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SYNOPSIS The January 17, 1994, Northridge Earthquake severely shook the Van Norman Complex, in the northern San Fernando Valley. Located in the near-field, over the vicinity of the ruptured fault, the Van Norman Complex was subjected to many types of ground movements, including strong ground motions, tectonic displacements, ground deformation of natural soil deposits, and deformation of embankments and other engineered fills. The complex provides a well documented case of how these various types of ground movements interact and their effects on engineered facilities. Throughout the complex, sand boils, liquefaction induced lateral spreading, and ground cracks were observed. Eleven water retaining embankments, including the Los Angeles Reservoir, underwent measurable movement. One small dike failed at the San Fernando Tailrace Channel at the northern end of the site. A great number of large diameter pipes and channels broke throughout the complex.

INTRODUCTION

The Van Norman Complex is owned and operated by the City of Los Angeles Department of Water and Power. As shown in Figure 1, it is located in the northern San Fernando Valley along Interstate 5 between the 405 and 210 interchanges approximately 11 km north of the January 17, 1994, Northridge Earthquake epicenter. As shown in Figure 2, the complex includes major water facilities which are critical to the Los Angeles Area, and controls 50 to 75 percent of the city's annual supply of water. The Northridge Earthquake caused damage to water and power facilities estimated to exceed $75M.

The Northridge Earthquake occurred at 4:31 AM (PST) on January 17, 1994, with a moment magnitude of 6.7 (USGS and SCEC, 1994). The main release of energy occurred on an unmapped blind thrust fault which dips to the south under the San Fernando Valley. The hypocenter was located at 34.211°N; 118.537° W at a depth of 18.5 km (Wald and Heaton, 1994). The duration of strong shaking was 6 to 10 seconds.

This paper summarizes the most significant geotechnical observations of ground movement in the Van Norman Complex after the Northridge Earthquake. Various types of ground movements were observed and documented throughout the complex including strong ground motion shaking, tectonic displacement, permanent ground deformation of natural soil deposits, and deformation of embankment fills. Evidence of the different types of ground movements can be found in the recorded seismographs, measurements of the many survey monuments on bedrock, native soils, and embankment fills; maps of ground cracking and sand boils, and by the location of the extensive pipe and channel breaks throughout the complex. More complete and comprehensive reports of observations, field measurements, and strong motion recordings are presented in Bardet and Davis (1995a and 1995b), Davis and Bardet (1994, 1995a, and 1995b), and Davis and Sakado (1994).

STRONG GROUND MOTION RECORDINGS

The Van Norman Complex yielded a large number of recordings in the close proximity of the ruptured fault adding a unique data set to the unprecedented number of near-source seismic recordings produced by the Northridge Earthquake. Figure 2 and Table 1 present the site locations and recorded peak ground accelerations of the dense array of seismic instruments on and around the Van Norman Complex. The instruments include eighteen

Figure 1. Los Angeles Area and location of the Van Norman Complex.

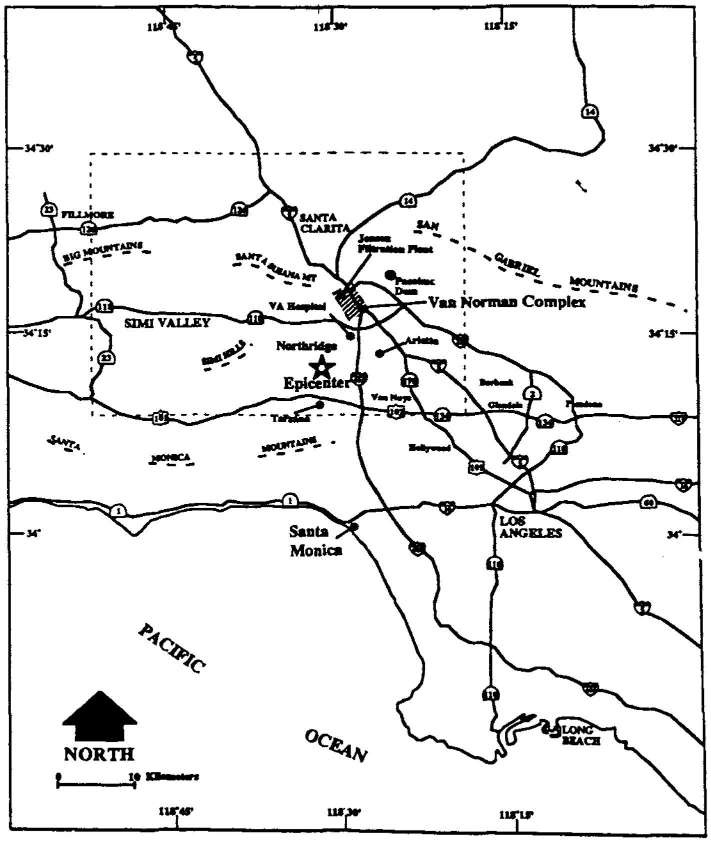


Figure 2. The Van Norman Complex showing location of the main facilities, embankment dams, strong motion recording stations, pipe and channel breaks, and areas of permanent ground deformation.

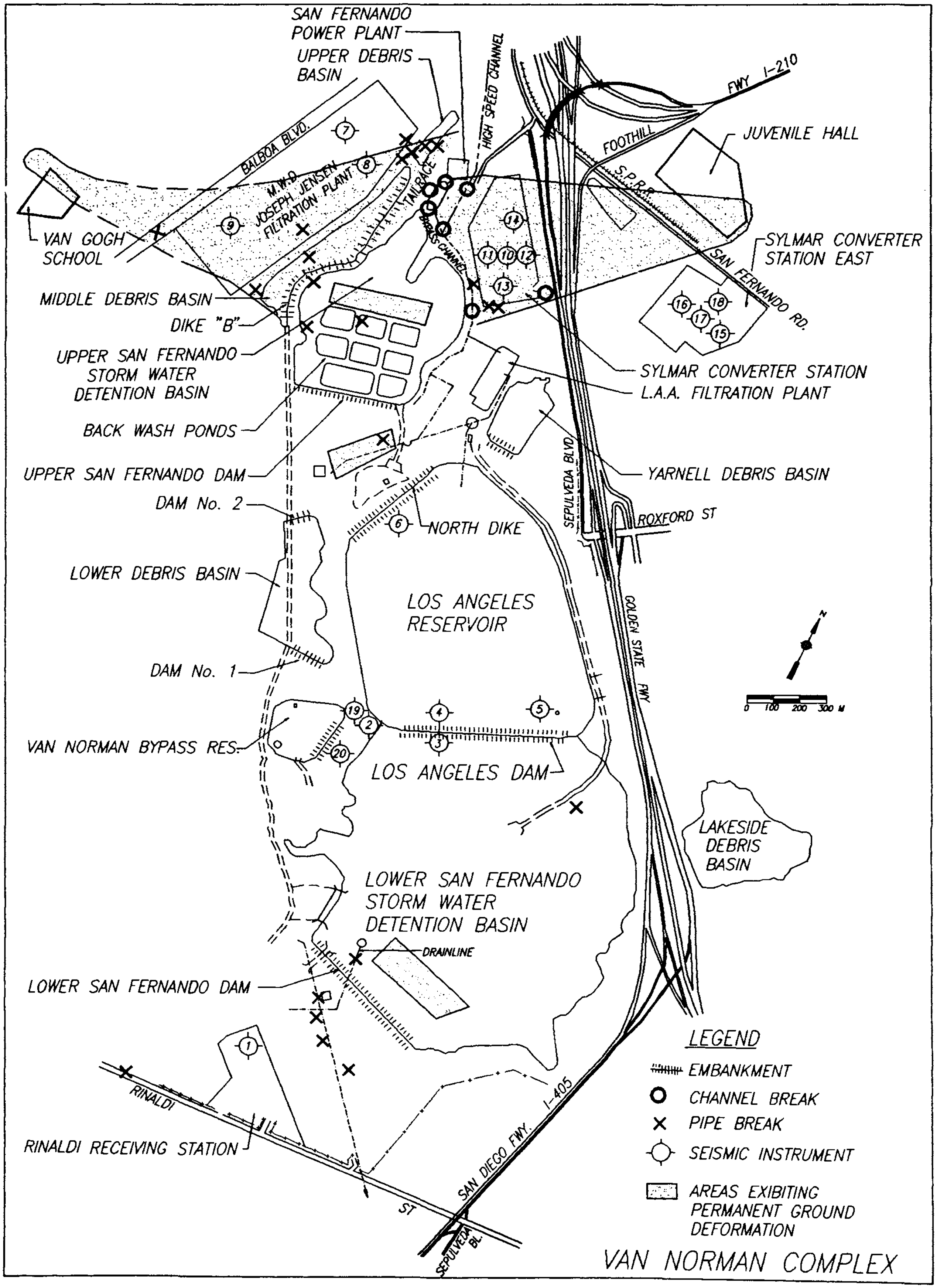


Table 1. Characteristics of strong ground motion recordings in the vicinity of the Van Norman Complex during the 1994 Northridge Earthquake.

Facility	Station number	Station Name	Owner	Geology/ Foundation	Coordinates		Epicentral Distance (km)	Peak Acceleration (g)		
					Latitude	Longitude		Horizontal 1	Vertical	Horizontal 2
	1	Rinaldi Receiving Station	DWP/ Power	Alluvium	34.281	118.478	10	0.84	0.85	0.48
Los Angeles Reservoir	2	L. A. Dam west abutment	DWP/ Water	Nonmarine dep	34.294	118.483	11	0.43	0.32	0.32
	3	L.A. Dam foundation	DWP/ Water	Nonmarine dep	34.295	118.479	11	0.32	0.13	0.28
	4	L.A. Dam crest	DWP/ Water	Dam Fill	34.294	118.481	11	0.56	0.39	0.43
	5	Outlet Tower	DWP/ Water	Conc.structure	34.296	118.478	11	1.34	0.29	1.18
	6	North Dike crest	DWP/ Water	Dam Fill	34.300	118.487	12	0.65	0.38	0.56
MWD Jensen Filtration Plant	7	Generator Building	MWD/ USGS	Nonmarine dep	34.313	118.498	12	0.98	0.52	0.56
	8	Administration Building	MWD/ USGS	Alluvium/Fill	34.312	118.496	12	0.62	0.40	0.40
	9	Reservoir Roof	MWD/ USGS	Conc.structure	34.309	118.499	12	0.84	0.51	0.65
Sylmar Converter Station	10	Valve Group 7 free-field	DWP/ Power	Alluvium	34.311	118.490	12.5	0.90	0.64	0.61
	11	Valve Group 7 ground floor	DWP/ Power	Alluvium	34.311	118.490	12.5	0.75	0.79	0.60
	12	Valve Group 7 roof	DWP/ Power	Steel Structure	34.311	118.490	12.5	1.12	—	—
	13	Valve Group 1-6 basement	DWP/ Power	Alluvium	34.311	118.490	12.5	0.58	0.53	0.37
	14	Sylmar Switching Station	DWP/ Power	Alluvium	34.313	118.491	12.5	DID NOT RECORD MAIN EVENT		
Sylmar Converter Station East	15	Free-Field	DWP/ Power	Nonmarine dep	34.312	118.481	13	0.83	0.38	0.49
	16	Valve Hall floor	DWP/ Power	Nonmarine dep	34.312	118.481	13	0.79	0.43	0.45
	17	Valve Hall roof	DWP/ Power	Steel/ masonry	34.312	118.481	13	1.13	1.30	1.15
	18	Control Room 2nd floor	DWP/ Power	Steel Structure	34.312	118.481	13	1.01	1.06	0.50
Bypass Reservoir (Seismoscopes)	19	Bypass Reservoir abutment	DWP/ Water	Nonmarine dep	34.294	118.483	11	>0.31	—	—
	20	Bypass Reservoir dam crest	DWP/ Water	Dam Fill	34.292	118.484	11	>0.31	—	—

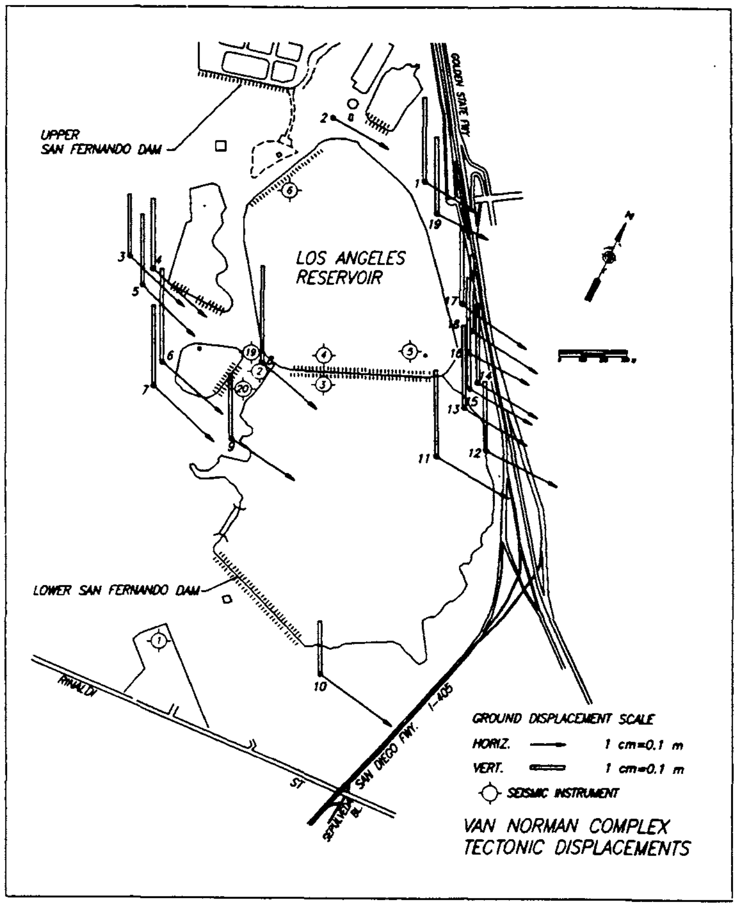
accelerograms (1-18) and two seismoscopes (19-20). The complex was dominated by large pulses ranging in period from 1 to 2.5 seconds. These long period pulses produced many of the peak ground accelerations presented in Table 1 and the largest velocity, 177 cm/sec (Bardet and Davis, 1995a), ever recorded from any earthquake (Wald and Heaton, 1994). Throughout the complex, the horizontal accelerations reached maximum peak values ranging from 0.56 to 0.98 g, except for at the complex center, at the Los Angeles Reservoir, where the maximum peak acceleration remained below 0.43 g, providing a remarkable example of how rapidly ground motion accelerations can vary over short distances. The vertical accelerations reached maximum peak values equaling and exceeding horizontal accelerations. Evaluation of the acceleration response spectra (Bardet and Davis, 1995a) reveals that shaking in the longitudinal and transverse directions were significantly different, regardless of soil conditions, indicating that the frequency content of the ground motion was directionally dependent. Time histories, acceleration response spectra, and detailed discussions of the strong ground motions recorded at the Van Norman Complex can be found in Bardet and Davis (1995a).

TECTONIC DISPLACEMENTS

During the Northridge earthquake, the fault movement did not create any surface rupture in the Van Norman Complex, but caused measurable permanent ground movements, referred to as tectonic displacement. Tectonic displacements result from a global uplift of the valley floor and mountains in the epicentral region. They are not to be confused with the permanent settlement and lateral displacement of superficial soil and alluvium layers which are induced by ground shaking. During the Northridge earthquake, the tectonic uplift exceeded 70 cm in the Santa Susana Mountains and was associated with a horizontal displacement of 21 cm (USGS and SCEC, 1994).

Figure 3 shows tectonic displacements at the Van Norman Complex measured by Global Positioning Systems at 19 monument stations in the vicinity of Los Angeles Reservoir. Most of these displacements were measured on bedrock stations relative to one absolute benchmark point within the complex, the displacement of which was determined by connecting the 1994 post-earthquake leveling networks of the City of Los Angeles and Caltrans. Figure 3 represents the horizontal movement by using vectors and the vertical uplift by using vertical bars. The vertical uplift on the Van Norman Complex ranges from 15 to 30 cm, while the horizontal movement in the southern direction varies from 0.3 to 7 cm and the horizontal movement in the eastern direction ranges from

Figure 3. Horizontal and vertical tectonic movement in the Van Norman Complex.



16 to 24 cm. The vertical uplift increases to the north and west. Movements in the southern direction increase to the west, whereas those in the eastern direction decrease to the north. The tectonic displacement was not consistent throughout the complex. At the Los Angeles Reservoir, the bedrock uplift was found to have a consistent slope with higher elevations to the west across most of he reservoir, and a rapid variation in uplift at the southeast corner (Davis and Bardet, 1995a). Compared to the Santa Susana Mountains, the Van Norman Complex underwent nearly half the vertical uplift, and slightly larger horizontal displacements. Further detail on tectonic displacements can be found in Bardet and Davis (1995a) and Davis and Bardet (1995a).

GROUND DEFORMATION

Figure 2 shows the location for the many cases of ground deformation and liquefaction induced lateral spreading on the Van Norman Complex. Lateral spreading, accompanied by sand boils, was observed below the Upper San Fernando Dam creating tension cracks on the east side of an asphalt road and a compression failure at the west end (Bardet and Davis, 1995b). Compacted fill at the north end of the backwash pond dikes spread northerly creating large scarps (Davis and Sakado, 1994).

As indicated in Figure 2, large zones of lateral spreads occurred on each side of the Upper San Fernando Detention Basin and tailrace channel. These spreads resemble descriptions of ground movements and alluvial slides described by Youd (1971, 1973) following the 1971 San Fernando Earthquake. The Juvenile Hall Slide (Youd, 1971, 1973), extending east, was reactivated causing damage to Interstate 5, San Fernando Road, the Sylmar Converter Station, large water distribution pipes, aqueduct and storm channels, and other important facilities. Much of the Juvenile Hall Slide ground deformation was similar to that reported following the 1971 San Fernando Earthquake, however, during the Northridge Earthquake, lateral spreading covered a wider area and moved less than what was documented in 1971. Surface ruptures on and around the Juvenile Hall Slide, in the area located in Figure 2, were not continuous and did not cause observable pavement failures on Sepulveda Boulevard, the north bound lanes of Interstate 5, or the northern end of the Sylmar Converter Station. Although smaller cracks and pavement fractures were found in Sepulveda Boulevard and the north end of the Converter Station.

On the west side of the Upper San Fernando Storm Water Detention Basin there was evidence of permanent ground deformation and lateral spreading extending west of Balboa Boulevard. This permanent ground deformation was not observed to be continuous throughout the area noted in Figure 2, but, nevertheless, caused damage to the San Fernando Power Plant and Tailrace Channel, pipes, slopes, Jensen Filtration Plant, and other facilities including the Van Gogh Street School west of Balboa Boulevard, all of which are located on the alluvial deposits from Bull Creek which flows easterly from the Santa Susana Mountains. Detailed descriptions of the damage caused to the San Fernando Power Plant and Tailrace Channel are provided by Davis and Bardet (1995a).

As shown in Figure 2, ground deformation resulting from liquefaction and lateral spreading occurred on the upstream berm of the Lower San Fernando Dam. Evidence of liquefaction was provided by the fifty large sand boils which erupted on the ground surface. The liquefaction was found to have occurred within the old hydraulic fill slide debris which was saturated and has remained in placed since the 1971 San Fernando Earthquake (Bardet and Davis, 1995b). The area of ground deformation was accompanied with large ground fissures and 100 m of laterally crushed corrugated metal pipe located along the western boundary of the ground movement. Detailed maps of ground cracking and sand boils are presented by Bardet and Davis (1995b) and a discussion of the crushed pipe is presented by Davis and Bardet (1995b).

Within the areas of documented permanent ground deformation and lateral spreading, shown in Figure 2, ground cracking was observed throughout the zones, and sand boils were observed around the tailrace channel, in the Middle Debris Basin located down slope from the Jensen Filtration Plant, on the backwash pond dikes (Davis and Sakado, 1994), around the Upper San Fernando Dam, and on the upstream berm of the Lower San Fernando Dam. Strong motion recordings were made on the non-linear alluvial response on each side of the complex during the Northridge Earthquake (Bardet and Davis, 1995a; Porcella, et al., 1994).

At the time of this writing, the available data is inconclusive in determining the magnitude of permanent ground deformation in the lateral spreading zones. This is a result of lack of monumentation in the spread zones, existing monuments which were not surveyed, unavailable survey data, and difficulty in interpreting the available data as a result of the tectonic uplift described above. Therefore, no numerical values are presently available to describe the amount of ground deformation. Further work will be performed in this area as more information becomes available. Preliminary evaluation of two survey level networks, having monuments located in the large spreading zones on the north end of the site, indicate the amount of settlement may be less than the amount of bedrock tectonic uplift under the sediments, as evidenced by a net uplift of the sediments. As a result of the tectonic uplift having the same order of magnitude as the permanent ground deformation, an understanding of the bedrock uplift under the deformed sediments must be achieved before an accurate interpretation of the actual ground deformation can be attained.

PIPES AND CHANNELS

Figure 2 shows a map of the Van Norman Complex indicating breaks on pipes and channels used for transporting water by the Los Angeles Department of Water and Power and the Metropolitan Water District. Pipe alignments are not shown for clarity. All of the pipe breaks shown in Figure 2 occurred on 61 cm diameter and larger pipes. For the purposes of this discussion a break is defined as a failure of the conduit or a water leak requiring repair. Approximately 30 breaks were experienced in the many pipes and channels throughout the complex. The majority of trunk line breaks from the Northridge Earthquake occurred on or within 2 km of the complex. Most pipe and channel ruptures north of the Upper San Fernando Dam correlate with the area of observed permanent ground deformation described above.

On the south end of the complex numerous breaks occurred within a concentrated area. However, there was not extensive ground failure observed in the associated region. Erosion from the large pipe breaks may have masked signs of permanent ground displacement. These breaks occurred near the Rinaldi Receiving Station which recorded large accelerations and the highest ground velocities ever noted in any earthquake (Bardet and Davis, 1995a; USGS and SCEC, 1994; Wald and Heaton, 1994).

Pipe and channel breaks provide a good indication of large ground movement. The breaks may result from permanent ground deformation, as observed on the north end of the complex, or from stress induced by strong ground motions. The breaks on the southern end of the complex may be a result of the latter, or a combination of the two effects.

EMBANKMENT DAMS AND COMPACTED FILLS

Table 2 lists 11 water retaining embankment dams located on the Van Norman Complex in Figure 2. The major earth embankment structures include the Upper and Lower San Fernando Dams, and the Los Angeles Dam and North Dike comprising the Los Angeles Reservoir. Descriptions of these structures including aspects of their performance during the Northridge Earthquake and detailed crack maps can be found in Bardet and Davis (1995b) and Davis and Bardet (1995a). Other structures include the Lower Van Norman Bypass Reservoir Dam used for water distribution, Dike "B" at the Middle Debris Basin, the Yarnell Debris Basin, and two embankments at the Lower Debris Basin used for storm water control, backwash pond dikes used for sedimenting filtration plant backwash water, and a dike on the Tailrace Channel used to divert aqueduct water flow. All of these embankments were constructed with compacted fill except for the Upper and Lower San Fernando Dams which were constructed mainly with hydraulic fill. At the time of the earthquake, the

Table 2. Van Norman Complex water retaining embankment characteristics and performance during the 1994 Northridge Earthquake.

Embankment	Crest width (m)	Fill height (m)	Slope		Year placed	Year altered	Fill method	Foundation	Purpose	Crest		
			up-stream	down-stream						Settlement (cm)		Movement* (cm)
										measured	corrected	
Lower San Fernando Dam	18.3	33.5	3:1	4.5:1	1913	1975	Hydraulic	Alluvium	Storm	-20.4	-21.3	-10.1
Upper San Fernando Dam	6.1	21.3	2.5:1	2.5:1	1921		Hydraulic	Alluvium	Storm	-42.7	-42.7	18.0
Los Angeles Reservoir												
Los Angeles Dam	9.1	47.2	3.5:1	3:1	1977		Compacted	Bedrock	Storage	-8.8	-7.6	3.0
North Dike	9.1	35.7	3:1	3:1	1977		Compacted	Bedrock	Storage	-3.0	-4.0	0.6
Bypass Reservoir Dam	9.1	30.5	2.5:1	3:1	1971		Compacted	Bedrock	Storage	-1.5	-1.5	-1.5
Lower Debris Basin												
Dam No. 1	6.1	15.2	2:1	2:1	1942		Compacted	Bedrock	Storm	-3.4		0.3
Dam No. 2	7.3	7.0	2:1	2:1	1973		Compacted	Bedrock	Storm	-5.5		-1.8
Middle Debris Basin Dike "B"	4.6	10.7	2:1	2:1	1941	1972	Compacted	Alluvium	Storm	Unknown		
Yarnell Debris Basin	6.1	10.7	2.5:1	2:1	1963		Compacted	Bedrock	Storm	0.9	-0.6	0.3
Tailrace Dike	10.7	6.1	3.5:1	3.5:1	1941	1994	Compacted	Alluvium	Channel	Breached		
Backwash Pond Dikes	6.1	7.5 +/-	2.5:1	2.5:1	1986		Compacted	Alluvium	Sediment	15 +/-		

* Positive (+) indicates downstream movement

storm basins contained little or no water while all other embankments were retaining water at normal operating levels.

Table 2 presents a summary of embankment characteristics along with their performance during the Northridge Earthquake. Maximum settlement values reported in Table 2 were measured relative to a single monument set in bedrock and obtained by comparing the available pre- and post earthquake data. Movement values were measured relative to two monuments set on opposite ends of the line being measured. From the available data, it can be seen that the newer constructed embankments performed better during the shaking. All of the embankments were able to maintain their operational functions during and after the shaking except the tailrace dike which breached soon after the earthquake (Davis and Bardet, 1995a).

Movement and settlement networks were established to measure deformation across embankment fills relative to the surrounding bedrock, but this does not account for tectonic displacement. The variation in tectonic displacement, described above, was found to have an effect on the measured embankment displacement values. On the Van Norman Complex, variation in tectonic horizontal movements across the site was not rapid enough to significantly effect measured embankment lateral movement values. Table 2 shows corrected settlement values which represent adjusted settlement accounting for variation of tectonic uplift, along the line of monuments where the settlement is measured, and provides a more accurate level of displacement. The variation in tectonic uplift across the length of the embankments were found to be of the same order of magnitude as the settlement on the newer structures. As a result, the correction for sloping and inconsistent tectonic uplift increased settlement in the newer compacted fill embankments by as much as 30%. The older Upper and Lower San Fernando hydraulic fill dams had corrections of the same order of magnitude as the newer embankments but were not influenced as significantly by the variation in tectonic uplift as a consequence of their larger settlement. The variation in bedrock uplift has greater influence on interpretation of embankment settlement as the distance from the origination monument (i.e. the monument for which all settlement is relative to) increases. A more detailed discussion on effects of near-field tectonic uplift on newer embankments structures is provided in Davis and Bardet (1995a).

Other facilities where compacted fill deformations were observed include the Sylmar Converter Station, Los Angeles Aqueduct Filtration Plant, and the Jensen Filtration Plant. Compacted fills at other important facilities on the Van Norman Complex, which have not been reported, performed well having insignificant movement. The fills at the Sylmar Converter Station facility interacted with the lateral spreading of the Juvenile Hall Slide, previously discussed. As a result of the interaction between tectonic uplift, lateral spreading, and fill deformation, the magnitude of fill deformation at the Sylmar Converter Station is unknown and unable to be reported at this time. Completed in 1987, the Los Angeles Aqueduct Filtration Plant had settlement in fill ranging from 2.5 to 30 cm. This variation in settlement occurred in compacted fills of the same construction having a depth of 5.2 m. The 30 cm settlement ruptured power conduits and temporarily disabled a portion of the plant. The Jensen Filtration Plant has been discussed by others (EERI, 1995) and will not be reported here.

CONCLUSION

The Van Norman Complex sustained substantial damage from the 1994 Northridge Earthquake. A major part of the damage was related to seismically generated ground movements. Sand boils, liquefaction induced lateral spreading, cracks and fissures were observed. The two hydraulic fill dams (Upper and Lower San Fernando) sustained substantial cracking along with settlement and lateral movement. One small dike failed on the San Fernando Tailrace Channel at the northern end of the complex. Eight rolled fill embankments, including the Los Angeles Reservoir, and other compacted fills sustained measurable movement. There were many pipe and channel breaks throughout the complex. Large and moderate levels of shaking were recorded within the site, with the Los Angeles Reservoir receiving a lower level of shaking than that at other nearby locations.

The coexistence of the many varieties of near-field ground movement which occurred on the Van Norman Complex during the Northridge Earthquake has important implications on evaluating the seismic response of engineered facilities. For example, the variation in ground motions, such as that between Rinaldi Receiving Station and Los Angeles Dam, requires caution when extrapolating levels of shaking to other nearby locations for evaluation of a site specific response, such as the collapsed Lower San Fernando drain line. The influence of tectonic displacement on long structures, including natural and artificial fills, affects the interpretation of permanent deformations. Compounding this effect are embankments, such as the Middle Debris Basin and tailrace dike, heavily shaken by strong ground motions and founded on alluvial deposits which underwent permanent deformations above tectonically displaced bedrock. Near-field seismic response at the Van Norman Complex has shown how interpretation of deformation in engineered fills can be influenced by seismically induced ground movements in the underlying geologic materials. For important structures, such as the Los Angeles Reservoir founded on bedrock, the components of movement in each of the respective materials need to be deciphered in order to obtain an accurate understanding of embankment deformation and the relative effects of stress induced by ground displacement and strong shaking.

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