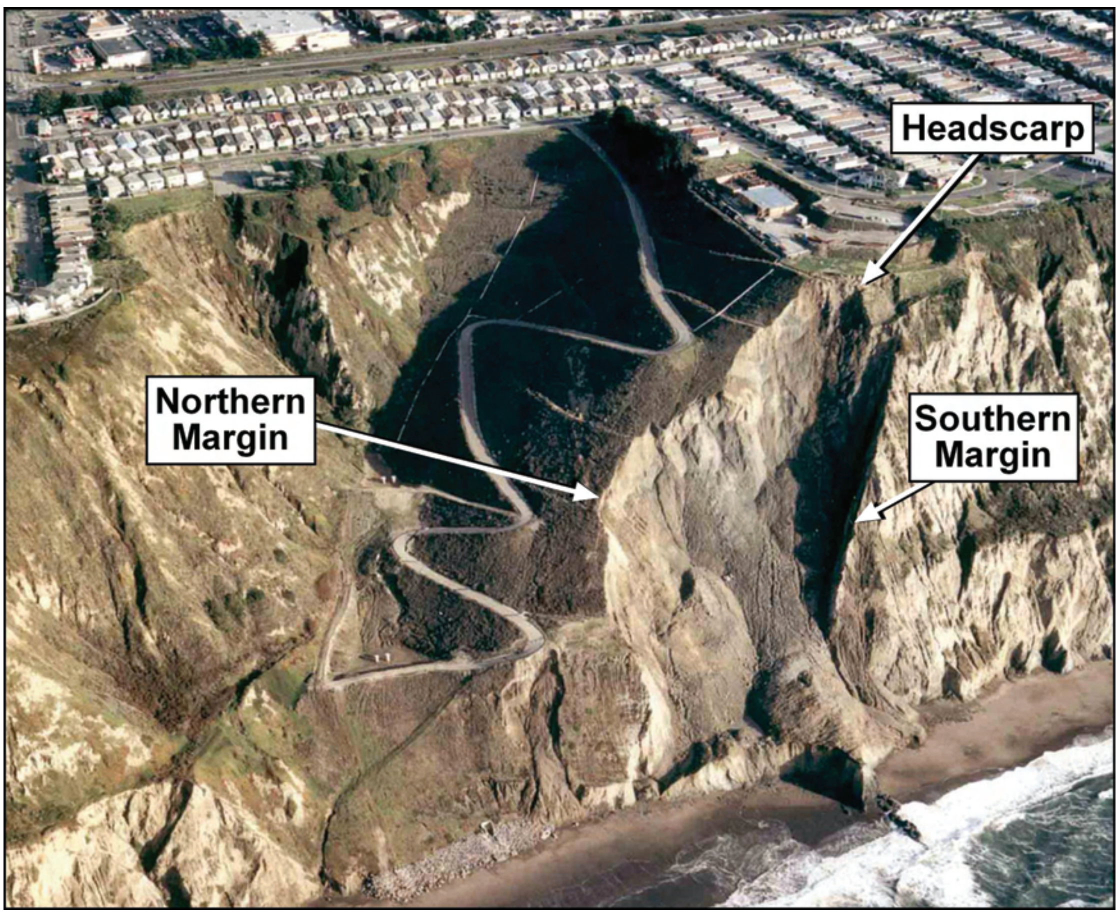

Figure 1. Oblique aerial photograph of the Northridge Bluff Landslide taken within two weeks after the December 2003 failure.

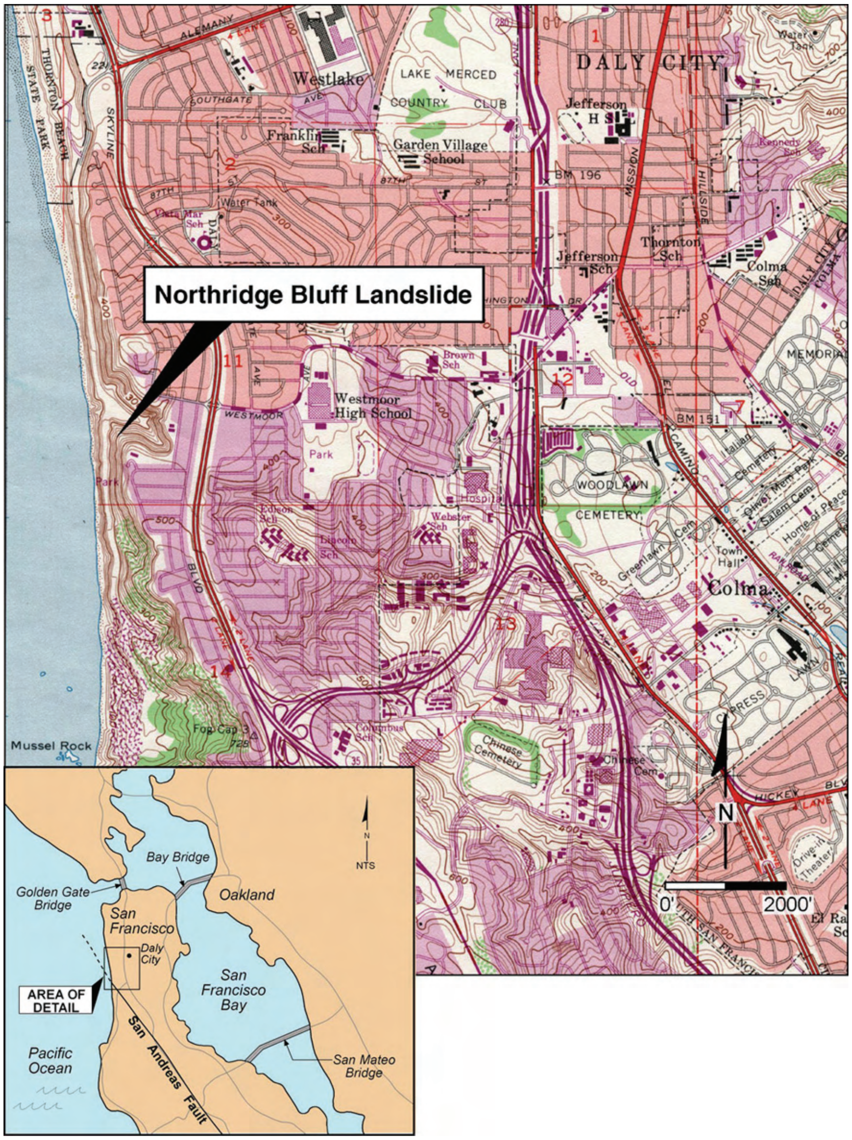

Figure 2. Location of the Northridge Bluff Landslide. Map base taken from the USGS San Francisco South 7.5' Topographic Quadrangle.

Site History

The earliest aerial photographs of Northridge Bluff show no evidence of a deep-seated landslide mass at the current location of the NBL. However, numerous shallow historical failures have locally stripped away surficial deposits and vegetation to expose the underlying bedrock within the bluff. Northward-dipping stratification is visible in oblique aerial photographs of the bluff (Figure 3).

Figure 3. Oblique aerial photograph of Northridge Bluff taken during October 1972. Published by permission of Kenneth and Gabrielle Adelman, California Coastal Records Project.

Significant grading has taken place surrounding the NBL site. During the early 20th Century, a highway was graded at a mid-bluff elevation, and fill was placed in the lower reaches of Avalon Canyon, a major drainage valley located north of NBL. Within a few years of completion, bluff failures resulted in closing of the highway and subsequent re-alignment to a location farther inland. In aerial photographs from 1972, several failures within the old highway fill in lower Avalon Canyon are apparent (Figure 3). During the later 1990's a major city storm drain line and outfall facilities were constructed in Avalon Canyon. As part of this project, additional fill was placed in the canyon and on the north-facing slope.

Based upon interpretation of historical aerial photographs, the NBL initially failed during the spring of 1998, following the heavy winter rains. The toe of this early failure extended onto the beach at the base of the bluff, but the head did not intercept the development (a church site) along the surface at the top of the bluff. At the time of the December 2003 failure, the head of the landslide undermined the western portion of the church property. Along the northern margin of the failure, the landslide appeared to threaten the recently completed Avalon Canyon storm drainage project and the access road leading to the outfall facilities.

Geologic Setting

The NBL is located approximately 360 meters east of the offshore segment of the San Andreas fault within an uplifted block of Pliocene Merced Formation bedrock. Along the bluff, the Merced Formation is tilted steeply to the north. The Merced Formation bedrock consists of interbedded siltstone, very fine sandstone, and lesser interbedded claystone. These rocks are weakly cemented which, in part, accounts for their unstable behavior in steep slopes.

Seismicity may have impacted the stability of the sea bluffs in the past. The 1906 San Francisco earthquake produced intense shaking, damage, and large slope movements along nearby sea bluffs; Lawson et. al. (1908) reported large cracks 0.3 to 1 meter wide found within tens to hundreds of meters from the cliff edges. The 1957 earthquake, centered near Mussel Rock (approximately 1800 meters to the south), produced extensive damage to homes in Daly City, with damage increasing toward the ocean and bluff edge (Bonilla, 1959). The 1989 Loma Prieta earthquake triggered a large sea bluff failure approximately two kilometers north of the NBL site.

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Landslide Characterization

The Northridge Bluff Landslide failed dramatically sometime during the morning of December 20, 2003. Local residents noted that the landslide had extended out in to the surf zone more than 100 meters from the base of the sea cliff (Figure 4). A review of aerial photographs indicates that an initial stage of failure of the NBL began by the spring of 1998, and by August of 2000 the boundaries of the landslide were fully formed.

Figure 4. Photograph of the toe of the Northridge Bluff Landslide during December 21, 2003, within approximately 36 hours of the failure. Muscle rock is the prominent headland in the background, and the toe of the NBL (small peninsula) is in the center of the photograph. A person walking on the beach in foreground provides an approximate scale. Photograph by Jeff Poskanzer.

The NBL can be divided into two segments: the upper body of the landslide that consists of failing blocks that move downslope slowly and the lower body and toe that are composed of landslide debris that flowed rapidly over the beach and into the surf zone. In addition, there are steep escarpments (i.e., headscarp, flanks) that surround the upper part of the landslide mass, and a zone of unstable blocks of bedrock that borders the landslide along the north margin and at the head of the failure (Figure 5). The headscarp is approximately 170 meters wide, ranges in height from 20 to 60 meters, and is oversteepened at slope angles of 45 degrees to locally 90 degrees. Presently, the entire headscarp region is extremely unstable. Hazardous field conditions prevented detailed field inspections of the escarpments. We were able, however, to map structural information in deep boreholes and exploratory trenches that were placed adjacent to the margin of the landslide (Figure 5). The landslide mass at the time of failure was about 300 meters long and had an average width of approximately 110 meters. A rough estimate of the average thickness is approximately 12 to 15 meters. We estimate that the landslide volume ranges from about 400,000 to 500,000 cubic meters of failed material. Surf erosion has removed a large portion of the toe of the landslide and has resulted in the development of 12-meter high, oversteepened slopes that are critically unstable around the perimeter of the toe.

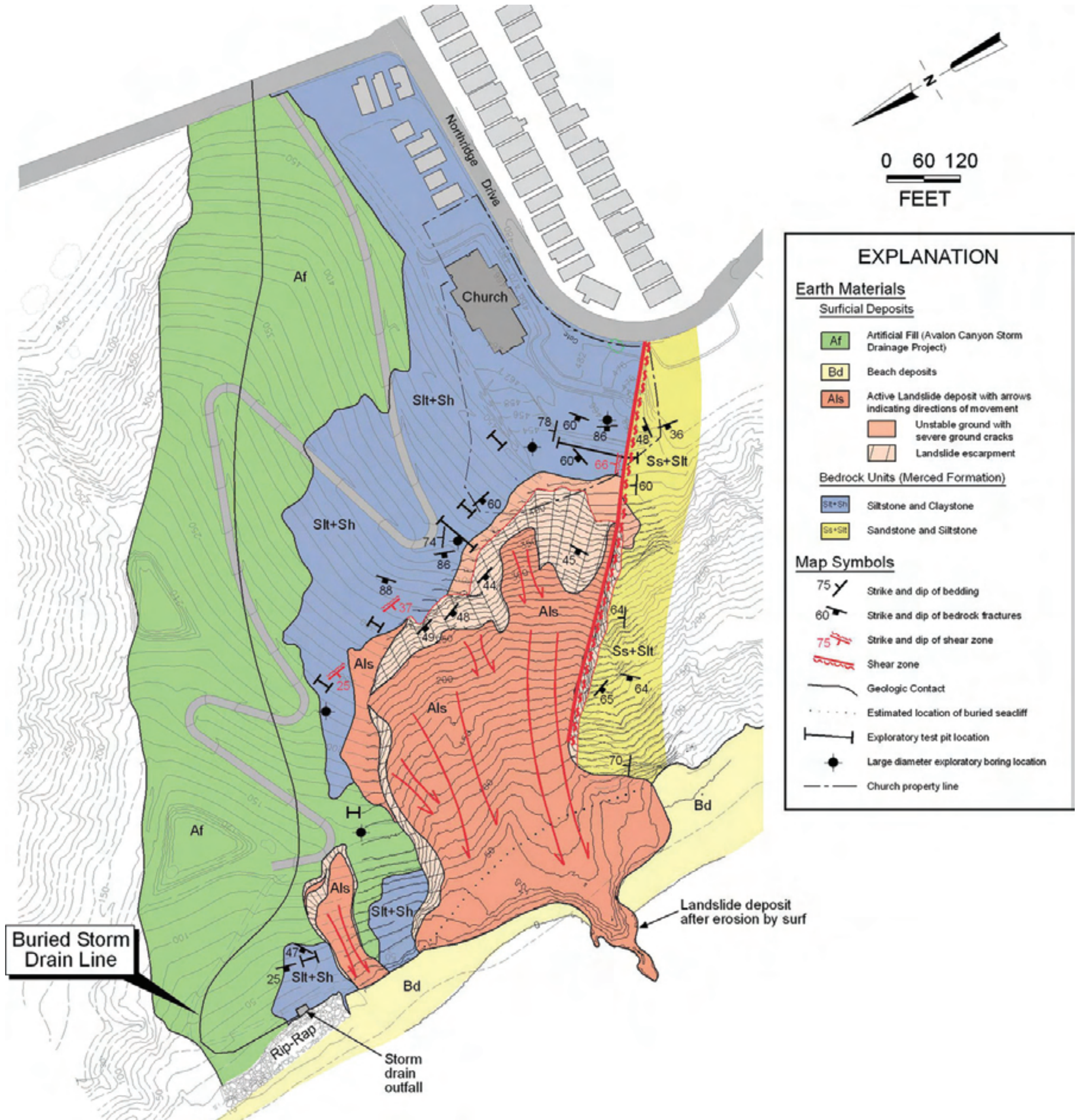


Figure 5. Engineering geologic map of the Northridge Bluff Landslide.

A sharp ridge that follows bedding within the Merced Formation defines the southern margin of the NBL. Bedding within this area of the bluff is oriented N60W and dips of 50-70 degrees to the north. The contact between resistant sandstone and the overlying highly sheared and weak claystone forms this apparent "strike-ridge". This sheared claystone is laterally continuous and can be followed eastward from the bluff and outside the landslide area. Within this sheared claystone bed, there is a 1-meter thick highly plastic clay gouge. Given the lateral extent and the degree of gouge development, it appears that shearing must predate the recent landsliding. This prior deformation may be related to flexural slip during regional tectonic folding of the Pliocene bedrock (Bonilla, 1971). The presence of this highly sheared claystone bed within the Merced Formation provided a weak surface for failure of the landslide.

The relationship between the nearly due-north trend of the coastal bluff (N5W) and structural trend of the bedrock (N60W to N65W) combined with the steep bedding dip creates an apparently stable slope condition. That is, the bedding is oriented oblique to the bluff face and inclined somewhat into the slope. For this reason, the potential for bluff failure at this location may not have been recognized during a cursory review of the local geology and without more substantial geologic characterization.

Clearly though, the failure of these high bluffs could not be controlled entirely by sliding along weak bedding planes. We mapped several sets of well-defined bedrock fractures within the bluff surrounding the NBL, and based upon our analysis of 414 measurements of fracture and bedding orientations, it appears that fractures played a significant role in the failure of the NBL. The orientations of distinct fracture sets are shown in a stereonet plot (Figure 6). These fracture sets can be grouped as either sliding fractures that dip shallowly seaward and allow sliding of blocks or releasing fractures that dip steeply and open in tension to allow release of blocks that slide downslope. These sliding fractures and releasing fractures, along with weak bedding planes combined to form a series of wedge failures (Figure 7). Large releasing and sliding fracture surfaces are exposed in the portion of the escarpment that forms the headscarp and the northern perimeter of the NBL (Figure 7). Along the southern margin, the failure followed the sheared claystone bed.

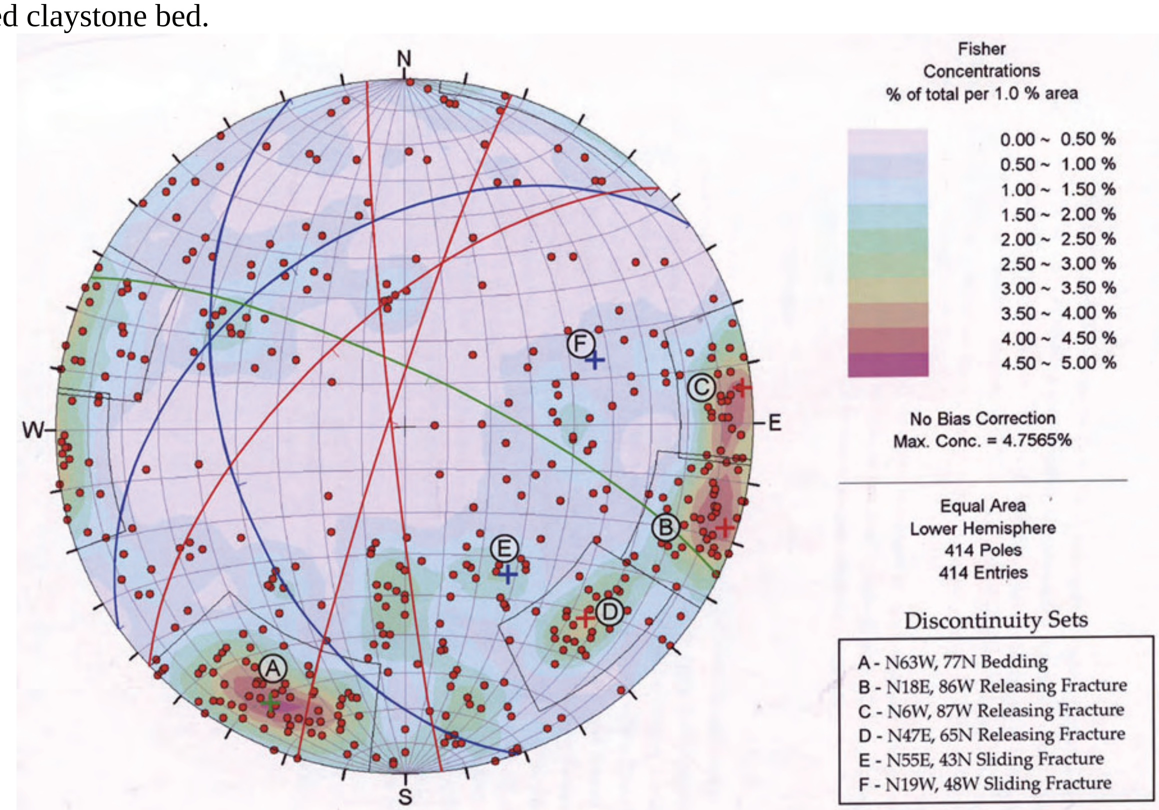
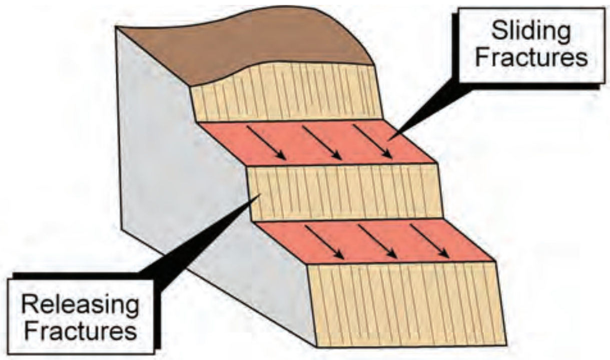


Figure 6. Stereonet plot of orientations of fractures and bedding measured in the area surrounding the landslide.



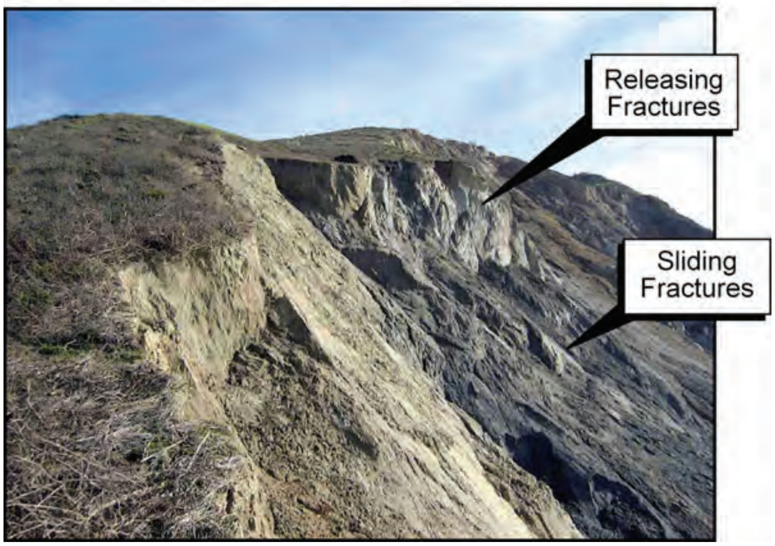


Figure 7. A block diagram and photograph showing sliding and releasing fractures identified during investigation of the landslide. Photograph by Dale R. Marcum.

The kinematics of the NBL are two-fold: initial deep-seated block failure in the upper bluff followed downslope by disaggregation and rapid flow. In the upper portion of the landslide, large blocks slowly begin to slide along sliding fractures and weak bedding planes while releasing fractures open as tension cracks. In the upper portion of the NBL, sliding is controlled by the location and orientation of these planes of weakness. Over time and with introduction of rainwater, these critically unstable blocks mobilize rapidly. The sedimentary bedrock appears to partially disaggregate as the failure accelerates and flow is initiated. The rapidly moving, fluid nature of this mass allowed it to flow across the beach and into the ocean approximately 100 meters from the bluff (Figure 4). Presently, the toe has been eroded back toward the original base of the coastal bluff as the surf rapidly eroded the landslide debris that extended beyond the bluff.

Landslide Hazard Zonation

A major result of our investigation is the landslide hazard map (Figure 8), which defines a zone of high landslide risk. We established the perimeter of the zone by constructing a series of topographic profiles through critical slope locations. Then using these profiles, we developed geologic cross sections through the landslide deposits and the headscarp regions (Figure 9). To establish the limits of the high landslide risk zone we estimated the subsurface geometry of the landslide basal rupture surface, measured the inclinations of those surfaces and projected them upslope to intersect the ground surface. The upslope projection of the potential failure surfaces along several profiles established points beyond the edge of the NBL that we believe define ground that is vulnerable to continued failure. These points typically ranged from 170 feet above the headscarp to about 90 feet along the north margin of the NBL. To compensate for the uncertainty in our evaluation, we increased these distances by 50% along the margins of the NBL to define the Zone of High Risk. We expect that additional landsliding along the margins of the NBL will be limited to this high risk zone (Figure 8). Failures within the headscarp region subsequent to our 2004 investigation have been limited to this zone (Figure 10).

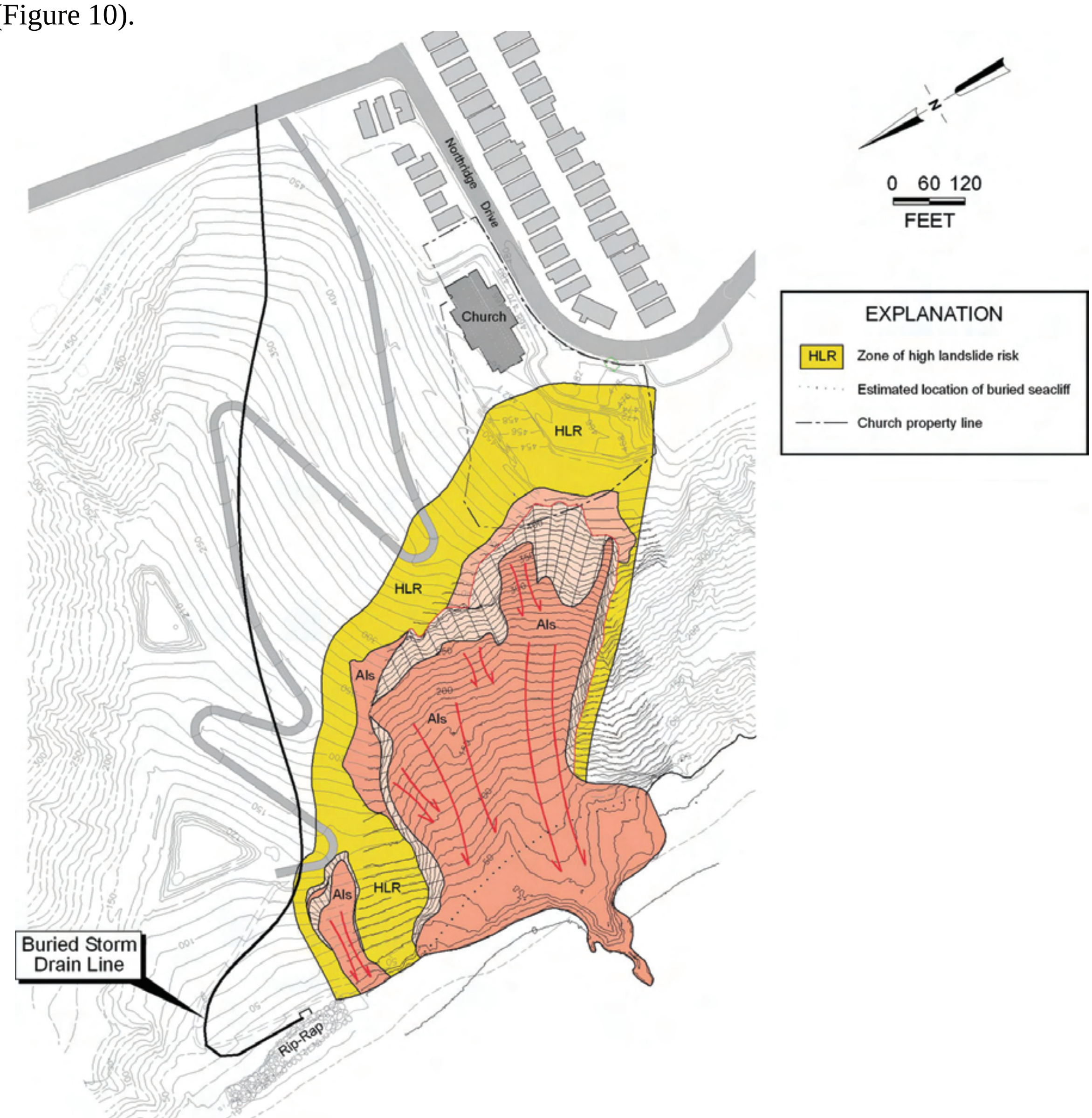


Figure 8. Landslide hazard map for the Northridge Bluff Landslide and surrounding area.

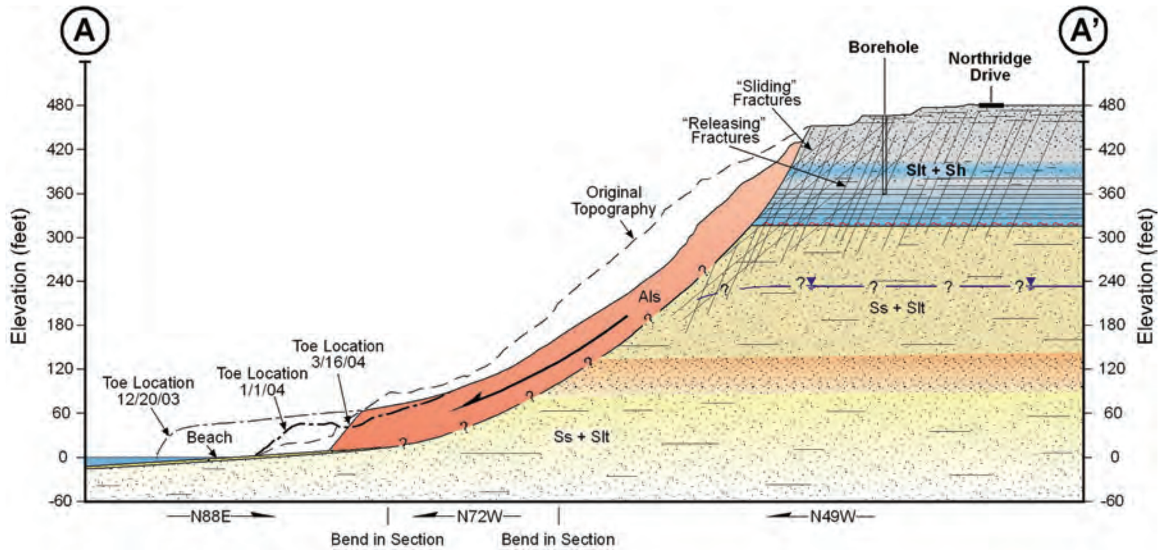


Figure 9. Engineering geologic cross section A-A' through the Northridge bluff Landslide.

Figure 10. Aerial photograph of the landslide taken on October 5, 2005, after completion of the NBL investigation. Portions of the church property at the head of the landslide and blocks along the north margin have failed since landslide mapping was completed during 2004 (Figure 5). Note that a hairpin turn in the access road for the Avalon Canyon storm drain project was relocated in 2005, because slow, steady movement of headscarp blocks began to open releasing fractures and undermine a portion of the road. Published by permission of Kenneth and Gabrielle Adelman, California Coastal Records Project.

There is no reliable method by which we can define a timetable for failure of the unstable slopes in the high risk zone. At this site, the best estimate that can be offered is a qualitative forecast that the upslope progression of landsliding will extend into the high risk zone during the design life of the Avalon Canyon storm drain project north of the NBL and the church development located adjacent to the headscarp.

Land located immediately to the north and east of the Zone of High Risk, has a moderate landslide risk. Moderate risk is normally reserved for hillside regions that bound high risk regions and transition between high and low risk zones. The potential for enlargement of the landslide down-section from the stratigraphically controlled weak southern margin appears to be lower due to the relative stability of the resistant sandstone to the south and the weakness of the overlying sheared claystone.

CONCLUSIONS

The Northridge Bluff Landslide is an example of a large, deep-seated failure of a coastal bluff at a location that did not experience significant historical bluff retreat. Methodologies for evaluating potential bluff retreat based upon an average annual retreat rate would tend to underestimate the occurrence of such events. Annual retreat rates based upon analysis of shoreline locations identified on historical aerial photographs may have utility where retreat events are frequent. In settings where sea bluffs expose weak and fractured rock, annual retreat rate studies may be inadequate.

Prior to development adjacent to coastal bluffs, the risk associated with bluff failure should be evaluated utilizing geologic characterization and detailed quantitative analyses to identify unstable geologic conditions and accurately evaluate the risk. These analyses should be performed to develop hazard maps and define meaningful setbacks prior to development of coastal sites.

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REFERENCES

BONILLA, M.G., 1959, Geologic Observations in the Epicentral Area of the San Francisco Earthquake of March 22, 1957, California Division of Mines and Geology Special Report 57, p. 25-37.

BONILLA, M.G., 1971, Preliminary Geologic Map of the San Francisco South Quadrangle and Part of the Hunters Point Quadrangle, California, U.S. Geological Survey Miscellaneous Field Studies Map MF-311.

GRIGGS, G.B., 1997, The armoring of California's coast *in* Magoon, O.T., Converse, H., Baird, B., and Miller-Henson, M., eds., California and the world ocean '97: American Society of Civil Engineers, p. 515-526.

LAWSON, A.C., 1908, The California Earthquake of April 18, 1906, Report of the State Earthquake Investigation Commission, two volumes and atlas, Carnegie Institute, Washington D.C.

LAJOIE, K.R., and MATHIESON, S.A, 1985, San Francisco to Año Nuevo, *in* Living with the California Coast, Duke University Press, Durham, North Carolina, p. 140-177.

JOHNSSON, M. J., 2002, Establishing development setbacks from coastal bluffs, in Magoon, O., ed., Proceedings, California and the world Ocean '02: Reston, Virginia, American Society of Civil Engineers, p.1-21.

SAYRE, T., SHIRES, P. O., and SKELLY, D. W., 2001, Mitigation of the 1998 El Nino sea cliff failure, Pacifica, California, *in* Ferriz, H. and Anderson, R., eds., Engineering Geology Practice in Northern California, California Department of Conservation, Division of Mines and Geology Bulletin 210, p. 95-106.

STORLAZZI, C. D. and GRIGGS, G. B., 2000, Influence of El Nino Southern Oscillation (ENSO) events on the evolution of central California's shoreline: Geological Society of America Bulletin, v. 112, p. 236-249.