1995 Annual Report – Lone Tree Landslide

1. Summary

Over 1/10 of the original fill has eroded and moved into the nearshore marine environment. The primary mechanisms of erosion have been wave cutting at the fill toe and especially large slumping events triggered by rain. The toe of the fill has become well armored with large boulders to cobble-sized rocks, and the major erosional gullies along the slide face are armored, at least partially, by small rocks. Nevertheless, the potential for additional mass wasting is still high. Large extensional cracks along the top of the fill show continued growth and movement of a massive region of the slide fill. The future movement of this material is likely to have significant impacts on rocky intertidal and very shallow subtidal communities and habitats.

The ecological impacts of sediment movement from the fill have largely been restricted to the rocky intertidal area below and south of the fill as well as to the very shallow subtidal environment. A new intertidal community is developing and is periodically disturbed by sediment burial and scour. The most prominent recovery pattern is the colonization of rocks by ephemeral algal species and by more long-lived sessile animals (mussels and goose-neck barnacles) on boulders at the base of the slide face. No ecological impacts have been detected on subtidal rock communities beyond the shallow subtidal zone, or to the intertidal or subtidal sand communities. While the impacts to subtidal rock communities are less than expected, impacts to the rocky intertidal communities are likely to persist for a decade or more.

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2. Introduction

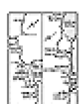
Figure 1

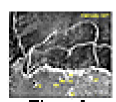
Figure 2


Figure 3

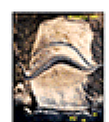
Figure 4

The 1994-95 annual report summarizes the physical and ecological impacts of manipulating the Lone Tree landslide by disposing of slide sediment into the nearshore marine environment. This annual report differs from our previous annual reports, in that we illustrate the major physical and ecological patterns using photographs and maps as much as possible, with a narrative description of significant features. The photos were chosen from our collection of many hundreds of photos of the Lone Tree Slide to illustrate some of the long-term trends we have observed. Previous reports have relied more on tables of data, which are sometimes difficult for non-technical readers to interpret. Although all data has been collected as in the past, we include here only data that describe temporal changes in the cover of algal communities in the rocky intertidal zone, where the impacts of the eroding slide fill are most severe and still present. The final report, to be completed next year, will include a comprehensive data report for the years 1991-1996, and a pictorial-based summary report illustrating the study results.

The Lone Tree landslide slumped with the Loma Prieta earthquake in October 1989 (Figures 1,2, & 3). The slide closed Highway One between Muir Beach and Stinson Beach (Figure 3).The road was reopened in June 1991 after over 1,000,000 cubic yards of soil and rock were moved, placing the road behind the slide plane onto stable ground, and disposing of the slide material on the west side of the road in a large fill (Figure 4).The seaward edge of the fill extended over 200 feet into the marine environment directly burying marine intertidal and subtidal rock and sand environments.

The present study began in the summer of 1990, one year before the slide was manipulated and the fill was placed in the ocean. It includes one year of baseline monitoring of the local marine environment and five years of post-disturbance monitoring to assess the ecological impacts of the fill on marine communities. The monitoring program is divided into two main components: the physical and ecological studies. The monitoring is performed to document the movement of sediment eroded from the fill through the local and regional marine environment. The potential ecological impacts of this new sediment are being monitored in biological communities that live on intertidal rocky shores, sand beaches, subtidal rocky reefs, and subtidal sand bottoms (Figure 1). Therefore, the first section of the report summarizes the results of the physical studies and the next section presents the results of the ecological studies, focusing on significant impacts of the fill.

This research was supported by contract number 04G233-EP and several previous grants from the California Department of Transportation to Moss Landing Marine Laboratories through the San Jose State University Foundation. We appreciate the assistance of our present and former Project Managers, Chuck Morton and Sid Shadle of the CalTrans District 4 Environmental Branch, and the guidance of the people and agencies of the Lone Tree Technical Advisory Committee.

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3. Physical Impacts

The physical studies document the movement of slide sediment from the fill to the slide beach and then through the local marine environment. The movement of sediment from the fill is the first and most important component in a budget of sediment movement into and through the marine environment. The sediment budget estimates are most accurate near the fill. The estimates from the new beach and the subtidal bottoms are less accurate, because these environments are less accessible and fill sediment mixes with the surrounding natural deposit.

The primary goal of the physical portion of the project is to document sediment movement from the slide fill that may have a negative impact on biological communities living in the adjacent marine environment. Therefore, we monitor changes in the geomorphology of the slide fill and adjacent beaches; estimate the short-term and long-term sedimentation rates from the fill to the marine environment; describe changes in the distribution of seafloor sediments around the fill; and compare the relative input of sediment into the marine environment from both natural sources and the slide fill.

The Lone Tree slide is located within the Franciscan complex which is an ancient sedimentary deposit that is highly prone to land sliding. As a result, although the slide fill is the most active single source of sediment to the local marine environment from Rocky Point to Muir Beach (Figure 1), the entire region is highly erodable and provides significant inputs of sediment to the marine environment.

3.1. Slide Fill Erosion


Figure 5

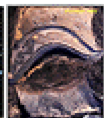
Figure 6

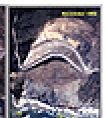
Figure 7


Figure 8


Figure 9

The slide fill was completed in the summer of 1991, burying a large region of rocky intertidal and subtidal habitat (Figure 4). The position of the large intertidal rock below the slide clearly illustrates the burial and loss of beach habitat. The intertidal rock was partially buried by the fill (Figures 2 & 3 show before compared to Figure 4 after the fill was dumped). The two most active slumping periods of the slide fill were immediately after the fill was in place (Figure 4). By the end of the first summer, the two regions of future slumping were marked by distinct cracks in the fill deposit (Figure 4). The first major sliding from the fill occurred along the south face. This resulted in a steep cliff which was well developed by the second year, 1992 (Figure 5). The south cliff gradually eroded inland (Figures 4 ,5, 6, 7, 8, & 9). The position of the intertidal rock shows the erosion of the toe of the slide fill from 1991 to the present (Figures 4 ,5, 6, 7, 8, & 9).

The second major fill slump formed as a large bowl in the center of the slide fill. Although the major slumping had not occurred by the second year (1992), the slumping feature was already clearly defined (Figure 5). During the next year, (1993), there was a large slumping event in the upper part of the bowl (Figure 6), followed by a second event within the bowl during the next year, (1994) (Figure 7).

The steepest northern section of the slide fill gradually developed vertical erosion gullies. These gullies have become deeper, wider and more defined over time (Figures 4,5, 6, 7, 8,&9). This section of the fill is most protected from wave action (Figure 2). In contrast to the large slumping events from the slope of the fill, the fill plateau is gradually settling and defined by a complex series of extensional cracks. The slope break from the fill plateau to the fill slope is well defined (Figures 4, 5,6, 7,8,& 9). The extensional cracking on the plateau was already evident by the second year, 1992 (Figure 5). During subsequent years, the cracks became wider and the vertical displacement between cracks increased. The cracks collect drainage water forming narrow wet areas where rushes and willows have successfully colonized.

Heavy rains and large waves are the two major processes causing the erosion of the slide fill. Rainfall has had a significant impact on the movement of fill material, through surface erosion and mass wasting events- sediment slumping and sliding. Heavy rains increase the pore water pressure within the sediment which is known to facilitate landslides (Hungr et. al, 1981). Rain also contributes to rising groundwater which can move along the slide plane, and substantially increase the risk of mass wasting. Since the initial erosion of loose fill material following construction of the fill in July of 1991, slumping and sliding events have been correlated with increased rainfall.

The erosion of the toe of the fill by wave action was most significant during the first year or two. The landward retreat of the fill and the armoring of the slide toe by boulder to cobble sized rocks has reduced the effects of wave erosion (Figure 9). Consequently, now, the potential for erosion on the upper fill slope and plateau outweigh the effects of wave erosion at the toe. The slide fill is moving downward and seaward at a rate of approximately 0.1 foot per month. The average rate of sediment erosion from the Lone Tree fill was extremely high, 62.2 cubic yards per linear foot per year, with a yearly high of 84.1 cubic yards during 1991-1992 and a low of 40.2 during 1992-1993. In comparison, Griggs and Savoy (1985) estimated the rates of cliff erosion between Duxbury Point and Bolinas Point at 8.5 cubic yards per linear foot per year, ten times lower than the 1991-92 Lone Tree rate. Their estimates from other less active sections of the north coast were 3.7 cubic yards per linear foot of cliff per year or less.

The slumping of material from the fill slope resulted in the erosion of approximately 100,000 cubic yards of sediment from the fill into the adjacent marine environment (Figure 10). The fill region potentially impacted by the extensional cracks in the plateau contains approximately 300,000 cubic yards of sediment, but this is only the fill material. Below this region, there is a 100 foot layer of old slide material between the bottom of the fill and the historical slide plane. These and other past and potential erosional events are illustrated in the geologic hazards map (Figure 11).

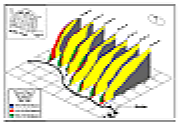
Figure 10


Figure 11

3.2. Slide Beaches


Figure 12


Figure 13

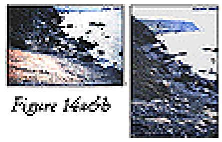

Figure 14a&b

Figure 15 a&b

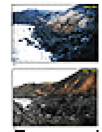

Figure 16 a&b

Before the fill was constructed, the beaches below the slide were covered with boulders and patches of large cobbles (Figures 12- 13). Almost all of the intertidal habitat directly below the fill was buried by the toe (Figure 4). The beach south of the slide, in contrast, was buried more gradually by sands, gravel, and cobble.

The south slide beach changed from being mainly sand dominated during early post-construction to mostly armored by cobble and larger rocks at the present (Figures 14-15). The south slide beach is now similar to natural pocket beaches between Muir and Stinson, which generally contain little sand, but with regions between boulders usually covered with gravel and especially cobble. In contrast to the local pocket beaches, the extensive sand beaches at Muir and Stinson are covered with finer deposits containing more than 70% sand.

The rocky intertidal habitat directly below the slide fill was buried (Figure 4), but was rapidly replaced by a new boulder habitat (Figure 16). Wave action eroded the fill toe creating a wider intertidal zone covered with boulders (Figure 16). The fill cliff moved inland (Figure 16) and the new boulder deposit became larger and now effectively armors the toe from the effects of most waves (Figures 9 and 16).

3.3. Slide Plumes

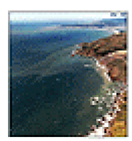

Figure 17

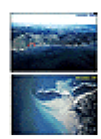

Figure 18 a&b

Plumes of suspended sediment are common along the north coast, particularly from the mouth of San Francisco Bay to Double Point (Figures 17- 18). These plumes are related to regional erosion of the Franciscan complex and transport of suspended sediment from the San Francisco Bay. Although the input of suspended sediment from the Lone Tree slide is the most significant source between Stinson and Muir Beaches, the regional load of suspended sediment is highly variable in time and space and is much greater than any local inputs (Figures 17-18).

Fine sediment enters the nearshore environment from the fill and is transported in a suspended plume either along shore to the north or south or offshore, depending on the prevailing winds and currents. Patterns of transport are indicators of the general direction of sediment transport and of potential locations of ultimate sediment sinks. One way of tracking suspended sediment movement is by aerial photography. The aerial photographs used were taken only after significant storm events and therefore represent relatively extreme transport patterns (Figures 17,18, & 19). Rare, large-scale events are known to be most important in moving sediment in most sedimentary systems, especially along this high-energy marine coast.

The predominant direction of plume transport at Lone Tree was documented by aerial photographs and has been south to north (Figure 19b). However, on any given day this sediment transport could be in either direction. Barbara Hickey at the University of Washington has documented that currents farther offshore flow primarily from north to south. Aerial photographs have shown that there is a relatively persistent eddy trending northward in front of the slide, west past Gull Rock, and then south with the general offshore transport patterns as documented by Hickey (Figure 19a).

3.4. Nearshore Habitats

Bathymetric and sidescan surveys of the seafloor off the Lonetree slide were performed in June and October of 1994. The June surveys were made after a period of large swell, before accretion had taken place. They show a small underwater footprint of the slide toe (Figure 20a). In contrast, the October survey (Figure 21a) reveals a far greater extent of burial. An offshore movement of sediment is indicated by the displacement of the contour lines to a depth of 13 meters.

The dramatic changes in the subtidal slide toe footprint demonstrate the dynamic nature of the slide vicinity. The seasonal onshore-offshore movement of sediment is characteristic of the California coast. It is difficult to determine the relative contribution of material coming directly off the slide versus material moving along-coast through longshore transport. The armoring of the slide face has reduced the input of slide material. Future large sediment inputs will probably be due mostly to large-scale slumping followed by wave cut-back.

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4. Ecological Impacts

There are three major ecological impacts from the movement of slide sediment: direct burial, sand scour and deposition from a suspended plume. These impacts are monitored in the intertidal and subtidal environment, from both the rocky habitats and soft sediments. Soft sediment communities are less likely to be impacted from sediment scour and deposition than the rocky habitats, but they cover a much larger area of the sea floor. Rocky habitats occur as local islands in a sea of sand and mud.

The only ecological impacts detected from the monitoring occurred in the rocky intertidal below and directly adjacent to the slide, and in the very shallow subtidal habitats which are continuous with these intertidal environments. The most significant impact has been from direct burial of habitat by the slide fill (Figures 20-21). A new intertidal habitat is still forming as the toe of the fill erodes and retreats landward (Figure 16). The slide south beach has been impacted by more gradual burial of habitat but also by sediment scour as waves transport slide sediment into the offshore environment (Figures 14- 15). No impacts were detected to animal communities living in sandy beaches or sand bottoms in the offshore environment. These communities live in sediment and tolerate sediment movement and burial much better than communities living on rocky substrates.

4.1. Intertidal Communities


Figure 22

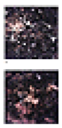
Figure 23


Figure 24


Figure 25

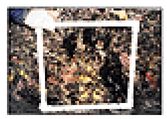
Figure 26

The rocky intertidal environment continues to be the most ecologically impacted from eroding slide fill. The most significant impacts are limited to the coastline under the slide fill and directly to the south. Before the slide fill was constructed, the intertidal communities below the slide were similar to areas found along this section of the coast (Figures 12-13). The most extensive rocky intertidal habitat between Muir and Stinson Beaches is at Slide Ranch, a reference site for the slide monitoring (Figure 22). Red and brown algae dominate the composition and cover of these communities, which were similar at Slide Ranch and under the fill before the fill site was buried (Figure 23). Intertidal communities along the south slide beach were buried more gradually by sands and gravels transported from the slide (Figure 24). In addition to direct habitat burial, new deposits transported over the beach caused extensive scouring (Figure 25). Many intertidal animals live under and within the algae, and especially on the sides of rocks where light is low (Figure 26). In general, intertidal animals are more sensitive to burial and scour than shallow sandy subtidal animals. Many algae can tolerate limited periods of burial and are good colonizers of newly exposed rock.

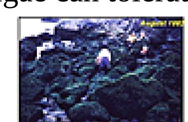
Figure 27

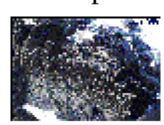
Figure 28

There are two significant colonization patterns in the slide-impacted areas observed in the slide fill toe and slide south beach. The first is the colonization of rocks with ephemeral and weedy species of primarily green algae, especially under the slide fill toe (Figure 27). The second is the establishment and persistence of patches of sessile animals on large boulders. Populations of *Pollicipes polymerus*, gooseneck barnacles, and *Mytilus californianus*, ribbed mussels, have colonized mostly the tops and some sides of large boulders (Figure 28). The ephemeral algal species and patches of mussels and barnacles are uncommon at the reference sites. The change in intertidal habitat and communities is illustrated in a map of the most impacted sites (Figure 29).

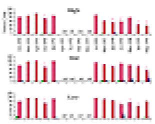

Figure 30

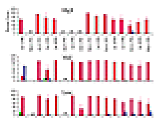

Figure 31

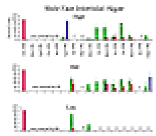

Figure 32

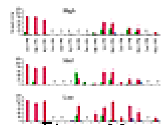

Figure 33

Since intertidal communities are most impacted by the slide fill, the monitoring data show dramatic differences between the structure of communities at the reference sites compared to the slide-impacted sites. (Figures 30, 31,32, & 33). Perennial red algae dominate the cover and composition of reference sites, Slide Ranch and Pelican Point (Figure 30- 31). Algal cover is also more persistent through time. In contrast, algae are more variable under the slide and are dominated by ephemeral species. Green algae are well know colonizers of open space in rocky intertidal environments. They are best developed under the slide toe (Figure 32). The algal communities at the south slide beach include remnant patches of communities which were not completely buried or scoured by slide sediment, as well as newly exposed rocks where the past communities were killed (Figure 33). These data indicate that the rocky intertidal habitats and communities have not recovered below and around the slide.

4.2. Subtidal Communities

The very shallow subtidal communities are highly wave swept and difficult to sample or even observe because of poor water clarity and breaking waves. Impacts of sand scour are most severe here. This wash zone is essentially a continuation of the intertidal area. Although we cannot monitor ecological impacts here, the area impacted is well known (Figures 20-21).

The first subtidal monitoring stations are located directly in front of the slide fill on the vertical faces of three pinnacles (Figures 2 and 9). These walls are covered with low growths of sessile invertebrates that can be highly sensitive to sand scour or burial. The only vertical walls on the mid and south pinnacles are located on the offshore side of the pinnacles. The inshore side is a jumble of boulders and is clearly impacted by the slide fill, although this zone can only be observed qualitatively when sea conditions permit. Pinnacle north is the largest of the three slide pinnacles, and slightly offshore. Here the monitoring stations are located along the inland side of the pinnacle directly at the subtidal toe of the slide fill (Figures 20-21). Despite the proximity of fill sediment, the monitoring program has detected no significant changes in vertical wall communities attributable to the fill. There is a natural zonation of invertebrates from the upper walls to the sea floor.

Communities nearest the sea floor are often dominated by flat colonial animals with tough body surfaces that resist sand scour. These communities grade rapidly into more soft-bodied and delicately branching forms (Figures 34- 35). However, there has been no change in this zonation since the fill was constructed (Figures 34- 35). In contrast, pinnacle communities around the McWay landslide in Big Sur have been severely scoured and subsequently colonized by small barnacles which live long enough to be scoured off the rocks in the next winter storms (Figure 36). None of these severe sand scour patterns have developed around the Lone Tree slide.

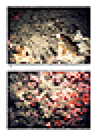
Figure 34

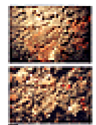
Figure 35


Figure 36

5. References

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Hungr, O., Janda, R.J., and Nolan, K.M. 1978. Mass Movement and Storms in the Drainage Basin of Redwood Creek, Humboldt County, California - A Progress Report: U.S. Geological Survey Open-File Report 78-486. 161 p.