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SYNOPSIS: Many hillside fills located in the Santa Monica, Santa Susana, and San Gabriel Mountains were damaged during the 1994 Northridge Earthquake. While no deaths have been attributed to fill movement, on the order of tens of millions of dollars in property damage was caused by fill movements which typically involved less than about 7.5cm (3 inches) of localized displacement. Some of the damage was induced by permanent deformations of underlying native materials, but most appears to have resulted from ground failure or ground shaking phenomena associated directly with the fill materials. These phenomena include cyclic compaction, lurching, and amplification of shaking within the fills. This paper presents a preliminary summary of the typical distress to fills caused by the Northridge Earthquake, and discusses the probable mechanisms of failure.

INTRODUCTION

An important geotechnical aspect of the $M_W=6.7$ Northridge Earthquake was the performance of artificial fill materials. Thousands of structural fills have been constructed in mountainous areas in and around Los Angeles. These fills vary widely in size, age, and quality, though they can generally be classified geometrically as "wedge" fills (constructed on a slope face) or "canyon" fills (typically constructed by cutting off the top of a ridge and filling in an adjacent canyon). The primary focus of this paper is on the deformations of these earth structures during the Northridge Earthquake, and the associated damages to surface improvements (such as buildings, pavements, swimming pools, and buried utility pipes). Fill movements were noted in both modern and older construction, and were often observed in the absence of any apparent shear failure within the fills. Some of the damaged fills had been constructed as recently as one month prior to the earthquake, apparently in conformance with or exceeding current local standards and practices. Over 1000 residences and three schools appear to have been adversely affected by fill movements. In all, these failures are estimated to have resulted in tens of millions of dollars worth of damage.

Fill movements in relatively flat basin, valley, and coastal areas are not the focus of this study. Descriptions of liquefaction-induced fill failures in coastal moles and port facilities can be found in Stewart et al. (1994); several cases of significant fill movements along existing or former stream channel alignments are described in Stewart et al. (1995) and Barrows, et al. (1994). Also not emphasized here is the performance of earth or tailings dams, which are discussed in Stewart et al. (1994), Davis and Bardet (1995), and Harder and Stewart (1995).

CONSTRUCTION HISTORY AND STANDARDS

Hillside fills constructed prior to World War II were typically placed using Fresno scrapers or relatively light construction equipment, without keying and benching, as shown in Figure 1. Hillside residential development in these areas was relatively sparse and generally occurred on a lot by lot basis, hence the fills were limited in size, and varied considerably in quality. In the years since World War II, substantial residential development has occurred in the San Fernando Valley, Santa Clarita Valley, and in the Santa Monica, San Gabriel and Santa Susana Mountains. In the 1950s, fills were generally constructed using heavier grading equipment, and were more likely to involve mass grading over an entire tract. The most gently sloping sites were generally developed first, typically with small wedge fills having cut/fill transitions on each lot (Figure 2). Later development of steeper areas often consisted of cutting ridgetops and filling canyons, with the cut/fill transition areas extending across several lots, and with increasing fill depths.

Unusually heavy rainstorms in the Los Angeles area in 1952, 1956 and 1962 caused settlement and shallow surficial failures (shallow sliding and debris flows) in some fills, as well as relatively deep-seated sliding in the upper portions of

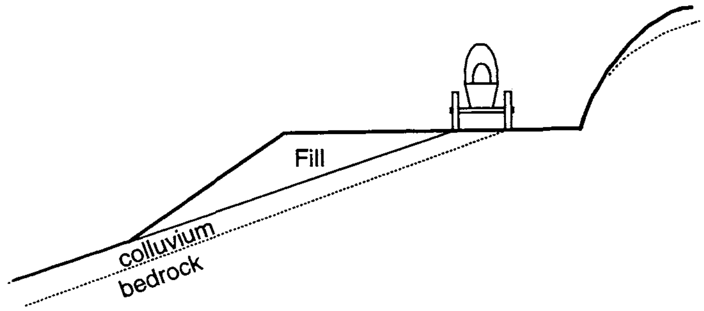


Fig. 1: Schematic of typical pre-World War II road fill geometry (after Rogers, 1988)

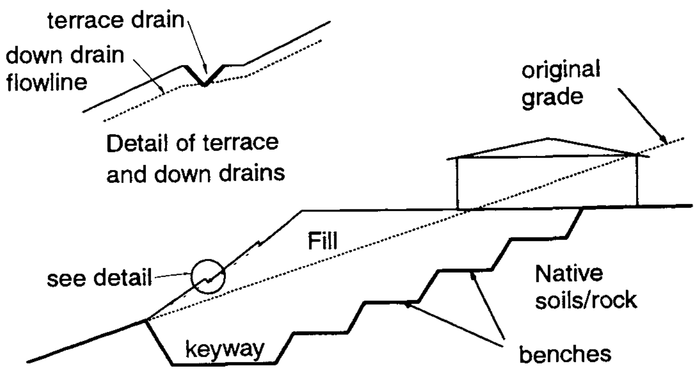


Fig. 2: Schematic of typical wedge fill geometry

underlying native soils and rock. This resulted in significant changes in the grading codes and standards of practice (Scullin, 1983), including requirements for geologic and geotechnical reports, inspections, subdrains, surface drains, clearing, grubbing and removal of organic surficial soils, and keying and benching of the fills into competent materials. The standards required the design of slopes to maintain static, surficial and dynamic slope stability. The standards also called for increased setback distances from the top of slope, construction observation by licensed professionals, and testing of the density and relative compaction of fills. These changes in grading standards were intended to provide not only for life safety, but to limit property damage as well. For example, the purpose of the Uniform Building Code earthwork provisions has, since at least 1952, been to "provide minimum standards to safeguard life or limb, health, property and public welfare by regulating and controlling the design, construction, quality of materials, use and occupancy, location and maintenance of all buildings and structures" (International Conference of Building Officials, 1994).

There were essentially no changes in residential grading practices after the 1971 San Fernando Earthquake, despite several cases of fill movement and consequent structural damage resulting from that event. The current minimum standard for residential compacted fills is that the soil be compacted to achieve densities of at least 90 percent of the maximum dry density achieved by ASTM D-1557-91 (a moisture-density relationship test). Specifications of higher relative compactions and specific ranges of as-compacted water contents (i.e. wet of the optimum water content) have been used for some recent, relatively deep fills, due in large part to concerns about long term settlement caused by consolidation or collapse due to wetting (Kropp et al., 1994).

OBSERVED DISTRESS

The locations of a number of damaged hillside fills are presented in Figure 3. The site locations shown in this figure were compiled from engineers, geologists, and public agencies involved in investigations of fill damage. It should be noted that Figure 3 represents only site location data collected to date, and that additional data may become available as a result of ongoing studies by the authors. In addition, some sites known to have had fill movement are not plotted in Figure 3 due to concerns about client confidentiality. Fill failures are also not shown for older roads where the fills had not been keyed, benched or compacted in accordance with modern practices. Further, fill movements were generally not reported at undeveloped sites, or where permits were not required for re-construction of damaged "minor" improvements (such as masonry fences or pavements).

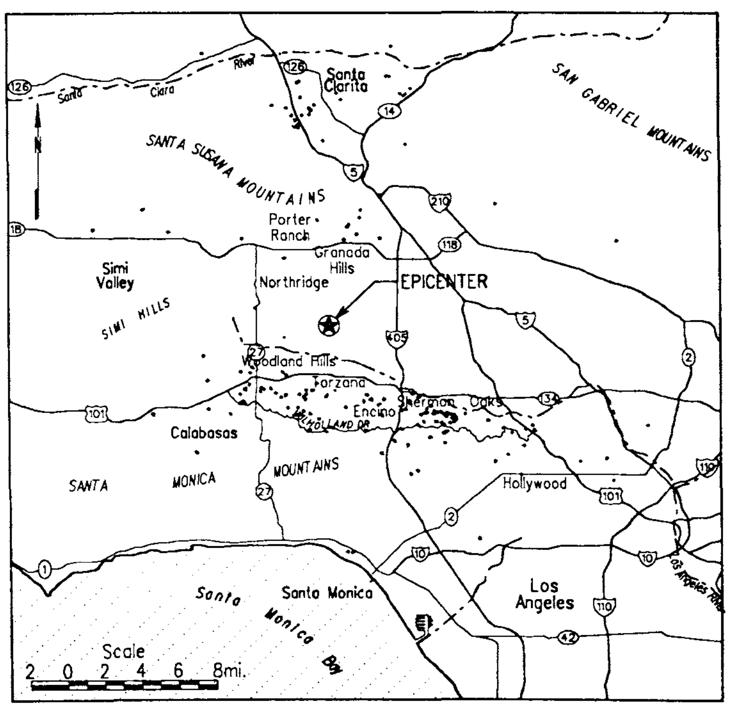


Figure 3: Locations of fills damaged by the Northridge Earthquake.

As can be seen from Figure 3, heavily damaged areas include the north flank of the Santa Monica Mountains, including the communities of Sherman Oaks, Tarzana, Encino, Woodland Hills, and Calabasas; the north rim of the San Fernando Valley including portions of Porter Ranch and Granada Hills; and several areas in the Santa Clarita Valley. Other areas where less intense damage has been reported include the north side of Simi Valley and the south flank of the Santa Monica Mountains, including Santa Monica, Beverly Hills, Hollywood, and downtown Los Angeles.

Many of the fills in the Sherman Oaks area were constructed between the 1940s and 1960s. Differential settlement and extensional cracking was observed across the surface of many of these fills, and many homes were heavily damaged in the area (as evidenced by concentrated distributions of red-tagged structures, Stewart et al., 1994). Further west in Tarzana, Encino, Woodland Hills, and Calabasas, the concentrations of red-tagged structures were considerably less acute, but many cases of fill movement were nonetheless reported. These fills vary significantly in age, with increasingly modern developments occurring to the west.

Pronounced structural damage and pipe breakage occurred on the north side of the San Fernando Valley in Granada Hills. While there are several documented cases of fill movement in the area, the majority of these damages have been attributed to strong levels of shaking and significant occurrences of ground failure (Stewart et al., 1994).

Further north in the Santa Clarita Valley, settlement and lateral movements of fills are known to have occurred in housing tracks east and west of Interstate Highway 5, in the Newhall area south of Lyons Avenue, in Canyon Country near the Santa Clara River, and between Sierra Highway and Highway 14. Most of these fills have been constructed since the 1960s.

The characteristics of the fill distress induced by the earthquake in each of these regions are fairly similar, and are illustrated in Figure 4. The distress features can be broken down into several categories, including cracks at the cut/fill contact, cracks in the fill pad parallel to the top of slope, deformations on the face of the slope, differential settlements in the fill, separations between foundations and adjacent soils, and cracks in cut areas. Typical observations of these distress modes follow:

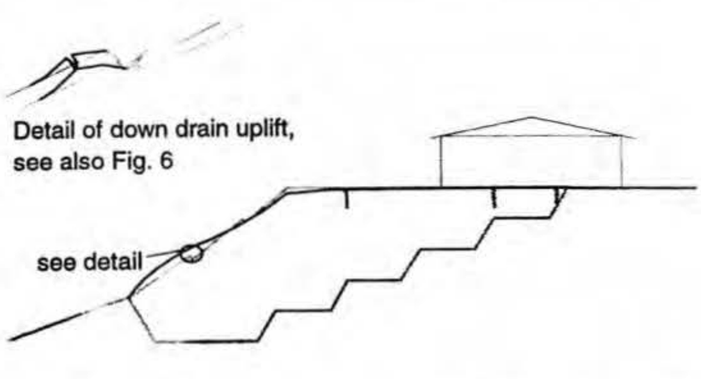


Fig. 4: Schematic showing typical damage to fill slope

Cracks at the cut/fill contacts: Ground cracks commonly occurred at the cut/fill contact, or above the closest bench to the cut/fill contact (Figure 5). These cracks were typically less than 7.5cm (3 inches) wide, and usually had less than 1.3cm (½ inch) of vertical movement, although there were

Figure 5: Typical crack at the cut/fill contact. The top of slope is visible on the right side of the photograph.

Figure 6: Typical down drain uplift, at one-third of the slope height up from the base of the fill (see also Figure 4).

cases where the differential movement across cracks was on the order of 2.5cm (1 inch). Even in these cases, differential vertical movement was normally less than the horizontal movement. Where there was differential vertical movement across the crack, the fill moved down relative to the cut, except in one unusual case, where the fill apparently moved up about 2.5cm (1 inch) relative to bedrock cut. Where investigated with trenches or down-hole logging in borings, these cracks became thinner with depth, and could only be traced to a depth of 1 to 2m (3 to 6 feet) below the surface. The cracks did not appear to be related to any detectable localized shear movement through or along the base of the fill. There was severe damage to buildings, pools, or pavements spanning across the cut/fill contacts.

Cracks in the fill pad, parallel to the top of slope: Ground cracks were also common along relatively linear patterns parallel to the top of slope, curving near the edge of the fill at the cut/fill contact. The distance of these cracks from the top of slope appeared to increase with increasing depth of fill. These cracks were typically less than 2.5cm (1 inch) wide, but were found up to 10cm (4 inches) wide in deeper fills. Where investigated with trenches or borings with down-hole logging, these cracks became thinner with depth, and could only be traced to a depth of 1 to 2m (3 to 6 feet) below the surface. Because of code requirements for house setbacks from the top of slope, these cracks did not normally directly damage houses, but they did affect other improvements such as masonry fences, pavements, and swimming pools.

Face of fill slope distress: Distress on fill slope faces was generally observed in terrace or down drains. The typical locations of terrace and down drains on the slope face are illustrated in Figure 2. Terrace drains generally had irregularly spaced cracks oriented perpendicular to the slope contours. Typical crack widths were 1.2mm (0.05 inches), widening to 2.5mm (0.1 inches) on the downslope side, with no vertical differential movement or shear across the crack (except at the sides of fills near the cut/fill contacts). In deeper fills, down drains, which collect water from terrace drains, were locally uplifted as much as 30cm (1 foot) relative to adjacent terraces (Figures 4 and 6). The uplift typically occurred at one-third of the slope height up from the base of the fill. Other than distressed terrace and down drains, fill slope face deformations were generally only observed as ground cracks along the sides of the fill, oriented in the downslope direction, parallel to the fill/native material contact. The observed movements in the terrace and down drains indicate bulging of the fill near the center of the fill (in plan), and bulging with possible shortening of the fill surface near the base of the slope (in profile), respectively. To date, consultant and agency investigations have focused on the flatter portions of fills that support structures, and few subsurface investigations have been performed on slope faces to investigate the causes of these bulging features.

Differential settlement in fill: Settlement within fill tended to increase with the depth of fill, resulting in differential settlements across the surface of the fill. The differential settlements were generally less than about 7.5cm (3 inches) across a typical house (10m wide) or less than 4cm (1½ inches) across a typical pool (5m wide), although larger differential settlements occurred across larger houses, or when the fills extended beneath several houses. It was common to see a slight increase in the fill surface gradient within 1 to 9m (3 to 30 feet) of the top of slope, as evidenced by cracks in masonry fences. This change in surface gradient sometimes correlated with ground cracks parallel to the top of slope. Recent practice is to provide a minimum surface slope of 2 percent towards positive drainage devices to maintain good drainage, although gradients of 1 percent or flatter are common in older developments. In some cases, particularly older developments, differential settlements were sufficiently large to reverse the flow of drainage, sometimes directing surface runoff into ground cracks.

Separations between foundations and the surrounding soil or pavements: It was common to observe separations between foundations and adjacent soils, walkways or driveways. Sometimes this type of cracking was observed on only two opposing sides of a structure, but often the separations extended around the entire structure. These separations were typically less than 2.5cm (1 inch) wide. Occasionally there was cracking or uplift of adjacent slabs, but more often than not, the distress was relatively minor. In some cases, these types of separations appear to have occurred in the absence of significant permanent fill movement.

Ground cracks in bedrock cut areas: Cracks in some cut areas beneath pre-existing ridges were up to about 7.5cm (3 inches) wide, and where investigated, became thinner with depth, typically becoming untraceable at depths of about 7.5 to 10.5m (25 to 35 feet). Evidence of shear movement was found across the lower portions of some cracks, while others were open across their entire length and showed no evidence of shear movement. Sometimes, the cracks had in-fillings of various ages. When located near the tops of ridges or former ridges, the sources of these cracks probably include induced tension due to stress relief (Rogers, 1982), which are sometimes related to ridge-spreading movements (Varnes et al, 1990), combined with previous earthquake shaking. In strongly shaken areas of high topographic relief, local site response effects appear to have combined with the pre-existing cracks to produce localized areas of intensely cracked and shattered ground, a phenomena known as "ridge shattering". Another source of ground cracking in bedrock occurred in one area west of Santa Clarita, and has been attributed to bedding plane slip associated with regional tectonic warping above the fault plane, and/or sudden shaking-induced rebound associated with previous overburden stress removal (Seward, 1994).

Ground cracking not only affected fills as discussed above, but also occurred in relatively dispersed patterns without consistent orientations. Such deformations were common in strongly shaken regions, and are generally attributed to surface waves or spatial incoherence of the ground motions.

POTENTIAL MECHANISMS

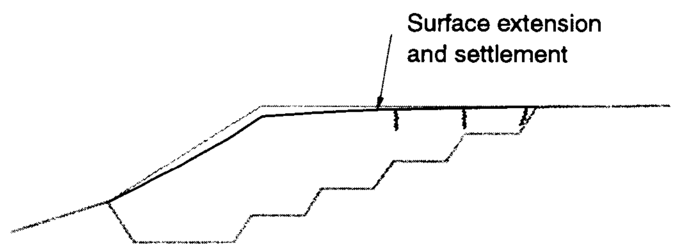
Several mechanisms are believed to have contributed to the observed permanent fill deformations in different areas, including:

1. Cyclic Compaction of Fill Soils: In unsaturated fills, particularly those comprised of cohesionless soils, strong shaking may have induced volumetric compression of the fill soils due to cyclic compaction. These deformations would occur in the direction of principal stress (slightly downslope from true vertical), which would tend to induce both settlement and downslope lateral movement of the fill materials (Rogers, 1992). These movements would cause differential settlement and minor extension of the fill surface (Figure 7a), as was observed in many cases. However, this mechanism does not explain the observed bulging of the fill slope face.

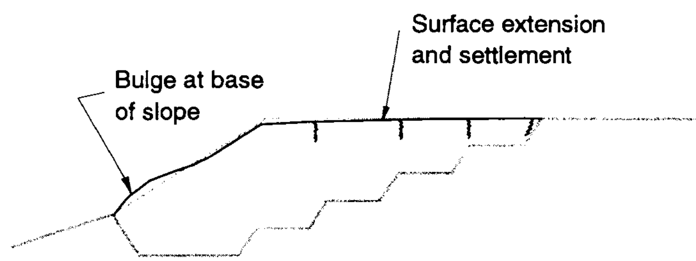
2. "Lurching" deformations of fill soils: Permanent shear deformations (without shear failure) are likely to have occurred over the depth of the fill sections in many of the fills investigated. These lurching effects would tend to induce deviatoric downslope "slumping" of the fills (Figure 7b), leading to crest settlements and associated toe/face bulging, as was commonly observed. However, this mechanism cannot explain shortening of the lower portions of the fill slope face.

3. Differential Dynamic Response: Differential ground shaking levels may have occurred between the cut and fill portions of the building pads (Figure 7c). The differential shaking intensities would have resulted from a combination of topographic/geometric amplification (Ashford and Sitar, 1994), and amplification of ground motions in the fills due to impedance contrasts between the fills and underlying stiffer native soils or rock. These amplification effects would tend to produce spatially incoherent ground motions between the fill and cut portions of building pads, with greater shaking intensities typically occurring in the fill. This spatial incoherence could potentially induce some minor lateral cracking of the fill surface, but does not explain differential settlement of the fill surface, or fill toe/face bulging or shortening.

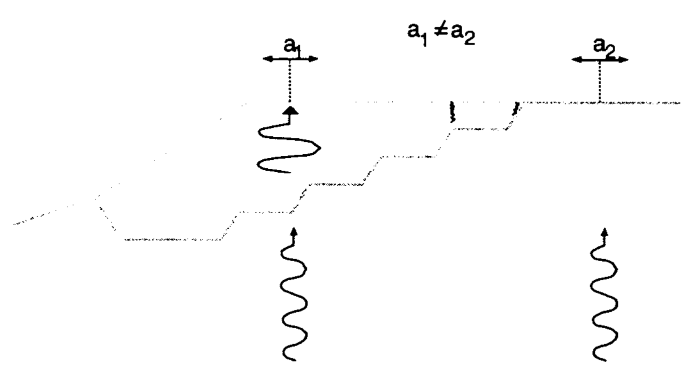
4. Underlying Ground Failure: Permanent deformations beneath the fill in native soils or rock may have resulted from (a) landslides, (b) liquefaction, partial liquefaction, or cyclic compaction, (c) flexural slip along bedrock bedding planes or other geologic features, or (d) ridge shattering. Landsliding on bedrock joints, fractures, or bedding planes was common in the Modello Formation, particularly in the Sherman Oaks area (Tan, 1994). In some cases, the earthquake re-activated older, previously unrecognized landslides buried beneath fills. In several cases,



(a) Cyclic compaction of fill



(b) "Lurching" due to permanent shear deformations in filll



(c) "Differential Dynamic Response", i.e. spatial incoherence due to ground motion amplification in fill

Fig. 7: Schematic illustrations of fill deformation mechanisms

surficial distress patterns were traced to underlying alluvium or colluvium which had been subject to liquefaction or cyclic compaction. Further, as noted previously, flexural slip on bedding planes may have contributed to bedrock deformations in cut in a portion of the Santa Clarita Valley west of Interstate Highway 5, and ridge shattering may have occurred in a number of areas.

5. Localized Sliding within Fill: Localized shear failures at the fill-native soil/rock contact or landsliding within the fill could explain some of the observed ground deformations, particularly bulging of the toe areas, cracking at the cut/fill transition, and settlement of the fill surface. However, trenching data from several sites suggests that significant slippage within the fill materials was unlikely. No cases of confirmed sliding along distinct shear planes within modern fills have been reported to date, although several old road fills may have been affected.

These mechanisms are not mutually exclusive; in many cases, several different mechanisms likely contributed to the observed distress features. Based on the typical distress patterns, it appears that essentially all of the fill movement sites suffered from a combination of the first three mechanisms listed above. In many cases, however, permanent deformations of underlying alluvium, colluvium, or bedrock appear to have significantly contributed to ground surface distress. It should also be noted that in many cases, the Northridge Earthquake appears to have exacerbated long-term static deformations resulting from slope creep, consolidation and/or collapse phenomena.

CONCLUSIONS

The Northridge Earthquake provides a unique opportunity to evaluate the seismic performance of fills constructed under various design and construction standards. In general, relatively modern fills constructed to higher standards performed better than older fills, though a particularly significant finding from this research is that even modern fills suffered movements on the order of 7.5cm (3 inches), which was sufficiently large to damage improvements such as buildings, pavements, and swimming pools. Much of the significant fill distortion and associated damage appears to be related directly to the performance of the fill soils via mechanisms such as cyclic compaction, lurching, and ground motion amplification within the fill. These mechanisms have not been widely recognized as potentially significant hazards for residential fills in this region. Hence, there are no widely recognized or utilized methodologies for predicting or mitigating against these types of movements.

The poor performance of many fills during the Northridge earthquake is of considerable importance to the geotechnical engineering profession. The standards of practice in the construction of these fills have evolved considerably since World War II to address long-term, static deformations resulting from landsliding, surficial failures, consolidation, and soil collapse. This evolutionary process has improved the static performance of fills, but the potential for poor dynamic performance has not been suitably addressed. Based on the performance of fills during the Northridge Earthquake, it appears that current standards of practice for the design and construction of fills satisfied life safety criteria, but were not always effective at limiting permanent deformations and controlling property damage. While permanent deformations of fills are unavoidable during earthquakes, further evolution of the standards of practice may help reduce these movements and/or provide appropriate criteria for the design of structures to better withstand fill movements.

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