05 Apr 1995, 6:30 pm - 10:00 pm

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Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
April 2-7, 1995; Volume III, St. Louis, Missouri

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Paper No. 14.04

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SYNOPSIS The performance of 22 landfills in the Los Angeles area during the January 17, 1994 Northridge earthquake has been investigated. Observations of damage at these landfills indicate that the overall performance of solid waste landfills was encouraging. None of the surveyed landfills showed any signs of major damage. However, one geosynthetic-lined landfill experienced two tears in the geomembrane liner. Most landfills within 30 km of the zone of energy release experienced some form of cracking in the soil cover. Beyond approximately 40 km from the zone of energy release, little to no damage was observed.

INTRODUCTION

Federal Regulations ("Subtitle D") require that solid waste landfills located in seismic impact zones be designed to resist earthquake hazards. However, seismic design procedures for solid waste landfills have been developed largely without the benefit of well-documented case histories. Consequently, established design procedures for evaluating the seismic performance of waste fills largely rely upon unverified assumptions about the waste fill's dynamic behavior.

The January 17, 1994 Northridge Earthquake (M_w = 6.7) provides important observational data on the response of solid waste landfills to strong levels of ground shaking. Because of the difficulties associated with laboratory evaluation of the dynamic properties of waste materials, these full-scale case histories present an invaluable opportunity to study the dynamic response characteristics and performance of waste fills and to back-calculate bounding values for key properties of these systems.

There are numerous active, inactive and closed solid waste landfills within 100 km of the epicenter of the Northridge Earthquake. Figure 1 shows the location of 22 of these landfills that experienced significant levels of shaking (i.e., free-field ground accelerations in excess of 0.05g). A brief description of the damage that occurred at these 22 landfills is provided herein. The performance of five landfills that are particularly noteworthy is described in detail; these landfills are the Operating Industries, Inc. (OII), Chiquita Canyon, Sunshine Canyon, Lopez Canyon and Bradley Avenue landfills. Stewart et al. (1994) provide a more detailed description of the damage to these five landfills along with numerous photographs and plan views of these landfills.

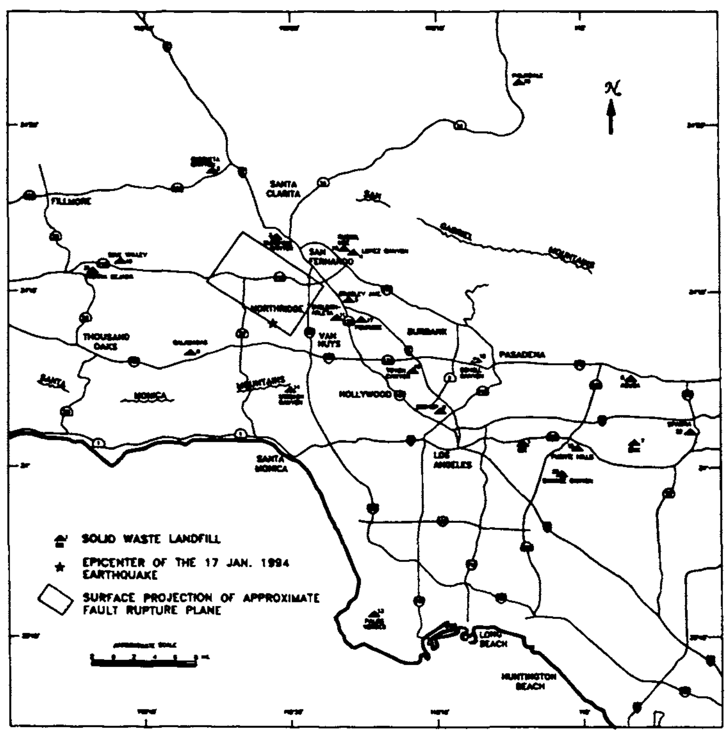

Figure 1. Major solid waste landfills within 100 km of the January 17, 1994 Northridge Earthquake Epicenter (after Matasović et al., 1995).

LANDFILL CHARACTERISTICS

The 22 landfills in this survey were classified according to the following categories: landfill type, size, number of active, inactive and closed landfill cells at the time of the earthquake, and the type of waste containment. Matasović et al. (1995) provides a brief description of the solid waste landfills investigated in this study based upon this classification scheme. The details of the containment systems (bottom liner, leachate collection and removal system, gas control and cover system) depend largely on the date of construction. Current federal regulations (effective October 9, 1993) require that new waste units or lateral expansions of existing units have composite liners (a geosynthetic membrane overlying a low permeability soil layer) and a leachate collection and removal system (LCRS) on their base and side slopes. Landfills built prior to this date were typically either constructed with no liner system or with only a low permeability soil liner. Only eight of the 22 landfills (Chiquita Canyon, Lopez Canyon, Bradley Avenue, Azusa, Puente Hills, Simi Valley and Spadra) have composite liner systems.

With the exception of the OII, BKK, Calabasas, Palos Verdes, Spadra and Simi Valley landfills, the solid waste landfills in this study are classified by the State of California as Class III, municipal solid waste landfill facilities (MSWLF). The OII, BKK, Calabasas, Palos Verdes, Spadra and Simi Valley landfills have received hazardous waste (California Classes I and II) in addition to receiving municipal solid waste (MSW). MSW in the greater Los Angeles area has the following typical composition (by volume): residential waste (39%); demolition and construction debris (29%); commercial waste (21%); industrial waste (5%); miscellaneous wastes (3%); and non-hazardous liquid waste (3%) (CoSWMP,1984). The disposal of non-hazardous liquid wastes in solid waste landfills was banned in California in 1985. Sewage sludge is occasionally disposed of at MSWLFs, but it forms less than 1% of the waste accepted (based on typical composition of MSW in Southern California).

California regulations require that MSW be covered with at least 150 mm of daily cover. Furthermore, on surfaces where waste has not been placed for more than 180 days, an interim soil cover at least 300 mm thick is required. Since the Northridge earthquake occurred in the early morning hours all of the active faces at the solid waste landfills surveyed were covered by daily soil cover. All of the closed landfills in this study had compacted soil covers at the time of the earthquake. Soil covers for most of the closed landfills consisted of a 300 mm thick vegetative soil layer underlain by a compacted foundation layer at least 600 mm thick. No geosynthetic cover systems were in place at the time of the Northridge earthquake. The inclination of active and interim waste slopes was typically 1.75H:1V to 2H:1V (horizontal to vertical). At BKK and OII landfills, interim waste slopes were locally as steep as 1.3H:1V to 1.4H:1V. At the closed landfills, waste slopes were typically 2H:1V or flatter. Side slopes that underlay the waste fill in canyon fills and gravel pit landfills ranged from 1H:1V to 1.5H:1V for natural slopes and 1.5H:1V to 2H:1V for excavated side slopes.

Gas collection and/or control systems were in place at over 50% of the surveyed landfills at the time of the earthquake. Bradley Avenue, Toyon Canyon, Sheldon-Arleta, Puente Hills, Simi Valley and Spadra landfills either directly convert landfill gas to energy to run on-site operations or sell the gas to the City of Los Angeles. Approximately 50% of the surveyed landfills had some type of leachate collection and removal system (LCRS). For the landfill cells constructed prior to "Subtitle D", this system typically consisted of extraction wells, drains on the landfill faces, and/or subsurface barriers. For newer landfill units, the LCRS typically consisted of a network of pipes placed into a drainage layer above the base geomembrane liner. Some of these newer units had a LCRS on the side slopes of the landfill. All of the landfills had some type of surface water control system that typically included grading of landfill faces for water conveyance along with run-off, conveyance, retention and sedimentation storage structures. A detailed description of the primary elements of each of the 22 surveyed landfills, including waste units, liner and cover systems, leachate collection and removal systems, gas collection systems and ancillary structures will be provided in a future report.

OBSERVED DAMAGE

General

Given the variety in landfill type, size, age and primary elements, it is difficult to define damage categories for solid waste landfills. This study uses the simplified damage categorization scheme presented in Matasović et al. (1995) based upon impairment to the waste containment system and requirements for post-earthquake repair. These landfill damage categories are reproduced in Table 1. It should be noted, in establishing these damage categories, damage to structures beyond the waste mass footprint, including sedimentation basins, water and leachate conveyance and storage systems, flare stations, and other ancillary facilities, was not considered as critical as damage to the waste containment system.

The closest distance to the zone of energy release, estimated free-field peak horizontal ground acceleration on bedrock (MHA) and the level of damage for the 22 landfills of this study are provided in Table 2. The closest distance to the zone of energy release refers to the distance from the "effective" fault plane as interpreted by Wald and Heaton (1994) to the approximate geometric center of the landfill. The peak horizontal ground acceleration was estimated as the geometric mean value from the Idriss (1991) rock attenuation relationship for a M_w = 6.7 reverse fault event. This attenuation relationship has been shown to fit the recorded rock data well (Stewart et al., 1994). At the OII landfill, the free-field peak ground acceleration at the base of the fill was

Table 1. Damage categories for solid waste landfills (after Matasović et al., 1995).

DAMAGE CATEGORY	DESCRIPTION
V. Major Damage	General instability with significant deformations. Integrity of the waste containment system jeopardized.
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.

also obtained from strong motion instrumentation installed at the landfill (Hushmand Associates, 1994).

Surficial cracking in the cover soil, primarily near the transitions between the waste fill and natural ground areas, was the most commonly observed damage to landfills due to the Northridge earthquake. Cracks of this type were observed at the Sunshine Canyon, Lopez Canyon, Bradley Avenue, Calabasas, Toyon Canyon, Scholl Canyon, and Terra Rejada landfills (Table 2). This type of cracking may be attributed to the contrast in the dynamic response characteristics between the relatively softer waste materials and the stiffer adjacent native ground. Cracking of the relatively brittle cover soil overlying the more ductile waste fill was observed at many landfills (e.g., OII, Chiquita Canyon, Sunshine Canyon, Lopez Canyon, Bradley Avenue, Calabasas, Bishop Canyon, Toyon Canyon, Sheldon Arleta, Scholl Canyon, Russell Moe and Terra Rejada). At most landfills where cracking of the soil cover was observed, the cracks were typically 10 to 75 mm wide with 10 to 75 mm of vertical offset. However, at some landfills larger cracks were observed. For example, at Sunshine Canyon landfill, cracks as much as 300 mm wide with approximately 150 to 300 mm of vertical offset were observed. At several sites, cracking of the soil cover due to limited amounts of downslope movement (typically less than 150 mm) was observed. Damage of this type occurred at the Chiquita Canyon Landfill, were localized tears in the HDPE liner of two cells of the landfill were observed.

A temporary shutdown of the landfill gas extraction system occurred at a number of landfills due to power loss as a result of the earthquake. At several landfills, breaks in the landfill gas extraction system headers and gas condensate lines were reported. In all cases, operation of the gas extraction system was restored within 48 hours. Landfill operators report that it typically takes about 48 hours after shutdown of the landfill gas system for positive pressures to develop. Therefore, a disruption of less than 48 hours to the landfill gas extraction system is not considered to be major or significant damage. However, at the Scholl Canyon Landfill, a gas well cap dislodged due to a build-up of pressure after the flare station had been shut down for only 6 hours.

OII Landfill

The OII landfill is a Class I facility that has accepted non-hazardous and hazardous liquid wastes in addition to municipal solid waste. The landfill stopped receiving waste in 1984 and is awaiting final closure as a Superfund Site. The landfill was constructed without a liner system and currently has an interim soil cover. The OII landfill is well instrumented with survey monuments, inclinometers and a pair of strong motion recording stations, one on the top of the landfill and one adjacent to the toe of the landfill. The base station recorded a peak ground acceleration of approximately 0.24g (longitudinal or east-west direction) and the top station recorded a peak ground acceleration of approximately 0.25g (longitudinal direction) during the Northridge event.

Minor cracking occurred at a number of locations on the faces of slopes of the OII landfill, primarily, but not exclusively, at or near the berm roads. The cracks were generally on the order of 50 to 150 mm or less at their widest point and did not appear to extend fully through the soil cover system into the underlying waste. Figure 2 shows a crack along a berm road on the north face of the OII landfill. Instrumentation data collected after the earthquake indicated that the landfill has not experienced significant horizontal or vertical deformations as a result of the earthquake ground motions. This observation is consistent with previous studies which have indicated that seismic shaking does not induce significant settlement or lateral displacement of solid waste (e.g. Coduto and Huitric, 1990).

The Idriss (1991) rock attenuation relationship would predict a median acceleration of 0.1 g and a median plus two standard deviations MHA of 0.25g at the OII landfill for a M_w = 6.7 event. Hence, the MHA values recorded at the base of the OII landfill fall just below the median plus two standard deviation value. Based on the site data provided by Anderson et al. (1990), it is not clear if the OII base station is truly a bedrock station.

Acceleration response spectra for the longitudinal and transverse motions are shown in Figure 3. For both records,

Table 2. Seismic performance of solid waste landfills during the 1994 Northridge Earthquake.

SOLID WASTE LANDFILL	DISTANCE FROM ZONE OF ENERGY RELEASE (km)	ESTIMATED ROCK PEAK HORIZONTAL ACCELERATION (g)	DAMAGE CATEGORY (I - V)	DAMAGED ELEMENT
1. OII	43	0.1 (0.24)[1]	Minor Damage (II)	Cover Soil
2. Chiquita Canyon	12.2	0.33	Significant Damage (IV)	Cover Soil
3. Sunshine Canyon	7	0.46	Moderate Damage (III)	Cover Soil
4. Lopez Canyon	8.4	0.42	Moderate Damage (III)	Cover Soil; Gas System
5. Bradley Avenue	10.8	0.36	Moderate Damage (III)	Cover Soil
6. Calabasas	23.1	0.20	Moderate Damage (III)	Gas System; Cover Soil
7. BKK	57.2	0.07	No Damage (I)	None
8. Azusa	51.7	0.08	No Damage (I)	None
9. Bishop Canyon	30.7	0.15	Little Damage (I)	Cover Soil
10. Toyon Canyon	22.2	0.21	Minor Damage (II)	Cover Soil; Gas Collection Headers
11. Sheldon-Arleta	10.7	0.36	Minor Damage (II)	Cover Soil; Gas Collection Headers
12. Scholl Canyon	28.4	0.16	Moderate Damage (III)	Cover Soil
13. Palos Verdes	50.8	0.08	No Damage (I)	None
14. Mission Canyon	18.4	0.25	No Damage (I)	None
15. Puente Hills	49.7	0.09	No Damage (I)	None
16. Simi Valley	22.3	0.21	Minor Damage (II)	Cover Soil; Gas System; Leachate Pump
17. Penrose	12.3	0.33		
18. Russel Moe	7.8	0.43	Moderate Damage (III)	Cover Soil
19. Palmdale	41.1	0.11	Minor Damage (II)	Cover Soil
20. Savage Canyon	52.8	0.08	No Damage (I)	None
21. Terra Rejada	22.4	0.21	Minor Damage (II)	Cover Soil
22. Spadra	55.1	0.13	No Damage (I)	None

1. Recorded MHA at toe of Landfill.

Figure 2. Crack along berm road, northside of the OII landfill.

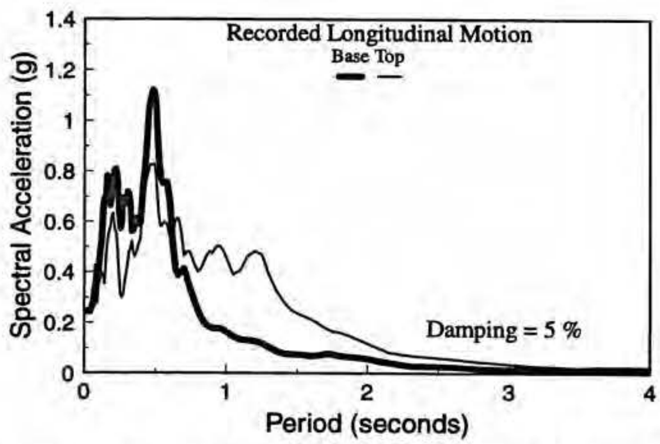

Figure 3. Acceleration response spectra from the recorded longitudinal motions at the OII landfill.

there was attenuation in the high frequency range. At periods beyond approximately 0.6 seconds, these records show amplification of motion from the base to the top. This was most pronounced in the longitudinal direction at periods of 1 to 1.25 seconds, where the amplification factor was on the order of three. The amplification functions indicate that the fundamental period of the OII landfill is approximately 1.2 seconds in both the longitudinal and transverse directions and that the landfill responded primarily in its first mode (Stewart et al., 1994). This observation is consistent with those made from previous earthquakes which induced motions of lower intensity at the landfill (Hushmand Associates, 1994).

Chiquita Canyon Landfill

At the Chiquita Canyon landfill, a significant amount of damaged occurred due to limited downslope movement as a result of the earthquake. This damage includes cracks in the soil cover systems, tears in the geosynthetic liner system, and a temporary shut down of the gas removal system due to a loss of external power. The Idriss (1991) rock attenuation relationship would predict a mean peak ground acceleration of 0.33g at the Chiquita Canyon site for a M_w = 6.7 event.

The Chiquita Canyon landfill is separated into 5 different units (Primary Canyon and Canyons A,B,C and D), some of which are separated by canyons. The Primary Canyon Landfill is unlined but Canyons A,C and D are lined with a single composite liner system. Some of the Canyon B Landfill was lined with a single composite liner system, the remainder of this area is lined with a compacted low permeability soil liner. At the time of the earthquake, only one unit (Canyon C) was accepting waste fill. After the earthquake, cracks in the soil cover were observed in all cells of the landfill. In Phase I of Canyon C, longitudinal cracks were observed at the top of the landfill along the interface between the landfill liner and the waste fill. The largest cracks were approximately 300 mm wide, with vertical offsets of 150 to 300 mm. A localized tear in the geomembrane was observed in one area of Canyon C. The tear, which occurred at the top of the slope near the anchor trench where the largest static (pre-seismic) stresses in the HDPE would be expected, was approximately 4 m long and 230 mm wide. Figure 4 shows the tear in the Canyon C geomembrane liner.

Minor cracking was observed in the Primary Canyon and Canyon B landfills. In Canyons A and D, cracks parallel to the top of the slope were observed in the soil cover. In Canyon A, typical cracks were on the order of 150 mm wide with approximately 130 mm of vertical offset. The cracks in Cell D were somewhat more pronounced. These cracks were

Figure 4. Tear in the HDPE geomembrane liner system, Canyon C, Chiquita Canyon Landfill (Photo courtesy of Calif. EPA, Integrated Waste Management Board).

as wide as 300 mm, with 200 mm of vertical offset, exposing the HDPE liner in some areas. In February 1994, a second tear in the geomembrane liner was found in Cell D. This tear was approximately 23 m long and 30 mm wide.

One hypothesis is that these geomembrane tears were caused by the limited downslope movement (300 mm) of the waste fill along the geosynthetic-lined back slope. In both cases, the tears were above the level of the waste and were repairable, though specialty contractors were required to completed the repairs. No disruption of the low permeability soil liner beneath the geomembrane was reported at either canyon. Furthermore, no indication of disruption to the containment system below the top of the waste was reported.

Sunshine Canyon Landfill

The Sunshine Canyon landfill is located only 7 km from the zone of energy release. This side-hill fill landfill stopped accepting waste in 1991 and is currently awaiting final closure. The landfill was constructed without a liner system and has an interim soil cover approximately 2.5 to 3.75 m thick in most places. Strong motion stations in the area located on recent alluvium recorded a peak ground acceleration on the order of 0.9g, but this may have been influenced by site effects and/or topographic effects. The Idriss (1991) rock attenuation relationship predicts a mean peak bedrock acceleration on the order of 0.46g at this site for a magnitude 6.7 event.

Longitudinal cracks were observed at the top of the waste fill along the interface with the natural canyon walls. The cracks varied from less than 20 mm to as much as 300 mm wide, with 150 to 300 mm of differential vertical offset in some areas. Figure 5 shows the cracking observed in the soil cover of the top deck at the western end of the landfill. Cracking was also observed at the edge of several benches along the face of the waste slope. These cracks were generally less than 20 mm wide. This cracking did not appear to represent any threat to overall instability.

Lopez Canyon Landfill

The Lopez Canyon landfill is located in the San Gabriel Mountains approximately 8 km from the zone of energy release. CSMIP recording stations in the area recorded peak ground accelerations on the order of 0.44g. The Idriss (1991) rock attenuation relationship would predict a mean peak bedrock acceleration on the order of 0.42g at this site for a magnitude 6.7 event.

Lopez Canyon currently receives most of the household municipal waste for the City of Los Angeles. The landfill is separated into four areas designated Disposal Area A, Disposal Area B, Disposal Area AB+ and Disposal Area C.

Figure 5. Crack along top deck at the western end of the Sunshine Canyon Landfill (Photo courtesy of Calif. EPA, Integrated Waste Management Board).

Disposal Areas A,B and AB+ are no longer accepting waste and are awaiting final closure. These areas are unlined and currently have an interim soil cover. At the time of the earthquake, the western and northern sections of Area C were being filled. Area C has a single composite liner system.

Minor cracking was observed in the interim soil cover at the interface between the older unlined waste fills and the natural canyon slopes. Landfill slopes in the unlined cells are approximately 90 m high with an average slope angle of 2H:1V and locally as steep as 1.75H:1V. The cracks in this area were minor, typically being on the order of 2-3 cm wide. The landfill also suffered minor damage to the surface gas extraction system (broken gas header lines) which was quickly repaired.

Bradley Avenue Landfills

The Bradley Avenue East and Bradley Avenue West landfills are located in the Sun Valley district of the city of Los Angeles approximately 11 km from the zone of energy release. The Idriss (1991) rock attenuation relationship predicts a mean peak bedrock acceleration on the order of 0.36g at this site for a magnitude 6.7 event.

The Bradley Avenue landfills are located in an old sand and gravel pit. The slopes of the gravel pit are approximately 1.5H:1V, with slopes in some areas locally steeper. Bradley Avenue East is inactive and contains a sorting and recycling facility on top. This area of the landfill is unlined. A portion of the Bradley Avenue West landfill is at capacity, but the rest of this facility is currently accepting waste. The Western Extension (current active cell) was constructed with a geosynthetic liner system.

After the earthquake, cracks were observed at the contact between the natural side slopes and the waste fill along the eastern side of the Bradley Avenue East and West landfills. These cracks showed up to 25 cm of vertical offset. These cracks occurred along the waste/geomembrane liner interface and may have been the result of limited downslope movement along this interface. No tears were observed in the geomembrane liner at this landfill.

CONCLUSIONS

A number of solid waste landfills experienced some form of cracking in the soil covers as a result of the earthquake. This cracking may have resulted from one or more of the following: (a) brittle cracking of the stiffer soil veneer overlying the more ductile waste fill; (b) cracking resulting from the difference in relative stiffness between the softer waste fill and the stiffer adjacent natural ground; (c) seismically induced compaction (settlement) of the waste fill; (d) limited downslope movement; and (e) cracking caused by the build up of gas underneath the soil cover due to the rapid release of gas produced by the shaking and/or the temporary loss of the gas extraction system. Brittle cracking was observed at many of the surveyed landfills, especially at or near a free face or near changes in geometry, where there would be an accumulation of transient, seismically induced strains in the waste fill in these areas. For unlined landfills, it is difficult to differentiate cracking associated with ground shaking induced settlements and/or differences in relative stiffness between the solid waste and natural ground from cracking at the back of the waste fill due to limited downslope movement along a failure zone. Previous studies have suggested that seismic shaking does not induce significant settlement of solid waste (e.g. Coduto and Huitric, 1990). Finally, observations available to date indicate that it is unlikely that any of the observed cracks resulted from a build-up of landfill gas after the Northridge Earthquake. However, the temporary loss of a waste landfill's gas extraction system is an important consideration because of the potential for fire or explosion.

Overall the performance of landfills during the Northridge Earthquake was good. None of the surveyed landfills showed any signs of major damage (Damage Category V). However, one of the geosynthetic-lined landfills experienced significant damage (Damage Category IV), as a result of two tears observed in the geosynthetic liner system after the earthquake. Several unlined and lined landfills experienced moderate damage (Damage Category III), evidenced by cracking in the interim soil cover at waste/natural ground interfaces, cracking and limited downslope movement in cover soils, breaking of gas extraction header lines, and loss of power to the gas collection system. Typically, landfills of a distance greater than 40 km from the zone of energy release experienced little to no damage (Damage Category I).

ACKNOWLEDGEMENTS

Financial support was provided by the National Science Foundation under Grants CMS-9416261 and BCS-9157083 and by the David and Lucile Packard Foundation. This support is gratefully acknowledged. The authors would like to thank Robert Anderson, John Clinkenbeard and Darryl Petker of the California Integrated Waste Management Board, Pete Mundy of CDM Federal Programs and Charles Dowdell and John Hower of the Los Angeles County Sanitation Districts, all of whom visited several of the sites mentioned in this paper and generously provided their field reconnaissance data. Also, special thanks are extended to Rod Nelson of the California Regional Water Quality Control Board.

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