Title

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FAILURE OF TAPO CANYON TAILINGS DAM

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ABSTRACT: The failure of the Tapo Canyon tailings dam was one of the most striking failures of an earth structure to result from the January 17, 1994 Northridge, California earthquake. The failure involved a 60-m-wide breach of a tailings dam with a maximum height of 24 m, and 60 and 90 m downstream displacements of two sections of the dam. The failure resulted from liquefaction of the impounded tailings and possibly of the embankment materials. A significant volume of liquefied tailings passed through the breach in flows which extended hundreds of meters downstream within a natural drainage channel. The tailings dam failure, which occurred in a largely undeveloped area, caused no deaths or injuries, but did result in considerable economic losses for the owners of the tailings dam and a downstream water-treatment facility affected by the tailings flow slide. In this paper the writers will outline the construction history and geologic conditions at the site, and describe the strong influence of these factors on the characteristics of the embankment failure.

INTRODUCTION

The only significant flow slide to occur as a result of the January 17, 1994 $M_w = 6.7$ Northridge, California Earthquake involved the failure of a 24-m-high tailings dam in Tapo Canyon, north of Simi Valley (Fig. 1). Reductions in soil strength and stiffness caused by liquefaction of the tailings and possibly portions of the dam caused large and relatively intact blocks of the dam to slide downstream over 60 m, which, in turn, allowed the impounded tailings to flow out through the breach and travel several hundred meters downstream. The tailings dam was located approximately 21 km from the Northridge epicenter and 16.5 km from the fault rupture plane estimated by Wald and Heaton (1994). The seismographs nearest the site were located at a clayey soil site in eastern Simi Valley (Knolls School) and a soil site in Potrero Canyon (Trifunac et al. 1994). Recorded seismograms from these sites showed multiple cycles of horizontal shaking having acceleration amplitudes of about $0.4g$ (Fugro, Inc. 1995). The Idriss (1991) attenuation relationship for rock sites, which captured the Northridge data reasonably well, estimates a maximum horizontal acceleration on rock of approximately $0.3g$ in this area.

A number of earth structures other than the Tapo Canyon Tailings Dam were affected by soil liquefaction during the Northridge Earthquake, including (1) a coastal mole, which underwent up to 5 m of lateral spreading at King Harbor in Redondo Beach (Stewart et al. 1994); (2) an embankment dike at the San Fernando Power Plant Tailrace in the Van Norman Complex, which was breached as a result of liquefaction-induced spreading of the abutment areas; and (3) numerous fills undermined by liquefaction-induced lateral spreading and settlement in Simi Valley, the San Fernando Valley, and Santa Clarita (Stewart et al., 1996). These earth structures were all significantly smaller than the Tapo Canyon Tailings Dam, and none experienced a flow slide failure. Hence, the failure of the Tapo Canyon Tailings Dam is one of the most significant failures of an earth structure to result from the Northridge Earthquake.

HISTORIC TAILINGS DAM FAILURES

Numerous historical failures or near failures of tailings dams have resulted from liquefaction of embankment materials and/or the impounded tailings. The 1978 Izu-Ohshima-Kinkai Earthquake in Japan triggered multiple breaches of the Mochikoshi tailings dam, resulting in significant environmental contamination (Ishihara 1984). One of the Mochikoshi dikes was breached immediately after the earthquake as a result of liquefaction of impounded tailings, while the other failed 24 h later due to gradual pore-pressure redistribution and associated strength loss in the embankment materials (induced by upward migration of the phreatic surface due to liquefaction of underlying sediments during the main shock). The 1928 Barahona tailings dam failure in Chile, which is reported to have resulted from liquefaction of the core materials and inward sliding of the embankment, released 4,000,000 t of material and killed 54 people (Agüero 1929). The 1965 Eli Cobre tailings dam failure in Chile also resulted in part from liquefaction, and allowed more than 2,000,000 t of tailings to flow into a downstream valley destroying part of a town and killing more than 200 people (Dobry and Alvarez 1967). Dobry and Alvarez also reported that nine other Chilean tailings dams experienced distress and/or failure during this same earthquake.

Recognizing the hazards represented by tailings dams in seismically active areas, Casagrande (1950) noted: "Chemical and mining wastes consisting of flour-sized material, are usually deposited hydraulically in very loose condition. Although they may appear stable behind some of the flimsiest dikes and in some cases supported only by a thin wall of the same material which has dried along the slopes, they are extremely sensitive to disturbance and constitute treacherous conditions which in some instances have caused disastrous flow slides with much loss of life and property."

CONSTRUCTION HISTORY

The Tapo Canyon tailings dam and pond are owned by the P. W. Gillibrand Company as part of a sand and gravel aggregate mining operation. The particular pond which failed, known as Pond No. 6, is one of several ponds on the property that have been used over several decades to settle waste from the aggregate mining operation. According to the owner, Pond No. 6 was located partially within a former hill, which had been excavated and mined out in the 1970s for aggregate prior to construction of the pond. The former hill occupying the pond site was composed of weak rock materials of the Pico and Monterey formations. These formations are Tertiary marine sandstones, conglomerates, and shales of Pliocene and late Miocene age. The mining operations apparently hollowed out

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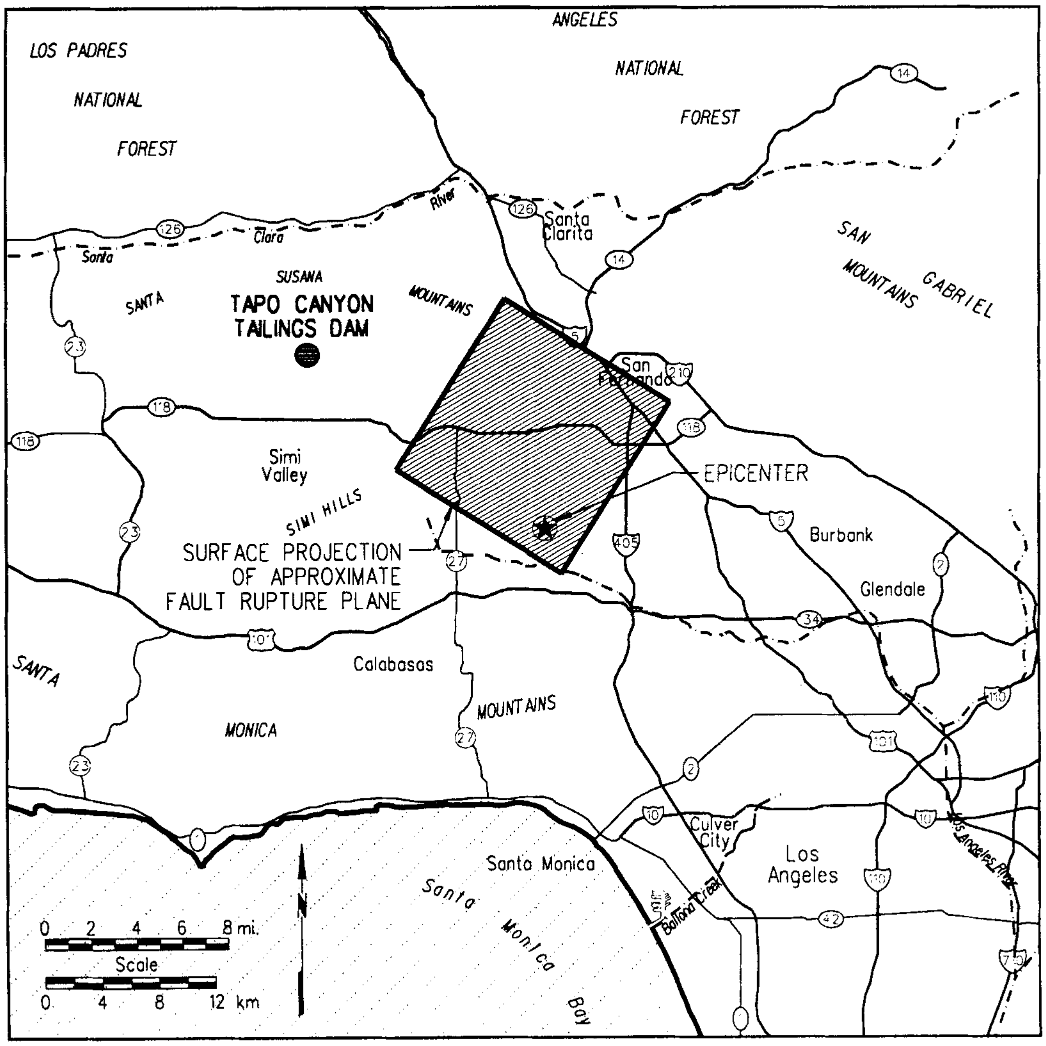


FIG. 1. Location of Tapo Canyon Tailings Dam Site

part of the hill, causing it to look very much like a natural bowl with natural rock ridges and piles of mine waste forming the enclosure. During later stages of the mining excavation, ground-water seepage into the pit was drained by excavating a gap in the rock ridge and mine waste piles, allowing ground water to run out by gravity flow to the adjoining creek.

According to the owner (Gillibrand, personal communication, 1994), much of the available aggregate within the pit was becoming exhausted by about 1980 and ground water was making further excavation difficult. Consequently, mining was stopped and the pit was converted for use as a settling pond. As with several other ponds on the property, Pond No. 6 was used to settle out fines washed out of the sand and gravel aggregate obtained during the mining process. The fines were conveyed in suspension by water flowing in trenches to the pond site. Within the pond, the fines would settle out and the water would be reclaimed for further use by means of pumps floating on rafts. Most of the fines and resulting tailings were apparently smaller than the No. 140 sieve size. However, examination of the tailings exposed near the surface of Pond No. 6 showed the presence of sandy soils as well. The tailings apparently consisted of stratified layers of soils ranging from fat clays with plasticity indices as high as 30–50 to nonplastic sandy silts and silty sands.

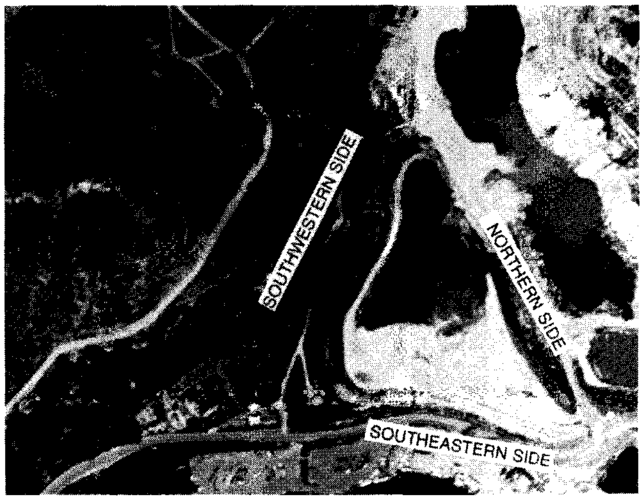


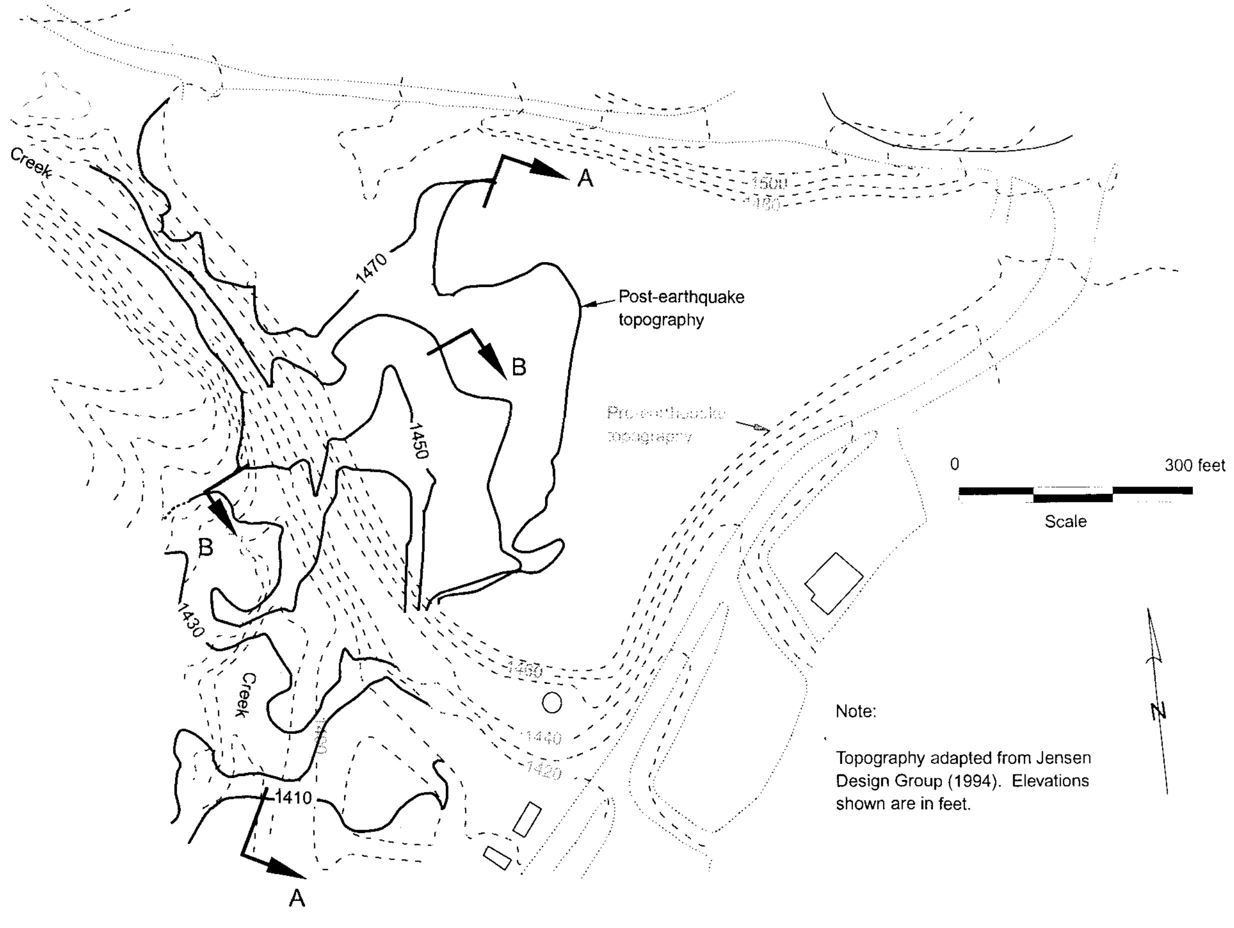
FIG. 2. Aerial Photograph of Pond No. 6 in Tapo Canyon before Northridge Earthquake (Photo by I.K. Curtis, Inc., April 1993)

The information currently available indicates that much of the retention for the early stages of the pond could have been provided by the natural sedimentary rock ridges remaining after excavation of the original hill. Rock ridges and cut slopes appear to have formed the early pond enclosure on the northern side, southeastern side, and southern corner of the pit. On the southwestern side, mine waste was apparently spoiled or piled in the dry to make wide embankments to form the early portion of the enclosure on this side of the pit. The only opening in this early enclosure would have been the gap excavated on the southwestern side to remove ground water during the mining phase. This gap would have required a retention embankment at the beginning of the ponding stages. As the pond filled up with tailings over the years, additional embankment stages were apparently added within the rock gap and, eventually, on top of the rock ridges and mine waste embankments in order to contain additional tailings. The owner indicated that the embankment stages may have been placed using the "upstream method," but that substantial material was added in each stage. The upstream method consists of constructing retention embankments in stages, with each stage being founded on top of the previous embankment stage and on portions of the retained tailings. Thus, the centerline of the retention embankment moves upstream as the height of the embankment increases.

FIG. 3. Aerial Photograph of Tapo Canyon Tailings Dam and Flow Slide on Day of Northridge Earthquake (Photo Courtesy of U.S. Air Force)

The tailings pond eventually took the shape of a triangle in plan view, with the northern side being approximately 300 m long and in an area entirely established by cut grading. The southwestern and southeastern sides are both about 270 m long with retention slopes approaching 24 m in height. In 1987, an approximately 180-m-long buttress was added to the outside slope of the southwestern retention embankment along the creek in order to provide additional stability. Unlike the other two sides, the southwestern side appears to be composed mainly of fill. According to the owner's engineer, the buttress was approximately 18 m wide and incorporated an internal drain to collect seepage. The drain consisted of a 150-mm perforated pipe placed within a gravel trench. The material used to construct the buttress appears to have been primarily a gravelly, silty sand. On the outside of the buttress, along the creek, riprap was added to provide slope protection. For portions of this reach, the creek channel had to be relocated outward (downstream) to provide space for the buttress.

The dam was eventually filled with sediment by about 1992, at which time ponding of the waste material was halted. Over the next two years, the eastern half of the pond was used by a nearby concrete batch plant as a spoil area for waste concrete. Concrete trucks would be driven onto the eastern pond surface and operators would wash out the waste concrete from their trucks, an operation which continued even after the Northridge Earthquake. This resulted in a discontinuous surface layer of waste concrete across the eastern half of the pond surface to a depth of about 1.2–1.8 m. The western half of the pond was apparently not used for this purpose, perhaps because water was sometimes still ponded on this half of the facility. The exact source of this ponded water is uncertain,



Note:

Topography adapted from Jensen Design Group (1994). Elevations shown are in feet.

FIG. 4. Topography of Tapo Canyon Pond No. 6 Prior to and Following Northridge Earthquake

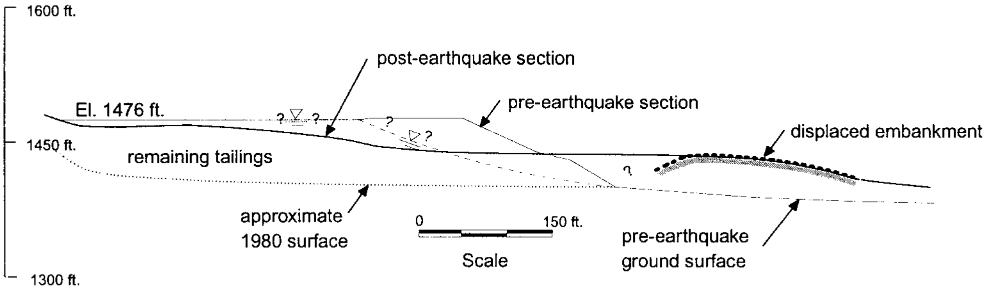


FIG. 5. Section A-A from Fig. 4 Showing Failed Tailings Dam and Resulting Flow Slide

FIG. 6. Edge of Lobe of Viscous Tailings Flow Near Creek, Photograph Taken 180 m Downstream of Failed Pond, Looking North

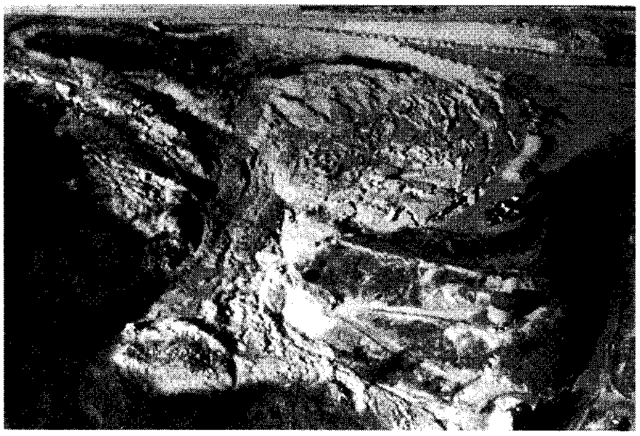


FIG. 7. Aerial View of Tailings Dam Failure (Photo Courtesy of Yoshi Moriwaki, Woodward-Clyde Consultants)

but it may have been due to leakage from conveyance ditches and ponds located immediately to the north. Fig. 2 is an aerial photograph of the completed pond taken in April 1993. This photograph clearly shows ponded water in the western half of the facility.

DESCRIPTION OF EMBANKMENT FAILURE AND FLOW SLIDE

The flow slide resulted from the failure of an approximately 60-m-long section of the tailings dam near the southwest portion of the pond, as shown in Fig. 3. At the breach location, the dam slid out and broke up into at least two pieces, which displaced approximately 60 and 90 m downstream from their original positions, respectively. The pre- and postearthquake topographies of Pond No. 6 are presented in Fig. 4. The postearthquake topography shows the subsidence of the pond surface caused by flow failure. The breach occurred in the same area where available information indicates that a gap was created in the natural rock ridge and mine waste embankments left from mining of the original hill. This is the location of the highest fill and is the only place where the pond was apparently being retained by the later-stage retention embankments alone. Fig. 5 presents a section through this portion of the facility showing the 1980 section and the pre- and postearthquake sections.

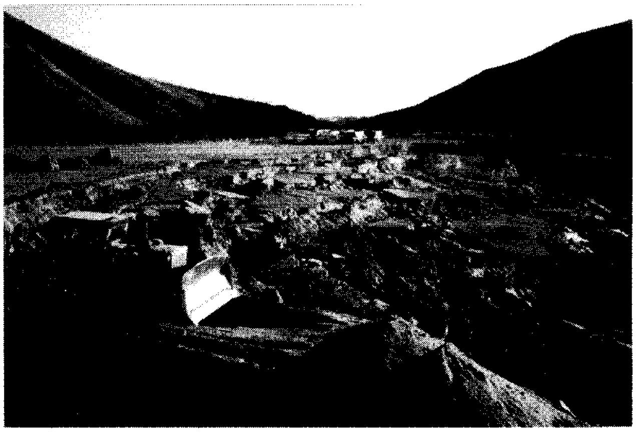


FIG. 8. Photograph of Displaced Concrete Blocks on Surface of Tailings (Note: Trucks in Background for Scale)

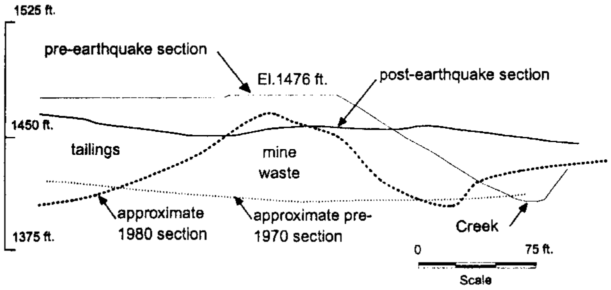


FIG. 9. Section B-B from Fig. 4, Showing Failed Embankment Section Northwest of Breach

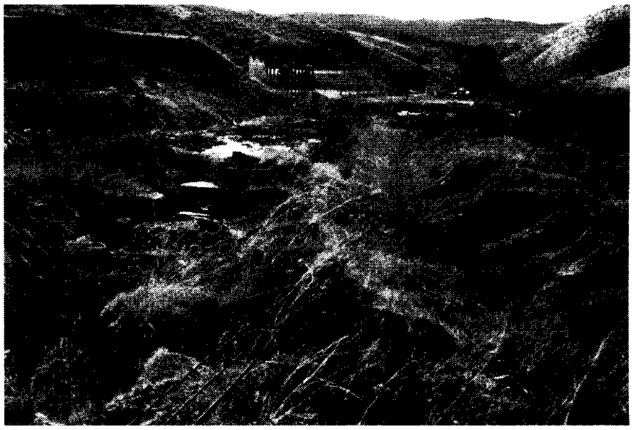


FIG. 10. View along Axis of Failed Southwest Embankment, Looking Southeast

FIG. 11. Pair of Concrete Blocks Which Traveled 26 m across Tailings Surface

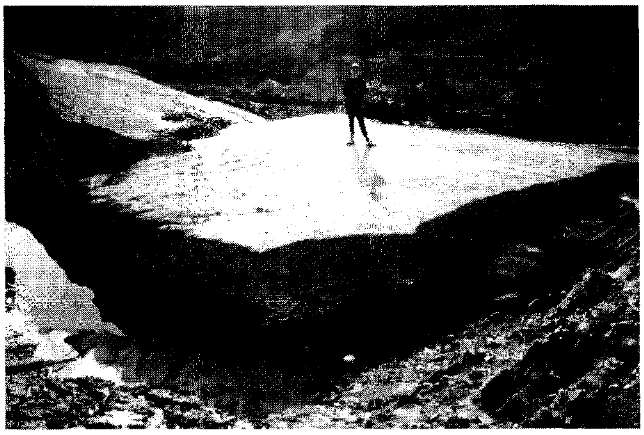


FIG. 12. Close-up Photograph of 200-t Concrete Block Which Traveled across Tailings Surface

Some of the retained tailings flowed out of the breach in a viscous flow which travelled over 180 m downstream, as shown in Fig. 6. Within the pond, the surface of the remaining tailings sloped down concentrically towards the breach in a manner similar to a viscous fluid passing through a funnel (Fig. 7). The surface layer of waste concrete on the eastern pond surface broke up into large blocks and spread apart, as shown in Figs. 7 and 8.

In addition to the main dam failure, the remaining portion of the southwestern dam was extensively damaged. Portions of the embankment on this side settled as much as 3 m and spread laterally in both the upstream and downstream directions, as shown in Figs. 9 and 10. The large displacements resulted in extensive cracking, with crack openings and vertical offsets exceeding 1 m at many locations. Portions of the buttress and riprap added in 1987 ended up on the opposite (western) side of the creek from where they had been constructed, temporarily damming the creek. The nature of the observed lateral spreading in this area (i.e., the lack of a complete flow failure; see Fig. 9) is probably due in part to the presence of the old mine waste piles and possible rock ridges beneath the dam. The embankment displacements in this area were also likely limited by the presence of the opposite (western) creek bank against which the debris came to rest.

The southeastern side of the dam did not appear to have been significantly damaged. This may be due to a lesser amount of saturation within the tailings on this side of the pond, or may be due to the fact that the rock ridge forming the base of the retaining embankment is higher on this side.

Downstream of the principal, relatively viscous flow slide, more "fluid" tailings were found to have splashed up across the creek and against the adjacent hillside. The splashed material appears to be composed predominantly of clayey soils. Further downstream, tailings entered the creek channel, filling much of the channel to unknown depths, and flowed hundreds to thousands of meters downstream. Trees were found in the channel surrounded by tailings with "splashes" running as much as 1 m up the upstream side of their trunks.

One of the more notable features of the flow slide was the fact that some of the blocks of concrete waste on the eastern surface of the pond underwent significant displacements on relatively mildly sloping tailings surfaces. These blocks, typically 1.2–1.8 m thick and weighing hundreds of tons, were found to have moved directly across the tailings surface as the surface sloped down toward the breach. Fig. 8 shows a portion of the broken concrete surface and the displacements between blocks. Track marks left in the surface of the tailings could be found behind the displaced blocks. Figs. 11 and 12 show a pair of blocks which slid over 26 m across the sloping tailings surface following the breach of the tailings dam. Each block is approximately 7.5 m across and weighs about 200 t. The surface across which the blocks travelled has a slope of approximately 12.5° from the horizontal. The blocks' lateral movements were apparently halted by either reaching the bottom of the slope, as in the case with the pair in Figs. 11 and 12, or by buildup of tailings material ahead of the block (note waves of pushed-up material in Fig. 8).

During an interview nine days after the earthquake, a neighbor indicated that rumbling/rushing noises were heard a few minutes after the main shock, and the neighbor believed that this was the beginning of the flow slide. The neighbor estimated that the elapsed time between the main shock and the rumbling noises was less than 10 min.

The failure and flow slide were caused by earthquake-induced liquefaction of the tailings, and perhaps, portions of the retaining embankments. Two sediment boils in tailings were found nine days after the earthquake, one near the northeast portion of the pond and the other near the western edge of the flow near a displaced embankment block at the creek. Both boils consisted of nonplastic silty sand, with the upper boil containing about 47% nonplastic fines and the lower boil containing about 16% nonplastic fines.

CONCLUSIONS

The breach of the Tapo Canyon tailings dam and resulting flow slide represent one of the most striking failures of an earth structure to result from the 1994 Northridge Earthquake. The lack of consequent deaths, serious injury, or significant collateral damage is a result of the very sparse development of the area along the creek within several miles downstream of the failed pond. Although the consequences of failure were relatively modest in this instance, the failure serves as a reminder of the potential hazards posed to earth structures by liquefiable soils.

The Tapo Canyon flow failure was probably a direct result of incorporating a significant amount of tailings slime within the southwest retention embankment in a modified form of the traditional upstream method of tailings dam construction. As demonstrated by this flow slide and other tailings dam failures, saturated tailings commonly have very low residual shear strengths and cannot be relied upon to contribute significantly to slope stability following strong earthquake shaking. Incorporating such material within major portions of the retention embankments or founding the embankments on such materials is unlikely to result in satisfactory postearthquake stability unless these very low residual shear strengths are incorporated into the design.

Liquefaction hazards to existing earth structures can normally be reduced by utilizing in-situ remedial techniques, though often at considerable cost. Most remediation techniques involve densification of relatively loose, cohesionless materials considered susceptible to liquefaction, and/or physical reinforcement or strengthening of the earth structure with berms or driven piles/piers. In the case of the Tapo Canyon tailings dam, the owner had spent a considerable sum in trying to reinforce the southwest embankment with a large berm. This berm was apparently only intended to improve static stability and to control seepage problems. The berm was unable to provide adequate postearthquake stability, presumably because of the very low postearthquake residual strengths of the embankment and tailings materials (an effect which was apparently not accounted for in the design). In the case of the Tapo Canyon tailings dam, proper compaction of the embankment materials as the retention embankments were being built would likely have prevented the failure.

A key element in the failure of the tailings dam was the fact that portions of the tailings and retention embankments were saturated at the time of the earthquake, even though the tailings pond had been filled and abandoned for tailings spoil two years earlier. The source of the saturation was presumably a combination of ground water, water remaining in the pore spaces of the tailings since the completion of filling, and continued ponding of water on the western half of the tailings fill. If this water could have been drained away so that the tailings were not saturated, then the risk of flow failure would have been substantially reduced.

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