Accelerated Movement of Large Coastal Landslide Following October 17, 1989, Loma Prieta Earthquake in California

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The January storms of 1982 mobilized an ancient landslide in the coastal bluffs of Marin County, California. Slow, intermittent movement of portions of the large slide mass required periodic maintenance by the local highway district through 1989. A significant increase in the rate of movement occurred following the October 17, 1989, Loma Prieta earthquake. Because the new rate of movement made it impossible to keep the highway open, the highway was closed for 13 weeks following the earthquake. The roadway was ultimately relocated behind the failure plane and the approximately 765 000 m^3 (1,000,000 yd^3) of excavation material placed in the ocean (as an erodible fill) against the lower slope of the landslide. Before the earthquake, approximately 5.5 m (18 ft) of intermittent downslope movement occurred between 1982 and October 1989. During the 17-month monitoring period between the earthquake and landslide repair some 28 m (92 ft) of downslope movement was recorded. The rate of slide movement increased to more than 50 mm/day between October 1989 and the spring of 1990, decreased, and then accelerated to 284 mm/day just before construction began in the spring of 1991.

In 1991, the California Department of Transportation (Caltrans) repaired a large landslide, called the Lone Tree landslide, in the coastal bluffs of Marin County (see Figure 1). Historic landsliding at this site began when the January storms of 1982 mobilized a portion of an ancient landslide. In the years following 1982, the remobilized landslide experienced relatively slow, intermittent, downslope movement.

The steep ocean-fronting cliffs of Marin County have long been associated with landslide processes. The combination of a young, geologically recent, uplifted terrain; active coastal erosion by wind and waves; and an inherently weak geologic foundation material (the Franciscan formation) has resulted in landslides' being the dominant erosional process in the region. The scalloped coastline is formed of overlapping active and dormant landslides and resistant narrow ridges (see Figure 2).

Before the October 17, 1989, Loma Prieta earthquake, movement on the Lone Tree landslide varied from 60 mm to 300 mm/month (2.4 to 12 in./month). After the earthquake, movement increased from 910 mm to 1220 mm/month (3 to 4 ft/month). The rate of slide movement following the earthquake made it impossible to maintain a traversable roadbed and the highway was closed on January 15, 1990.

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LONE TREE LANDSLIDE

The Lone Tree landslide extended from just above sea level to approximately Elevation 120 m (400 ft) mean sea level (MSL) and was about 140 m (600 ft) wide and 30 m (100 ft) deep under the roadway. State Route 1 traverses the landslide at Elevation 65 to 70 m (210 to 230 ft) MSL.

Portions of the larger landslide were active during the 1980s (see Figure 3). Between 1982 and 1989, the northern and southern parts of the slide were active. Landslide movement had occurred both above and below the road. The maximum amount of movement occurred in the northern portion, known as the Lone Tree landslide.

A foundation investigation and landslide analysis resulted in a repair strategy of unloading the upper portion of the slide approximately 765 000 m^3 (1,000,000 yd^3) and relocating the highway 70 m (230 ft) inland, behind the slide plane.

Because the project area is surrounded by overlapping and adjacent park land and public agency jurisdictions, selecting a geotechnically suitable and environmentally acceptable disposal site for the excavation material became a major part of the environmental processing of the project. In all, 13 public agencies had jurisdiction or permit authority over the project. Vigorous public debate and the concerns of permitting agencies resulted in about 15 months of environmental evaluation and alternative disposal selections while the highway remained closed.

Hauling the excavation material up to 26 km (19 mi) to existing disposal sites was opposed by the small communities both north and south of the landslide because of the anticipated lengthy community disruption from passing haul trucks. Hauling would also have caused substantial damage to the two-lane state highway. Exclusive of actual hauling costs, it was estimated that the 160-day continuous haul would cause pavement damage equal to 3 years of normal traffic usage, at an equivalent cost of $210,000 to $270,000.

On-land disposal of the material in upland areas was opposed by the adjacent state and federal public park jurisdictions and was geotechnically unacceptable because of the high probability of initiating other slope failures by overloading the already marginally stable slopes.

Ocean disposal was opposed by marine protection agencies because of the anticipated damage to marine organisms from direct burial and from future sedimentation from the eroding fill. A federal marine sanctuary is located approximately 460 m

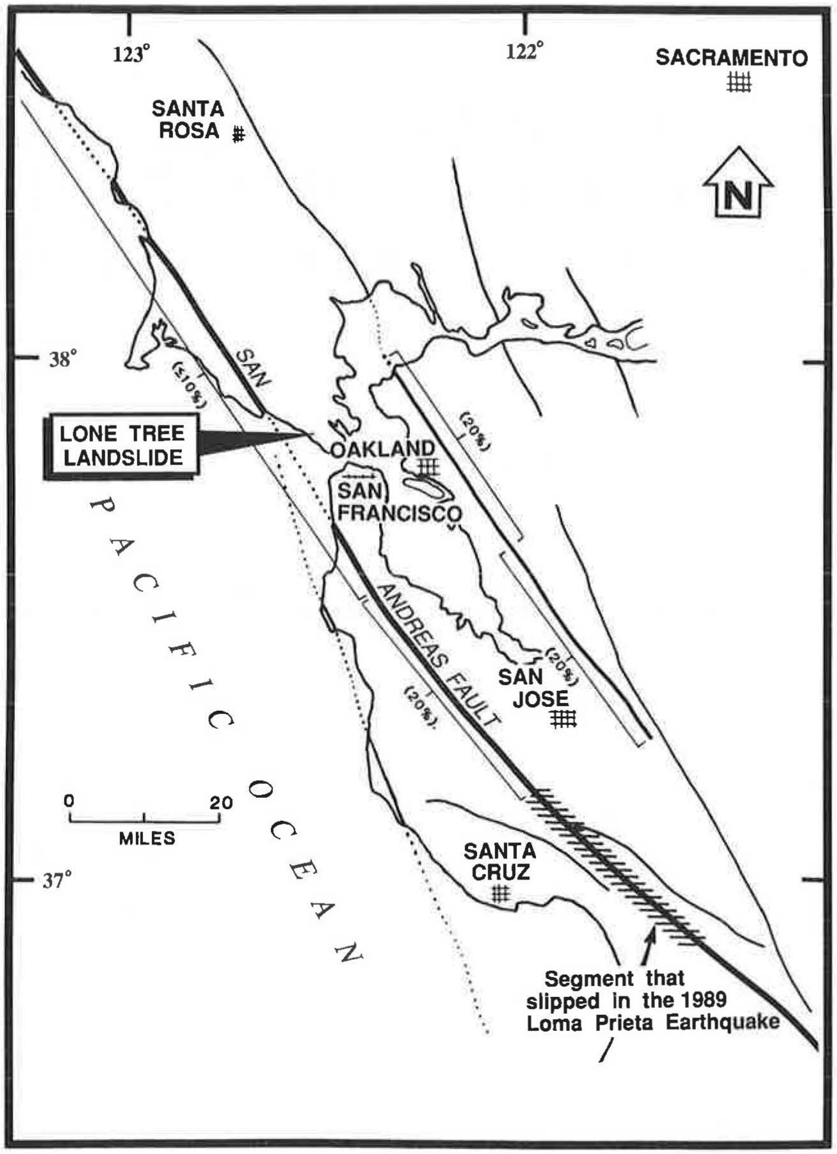

FIGURE 1 Location map; diagram shows conditional probabilities of major earthquakes in Bay Area (*12*).

(1,500 ft) offshore and was a major concern. Before landslide repair, 1525 to 1990 m^3 (2,000 to 2,600 yds^3) of soil and rock were already entering the marine environment each month because of slide movement. It was estimated that 2038 to 2650 m^3 (2,670 to 3,470 yds^3) would be eroded from the proposed fill each month, a 30 percent increase over the expected 25- to 30-year lifetime of the fill.

Lengthy discussions and negotiations with permitting agencies were required. Proposals to remove the excavation material by barges (estimated cost $1.8 million), installation of offshore cofferdams or Longard geotubes, and engineered construction of the proposed fill with a permanent rock revetment (estimated cost $550,000) were evaluated. All these alternatives were rejected on the basis of feasibility or likelihood of causing more environmental damage than was prevented.

Ultimately, approval was obtained to dispose of the 765 000 m^3 of excavation material by placing it on the rocky beach and near-shore area as a lightly compacted fill against the lower slope of the landslide below the highway (see Figure 4). The involvement of elected local, state and federal senators and representatives and the state or national heads of the jurisdictional agencies was required to obtain the needed permits.

The fill extends some 55 m (180 ft) into the ocean and is anticipated to erode gradually over a period of years. Aggressive erosion control on the erodible fill and new cut slope; removal of fill infringing on a coastal stream approximately 2 mi to the south, which had been placed in the past by non-highway agencies to create a parking lot for beach access; and a 5-year offshore sedimentation and biologic community monitoring program in the slide area were conditions required

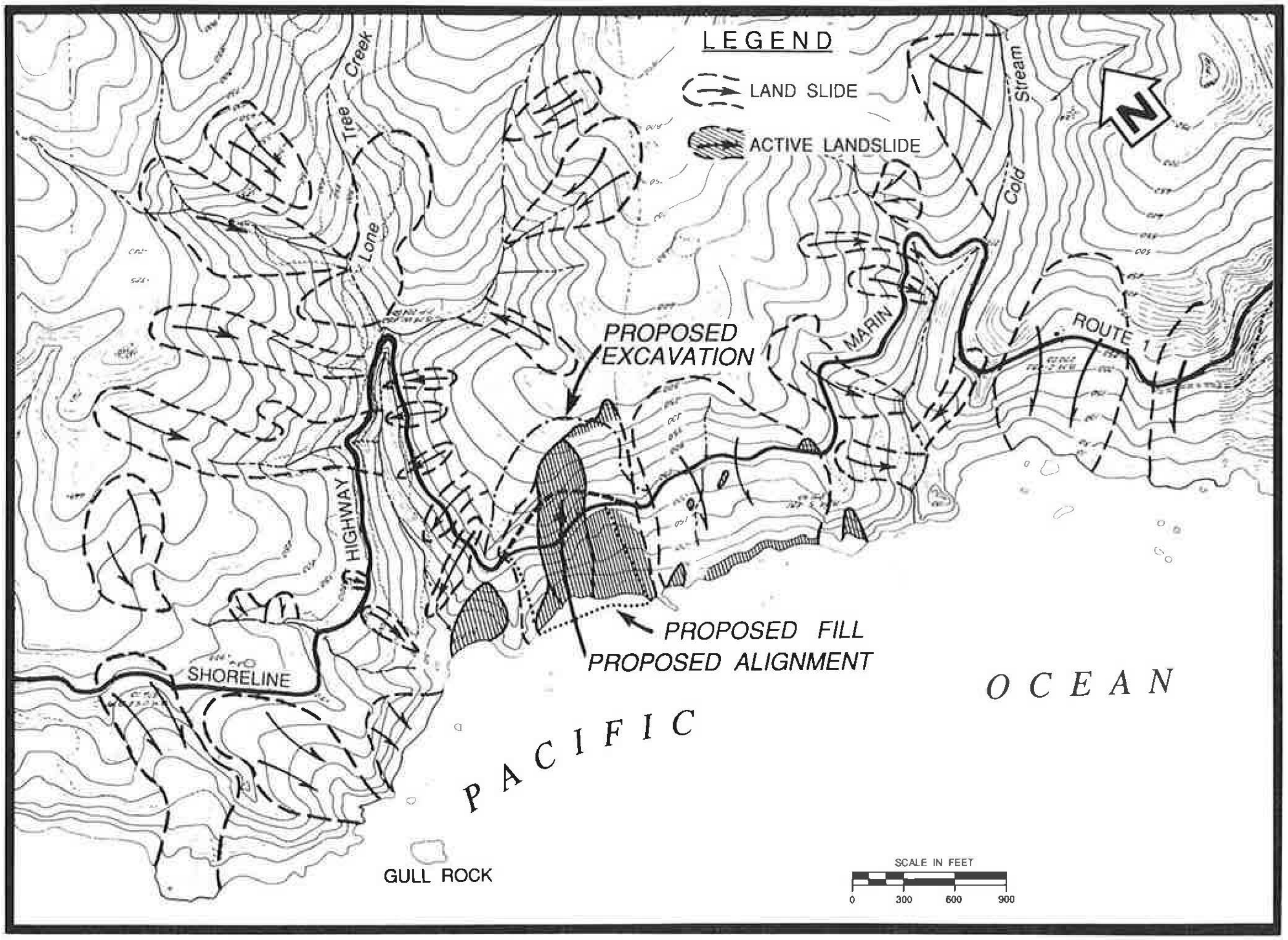

FIGURE 2 Regional landslide map.

by the permitting agencies as mitigation for the landslide repair. Mitigation costs are anticipated to reach at least 50 percent of the $2.1 million expended for actual construction to relocate the roadway to stable ground.

FOUNDATION CONDITIONS

The landslide is within the Jurassic-Cretaceous Franciscan formation. Eugeosynclinal deposits of greywacke, greenstone, chert, limestone, and exotic metamorphic rocks have been profoundly deformed and sheared by regional tectonics (*1*) in this region. The Franciscan formation is widely exposed over much of the California coast ranges and is often associated with large, deep-seated landslides. Landslides of all dimensions are present within the region.

The Franciscan formation is a complex assemblage of sedimentary, volcanic, and metamorphic rocks characterized as a melange—a heterogeneous mixture of disrupted rock masses in a pervasively sheared and crushed matrix material (*2*). Melange is believed to form at shallow depths in subduction zones where compressive forces between moving crustal plates crush and mix rocks of different origins.

Typically, repair of landslides in this type of formation is difficult. The heterogeneous and sheared nature of the Franciscan formation results in disrupted, unpredictable drainage paths, large boulders, and widely varying strengths of material.

Thirteen borings were placed for the investigation of this landslide. Borings SI-1 through SI-6, were placed for groundwater and inclinometer monitoring and were not sampled. Borings P-7 through P-13 were core borings placed to evaluate foundation conditions in the excavation back slope.

The rock recovered in the core borings was primarily highly friable and sheared black shale with sparse clasts [up to 7 m (23 ft) in diameter] of hard gray sandstone and lesser amounts of chert and metamorphic rock. Sieve analyses of core and bulk samples found 24 to 42 percent passing the 0.074-mm (#200) sieve. Dry unit weights averaged 2240 kg/m^3 (140 lb/ft^3) with moisture contents of 4 to 12 percent. Core recovery ranged from 76.5 to 100 percent and averaged 90.4 percent. The high core recovery rate in this difficult-to-sample material is due to the highly skilled state drill crew on staff with the District 4 Geotechnical Section.

The average rock quality designation (RQD), a measure of the degree of fracturing and therefore strength of a rock mass, was recorded for each core sample. RQD is defined as

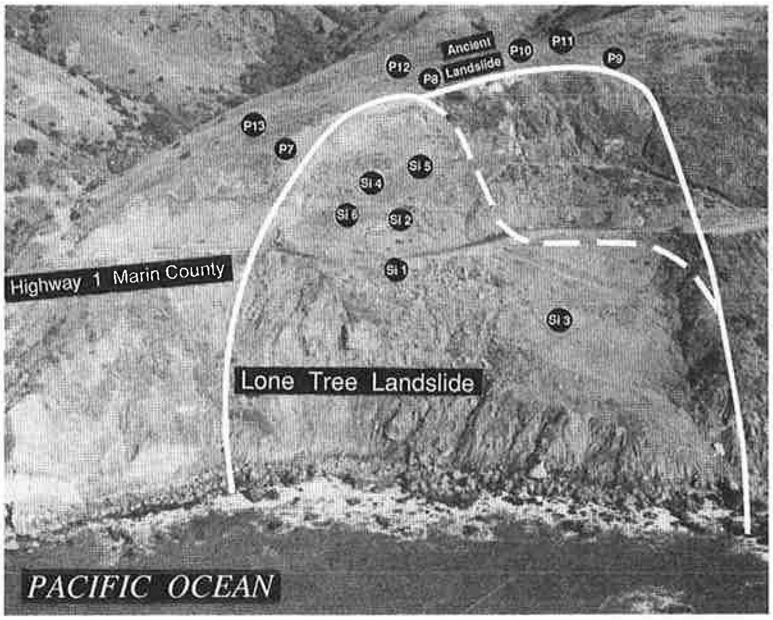

FIGURE 3 Aerial photograph of Lone Tree landslide.

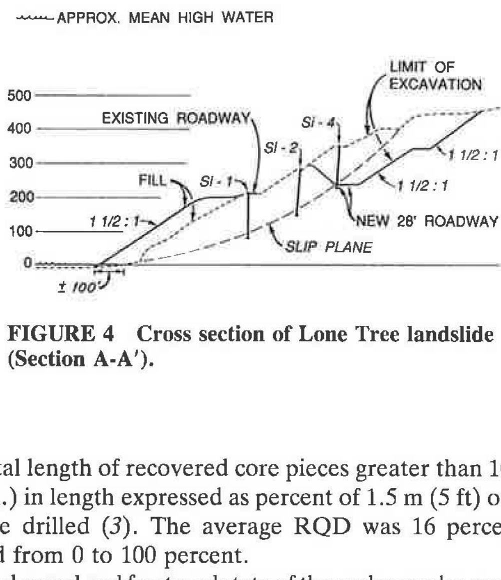

FIGURE 4 Cross section of Lone Tree landslide (Section A-A′).

the total length of recovered core pieces greater than 100 mm (4.0 in.) in length expressed as percent of 1.5 m (5 ft) or more of core drilled (*3*). The average RQD was 16 percent but ranged from 0 to 100 percent.

The sheared and fractured state of the rock was also expressed in the frequent severe water loss zones encountered during drilling. For 70 to 80 percent of the coring operation, drilling fluids were not returned to the surface but flowed into the fractured rock.

Samples recovered from the core borings were subjected to soil strength tests. The unconfined tests found cohesion ranging from 29 to 86 kPa (600 to 1,800 psf). Triaxial testing [confining pressures 27 to 90 kPa (4 to 13 psi)] indicated an average ϕ of 24 degrees and cohesion of 50 kPa (1,000 psf).

PRE-EARTHQUAKE SLIDE CONDITIONS

Because of the landslide-prone terrain and the chronic but intermittent and slow rate of slide movement, little documentation of slide movement before the earthquake exists. Available data consists primarily of personal recollection, aerial photographs, snapshots, records of maintenance expenditures, and sparse pavement profiles.

The movement history of this site is typical of many state routes with chronic maintenance problems. For a long time, landslide movement was not documented in any kind of consistent, scientific manner.

The winter of 1981–1982 brought unusually high rainfall to the San Francisco Bay Area (see Figure 5). Unusually high antecedent moisture conditions were aggravated by the storm of January 3–5, 1982, which caused substantial damage throughout the Bay Area and closed State Route 1 at the Lone Tree slide for several months. During the January storm some 300 to 400 mm (12 to 16 in.) of rain fell in the 30-hr storm, which is about equal to the total annual rainfall for the area.

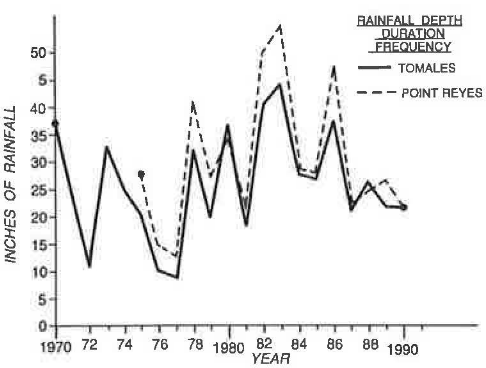

FIGURE 5 Rainfall data, Marin County, California, 1970–1990.

In 1982 it was recognized that the storm had reactivated a portion of an ancient landslide. In addition to landsliding above the road, which had occurred both above the subsiding roadway and to the north, subsidence below the roadway had occurred in the southern portion of the ancient landslide.

An inclinometer was installed at highway level in the southern portion of the landslide in May 1982 at a depth of 47 m (155 ft). The inclinometer was sheared off 8 to 12 months later, at a depth of 12 m (39 ft).

The $500,000 repair implemented in 1982 consisted of high, steep but relatively thin sliver cuts 3 to 4 m (10 to 15 ft) thick; a deep underdrain at highway level; improved surface drainage; and horizontal drains. To buttress the roadway, the excavated material was placed below the road at about Elevation 30 m (100 ft) MSL upward. Because of the steepness of the terrain and the need to minimize impacts to adjacent Mount Tamalpias State Park, the cut slopes were set at 1¼:1 (horizontal : vertical).

During the 1982 construction it was evident that the buttress itself was marginally stable because cracks quickly reappeared in the pavement and movement continued in the slope below the roadway. The 1982 repair was only temporarily effective because the landslide was deeper and laterally more extensive than originally believed. The roadway was reopened to traffic after a 4-month closure.

The northern slide area (the future Lone Tree landslide) began to develop between 1982 and 1983. By 1985 the landslide was clearly defined by cracks in the upper slope and pavement patches where the side scarps crossed the highway.

Unusually heavy rainfall occurred in 1982–1983 and landslide movement continued after the 1982 repair. Movement was generally slow (on the order of several centimeters per month) with brief localized episodes of movement of up to 300 mm/month (12 in./month). Highway maintenance staff repaved the highway periodically to maintain the road surface and highway maintenance expenditures were typically $20,000 to $40,000/year during this time.

During 1985–1986, cumulative subsidence of the roadway in the southern area became so pronounced that a lightweight fill (sawdust) was placed on the roadway in order to restore the highway grade and additional horizontal drains were installed.

The annual maintenance expenditures for this section of highway are graphically shown in Figure 6. About every fourth year there was a major reconstruction, reflecting the accumulation of slow displacement, which required periodic regrading.

In 1989 another increase in the rate of landslide movement was noticed, with almost a foot of vertical drop in August. Cumulative movement had once again lowered the highway profile, which resulted in an unacceptable vertical curve. The highway was once again leveled in August 1989 at a cost of $90,000.

Field reviews were conducted by Caltrans District 4 Geotechnical Section in August and September 1989. An attempt was made to install an inclinometer at roadway grade with a contract drill rig on October 10–11, 1989 because the District 4 state drill crew and rig were already committed to other projects. The contract rig supplied proved to be inadequate. After several equipment failures it was dismissed from the job and plans were made for installation of the inclinometer with a different drill rig. In view of the earthquake that followed on October 17, this delay was unfortunate.

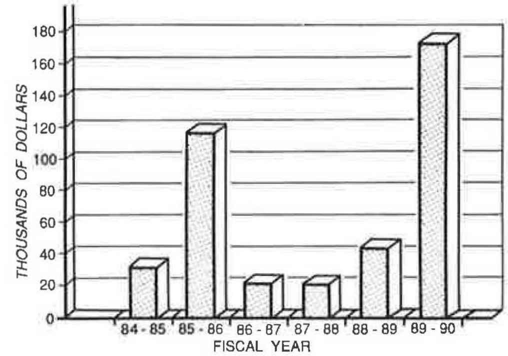

FIGURE 6 Maintenance expenditures at Lone Tree landslide, 1984–1990.

The inclinometer was successfully installed on October 23–24, 1989, 7 days after the Loma Prieta earthquake. Inclinometer depth was 33 m (108 ft), and it was initialized on October 26. By November 6, the inclinometer had sheared off at a depth of 31 m (102 ft). Even though the bottom of the hole was no longer accessible, groundwater levels continued to be recorded in the inclinometer on a regular basis. This inclinometer also became the reference point for surface movement recorded by surveys taken from October 30, 1989, until April 9, 1991, when reconstruction of the highway began (see Figures 3 and 4).

On the basis of various highway profiles, topographic maps, aerial photography, and maintenance records we have estimated that 5.5 m (18 ft) of vertical settlement occurred during the 90 months between the January 3–5, 1982, storm and the October 17, 1989, earthquake. The amount of settlement averages to 61 mm (2.4 in.)/month, or 2 mm (0.08 in.)/day. Actual rates varied seasonally and (by some estimates) approached 300 mm/month (12 in./month) during some winter months. In all cases over the 7-year period the intervals of faster movement were brief, lasting 1 to 2 months, and followed by lengthy periods of slower movement.

POSTEARTHQUAKE SLIDE MOVEMENT

In the extraordinarily difficult and busy period that followed the Loma Prieta earthquake, the magnitude of the accelerated movement at the Lone Tree landslide was not immediately reported, nor was it anticipated that the accelerated movement would continue. It took several months to determine that the accelerated movement was not a temporary anomaly (such as had been experienced at brief intervals in the prior 7 years) but instead a permanent change in the slide regime. In the meantime, the roadway was maintained as serviceable through the weekly paving efforts of the local maintenance staff.

On January 15, 1990, after more than 3 months of accelerated movement and a drop of the highway of more than 2.4 m (8 ft), it was recognized that it was no longer possible to keep the road open, and the highway was closed.

On January 17, 1990, a survey monitor line was established across the landslide and periodically monitored until April 9, 1991. In addition, the surface location of the inclinometer placed in October 1989 was monitored. Figure 7 is a plot of total movement from 1982 through 1990; the period from 1982 to 1989 depicts the reconstructed data. The period 1989 to 1991 is from survey data. The total resultant movement (vertical and horizontal) of the top of the inclinometer casing recorded by surveys between October 30, 1989, and April 9, 1991 is shown in Figure 8.

From January 19–21, 1990, five more slope indicators were installed in the landslide: one below the highway, and four in the slope above the highway. Groundwater was found at depths of 7.4 m (24 ft) in Boring SI-3 and 29.6 m (97 ft) in Boring SI-6. In 2 to 6 days, these slope indicators sheared at depths ranging from 14.5 to 23 m (48 to 76 ft).

STABILITY ANALYSIS

Three stability analyses were conducted for this landslide using the computer model PC-STABL4M (Purdue University). The initial analysis used the back-calculated soil strength parameters along the slide plane defined by inclinometer data. The second

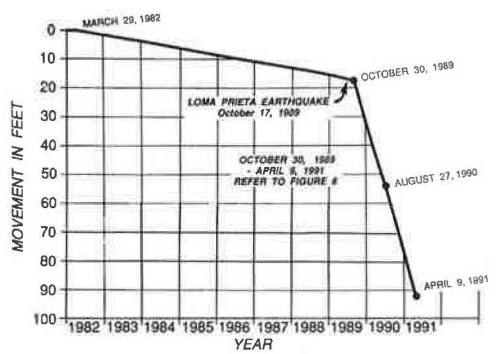

FIGURE 7 Resultant slide movement, 1982–1991, Lone Tree landslide.

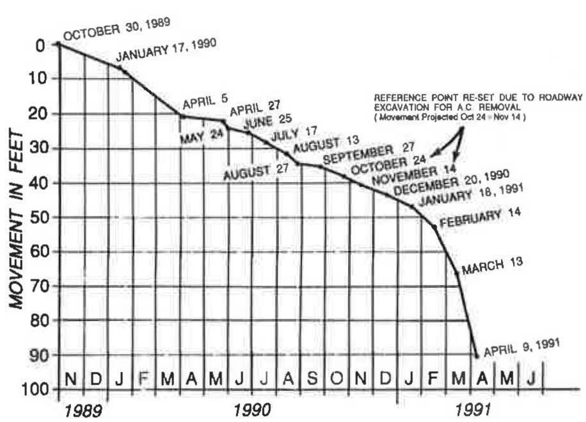

FIGURE 8 Resultant slide movement, October 30, 1989–April 9, 1991, Lone Tree landslide (resultant movement is vectorial summation of horizontal and vertical displacements).

analysis was conducted to evaluate the stability of the original slide plane after 765 000 m^3 of material were removed from the head of the slide and placed as a temporary buttress against the lower slope. This analysis also used the back-calculated soil strength parameters. The third analysis was conducted to design the back slope for the proposed excavation and used the soil strength parameters obtained by triaxial testing of core samples from the new back-slope material.

Back calculation of safety factors along the failure plane defined by the inclinometers resulted in soil strength values of $\phi = 11$ degrees, $C = 19$ kPa (400 psf), and factor of safety $= 0.99$. Using these same shear-strength parameters, and adding pseudostatic earthquake forces derived from those measured at the Point Bonita seismograph for the Loma Prieta earthquake (0.11 *g* horizontal, 0.06 vertical), the factor of safety drops to 0.826—a 17 percent drop.

Analysis of the proposed repair strategy yielded an initial factor of safety of 1.6 with the buttress in place. Removal of the buttress, as is anticipated to occur eventually through erosion, yielded a factor of safety of 1.24; therefore, the highway has been relocated behind the slide plane.

The excavation backslope was 60 m (200 ft) high. Stability analysis slope, using soil strength parameters of $\phi = 24$ degrees and $C = 50$ kPa (1,000 psf), resulted in the recommendation of a 1½:1 slope, a midslope bench 15 m (50 ft) wide, and extensive subdrainage (horizontal drains) to achieve a minimum factor of safety of 1.3 to 1.9.

EARTHQUAKE PARAMETERS

The Loma Prieta earthquake, which was 7.1 M_s (surface wave magnitude), occurred along a recently seismically quiescent portion of the San Andreas fault (see Figure 1). The fault segment had been identified as having a relatively high probability for an earthquake of this magnitude because of low microseismicity and the absence of historic earthquakes along this segment. A previous earthquake of a similar magnitude is believed to have occurred in the region in 1865, and the 1906 earthquake rupture zone included this segment.

Primary surface rupture was not found along the San Andreas fault following the Loma Prieta earthquake. The earthquake occurred at a depth of 19 km (11.5 mi), and fault rupture dissipated before it reached the surface. The duration of shaking was 10 to 15 sec; the strongest ground shaking recorded near the epicenter reached 0.64 *g* horizontal and 0.60 *g* vertical (*4,5*).

The Loma Prieta earthquake triggered 131 seismograph stations in the region; 77 recorded ground motion and the remainder were located on buildings. At the Lone Tree landslide, modified Mercalli intensities were estimated at IV. The recording station closest to the Lone Tree slide is the Point Bonita seismograph, located approximately 10 km (6 mi) to the east. The Loma Prieta earthquake recorded 0.11 *g* horizontal and 0.06 *g* vertical at this station. The Point Bonita seismograph is located on a fractured sandstone bedrock.

The epicenter of the Loma Prieta earthquake was located some 113 km (70 mi) southeast of the Lone Tree landslide. The primary wave motion at the site from the 7.1 M_s main shock and the subsequent aftershock swarm would have had a strong southeasterly component. In addition to the primary southeasterly wave, recorded ground motion also showed a strong transverse wave (Love wave). The direction of the transverse wave (Point Bonita) rotated clockwise from east to west and southwest to northeast, as frequencies increased from 0.4 to 0.8 Hz and 3.2 to 6.4 Hz (*6*).

The Lone Tree landslide is within a southeast to northwest trending ridge, and landslide movement is therefore to the southwest (S15°W). The higher frequency ground motion, (3.2 to 6.4 Hz) was therefore parallel to the direction of slide movement. The earthquake induced ground motion (normal to the free face of the slope) is seen as a factor in the change in the rate of landslide movement observed after the Loma Prieta earthquake.

ANALYSIS OF MOVEMENT AT LONE TREE SLIDE

Before the earthquake, the landslide moved at an average rate of 2 mm/day with brief episodes of 10 mm/day. Immediately after the earthquake, the landslide was moving at 22.8 mm/day (0.9 in.). During the period between October 30, 1989, and January 17, 1990, the landslide averaged 27 mm/day (1.0 in./day).

Varnes (*7*), Hungr (*8*), Morgenstern (*9*), and Cruden (*10*) have presented velocity classifications for landslides and separated them into six or seven classes. Each class covers a range of velocities within two orders of magnitude (see Table 1).

The Lone Tree landslide rate following the earthquake of 27 mm/day, or 3.1×10^{-4} mm/sec in SI units (ASTM E380-89), places this slide in Cruden's (*10*) slow category (Class 3). This rate is close to the middle of Class 3, with a lower limit of 50×10^{-6} mm/sec, or 1.6 m/year (5.25 ft/year), and a high limit of 5×10^{-3} mm/sec, or 13 m/month (42.6 ft/month). In our opinion, the SI units suffer from a lack of logical perception by the public and even the engineering community because of their small scale.

TABLE 1 CLASSIFICATION OF LANDSLIDE MOVEMENT RATES (*10*)

OLD		NEW			
m	mm/sec	CLASS	DESCRIPTION	m	mm/sec (SI Units)
		7	Extremely rapid		
3 m/sec	3×10^{3}		– – – – – – – –	5 m/sec	5×10^{3}
*600 ***		6	Very Rapid	*100 **	
0.3 m/min	5		– – – – – – – –	3 m/min	50
288		5	Rapid	*100*	
1.5 m/ day	17×10^{-3}		– – – – – – – –	1.8 m/hour	0.5
30		4	Moderate	*100*	
1.5 m/month	0.6×10^{-3}		– – – – – – – –	13 m/month	5×10^{-3}
12		3	Slow	*100*	
1.5 m/year	48×10^{-6}		– – – – – – – –	1.6 m/year	50×10^{-6}
25		2	Very Slow	*100*	
0.06 m/year	1.9×10^{-6}		– – – – – – – –	16 mm/year	0.5×10^{-6}
		1	Extremely slow	*100*	

** Velocity increment between classes*

Fukuzono (*11*) presented the results of the work of a number of authors who have studied the problem of developing predictive models for catastrophic failures. In discussing Salt's work (unpublished paper, Disaster Prevention Research Institute, 1988), Fukuzono reports that Salt's critical limit for the model velocity of a slide that has strained to its residual strength is 50 mm/day (5.8×10^{-4} mm/sec). At this velocity, Salt proposes that a landslide poses a substantial risk for imminent catastrophic failure. This rate is in the middle of the slow class (Class 3). Salt also suggests that the critical limit in terms of acceleration is 5 mm/day/day.

Salt suggests that had his limits been used, several days of forewarning would have been available on several catastrophic slides. The use of these values for real-time hazard prediction requires frequent reading of instrumentation and the immediate interpretation of the results. This is difficult to achieve with conventional instrumentation systems and geotechnical staffing levels in state highway agencies. This monitoring would perhaps lend itself well to some of the automated systems being marketed today.

After closing the roadway on January 15, 1990, a survey monitor line was established across the landslide at approximately roadway level. Between January 17 and April 5, the movement increased to an average of 54.7 mm/day (2.15 in./day), a critical rate by Salt's criteria, indicating possibly imminent failure. From April 5 to August 13 and August 13 to December 20, the average rates slowed down to 34.5 mm/day (1.4 in./day) and 23.8 mm/day (0.94 in./day), respectively. The slowing down gave a false indication of what was to happen over the winter of 1990–1991 (see Figure 7).

Monthly readings over the winter of 1990–1991 show successive rates of 38.9 mm/day (1.5 in./day), 67.7 mm/day (2.7 in./day), 145.6 mm/day (5.7 in./day), and 284.4 mm/day (11.20 in./day) or 3.3×10^{-3} mm/sec [still in the slow class defined by Cruden (*10*)] between December 20, 1990, and April 9, 1991. April 9 is the date of the last reading before any construction activity was started.

Salt's critical acceleration rate was exceeded sometime between February 14 and March 13 approximately a month after exceeding the 50 mm/day rate. The average acceleration for this period was 5.6 mm/day/day, 0.6 mm above Salt's critical acceleration rate. Some additional monitoring was performed during construction and the movement peaked at 800 mm/day (30 in./day) without catastrophic failure.

RAINFALL

Before the earthquake, slide movement responded to winter rains and the subsurface exploration program found zones of high permeability within the slide material. At the time of the earthquake in October 1989, however, it was the end of the summer and this region was experiencing the consequences of its third lower-than-average rainfall season. In October 1989, there were 31 mm (1.25 in.) of rainfall, the first of that rainfall season. Rainfall remained low, 53 mm (2.1 in.) in November and no rain occurred in December 1989, yet the rate of landslide movement did not diminish. The spring of 1990 received 440 mm (17.37 in.) of rainfall, and movement of the landslide continued. There were slight increases or decreases in the rate of landslide movement that appear to correlate with the seasonal rains; however, there was no change in the overall trend. The landslide continued to move over the summer of 1990, with very little reduction in the rate of movement. The winter of 1990–1991 also experienced below normal rainfall (see Figure 5). Acceleration in the rate of landslide movement occurred in December, when antecedent rainfall was still low [60 mm (2.34 in.)] and continued to accelerate over the spring of 1991. Substantial rainfall in February [105 mm (4.14 in.)] and March [312 mm (12.29 in.)] coincided with continued acceleration.

Because the acceleration of landslide movement began in 1989 and 1990 before substantial antecedent rainfall, and the rate of landslide movement failed to diminish significantly over the summer of 1990, the author believes the more than tenfold increase in rate (2 mm/day to 22.8 mm/day) immediately following the earthquake is not tied to a change in the groundwater regime.

FIGURE 9 Aerial photograph of completed landslide repair, Lone Tree landslide.

POSTCONSTRUCTION MONITORING

Six inclinometers were placed in the new back slope after construction. Potential slope movement and groundwater are being monitored in the inclinometers. A grid of survey points has been established across the erodible buttress to record its gradual removal by erosion and ocean waves.

CONCLUSIONS

The authors have presented the monitoring and analysis performed to correct a large, slow-moving landslide on State Route 1 in the northern coast of California. Also presented is a comparison of recorded rates of movement with critical velocities and accelerations proposed by others as warnings of imminent catastrophic failure.

Before the Loma Prieta earthquake, the slide was moving at a rate generally manageable by maintenance forces, although road closures were necessary from time to time. After the earthquake, the rate of movement increased to an intolerable, although still subcritical, level, according to published values. After continued movements over a long period, the slide accelerated to the critical values proposed by Salt, although sudden and rapid movements were never reached. Salt's critical velocity was reached in early 1990. Subsequently, there was a decrease in velocity, and the critical velocity threshold was again reached in early 1991, a month or so before reaching his critical acceleration threshold. During the earthwork for landslide repair (Figure 9), the rate of slide movement increased to 16 times the critical velocity and catastrophic failure did not occur.

Continued studies to provide a reliable method for predicting the time of rapid failure of a landslide is necessary. This landslide did not fit existing models.

The authors believe that the accelerated rate of movement at Lone Tree landslide is due to a combination of factors; large movements over the years lowered the shear strength of the material in the failure plane, and earthquake shaking accelerated the process. Other factors include seasonal rainfall and the continued erosion of the toe of the landslide by the ocean, which prevented natural buttressing. The linkage of increased landslide movement with earthquake acceleration is supported by statements in Salt's work, which shows that frictional materials in the fine fraction range are more sensitive to earthquake accelerations than cohesive soils. The lowering of the factor of safety by just a small percentage in these materials can lead to accelerated movement rates.

This case history documents a unique failure by deterioration of the shear zone because of long-term shearing and earthquake shaking. The monitoring program and analysis show that the increase in rate of slide movement coincides with the earthquake event and suggest that it was a major contributory factor.

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