10 Mar 1991, 1:00 pm - 3:00 pm

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Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991, St. Louis, Missouri, Paper No. LP27

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SYNOPSIS: This paper evaluates the performance of landfill slopes (refuse fill slopes) during strong ground motion from the October 17, 1989 Loma Prieta Earthquake (M7.1) that affected the Santa Cruz Mountains - San Francisco Bay region. The earthquake's occurrence in a highly populated area that contains the waste disposal sites for this large population offered a unique opportunity to review the performance of slopes on the landfills. Current state and federal regulations require the analysis of stability of landfills under seismic loading. To date, these evaluations have relied on gross simplified assumptions. This paper examines whether these assumptions are reasonably correct.

There are approximately 35 active landfills in the seven counties surrounding the epicentral area. The landfills are underlain by a variety of geologic materials ranging from Bay Mud (soft sediments) to hard rock. Fill slopes at the landfills range from a few feet to 250 feet high with inclinations as steep as 2:1 (horizontal to vertical). Contact with operators and regulatory agencies indicate that there was very little damage to landfill slopes during the earthquake.

The probable ground accelerations at the landfills during the earthquake are estimated based on comparison with accelerations recorded at nearby CSMIP stations or USGS strong motion stations and the site geologic conditions.

INTRODUCTION

The Magnitude 7.1 October 17, 1989 Loma Prieta Earthquake generated strong ground motion over a wide area of the Santa Cruz Mountains and the southern San Francisco Bay area of California. This area is occupied by a population of several million people. The trash generated by this large population is collected by public and private disposal companies and deposited in landfills throughout the area.

Landfill disposal sites in California operate under permits issued by the State of California Regional Water Quality Control Board (RWQCB) and other requirements of various federal, state, county, and city regulatory agencies. There are approximately 35 active landfills within the seven counties in the area most impacted by the earthquake. Ten of these landfills were selected for the subject evaluation. The information on landfill performance is based on telephone interviews with landfill personnel and the results of an Earthquake Damage Assessment Report by the California Waste Management Board (CWMB, undated). The CWMB report was prepared based on telephone surveys and site visits by CWMB staff. The results of surveys by the authors and by the Board indicate only minor ground failures at the landfills. No massive failures of landfill slopes were reported.

Our interest in performing the evaluation of landfill slope performance during the earthquake was a result of requirements of federal and State of California regulations to evaluate the stability of landfill slopes under seismic loading. The observed performance has added some insight to our current data base.

GEOLOGIC SETTING

The Loma Prieta earthquake occurred in the Santa Cruz Mountains of California. The Santa Cruz Mountains are part of the Coast Range Geomorphic Province of California. The province has a northwest-southeast alignment parallel to the San Andreas fault. The San Andreas fault is a transform fault boundary between the Pacific Plate and the North American Plate, and typically expresses a right lateral strike slip motion during earthquake offset.

The Santa Cruz Mountains are composed predominantly of sedimentary rocks consisting of moderately to well cemented sandstone, well indurated siltstone and claystone, and some conglomeratic units. Other rock types present include the Franciscan Complex of metamorphic and sedimentary rocks, and serpentine and highly weathered granite core. Valley areas surrounding the mountains are underlain by unconsolidated alluvial and marine embayment sediments. The sediments underlying San Francisco Bay are "Bay Muds" which vary from very soft clay Younger Bay Muds to stiff clays comprising the Older Bay Muds. The general geology is shown on Figure 1, Geologic Map.

EARTHQUAKE GROUND MOTIONS

Strong ground motion records from the Loma Prieta earthquake were recovered at some 93 stations by the California Strong Motion Instrumentation Program (CSMIP) and at some 38 stations by the United States Geological Survey (USGS) (Shakal, et al., 1989, and Maley, et al., 1989). These strong ground

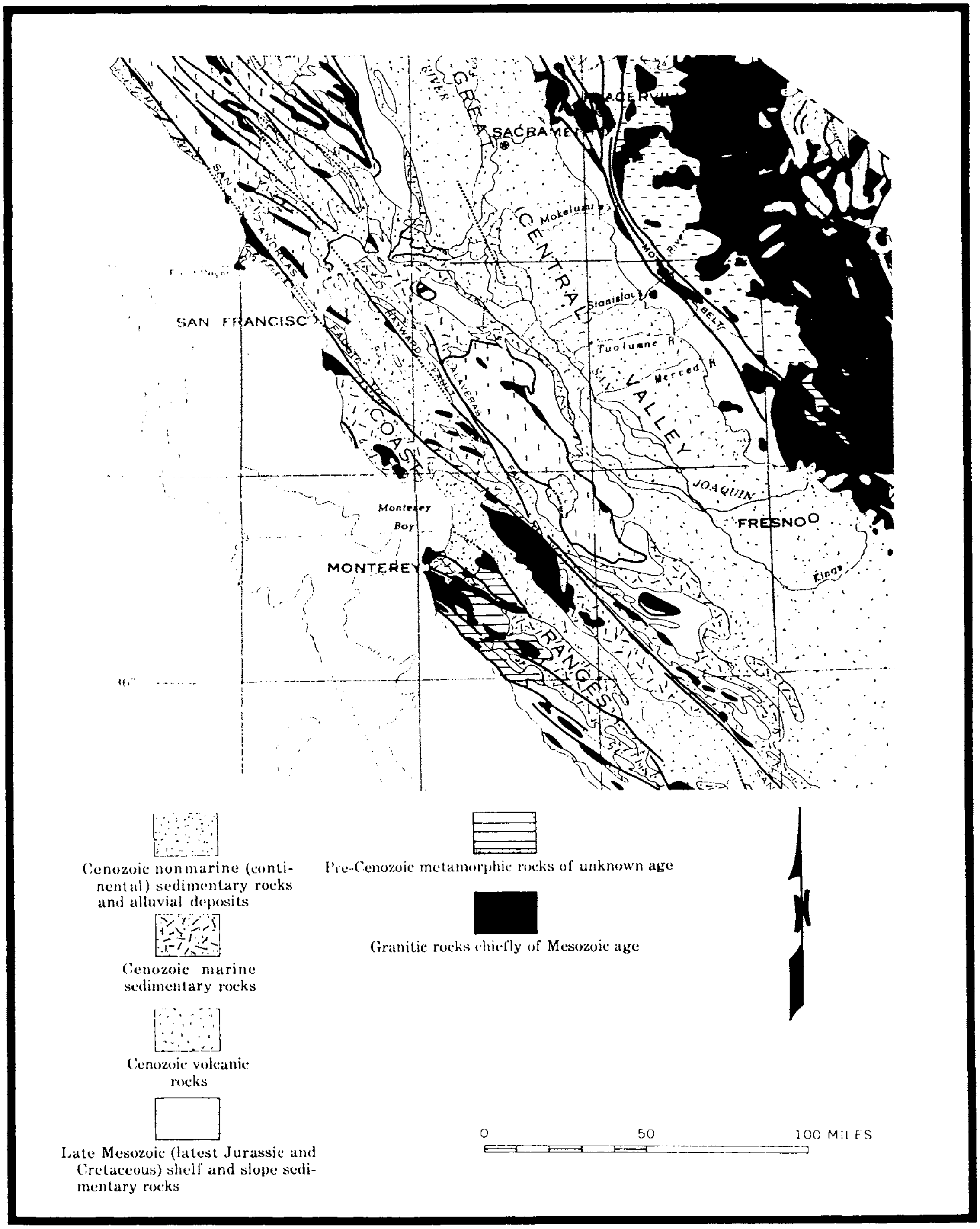

Figure 1. Geologic Map (Adapted from Bailey, 1966)

motion records were recorded at stations ranging from as close as 7 kilometers to as much as 175 kilometers from the epicenter throughout the Santa Cruz Mountains - San Francisco Bay region. This earthquake provided a large dataset of strong ground motion records in the near field within 40 kilometers of the epicenter.

The closest station was Corralitos, located very close to the San Andreas fault and 7 kilometers from the epicenter; Corralitos is also located near the center of the aftershock zone of the Loma Prieta earthquake. The maximum horizontal ground acceleration was recorded at 0.65g. Three other close-in stations provided important ground motion records in the heavily damaged Santa Cruz, Capitola, and Watsonville areas. The maximum horizontal accelerations ranged from 0.40 to 0.54g at these stations. Very high vertical accelerations were recorded at these stations ranging from 0.40 to 0.60g. Even at distances of greater than 90 kilometers from the epicenter, maximum horizontal accelerations on the order of 0.25 to 0.30g were recorded at Oakland and Emeryville, not far from the collapsed Nimitz (Interstate 880) Freeway Structure.

Although none of the strong ground motion records were recorded at any of the landfill sites, the abundance of records makes it possible to estimate with some degree of confidence the likely ground accelerations that may have been experienced at those landfill sites.

LANDFILLS

The landfills considered for this evaluation are commonly called sanitary landfills. These landfills are comprised of a mixture of domestic trash, construction/demolition debris and other wastes. The domestic trash generally contains a high percentage of paper (newspaper and packaging materials), plastic, and some metal. The trash is dumped from trucks and spread with heavy equipment which achieves minor compaction (consolidation) of the materials. A daily cover of soil material is placed over the trash and the face of exposed slopes. In California, completed landfill slopes receive a clean soil cover generally about 4 feet thick, to control erosion as well as migration of gas, as shown on Figure 2, Typical Landfill Construction. Thickness and design of the soil cover are dependent on type of landfill, liner characteristics, available soil materials, terrain, drainage, and climatic factors in accordance with California Administrative Code, Title 23, Chapter 3, Subchapter 15.

The types of landfills used in the study area include canyon fill, pit fills, and mounds. A canyon fill is a landfill placed in a natural canyon, with the canyon sides providing lateral constraint. A pit fill utilizes an excavation, such as a gravel or clay quarry excavation. A mound fill is mounded trash placed at or near the original flat ground surface. Typical examples of these types of landfills are shown on Figure 3.

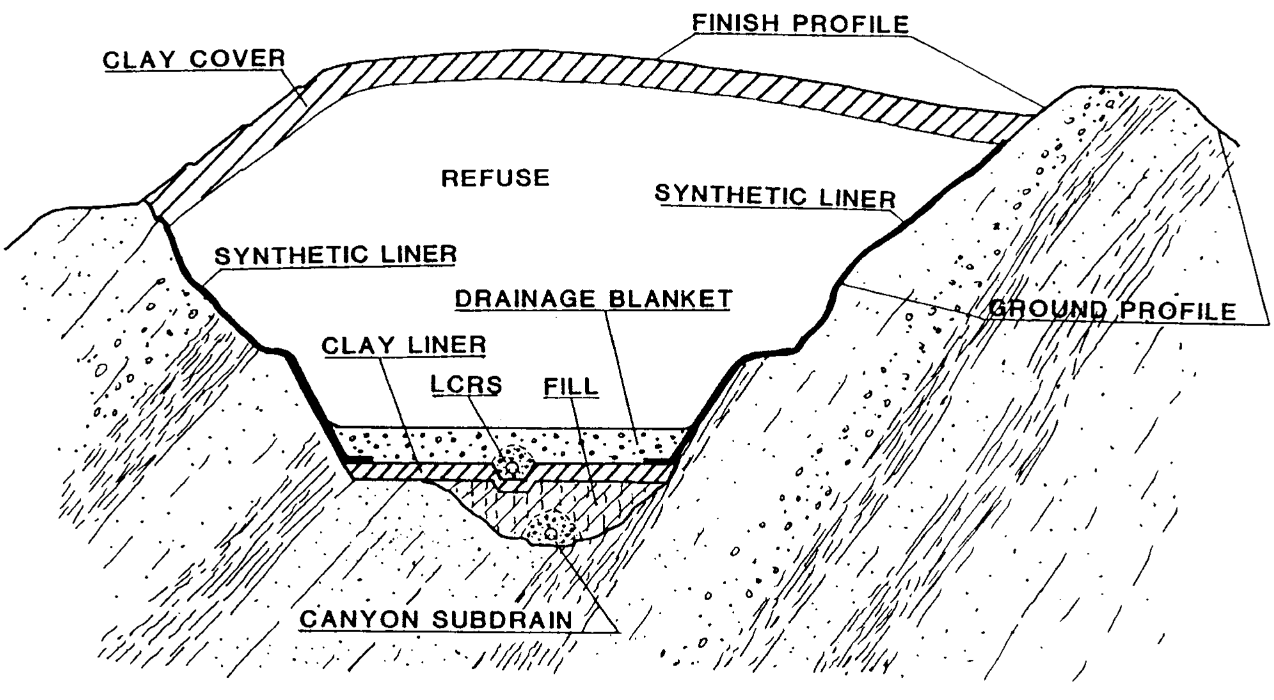

Figure 2. Typical Landfill Construction

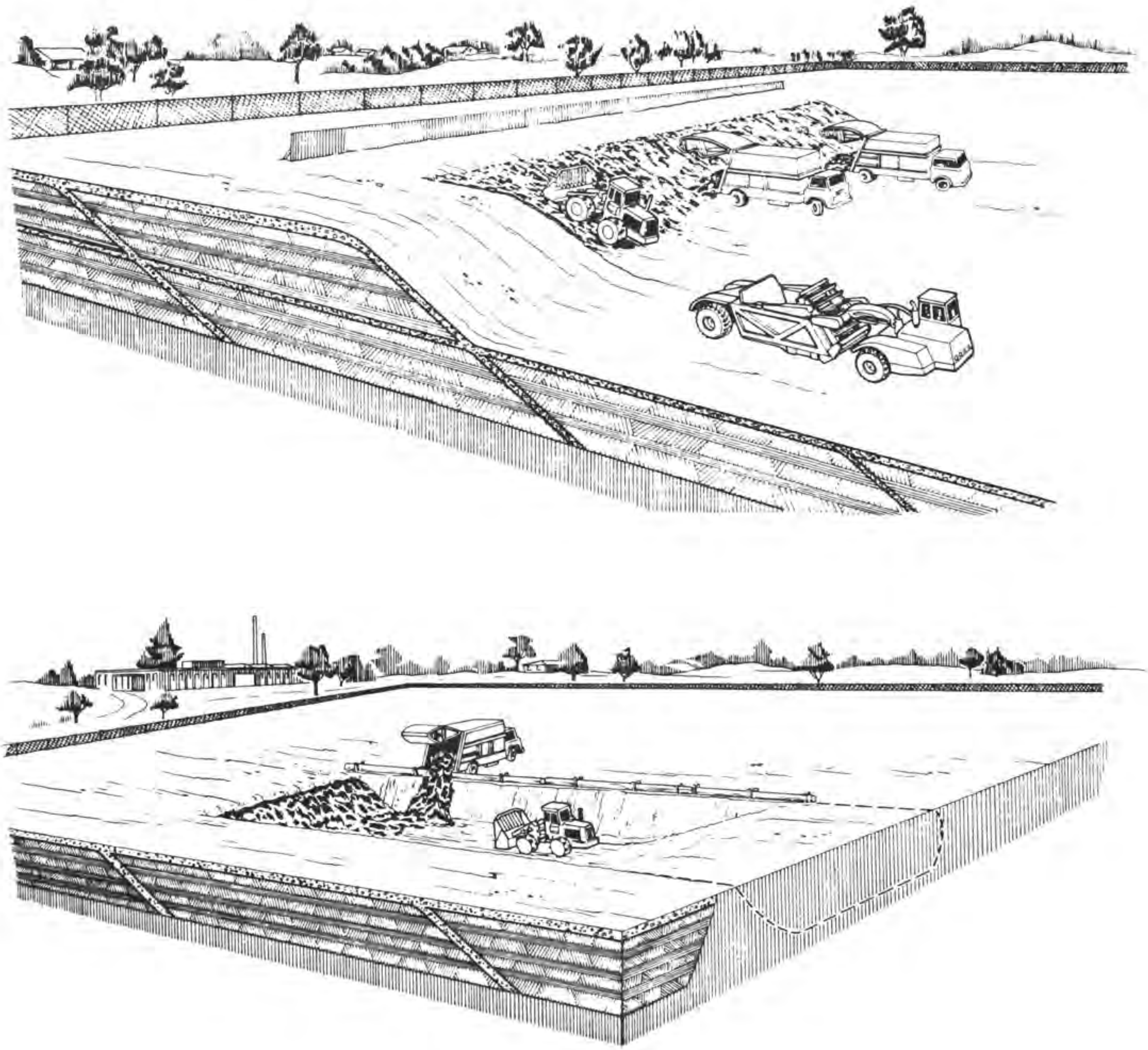

Figure 3. Examples of Landfill Types (After ASCE, 1976)

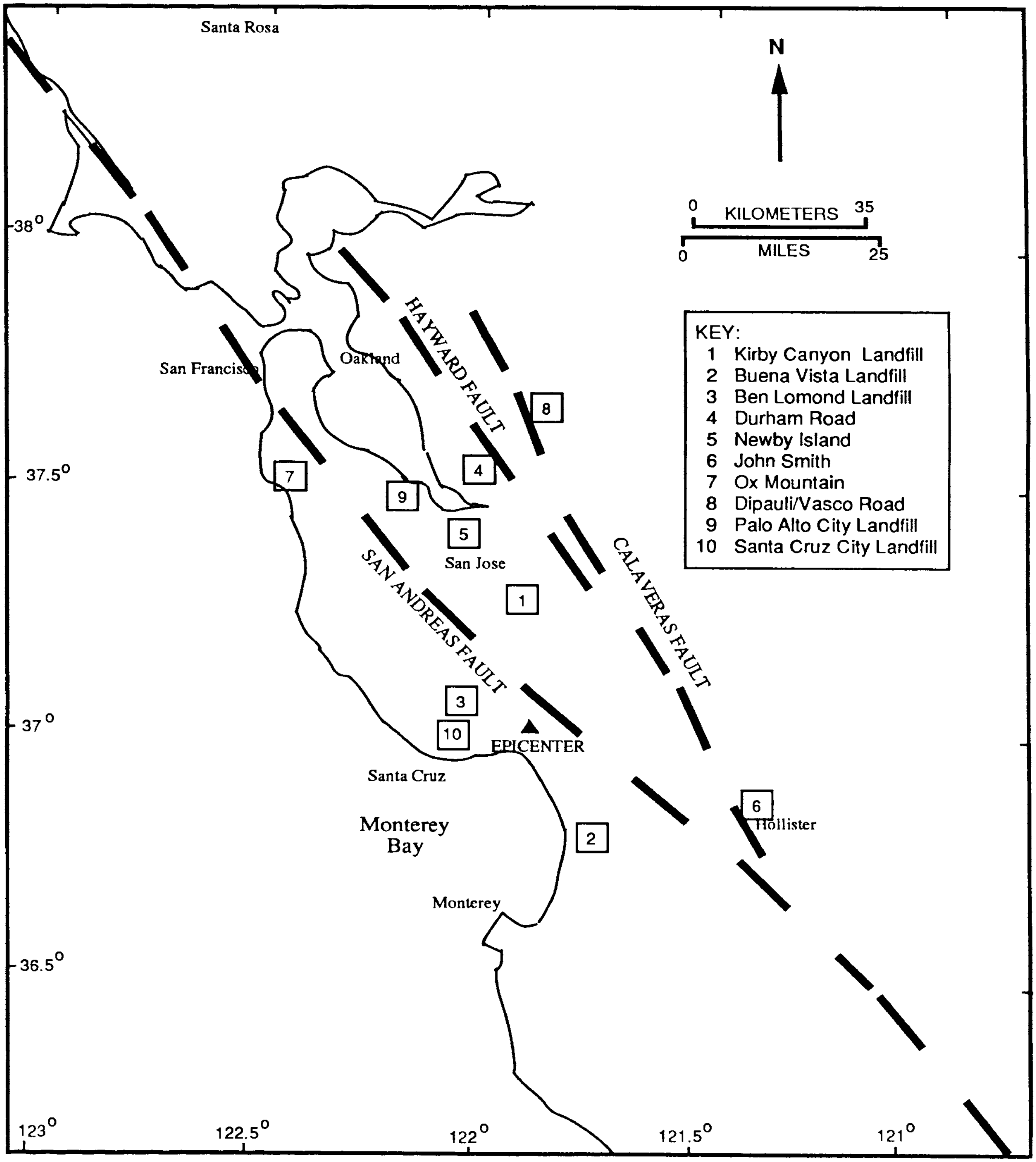

Figure 4. Locations of Sanitary Landfills

TABLE 1. Landfills Surveyed

Site No.	Landfill Name and Operator	Location	Geology	Landfill Type	Description of Landfill Slopes	Effects of Quake on Slopes	Comments
1	Kirby Canyon Landfill (Waste Management Co.)	San Jose	Serpentine	Canyon fill	200 to 250 feet high 2:1	No damage to slopes	326 acres 10 acres active
2	Buena Vista Landfill (Santa Cruz Co.)	Watsonville	Sand and gravel	Modified gravel pit (excavate below grade, fill and mound)	up to 100 feet high 3:1	none to minor cracks or failures on trash slopes	
3	Ben Lomond Landfill (Santa Cruz Co.)	Ben Lomond	Sandstone/shale	Side hill fill (modified canyon fill)	up to 150 feet high 3:1	Minor cracking at contact with natural and on slope benches	
4	Durham Road (Waste Management Co.)	Fremont	Bay Mud	Mound	up to 90 feet 3:1	No damage	
5	Newby Island BFI	San Jose	Bay Mud	Mound	100 feet 3:1	No damage	300 acres
6	John Smith (City of Hollister)	Hollister	Sandstone/claystone	Canyon fill	Gentle slope	No damage	
7	Ox Mountain BFI	Half Moon Bay	Decomposed granite	Canyon fill	200 feet 3:1	No damage to slopes Minor settlement	100 acres active
8	Dipauli/Vasco Road BFI	Livermore	Franciscan complex	Canyon fill	150 feet 3:1 to 4:1	No damage	70 acres active
9	Palo Alto City (City of Palo Alto)	Palo Alto	Bay Mud	Cut and fill Mound	60 feet 3:1 to 10:1	Minor settlement at cut/fill contact	
10	Santa Cruz City (City of Santa Cruz)	Santa Cruz	Mudstone	Canyon fill	150 feet 2:1	No failures of slopes Minor cracking at contact between fill and natural	100 acres

SELECTED LANDFILLS

The landfills selected for evaluation include five canyon fills, one side hill fill (modified canyon fill), one pit fill, and three mound fills. The slopes on the fills have heights up to 250 feet at inclinations of 2:1 (horizontal to vertical) to 3:1. The locations of the various landfills evaluated are shown with respect to the major faults and the Loma Prieta Earthquake Epicenter on Figure 4. Table 1 presents a summary of the landfills, locations, local geology, slopes, and the effects of the earthquake on the landfill slopes.

The results of the observed/reported damage survey indicate that no significant slope failures occurred. Damage to landfills was generally limited to surface cracks along the perimeter of the fill areas. This location of cracks suggest settlement due to variable shaking characteristics of the fill materials relative to adjacent natural ground. The landfills with the greatest observed cracking were the Santa Cruz City and the Ben Lomond landfills. These landfills are the closest to the epicenter of the earthquake as shown on Figure 4.

Estimates of the likely earthquake ground motions in the vicinities of the ten selected landfills were made from an examination of the ground motions recorded at the various stations by CSMIP (Shakal, et al., 1989) and USGS (Maley, et al., 1989). In some instances, the correlations were quite straightforward, with the landfill sites and the recording station sites being in close proximity and established in geologically similar materials. In other instances, the recording stations were not very close and not necessarily in the same geologic materials, making the correlations more difficult. It also is not possible to estimate the effects of local site effects that could cause some variations in the characteristics of the ground motions; of these, the most obvious condition is local topography which could cause significant variation. However, it is felt that the estimates are reasonable and should be within 25 percent of the actual peak ground motion levels. The estimated maximum horizontal ground accelerations in the natural soils at each of the ten landfill sites are summarized in Table 2.

TABLE 2. Estimated Maximum Horizontal Ground Accelerations at the Landfill Sites

Site No.	Landfill	Peak Ground Acceleration
1	Kirby Canyon Landfill	0.28g
2	Buena Vista Landfill	0.35g
3	Ben Lomond Landfill	0.50g
4	Durham Road	0.12g
5	Newby Island	0.10g
6	John Smith	0.23g
7	Ox Mountain	0.12g
8	Dipauli/Vasco Road	0.04g
9	Palo Alto City	0.25g
10	Santa Cruz City	0.45g

The landfills closest to the earthquake epicenter most likely experienced the strongest ground motions, as would be expected. The Ben Lomond and Santa Cruz City landfills probably experienced maximum ground accelerations on the order of 0.45 to 0.50g. The duration of strong ground shaking was probably on the order of 10 to 15 seconds.

Somewhat more distant landfills such as Kirby Canyon, Buena Vista, and John Smith were probably subjected to maximum accelerations on the order of 0.20 to 0.35g. The more distant landfills, which are all in the San Francisco Bay area, were probably subjected to less violent accelerations; we estimate those accelerations to be generally about 0.12g or less. The only exception to this may be the landfill in Palo Alto which is constructed over Bay Mud deposits; the strong-motion records collected at Bay Mud sites along the San Francisco peninsula would suggest horizontal accelerations on the order of 0.25g or greater.

CONCLUSIONS

Sanitary landfills within the earthquake-affected area experienced earthquake ground motions with maximum ground accelerations estimated to range from 0.04 to 0.50g. In general, the slopes of the landfills performed very well. No slope failures occurred on the relatively high slopes ranging up to 250 feet with slope inclinations as steep as 2:1. In spite of horizontal accelerations estimated to be as high as 0.45 to 0.50g at the Ben Lomond and Santa Cruz City landfills, only minor cracking occurred. The cracking was limited to areas where there existed a contact between dissimilar materials or had changes in geometry, such as benches.

The excellent performance of these man-made slopes may be a result of several factors, all of which influence the performance. These factors are believed to be the damping of ground motions by the "loose" trash, the strength and heterogeneity of trash, and the flexible nature of the slope face.

The trash fill is composed of a heterogeneous mixture of materials with a density perhaps ranging from 25 to 75 pounds per cubic foot. These low density materials have been placed over and adjacent to natural soil and rock with densities typically greater than 100 to 120 pounds per cubic foot. The damping or absorption or dissipation of energy at or near the interface between the natural and fill materials can effectively reduce the vertical and lateral forces reaching the landfill slope face, much as base isolators can reduce the lateral forces on a seismically base isolated building.

The strength of trash cannot be determined by conventional soil testing techniques due to the variability of materials. Landfill trash is known to contain abundant wood (lumber and tree branches) as well as plastic, cloth, wire, and metal. These relatively high-strength materials are randomly interwoven with less strong material; this probably results in a reinforced structure beneath the outer soil layer, performing much as a reinforced earth slope performs.

The low density and heterogeneous nature of the trash fill apparently causes it to be very flexible. This flexibility results in movement during earthquake ground motion that does not result in significant permanent deformation, but is reflected as minor cracks in perimeter areas. In a sense, this flexibility can be likened to the performance of a steel frame building as opposed to the performance of a more rigid masonry building during an earthquake.

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