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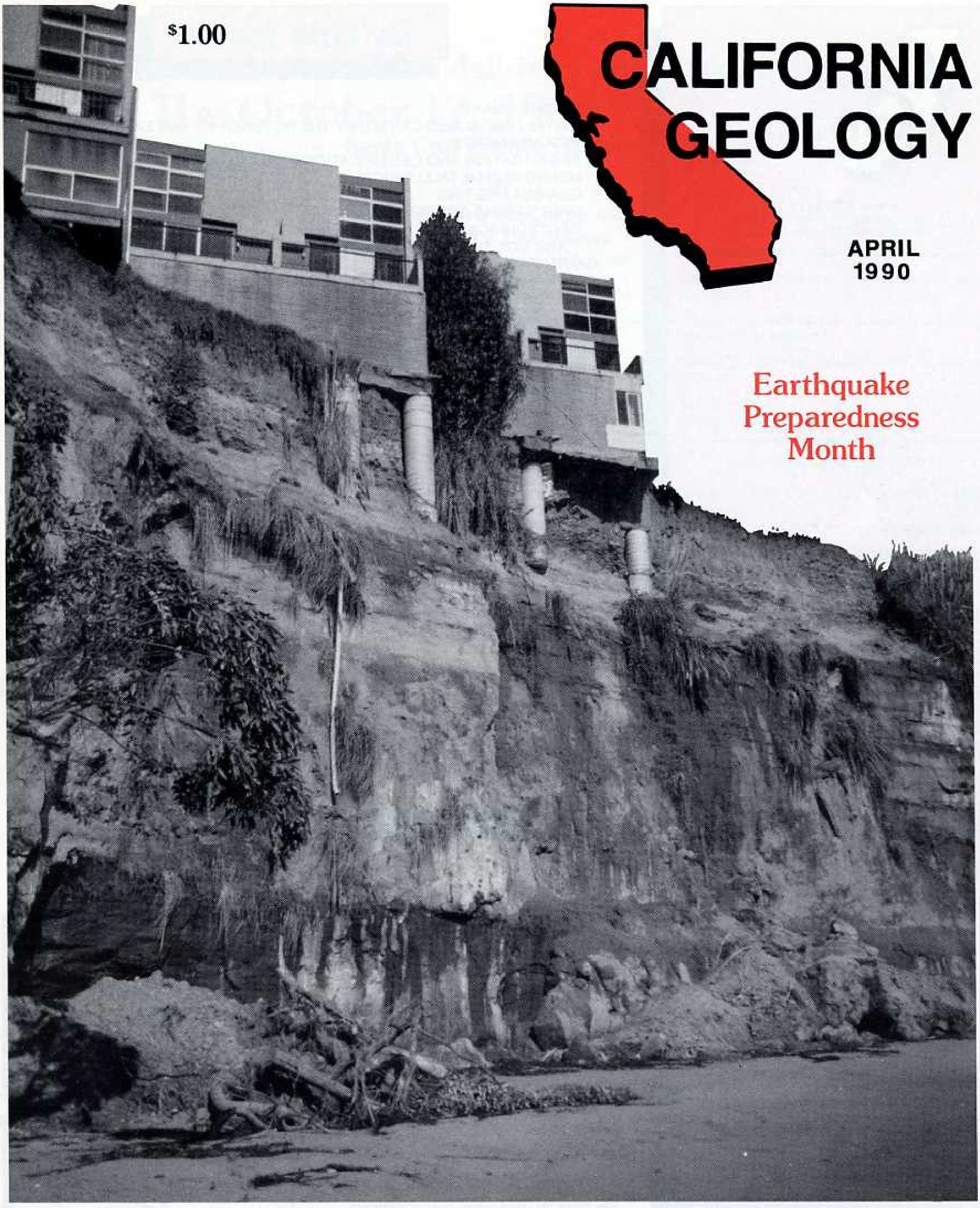

Earthquake Preparedness Month

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Coastal Landslides Caused By
The October 17, 1989 Earthquake
Santa Cruz County, California

By

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INTRODUCTION

The October 17, 1989 earthquake (magnitude 7.1) ruptured a 24-mile (40 km) long segment of the San Andreas fault zone in the Santa Cruz Mountains, about 54 miles (90 km) south of San Francisco (Figure 1). The hypocenter was at a depth of 11.5 miles (18 km), and peak recorded horizontal ground accelerations varied from 0.64 gravity (g) in Corralitos, 0.54 g in Capitola, and 0.47 g in Santa Cruz (Shakal and others, 1989). This was the largest earthquake in California since the 7.7 magnitude event on the White Wolf fault near Bakersfield in 1952, and the largest event on the San Andreas fault since the 1906 earthquake (McNally and others, 1989). The earthquake caused damage and local emergencies in Alameda, Contra Costa, Marin, Monterey, San Benito, San Francisco, San Mateo, Santa Clara, Santa Cruz, and Solano counties. At least $6 billion in damage resulted from the earthquake; 62 people died and 3,757 were injured (Plafker and Galloway, 1989).

Extensive ground fracturing and cracking in the Santa Cruz Mountains resulted from a combination of the severe shaking and the reactivation of a number of very large "ancient" landslide masses. Liquefaction led to subsidence and formation of sand volcanoes (also called sand boils) along the San Lorenzo, Salinas, and Pajaro rivers as well as in the Moss Landing area. Widespread failure of the sea cliffs also took place between San Francisco and Monterey.

HISTORY OF SEA CLIFF EROSION

Landsliding in marine terrace terrain has been recognized as a geologic hazard along much of the California coastline (Cleveland, 1975). The steep, often unvegetated sea cliffs bordering northern Monterey Bay clearly reflect the effects of active erosional processes. Erosion rates here, due to both marine and nonmarine processes, vary from several inches to several feet per year and are controlled primarily by lithology, structure, stratigraphy, and exposure to wave energy (Griggs and Johnson, 1979; Griggs and Savoy, 1985). These processes include both hydraulic impact and scour from winter storms, as well as mass movements associated with intense rainfall, and, less frequently, mass movements associated with earthquakes. Although construction

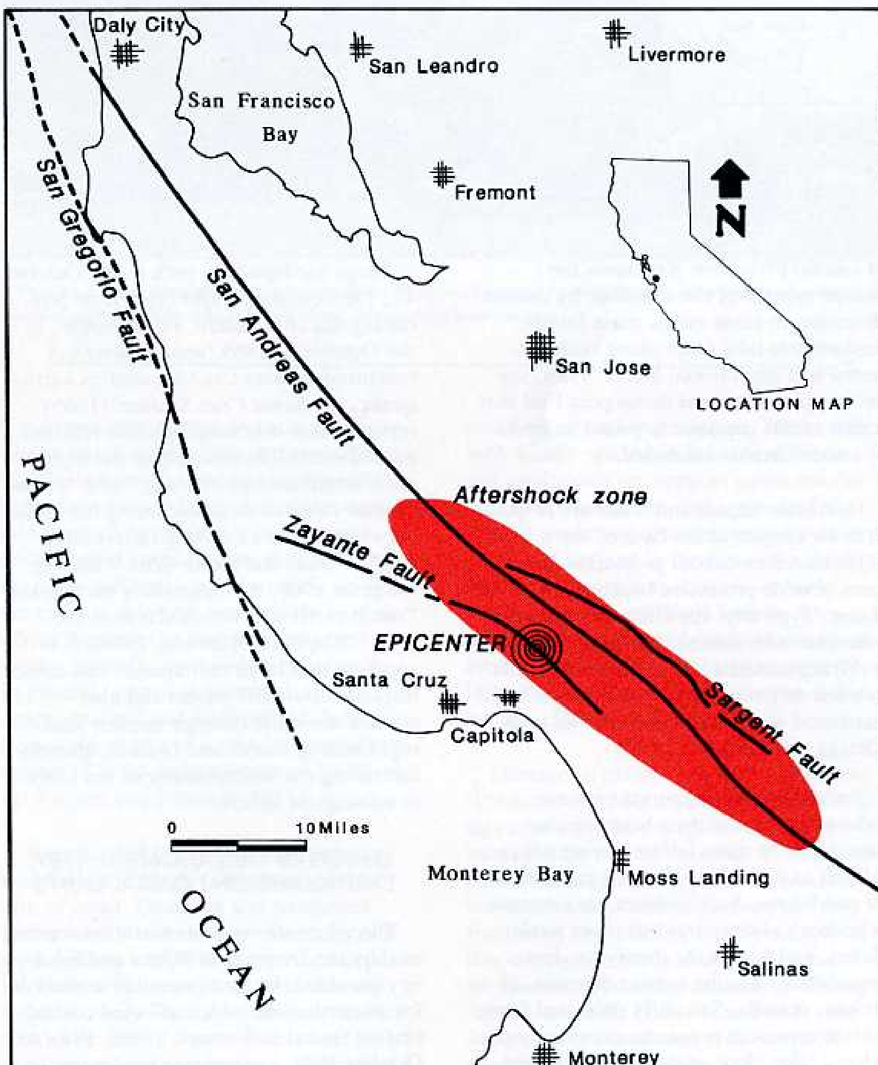

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Figure 1. San Francisco Bay area, showing the epicenter of the October 17, 1989 Loma Prieta earthquake in the Santa Cruz Mountains, aftershock zone, main trace of the San Andreas fault, and other nearby faults.

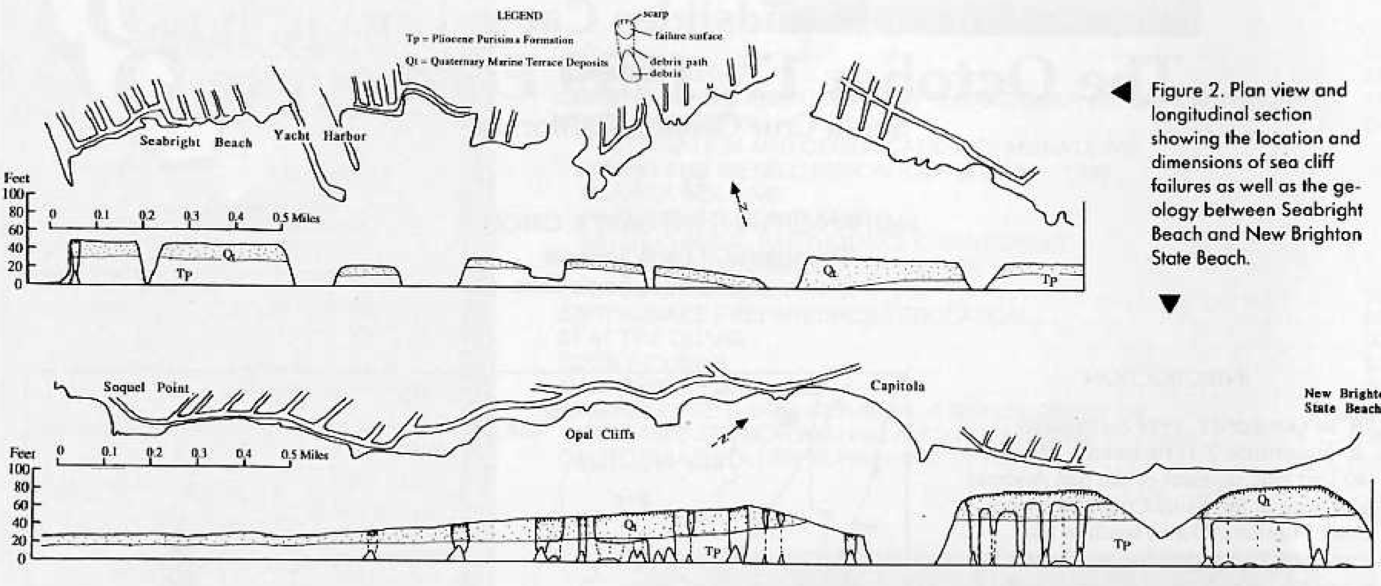


Figure 2. Plan view and longitudinal section showing the location and dimensions of sea cliff failures as well as the geology between Seabright Beach and New Brighton State Beach.

of coastal protection structures has slowed erosion of the coastline by marine processes in some areas, mass failure continues to take place along both protected and unprotected bluffs. Thus, scientists, planners, and developers find that recent events continue to push the limits of coastal erosion landward.

Hydraulic impact and scour are responsible for erosion at the base of the sea cliffs wherever coastal protection structures or wide protective beaches are absent. Typically, the cliffs are undercut over time with subsequent failure of the overlying material. As this material falls into the surf zone, it is broken down by continued wave action and carried away (Griggs and Johnson, 1979).

Sea cliffs over-steepened by wave induced erosion at their base are also susceptible to mass failure during heavy rainfall as a result of elevated groundwater conditions. Such failures are common in bedrock along joints* or other weak planes, and within the overlying, less consolidated marine terrace deposits, alluvium, or soils. Sea cliffs protected from marine erosional processes commonly develop a talus slope at their base whereas the upper portions remain steep. Heavy rainfall may induce failure in both the talus slopes and along the exposed upper portion of the cliff. For example, intense rainstorms in January 1982 caused widespread failure along the cliffs of northern Monterey Bay between New Brighton State Beach and Rio Del Mar. These storms endangered cliff top structures and damaged or destroyed beach houses (Griggs, 1982).

Large earthquakes, such as the October 17, 1989 event, are also capable of producing sea cliff failure. For example, in the October 8, 1865 (approximate 6.5 magnitude) Santa Cruz Mountains earthquake, the *Santa Cruz Sentinel* (1865) reported that overhanging cliffs fell into graded roads, "below Soquel the high cliffs crumbled into the sea," and "a continuous cloud of dust rose along the cliffs between Castro's Landing (now called Rio Del Mar) and Santa Cruz." During the great 1906, 8.3 magnitude earthquake "much earth fell from bluffs near the town" (Capitola) (Lawson, 1908). It is apparent that large earthquakes can cause instantaneous cliff retreat and also weaken sea cliffs through seismic shaking, forming cracks and fissures, thereby increasing the susceptibility of the cliffs to subsequent failure.

EFFECTS OF THE OCTOBER 17, 1989 EARTHQUAKE ON COASTAL BLUFFS

Three key strong-motion stations operated by the Division of Mines and Geology provided the first quantitative records for an earthquake which affected coastal bluffs (Shakal and others, 1989). Prior to October 1989, engineering geologists who studied coastal bluff stability were limited to descriptive interpretations of strong motion in the near-field, or had to extrapolate instrumental data tens of miles from an epicenter to the cliff site. By fortuitous circumstances, the epicenter, the coastal cliffs, and the strong motion instruments were all close to each other for the Loma Prieta earthquake. This provides a new and unique data set which will be helpful for quantitative analysis of coastal bluffs elsewhere.

These new strong-motion data for coastal Santa Cruz County are summarized on Table 1. It is significant for coastal bluff stability that *vertical* ground motion of about 0.40g to 0.60g occurred along the coastline in the near-field. It is inferred that *horizontal* ground motion was on the order of 0.47g to 0.64g for near-field coastal cliffs. The intensity of shaking was VIII on the Modified Mercalli scale. The duration of strong motion which affected cliff stability was on the order of 10 to 15 seconds.

On November 1, 1989, a team of geologists videotaped and photographed the coastline between Bolinas and Monterey, California from an airplane and noted many landslide scars, particularly between Capitola and Moss Landing (Figure 1). The videotape facilitated subsequent mapping of individual slides onto a topographic base map (1 inch = 100 feet).

TABLE 1. NEAR-FIELD STRONG MOTION
Loma Prieta Earthquake of October 17, 1989

Location of Station	Epicentral Distance	Accleration	
Corralitos SMIP	4.4 mi	90°	0.50g
		Up	0.47g
		360°	0.64g
Capitola SMIP	5.6 mi	90°	0.47g
		Up	0.60g
		360°	0.54g
Santa Cruz SMIP	9.9 mi	90°	0.44g
		Up	0.40g
		360°	0.47g

Data from *Shakal and others, (1989).*

*See Glossary, p. 83

More detailed ground observations compared lithologies, structural and stratigraphic weaknesses, and potential for additional failure (such as bluff top cracks landward of the failure area). A review of historic aerial stereo photographs and related literature, used to compare the October 17, 1989 event to both prior historic earthquakes and recent large storms, indicated that these observations typify the effects of large earthquakes on sea cliffs and that these effects are comparable to those resulting from heavy rainfall.

Coastal bluff failures resulting from the October 17, 1989 earthquake occurred between San Francisco and Monterey in a variety of lithologies and slope conditions. In northern Monterey Bay, between Seabright Beach to the north and Sunset State Beach to the south, there are excellent examples of the lithologic and morphologic control over earthquake-induced sea cliff failure. Three main differences in lithology along the coastline of northern Monterey Bay result in three distinct types of earthquake induced failures.

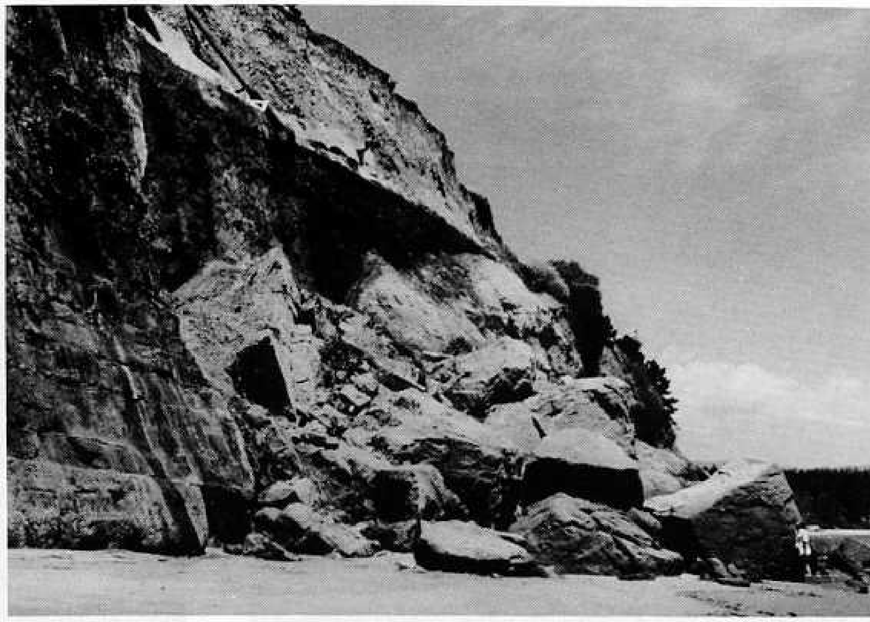


Photo 1. Joint controlled wedge failure in the Pliocene Purisima Formation. Marine erosion processes undercut these cliffs, which failed along intersecting joint planes.

Between Seabright Beach and New Brighton State Beach (Figure 2), sea cliffs are cut into a marine terrace that is up to 75 feet (25 m) high. This terrace consists of an uplifted wave-cut bedrock platform that is overlain by several feet of terrace deposits (Figure 3). The wave cut platform is in a thickly bedded to massive siltstone with prominent shell lags* (Pliocene Purisima Formation). Even though the Purisima Formation is well indurated, it is extensively jointed and susceptible to wedge failure along joint surfaces (Photo 1). The unconsolidated terrace deposits typically consist of marine cobbles overlain by shallow marine to eolian sands, and a fluvial conglomerate that is capped by a thin soil horizon. The nearly vertical sea cliffs in this area are actively eroding where they are not protected by revetments, seawalls, or a wide sandy beach. In general, where unprotected, the coarse-grained and well-jointed Purisima Formation erodes at a relatively rapid rate (about 12 to 24 inches per year; 30-60 cm/yr) (Griggs and Johnson, 1979).

*See Glossary, p. 83.

Seismic shaking initiated numerous rock falls and block falls along this section of coast. Undercut and weakened bedrock and fractured promontories collapsed along with bluff top terrace deposits. Failure along joint surfaces allowed large blocks to separate from more intact rock. The size of these failures was dependent on joint spacing and orientation, cliff height, and toe* support. High cliffs with widely spaced, sub-vertical joints and inadequate toe support sustained the largest instantaneous and incipient failures in weakened or undercut sedimentary rock. Toe support in the form of a shore platform, revetment, seawall, or wide beach generally inhibited failure. Although the density of failures diminished away from the epicentral region, several large slides and rockfalls occurred as far north as Daly City (Photo 2).

Damage to private property and public structures was minimal along the cliffs of this area with the exception of the cliffs immediately east of Capitola. In this area bedrock and terrace deposits toppled to the beach below and extensive bluff top fracturing also occurred. This caused further damage to walls and foundations of an apartment complex (already overhanging the sea cliff, Photo 3) and additional failure to an abandoned cliff top public road in the Capitola area.

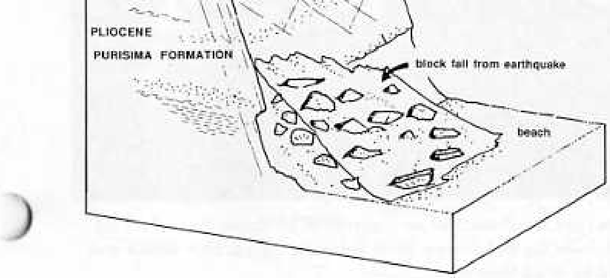


Figure 3. Block diagram showing sea cliff structure and typical failure style in sea cliffs underlain by well-jointed Pliocene Purisima Formation siltstone. Note the tension cracks in the Pleistocene terrace deposits and undercut sea cliff.

From New Brighton State Beach to Aptos Creek (Figure 4), an interbedded, pebbly, cross-bedded, moderately indurated, and weakly jointed sandstone member replaces the jointed siltstone member in the Purisima Formation and underlies 90-114-foot (30-38 m) high cliffs. Terrace deposits, consisting of poorly consolidated sands and interbedded pebbles, poorly sorted fluvial conglomerate, and a thin soil horizon, are about 15 feet (5 m)

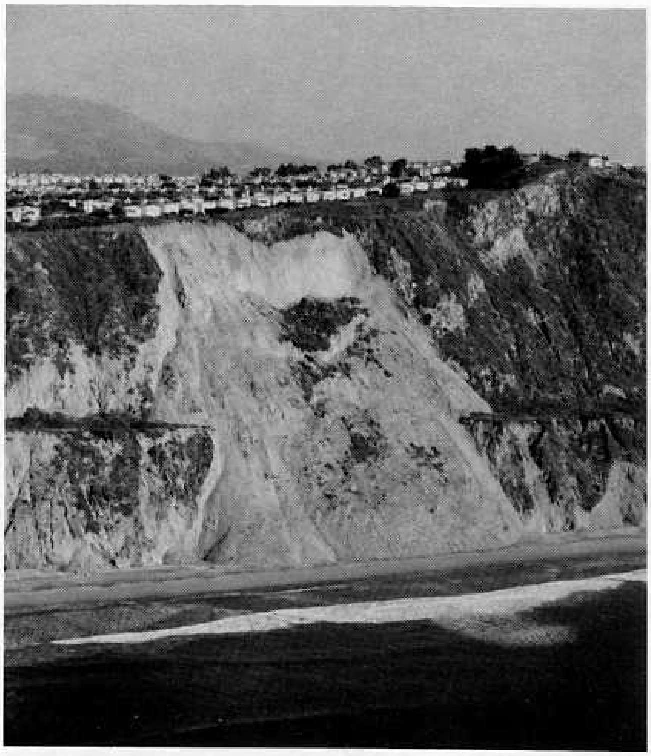
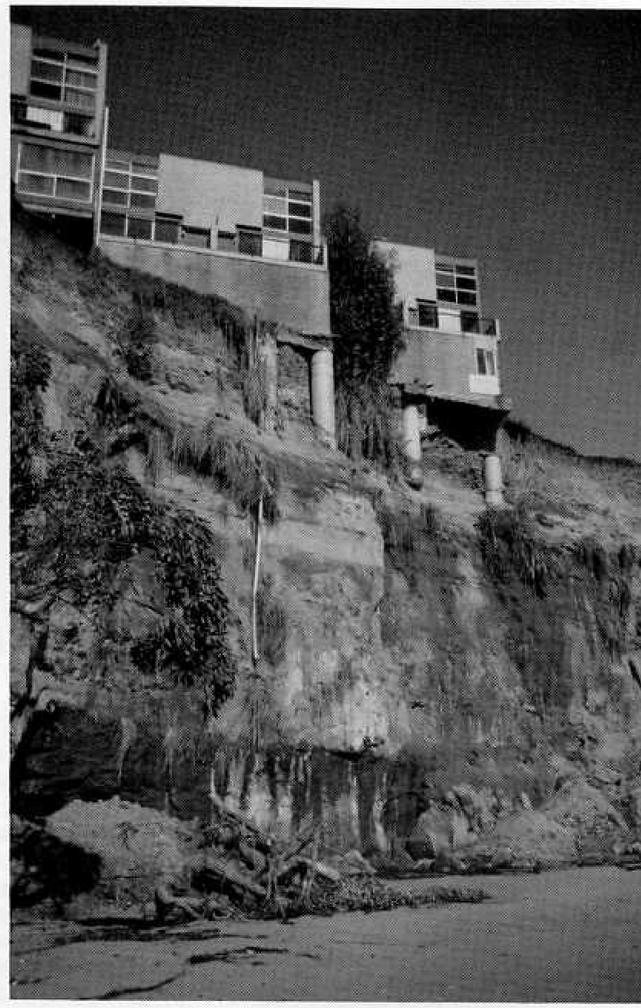


Photo 2. Large coastal landslide near Daly City. Note the proximity of cliff top houses to the head scarp.

Photo 3. Bluffs east of Capitola. Collapse of terrace deposits and underlying, extensively jointed siltstone further undermined the previously exposed foundation of this apartment building. ▶



thick and thin to the east. Seawalls and revetments, which protect the beach front development, isolate the base of the cliff from marine erosion; the upper portions of the cliffs continue to fail periodically.

Seismic shaking initiated two types of failure here. Translation* (uniform movement) along a joint or weathering surface produced many large slides up to 180 feet wide (60 m wide) that originated in the upper 36 feet (12 m) of the sea cliff (Photo 4). The scarps of these slides tend to cut vertically through the Quaternary terrace deposits and then flatten as they approach the Purisima Formation (Figure 5). Deep tension cracks cut through the terrace deposits (Photo 5) and soils 3-18 feet (1-6 m) landward of many of the scarps; depth of cracks tends to increase with the size of the scarp (Figure 6). Some intact blocks and much loose soil cascaded down the face of the cliff, forming 60 foot (20 m) high coalescing talus cones that partially buried some automobiles and blocked access to homes (Photo 6).

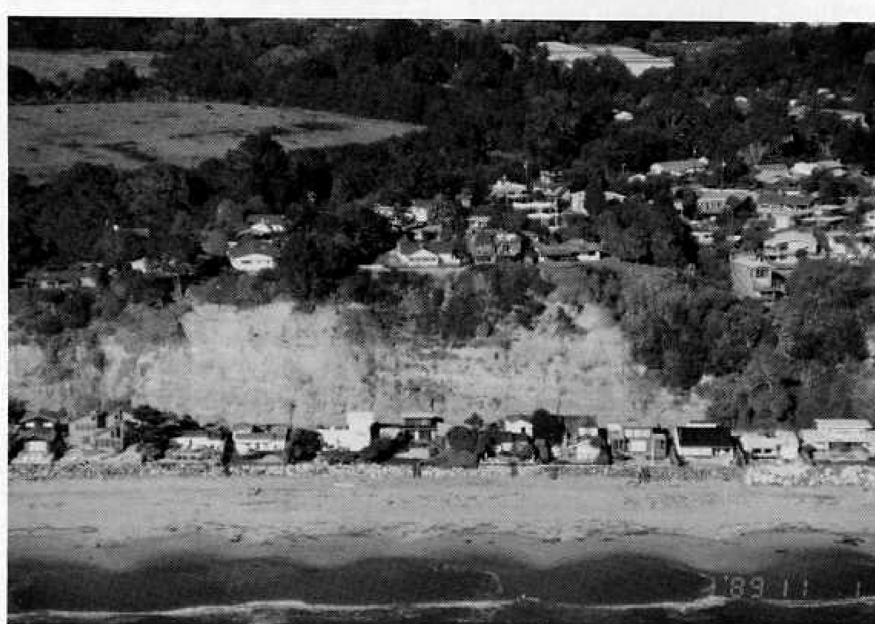
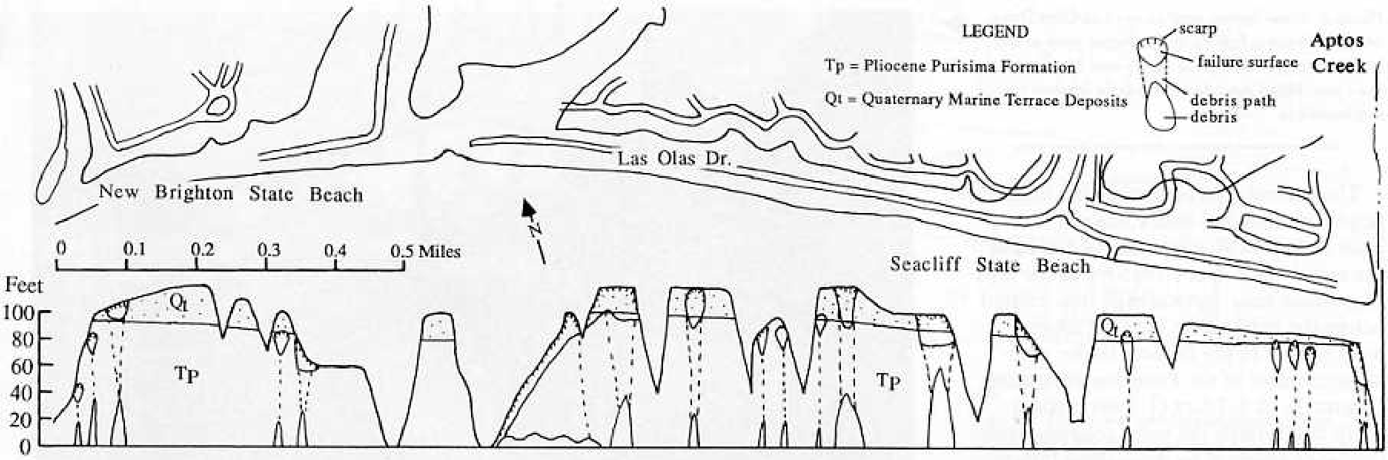


Photo 4. Extensive sea cliff failure above Las Olas Drive. Failure occurred in the upper 36 feet (12 m) of the cliff and loose material cascaded down the steep slope. Note the many houses both above and below the landslide that are jeopardized by slope failure.

*See Glossary, p. 83

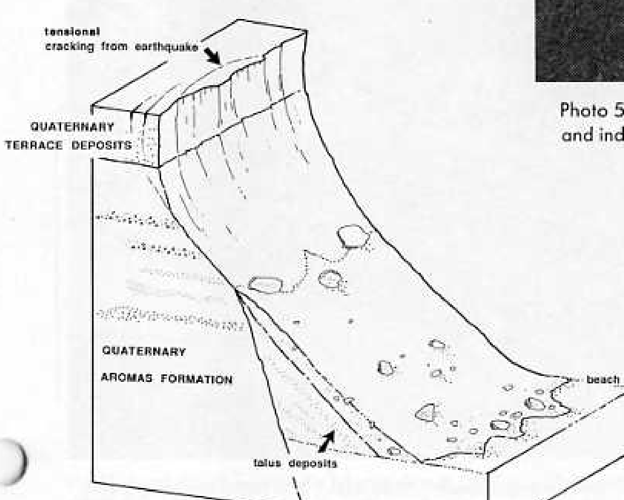


In the lower 30 feet (10 m) of the cliff, the sandstone was undercut by fracturing along intersecting conjugate joint sets. Blocks 3 feet (1 m) thick and several feet high broke up easily and formed small talus cones. Though fractured and partially detached from the cliff, many blocks did not fall and remain as unstable areas.

Between Aptos Creek and Rio del Mar, semi-consolidated eolian and fluvial sands of the Pleistocene Aromas Formation form 75-120 foot (25-40 m) high, steep cliffs (Figure 7). The upper 6-15 feet (2-5 m) are more cohesive than the underlying partly consolidated and weakly cemented sands. Sea walls and revetments that protect the back-beach development also protect the cliff toe from wave induced erosion. However, the bluffs continue to fail periodically, as they did in the 100-year storm in January 1982 that caused considerable property damage (Photo 7). The loose surficial sand liquified and flowed downslope over a weathered, less permeable surface and into homes at the base of the sea cliff (Griggs, 1982).

▲ Figure 4. Plan view and longitudinal section showing the location and dimensions of sea cliff failures as well as the geology between New Brighton State Beach and Aptos Creek. A sandstone member replaces the siltstone member of the Pliocene Purisima Formation (Tp) in this area.

Photo 5. Deep tension crack in terrace deposits. These cracks often cut through house foundations and indicate the potential extent of future failure.



◀ Figure 5. Block diagram showing structure and typical failure style in sea cliffs underlain by sandstone member of the Pliocene Purisima Formation. Note that the failure occurred in the upper portion of the cliff and material cascaded down the steep slope.

Three types of earthquake-induced failures prevailed along this stretch of coast. The first type was a shallow dry sand flow less than 3 feet (1 m) deep, 15-30 feet (5-10 m) wide, and 30-60 feet (10-20 m) long, which originated well below the bluff top (Figure 8, Photo 8). A vertical scarp cut through a thin, cohesive soil layer to a failure surface that paralleled the bluff face. Loose sand or small blocks of more cohesive material, often held together by roots, slid along this surface and then ramped over the less steep talus deposits at the base of the slope.

Photo 6. View facing east along Las Olas Drive. Material from a failure in the upper part of the bluff cascaded down the slope and blocked the road. Note the telephone pole broken by the landslide.

The second type of earthquake failure, larger translational slides, several feet deep and up to 90 feet wide, occurred in the upper 30-45 feet (10-15 m) of the cliff face where near-vertical cliff tops existed before the earthquake. These failures were similar to the failures in the sandstone member of the Purisima Formation (Figure 5). A 3-9 foot (1-3 m) vertical scarp cut through the more cohesive soils that were undercut by downslope failure of underlying, less cohesive soils. Large intact blocks, 3-6 feet (1-2 m) thick, and loose sand from the upper portion of the cliff cascaded down the slope and tension cracks up to 30 feet (10 m) formed landward of the scarps.

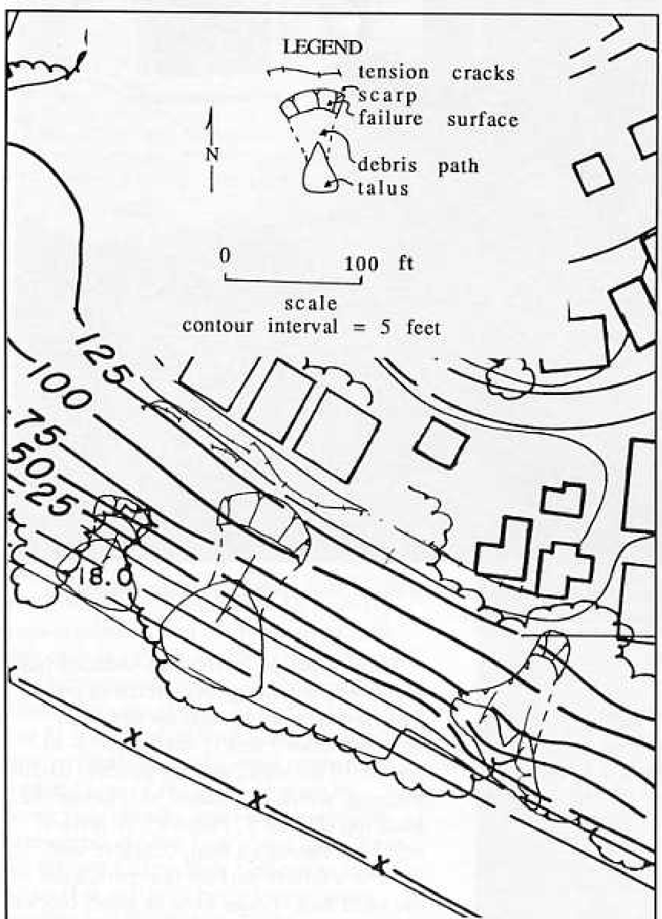


Figure 6. Details of sea cliff failures and tension cracks. Note the prevalence of tension cracks near the large failure.

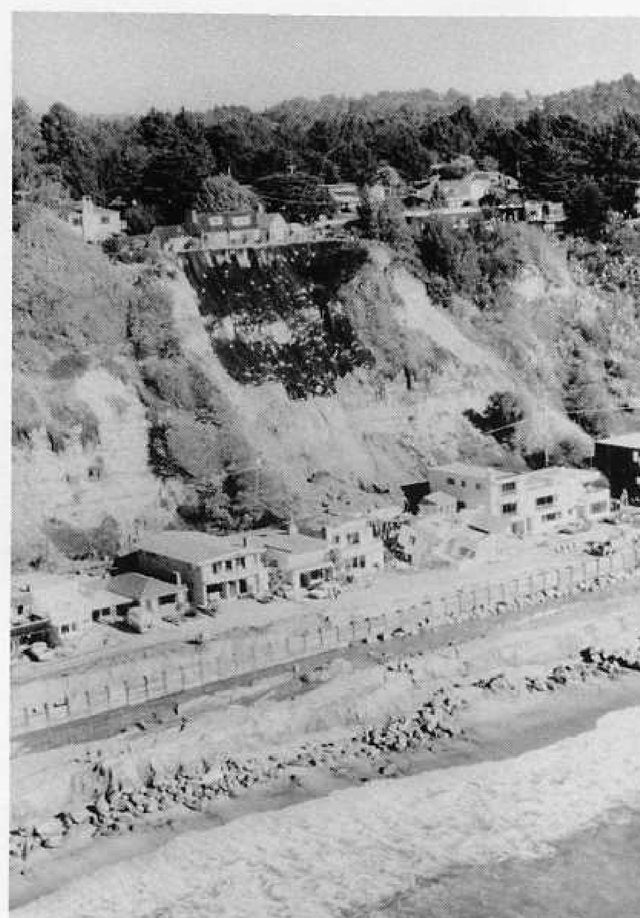


Photo 7. Slope failure in 1982 that destroyed a house on Beach Drive. This type of sea cliff failure is very similar to that caused by the October 17, 1989 earthquake.

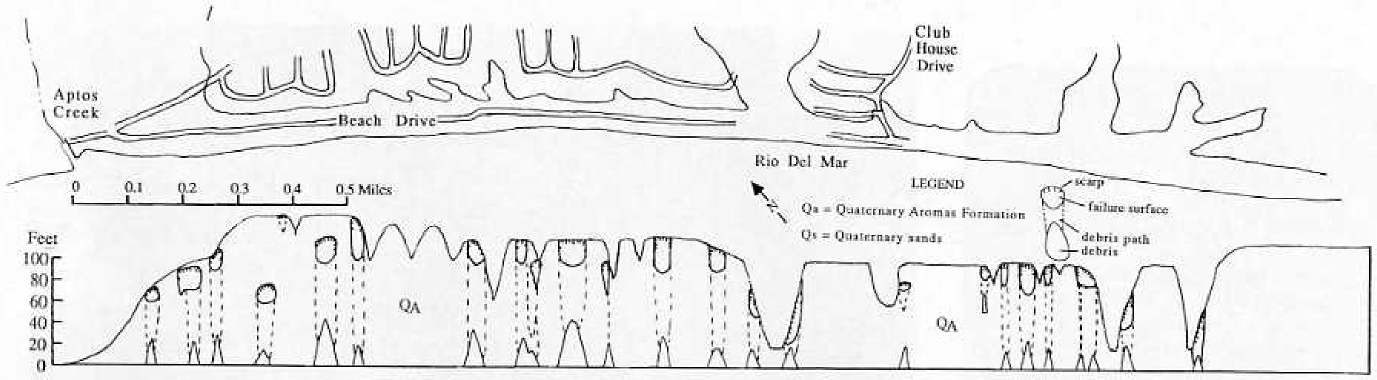


Figure 7. Plan view and longitudinal section showing the location and dimensions of sea cliff failures and the geology between Aptos Creek and Rio Del Mar.

The third type of earthquake failure is a translational slide. South of Manressa State Beach (Figure 9), sands composing the cliffs are less consolidated and the cliffs are therefore less stable. This stretch of cliffs is fronted by a wide protective beach. During the earthquake, a very large translational slide, 300 feet (100 m) wide and 6-9 feet (2-3 m) deep, undermined 15-30 feet (5-10 m) of the cliff top above the Place de Mer development (Figure 8, Photo 8). Large intact blocks toppled from the upper 15 feet (5 m) of slope while intact patches of soil, held together by roots, and loose sand slid down the slope to a roadway. One house and its retaining wall system were undercut by the slope collapse in this area; the house had to be demolished.

Further to the south, the coastal bluffs in the Sunset State Beach area (Figure 9) consist of weakly consolidated Pleistocene dunes (Wisconsin age; Dupré, 1975) which have been stabilized by vegetation. Homes have been built on the eroding edge of this ancient dune complex. Slope failure in this area occurred when shallow slabs up to 3 feet thick were detached and translated short distances downslope (Photo 9). This form of bluff retreat has threatened several homes and at least one will be relocated.

*See Glossary, p. 83

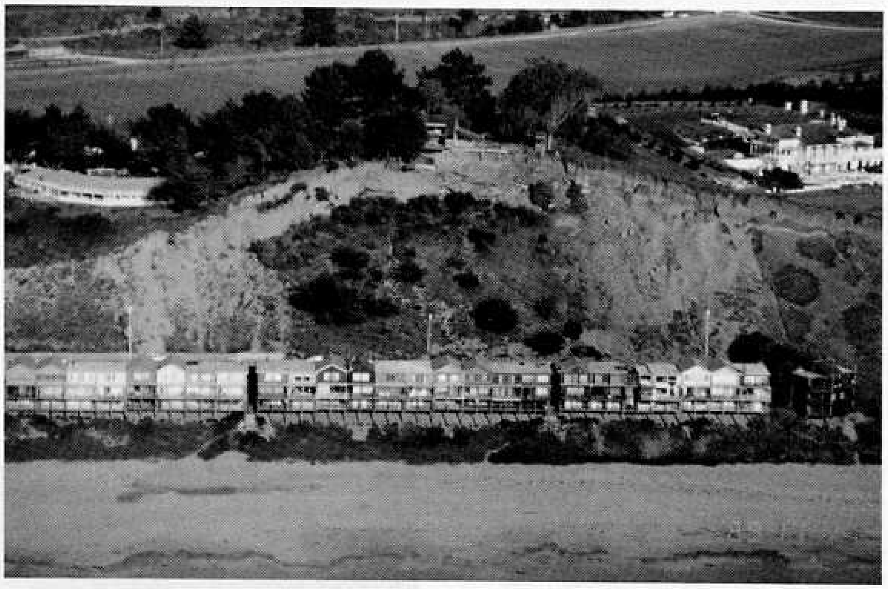


Photo 8. Very large dry sand flow above Place de Mer development. Houses at the top and base of this failure were at risk.

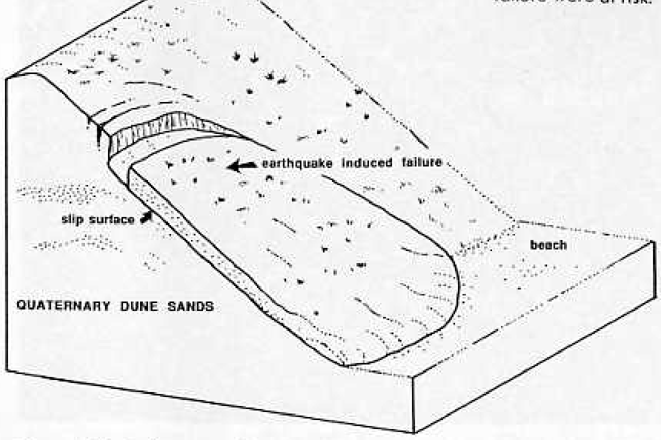


Figure 8. Block diagram of dry sand flow in weakly consolidated dunes. Note the tension cracks in the cohesive surface layer.

The lithology of the sea cliff materials controlled the mode of failure at most locations. Promontories, headlands, and narrow peninsulas or ridges along the coast were consistently the sites of the most extensive failure (Photo 10). On a larger scale, scientists also noted this effect in the Santa Cruz Mountains, as a result of this earthquake (Plafker and Galloway, 1989), and in other areas where large earthquakes have occurred in the past (Harp and others, 1981). In these non-coastal areas, the ground surface topography caused reflection of seismic

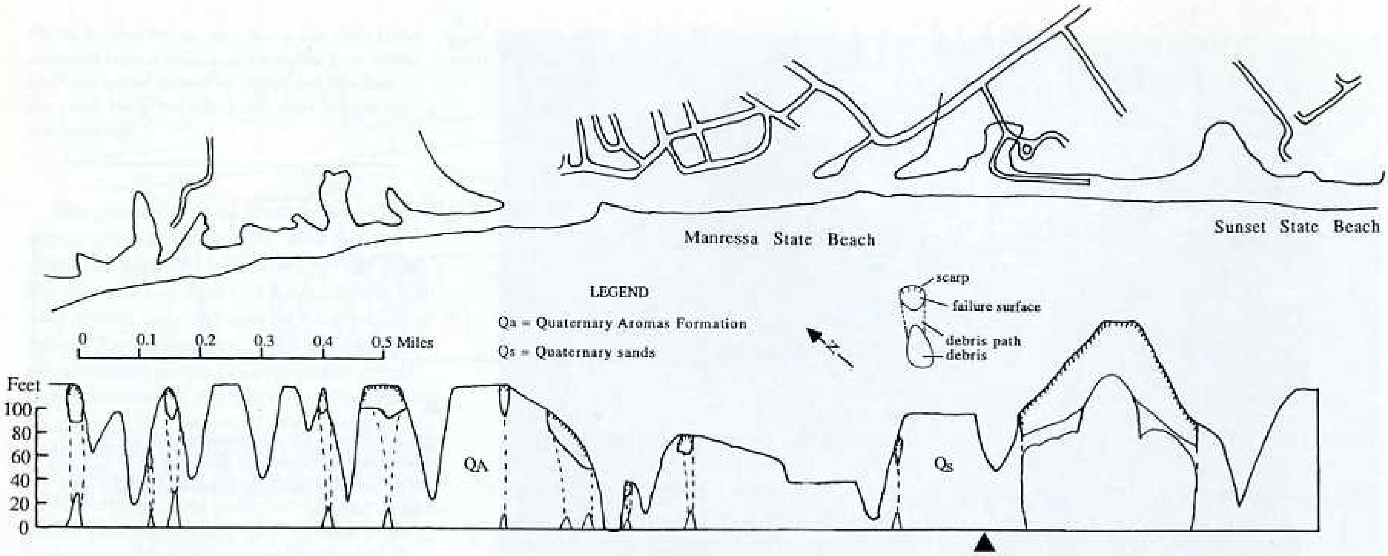


Figure 9. Plan view and longitudinal section showing the location and dimensions of sea cliff failures and geology between Rio Del Mar and Sunset State Beach.

waves; constructive interference* then amplified the incoming seismic energy, increased the dynamic stresses, and caused rock or soil failure. However, the size of the ground surface structure that can reflect incoming seismic waves must be on the same order as the seismic wavelength (Harp and others, 1981). Thus, variations of the topography with dimensions of tens of miles will interact with long seismic waves. On the other hand, sea cliffs which are tens of feet high will not respond to long wavelengths. Therefore, the repeated failure along the coastal promontories and narrow ridges is probably due to the lack of lateral support during the intense shaking rather than to topographic amplification.

IMPACT ON FUTURE LAND USE DECISIONS

Seismically induced coastal bluff failure was common up to 47 miles (75 km) from the epicenter of the 7.1 magnitude October 17 earthquake. The cliff failure in developed areas of the coast posed risks to structures on the bluff top as well as the private and public structures on the beach below. One death occurred on a beach north of Santa Cruz when a section of weak bedrock in a cliff collapsed onto a sunbather.

The two geologic hazards consistently identified at coastal sites in consulting reports are seismically induced slope failure and slope failure induced by excess water. Soil properties and slope configuration are commonly used in site-specific slope stability analysis. Study of historical stereo aerial photographs can indicate where and when slope failure has taken place in the past and aid in relating these failures to either seismic or rainfall events.

For example, the aerial photographs of the northern Monterey Bay coastline extend back to 1928 and show the changes over a period of 60 years. These photographs clearly show periodic shallow failure or sloughing of the bluffs and widespread bluff failures that occur after heavy precipitation. Most often, the failures are initiated in the bluff top terrace deposits and may extend all the way to the base of the bluff. Where the thickness of the failed material is great enough, the steep slopes produce flows that damage and destroy the homes below. The incidents of bluff failure of this type are relatively common, occurring every 10-15 years on the average.

If large scale, deep-seated bluff failure occurred during the 1906 earthquake, or in the two magnitude 6.0 events that occurred on the offshore San Gregorio fault in 1926, it might be expected that some evidence would be present in the 1928 aerial photographs. The photos, however,

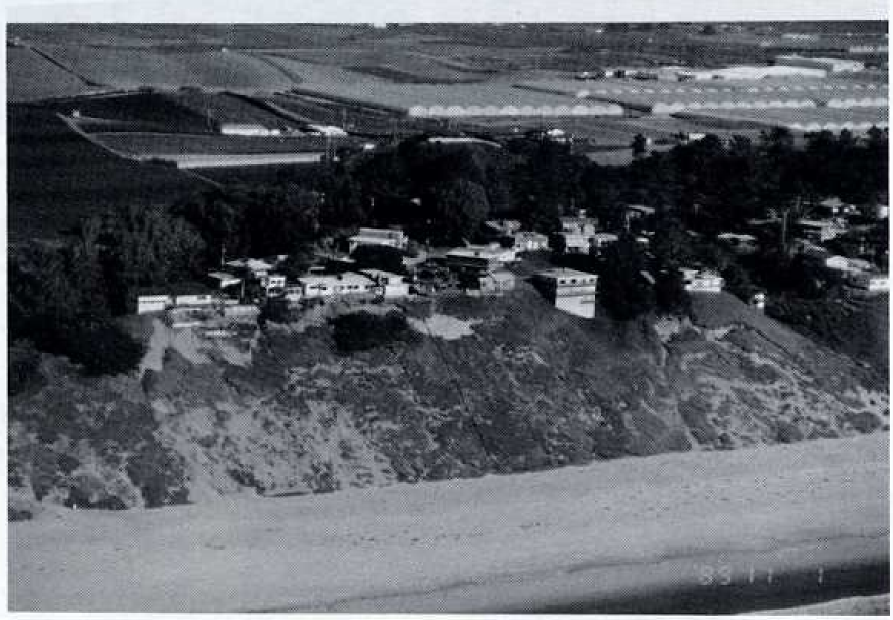


Photo 9. Large dry sand flows above Sunset State Beach. One of the bluff top houses will be moved farther back from the edge of the cliff.

*See Glossary, p. 83

Photo 10. Extensive slope failure and cracking on a narrow ridge. This house will be torn down and the slope will be graded to a safer angle. Houses below this failure were evacuated.

Glossary

constructive interference — when two seismic waves react to increase wave amplitude.

joint — a surface of fracture or parting in a rock.

lag (as in shell lag) — the residual accumulation of coarse, usually hard rock fragments remaining on a surface after finer material has been blown away by wind or washed away by water.

toe — the lower margin of disturbed material of a landslide or lower margin of a sea cliff

translational movement — a landslide classification involving downslope displacement of soil-rock material on a surface roughly parallel to the general ground surface.

show a bluff configuration without evidence of any major or deep seated failure. There are extensive areas along the upper bluffs in the Rio Del Mar area that appear devoid of vegetation in the 1928 photos, suggesting recent failure. In general, the aerial photo record indicates that the type of coastal bluff failure expected in this area during a major earthquake is similar to that expected during intense rainfall events, namely shallow surficial failures, up to several feet thick at most. The October 17, 1989 earthquake provided an opportunity to check these interpretations and hazard assessments.

The areas where the extensive damage occurred during the October 1989 earthquake, and where homes received the most damage, were those that failed most frequently during past episodes of intense rainfall as shown in aerial photographs. Along northern Monterey Bay, the areas of most frequent failure are the steep bluffs cut into the Pliocene Purisima Formation from the Las Olas Drive/Seacliff State Beach area to Aptos Creek, and the bluffs composed of the weakly consolidated Pleistocene Aromas Formation, which extend from Aptos Creek down coast to La Selva Beach.

The top, slope, and base of coastal bluffs are potentially endangered by earthquake-induced slope failure, necessitating costly mitigation measures. At the top of bluffs, several structures were immediately damaged when cliff failure undermined the foundations (Photo 3). In nearly all cases of failure, tension cracks up to 30 feet (10 m) formed behind the head of scarps, and in some cases cut through house foundations (Photos 5 and 10). Cracking and slope failure were so extensive at three bluff top sites that the homes had to be demolished. Two of these homes were built on very narrow peninsulas (Photo 10); the third was at the crest of a very high, steep, narrow section of bluff top (Photo 8). These bluff top cracks probably represent incipient slides that may fail under winter conditions of increased pore pressure. The depth and width of such cracks can be used as a reasonable indicator of potential bluff top failure during seismic shaking.

Most of the sea cliffs included in this study were too steep to support slope construction, and the hazard of building on such locations is verified by observations. In several locations, mid-slope sites received debris from upslope failures (Photo 8).

Hazards to houses at beach level resulted from failure of the cliffs behind them. Such failures led to the damage and evacuation of a number of houses in the Las Olas Drive and Beach Drive areas. The houses built closest to the base of the bluffs were most susceptible to this type of damage.

Mitigation and risk reduction measures began within one week of the earthquake and included fencing off dangerous sites, cutting back overhangs, and removing trees from the top and slope of the sea cliff. At sites where bluff top houses had to be demolished due to the threat they posed to houses at beach level, extensive grading was required to remove and stabilize the cracked bluff top areas.

CONCLUSIONS

The October 17, 1989 earthquake provided an opportunity to observe the effects of a large earthquake on slope stability. Sea cliff failures along the extensively developed northern Monterey Bay coastline demonstrated both the hazard induced by earthquakes and the general instability of coastal bluffs. Failures produced by the recent earthquake occurred in bluffs that were actively eroding (Photo 3) and in bluffs that were protected from marine erosion (Photo 4). Furthermore, narrow ridges or promontories were observed to be most likely to sustain severe damage (Photo 10). Although the earthquake caused massive instantaneous failure, residual, weakened bedrock and soils may experience increased erosion and failure rates as the typical cycle of winter storms batters the coastline. Current and future development proposals along the coast should consider the evidence and experience gained from this earthquake to evaluate both building constraints and the feasibility of hazard mitigation measures.