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# OBSERVATIONS OF THE PERFORMANCE OF SOLID WASTE LANDFILLS DURING EARTHQUAKES

Neven MATASOVIC and Edward KAVAZANJIAN, Jr.

GeoSyntec Consultants
2100 Main Street, Suite 150
Huntington Beach, California 92648
U.S.A.

## ABSTRACT

Interpretation and analysis of observational data on the performance of solid waste landfills during earthquakes is the most reliable source of information on the seismic response of solid waste. The data from several major California earthquakes indicate that the general performance of landfills during earthquakes is from good to excellent. None of the landfills investigated showed signs of major damage. However, recorded strong ground motion data indicate that significant amplification of both peak and spectral accelerations can occur at the top of a landfill. This, combined with the fact that only a limited number of landfills with geosynthetic liners and no landfill with a geosynthetic cover have ever been subjected to strong ground motions, indicate that caution is warranted in the design of modern, geosynthetic-lined and/or covered landfills in the areas of high seismicity.

## KEY WORDS

Solid Waste; Landfill; Damage Categorization; Earthquake Damage; Seismic Response; Strong Motion Records; Amplification

## INTRODUCTION

As with many other areas of earthquake engineering, observations of the performance of solid waste landfills during earthquakes provide the most reliable means of identifying modes of damage for which seismic performance analyses are required. Observations of seismic response are also available for calibrating the performance analyses that are developed to address the identified problems. Ideally, calibration of seismic performance analyses involve case histories where material properties and physical conditions are well-established, where instrumented recordings of performance during the event exist, and where secondary or combined effects do not lead to ambiguous interpretations of performance. Realistically, in geotechnical practice few case histories of any kind and no landfill case histories meet these ideal requirements. Despite the lack of ideal case histories, observations of the performance of solid waste landfills in past earthquakes represents the most important source of information for design of modern landfills to resist seismic loading. This paper critically summarizes the existing observational database of landfill response to strong earthquakes in California. Characterization information on the California landfills impacted by earthquakes, including data sources and the methodology employed for damage assessment is also provided herein in order to facilitate the application of the California experience elsewhere.

## CHARACTERISTICS OF CALIFORNIA SOLID WASTE LANDFILLS IMPACTED BY EARTHQUAKES AND LANDFILL DAMAGE CATEGORIZATION SCHEME

Most of the earthquake-impacted California landfills have been the so called *canyon fill type* landfills, i.e. landfills where a canyon is partially or completely filled vertically, while being filled across the breadth of the canyon. In the San Francisco Bay area, several of the impacted landfills were of the *area fill type*, where waste is placed on a broad flat base and excavation is limited to that necessary to install features such as liners. Also, several of the older landfills in southern California were of the so called *pit fill type*, once a popular method to reclaim sand and gravel pits. Finally, several landfills in southern California are filled against the side of the hill (*side hill fill type*). In addition to the landfill type, California landfills differ in the containment system details such as liners, covers and leachate collection and removal systems (LCRS). The inclination of active and interim waste slopes at California landfills is typically 1.75H:1V to 2H:1V (horizontal to vertical). At closed landfills, waste face slopes are typically 2H:1V or flatter. All solid waste landfills have some kind of surface water control system that typically includes water conveyance and storage structures.

Municipal solid waste disposed of in the major metropolitan areas of California has the following typical composition (by volume): demolition and construction waste (29%), residential waste (39%), commercial waste (21%), industrial waste (5%), miscellaneous waste (3%) and non-hazardous liquid waste (3%) (Matasovic et al., 1995a). Sewage sludge, occasionally disposed of at solid waste facilities, forms less than 1% of the waste. Disposal of non-hazardous liquid waste in solid waste landfills was banned in California in 1985 and therefore liquid waste can be found only in older solid waste landfills. Furthermore, due to California regulations which require that municipal solid waste is covered daily with at least 150 mm of soil cover and that an interim soil cover of at least 300 mm is placed periodically, the soil content of solid waste in California landfills is at least 20 percent and, in some older landfills, after decomposition of putrescible materials, biodegradation, and settlement as high as 50 percent.

The landfill damage categorization scheme employed in this paper was originally proposed by Matasovic et al. (1995a) in their study of landfill damage after the 17 January 1995 Northridge, California earthquake. This damage categorization scheme is presented in Table 1. Even though the contents of Table 1 are self explanatory, it should be noted that the "Significant Damage" category in the table does not imply a release of contaminants to the environment or impairment of the waste containment system. It merely notes that damage could not be repaired by landfill staff within 48 hours.

**Table 1. Damage Categories for Solid Waste Landfills (Matasović et al., 1995)**

| Damage Category | Description |
|---|---|
| V. Major Damage | General instability with significant deformations. Integrity of the waste containment system compromised. |
| IV. Significant Damage | Waste containment system impaired, but no release of contaminants. Damage cannot be repaired within 48 hours. Specialty contractor needed to repair the damage. |
| III. Moderate Damage | Damage repaired by landfill staff within 48 hours. No compromise of the waste containment system integrity. |
| II. Minor Damage | Damage repaired without interruption to regular landfill operations. |
| I. Little or No Damage | No damage or slight damage but no immediate repair needed. |

Peak horizontal ground acceleration (PHGA) is typically used as the index of the severity of earthquake loading in post-earthquake damage surveys. PHGAs presented in this paper were estimated for hypothetical <u>bedrock</u> outcrops at the approximate centers of the landfill sites using the Idriss (1993) attenuation relationships, which has been shown to give reliable estimates of PHGA for recent California earthquakes (e.g., see Stewart et al., 1994).

## OBSERVATIONAL DATABASE

The observational database of solid waste landfill response to strong ground shaking in recent California earthquakes includes data collected after seven earthquakes. These earthquakes are characterized in Table 2. It should be noted that all of the earthquakes characterized in Table 2 occurred in the vicinity of the two major metropolitan areas of California, the greater Los Angeles area and the San Francisco Bay area. Figure 1 shows the epicenters for the 1971 San Fernando, 1987 Whittier-Narrows, and 1994 Northridge earthquakes along with the corresponding fault rupture planes delineated after Dolan et al. (1995). The epicenter of the 1992 Landers event is approximately 110 km east of the limit of Figure 1. The 1989 Loma Prieta fault plane shown in Figure 2 is delineated in accordance with USGS (1989). The epicenters of the 1969 Santa Rosa earthquakes are not shown in figure 2 since they are approximately 35 km north of the northern part of Figure 2. Figures 1 and 2 also show locations of the solid waste landfills for which the post-earthquake observational data exists.

### *Santa Rosa Earthquakes*

The Redwood landfill in the Marin County, California, is probably the first solid waste landfill in California for which earthquake-induced damage has been reported. As quoted in Anderson (1995), in the 1969 series of two moderate earthquakes that occurred near Santa Rosa, California, a few interior cell walls made up of clay (San Francisco Bay Mud) collapsed, but the perimeter levee around the landfill was not damaged. The damage may have occurred due to amplification of the earthquake motions by the underlying soft sediments, as the estimated PHGA in bedrock at the site is 0.05 g from these events.

**Table 2. Main Characteristics of Strong Earthquakes from 1965 to 1994 in the Vicinity of Major Urban areas in California**

| Earthquake | Moment Magnitude | Style of Faulting |
|---|---|---|
| Santa Rosa<br>(1 October 1969) | 5.6 and 5.7 | Right Lateral |
| San Fernando<br>(2 February 1971) | 6.6 | Reverse and Left Lateral |
| Whittier Narrows<br>(1 October 1987) | 6.0 | Reverse |
| Loma Prieta<br>(17 October 1989) | 6.9 | Thrust and Right Lateral |
| Landers<br>(20 June 1992) | 7.3 | Right Lateral |
| Northridge<br>(17 January 1994) | 6.7 | Blind Thrust |

### *San Fernando Earthquake*

At the time of the 1971 San Fernando earthquake, eleven major landfills existed within 60-km radius around the epicentral region. No strong motion recordings were obtained during this earthquake on any of these landfills. However, many recordings on rock and soil sites were obtained in this earthquake at distances ranging from about 10 to 80 km. Based on these recordings, levels of shaking (in weak bedrock) at the eleven major landfills ranged from 0.05 g to 0.5 g.

One of the nearest landfills to the San Fernando earthquake fault rupture plane was the North Valley landfill, now called, as labelled in Figure 1, the Sunshine Canyon Landfill. This site was approximately 13 km from the 13 km-deep fault rupture plane. The other ten major landfills were located from about 23 km (the Scholl Canyon landfill) to approximately 65 km (the Palos Verdes landfill) from the fault rupture plane. The PHGA estimate for the Sunshine Canyon landfill is approximately 0.30 g and for the Scholl Canyon landfill is approximately 0.19 g.

No documentation of systematic investigations conducted following the San Fernando earthquake is available. Interviews with the key personnel of both owners and consultants indicate that no major damage was reported in any of these landfills. However, for the Sunshine Canyon landfill reports of minor damage are contradictory (Owner - no damage, Consultant - some failure in the soil cover after the earthquake, and unsubstantiated reports of three long parallel cracks on the east side of the landfill). Furthermore, interviews with long-time residents of a trailer park located on top of the closed Russell Moe landfill report eruption of landfill gas fires at the location of cracks in the cover soil following the earthquake (personal

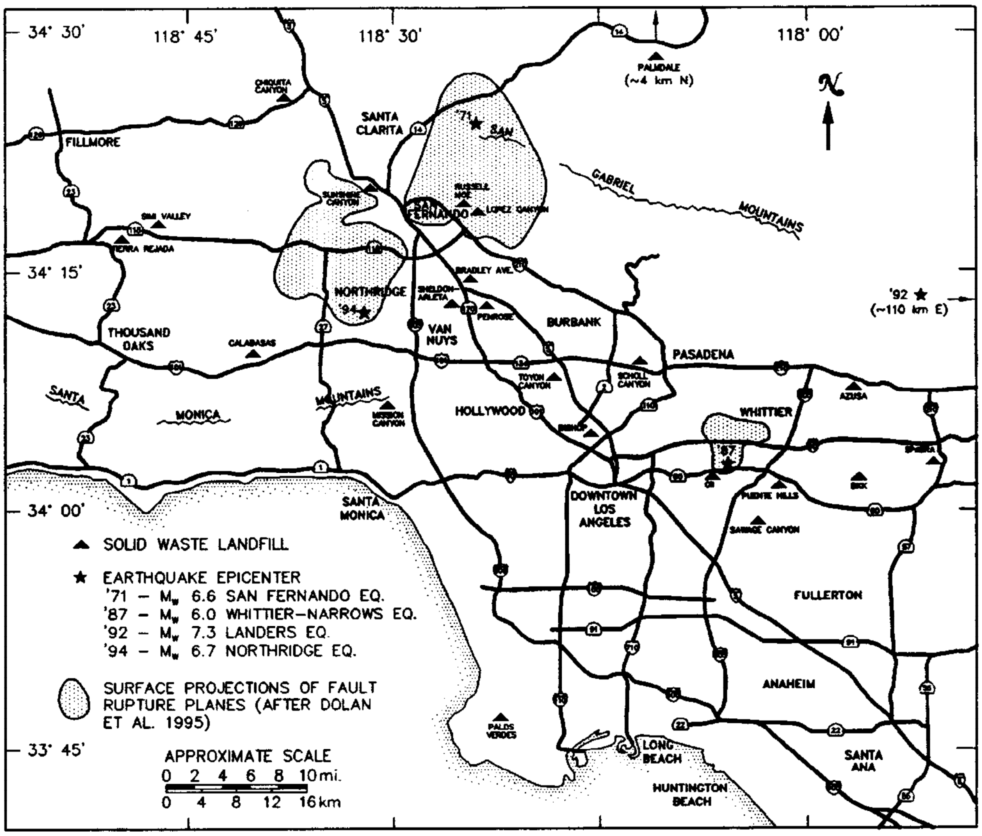

Fig. 1. Major Solid Waste Landfills in the Greater Los Angeles Area and the Zones of Energy Release of the Major Recent Earthquakes

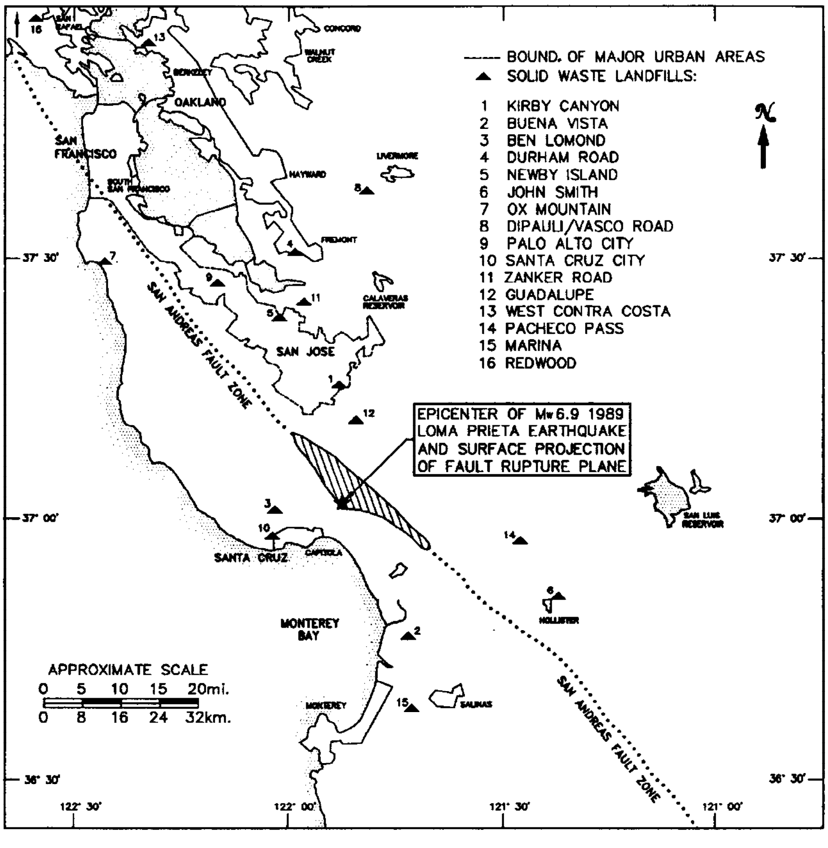

Fig.2. Major Solid Waste Landfills in the San Francisco Bay Area and the Zone of Energy Release of the Loma Prieta Earthquake

communication E. Kavazanjian). The Russell Moe landfill had no gas collection system and prior to the earthquake landfill gas was flared at the end of passive vents in the soil cover referred to by the residents as "Tiki" flares. The Russell Moe site was directly above the fault rupture plane and less than 1 km from the surface manifestation of fault rupturing. The above data suggest that cracking of cover soils was the only apparent damage that occurred to landfills in the San Fernando earthquake.

### *Whittier-Narrows Earthquake*

The main shock of the Whittier-Narrows earthquake occurred as a reverse (thrust) motion on a buried fault at an approximate depth of 10 to 14 km with no surface expression of fault displacement. Performance information from five unlined landfills within 15 km from the zone of energy release, the OII, Puente Hills, Savage Canyon, BKK, and Azusa landfills, is available.

Siegel, et al. (1990) report on observations at the OII Landfill made immediately following the Whittier-Narrows event. The survey team identified ground cracking in cover soils on the benches of the steeper side slopes (1.8 H : 1.0 V), but no evidence of solid waste slope instability was reported.

Davis et al. (1989) provide a cross-section through the Whittier-Narrows earthquake fault rupture plane. This cross-section enables a relatively accurate estimate of the site-to-source distance for the OII and other landfills in the area. For the site-to-source distance of 11.5 km for the OII landfill, the Idriss (1993) attenuation relationship predicts a PHGA of 0.24 g. A peak horizontal acceleration of 0.45 g was recorded at the Garvey reservoir which is located at approximately the same site-to-source distance as the OII landfill. However, recent surveys by GeoSyntec Consultants have shown that the Garvey Reservoir station may not be a bedrock station and that records may be heavily influenced by the local topography. This suggests that the PHGA at the OII site in the Whittier-Narrows event was probably on the order of 0.24 g. The relatively large acceleration recorded at the Garvey reservoir and the damage reported at the OII landfill prompted installation of the strong motion instruments at the base and top deck of the landfill.

Other landfills within 15 km of the zone of energy release, the Puente Hills, Savage Canyon, BKK, and Azusa landfills reported no damage in the Whittier-Narrows event.

### *Loma Prieta Earthquake*

The Loma Prieta earthquake was the first major earthquake that produced abundant observational data on seismic performance of unlined solid waste landfills. Orr and Finch (1990), Johnson et al. (1991) and Buranek and Prasad (1991) report on post-earthquake inspections of fifteen unlined landfills indicated in Figure 2.

The PHGA at the base of the landfills shown in Figure 2 in the Loma Prieta event was estimated to have ranged from 0.1 g to 0.5 g. All of the post-earthquake damage investigators report only minor damage, with the most common damage type being minor cracking of the cover soil on the landfill slopes. However, several of the investigators noted that it was often difficult to distinguish between "normal" cracks induced by waste settlement and/or decomposition and earthquake-induced cracking. Repair of this type of cover soil cracking is performed regularly as part of routine landfill maintenance activities. Repair of the earthquake induced cracks in the cover soil was typically carried out by landfill maintenance crews immediately following the earthquake without disruption to landfill operations. Orr and Finch (1990) note that some of the landfill gas recovery systems were temporarily affected by power loss and above-ground pipe breakage at a number of the landfills impacted by the Loma Prieta earthquake. However, all landfill gas recovery systems were repaired and back in operation within 24 hours of the earthquake and no post-earthquake changes in quantities of leachate and landfill gas recovery were reported.

Among the landfills closest to the Loma Prieta earthquake fault rupture plane, data exist for the Guadalupe, Ben Lomond, Kirby Canyon and Santa Cruz Landfills, for which PHGAs of 0.43 g, 0.38 g, 0.34 g and

0.30 g were estimated, respectively. As reported by Johnson, et al. (1991), even the highest slopes at these landfills, which includes 2H:1V slopes up to 45 m high at the Santa Cruz Landfill, 3H:1V slopes up to 45 m high at the Ben Lomond Landfill, and 2H:1V slopes up to 75 m high at the Kirby Canyon Landfill, performed well, with minor cracking (25 to 75 mm) of cover soils as the only observed damage. Only at the Guadalupe landfill, as reported by Buranek and Prasad (1991), minor downslope cover soil movement was observed. The various investigators note that cracking of cover soil on the slopes at these landfills was generally limited to contact zones between areas of dissimilar materials and areas of changes in geometry. These are the same areas where cracks tend to form in the cover soil under normal operating conditions.

*Northridge Earthquake*

The Northridge earthquake also provided abundant observational data on the seismic performance of solid waste landfills. The Northridge event provided, for the first time, observations of the behavior of geosynthetic lined landfills designed in accordance with the United States Subtitle D regulations (Subtitle D) under strong shaking from a major earthquake. The main shock of the Northridge earthquake occurred as a reverse (thrust) motion on a southward-dipping plane at a depth of approximately 15 km at the northern end of the San Fernando Valley of the greater Los Angeles area, as indicated in Figure 1.

About forty active, inactive, and closed solid waste landfills were located within 100 km of the earthquake epicenter. Stewart et al. (1994) provide preliminary data on the performance of nine major landfills in the epicentral region. Matasovic et al. (1995a) summarize information on the performance of 22 landfills that experienced shaking estimated to be in excess of 0.06 g. The locations of these 22 landfills are shown on Figure 1. At 16 of these landfills the PHGA is estimated to be in excess of 0.24 g and at six of these landfills the PHGA was estimated to be in excess of 0.38 g. At the OII landfill, a peak horizontal acceleration of 0.25 g was recorded at both the top deck and the base of the landfill. However, deconvolution analysis presented in Matasovic et al. (1995b), indicate a PHGA of 0.1 g consistent with the estimate developed using the site-to-source distance of 43 km and the Idriss (1993) attenuation relationship. This, as well as observations from ambient vibrations and strong motion records from the 1992 $M_w$ 7.3 Landers event and a series of eight pre-Northridge minor earthquakes with peak acceleration amplification factors of up to three and spectral acceleration amplification factors of up to twelve (Hushmand, 1994), provide direct evidence of the amplification potential of the municipal solid waste.

Three of the landfills subjected to the strongest shaking in the Northridge event had geosynthetic composite liner systems that met Subtitle D requirements. The Lopez Canyon Landfill and the Bradley Avenue Landfill, withstood the earthquake without significant damage, while damage to the geosynthetic liner system occurred at the Chiquita Canyon Landfill. The Lopez Canyon Landfill is located within 8.4 km of the fault rupture plane and was subject to an estimated PHGA of 0.42 g. The Bradley Avenue Landfill is located within 10.8 km of the fault rupture plane and was subject to an estimated PHGA of 0.36 g. At both sites, local tears in the geotextile overlying the side slope liner were observed by the California regulators post-earthquake inspections (CIWMB, 1994). In neither case was the geomembrane liner breached. Furthermore, at both landfills, subsequent investigations by the owners representative indicated that the tear was caused by operating equipment (GeoSyntec, 1994; Augello, et al., 1995) and was not attributable to earthquake ground motions.

Damage at the Chiquita Canyon Landfill, located approximately 12.2 km from the zone of energy release and subjected to an estimated PHGA of 0.33 g, may be attributable to the details of the design and the construction quality assurance for the geosynthetic liner. Damage at this landfill, classified as Significant Damage, consisted of tears in the geomembrane liner at two locations. In Area C, there was a single tear approximately 4 m in length. In Area D, there was a series of three parallel tears with a total length of approximately 23 m (EMCON, 1994). Both tears occurred parallel to anchor trenches on benches above the waste. Forensic analysis by the Geosynthetic Research Institute at Drexel University, Philadelphia, U.S.A., indicate that the tears initiated from the locations where a "coupon" was cut out during construction quality assurance activities for laboratory testing of seam strength. Both the cut for the coupon and the anchor trench appear to have been a factor in both the initiation and propagation of the tear (Anderson and

Kavazanjian, 1995; Augello et al., 1995). No disruption of the underlying low permeability soil liner was reported.

Matasovic et al. (1995a) report that, as in previous earthquakes, the most prevalent damage to landfills in the Northridge event was superficial brittle cracking in cover soil at transitions between waste fill and natural ground areas. Cracks were typically 10 to 70 mm wide and of similar vertical relief. The most pronounced cracking of this type was at the Sunshine Canyon Landfill, the closest landfill to the fault rupture plane. At that landfill, where PHGA was estimated to be as great as 0.46 g, the observed cracks were approximately 300 mm in height and width near the contact between the refuse fill and the canyon wall at the back of the landfill. This cracking can be attributed to the differential dynamic response of the waste fill and the natural ground and, possibly, earthquake-induced settlement of the cover soil and/or refuse.

As in previous earthquakes, disruption to landfill gas recovery systems was common during the Northridge earthquake. Loss of power was perhaps the most common source of disruption, followed by breakage of gas and condensate lines and well heads. In all cases, gas recovery systems were repaired by landfill maintenance personnel without disruption to landfill operations and were back in operation within 24 hours.

## CONCLUSIONS

The record of performance of solid waste landfills in the several recent earthquakes is from good to excellent. Three landfills located in the epicentral area of the Northridge event were lined with geosynthetic liner systems designed in compliance with modern (e.g., U.S. Subtitle D) regulations. Two of these landfills withstood the earthquake without damage to the liner system or disruption to landfill operations. The third landfill did suffer some damage to the containment system, but it was above the waste and did not result in a release of contaminants to the environment. Damage observed to the liner system of that third landfill, subjected to ground motions of lesser intensity than either of the other two geosynthetic-lined landfills, may be attributable to anchoring and construction quality assurance details indicating the importance of attention to these details in design and construction of geosynthetic lined landfills. It should be noted that no landfill with a geosynthetic cover has ever been subjected to strong ground shaking.

Observations at the one landfill in which strong ground motions have been recorded, the OII landfill, indicate that significant amplification of both peak and spectral accelerations can occur. The observations of amplification of peak and spectral acceleration, of seismically induced damage to a geosynthetic liner, and of cracking of cover soils at solid waste landfills presented in the paper, combined with the fact that no landfill with a geosynthetic cover has ever been subjected to strong ground motions, indicate that, despite the general observation of the good to excellent performance of solid waste landfills in past earthquakes, caution is warranted in the design of modern, geosynthetic-lined and/or covered landfills in the areas of high seismicity.

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