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ABSTRACT

The 21 January 2003 M_w 7.6 Tecomán, Mexico Earthquake caused significant damage to the coastal region of the state of Colima, Mexico. This paper presents an overview of observations made by the United States National Science Foundation (NSF)-sponsored geotechnical engineering reconnaissance team, which visited the affected region one week following the earthquake. The team visited and documented sites including major cities, industrial facilities, and transportation routes. There were a number of important geotechnical engineering features of the earthquake. Liquefaction and consequent strength loss, ground settlement, and lateral spreading, alone or in combination, damaged the Port of Manzanillo, the capital city of Colima and other locations. The earthquake triggered thousands of landslides, the vast majority of which were disrupted landslides, specifically rock falls, rock slides, soil falls, and disrupted soil slides. Damage surveys by the reconnaissance team in the conjoined cities of Colima and Villa de Álvarez clearly indicated localized areas of high structural damage concentrations, suggesting that site effects may have contributed to overall damage.

INTRODUCTION

On Tuesday, 21 January 2003, at 8:06 PM local time, a strong earthquake shook the coastal region of the state of Colima, Mexico. The earthquake was strongly felt in the states of Colima, Jalisco and Michoacán. The effects of the earthquake were also felt in Mexico City, though no significant damage was reported there. Initial reports of the earthquake magnitude varied from M_w 7.4 (Harvard CMT) to M_w 7.8 (USGS). In February 2003, the United States Geologic Survey (USGS) issued a revised magnitude of M_w 7.6. The state civil protection agency reports that the earthquake killed 30 people and left over 500 injured. Approximately 15,000 structures were reported to have suffered some degree of earthquake-related damage.

This paper presents a brief overview of observations made by the United States National Science Foundation-sponsored geotechnical engineering reconnaissance team, which visited the affected region one week following the earthquake. The team visited and documented sites including major cities, industrial facilities, and transportation routes. The major cities visited included Colima, Manzanillo, and Tecomán, whose locations are shown in Figure 1. Visits were also made to several smaller municipalities including Coquimatlán, Villa de Álvarez, Ixtlahuacán and Armería. The reconnaissance team documented the seismic performance of two major industrial facilities, the Port of Manzanillo and the Manzanillo power plant. Transportation routes connecting the major cities of the region were also visited.

SEISMICITY

The reported magnitude of the 2003 Tecomán, Mexico earthquake varies from M_w 7.4 to M_w 7.6. The reported location of the hypocenter also varies depending on the reporting agency. Table 1 lists the source parameters of the event as reported by various agencies. Figure 1 is a plot of the location of the epicenters as reported by various agencies, along with the locations of aftershock epicenters reported by the SSN (National Seismological Service of Mexico). The fault plane, as defined by the location of aftershock epicenters, extends approximately 80 km along strike and 50 km along dip.

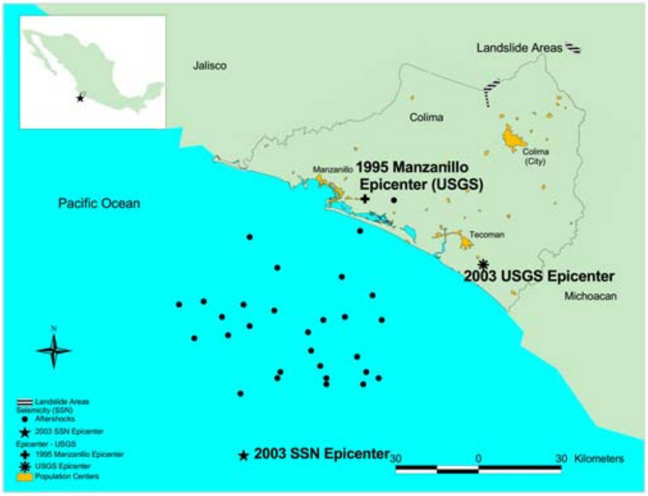

Fig. 1. Overview map of region. The epicenter location of main shock and aftershocks as reported by the USGS and SSN. Included also is the epicenter location of the M_w 8.0 1995 Manzanillo earthquake.

The 2003 Tecomán earthquake occurred near the juncture of three tectonic plates: the North American Plate to the northeast, the Rivera Plate to the northwest, and the Cocos Plate to the south. Both the Rivera Plate and the Cocos Plate are being subducted beneath the North American Plate. The slower-subducting Rivera Plate is moving northwest at about 20 mm per year relative to the North American Plate, and the faster Cocos plate is moving in a similar direction at a rate of about 45 mm per year. The 2003 earthquake is an interplate subduction event that occurred at the contact between the North American plate with either the subducting Cocos or Rivera plates. The event filled a seismic gap located between the rupture zones of the M_w 8.0 1995 Manzanillo earthquake and an M_w 7.6 earthquake in 1973.

Table 1. Seismological Data

Agency	M_w	***Hypocenter Coordinates***	***Hypocenter Depth***	***Strike/Dip /Slip (fault plane)***
USGS[1]	7.6	18.81N 103.89W	9 km	263º/10º/46º
Harvard [2]	7.4	18.77N 103.89W	32.6 km	305º/17º/103º
SSN[3]	7.6 [4]	18.60N 104.22W	10 km	
IISEE[5]	7.4	18.62N 104.12W	20 km	300º/20º/93º

(1) United States Geological Service. See http://neic.usgs.gov/neis/FM/neic_phac_q.html.
(2) Harvard CMT Catalog. See http://www.seismology.harvard.edu/.
(3) Servicio Sismológico Nacional (National Seismological Service of Mexico). See http://www.ssn.unam.mx.
(4) Energy Magnitude, M_E (See Singh and Pacheco 1994).
(5) International Institute of Seismology and Earthquake Engineering, Japan. See http://iisee.kenken.go.jp/special/20030122colima.htm.

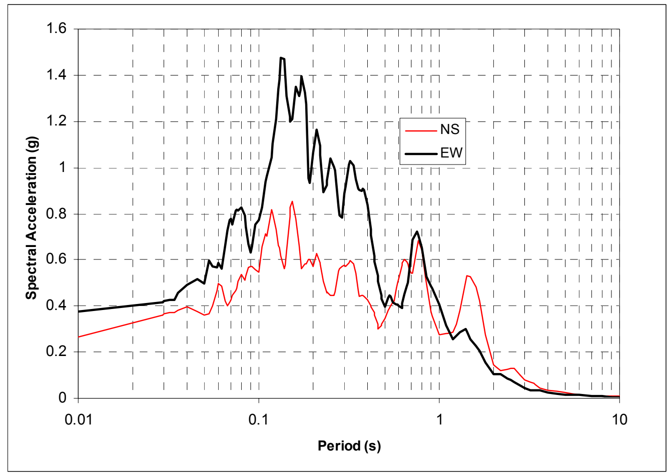

Fig. 2. Acceleration response spectra for horizontal components of ground motion recorded at the Manzanillo Power Plant (Damping = 5%).

GROUND MOTIONS

The Manzanillo power plant record is the only strong motion record of the earthquake that was obtained within 100 km from the rupture plane. In addition, various records at distances greater than 120 km were obtained from strong motion arrays in Guadalajara and Mexico City. The Manzanillo Power Plant record was obtained from the Federal Electricity Commission (Comisión Federal de Electricidad). The record registered maximum accelerations of 0.266g in the EW direction, 0.378g in the NS direction, and 0.192g in the vertical direction. The average significant duration ($D_{5\text{-}95}$) of the horizontal components of shaking was 18.1 s. The response spectra of both horizontal components of motion is shown in Figure 2. Based on the data presented in Table 1, it is estimated that the Manzanillo power plant is located close to 50 km from the epicenter. The lack of resolution on the depth of the rupture precludes an accurate estimation of distance to the fault. A possible range for this value is between 10 and 35 km. The station is located on 2 m of a fine, clean loose to medium sand, overlying at least 40 m of medium fine dense sand. Reported average shear wave velocity is 610 m/s (Tena Colunga 1997). It is not clear how this average shear wave velocity value is obtained. It is likely that near-surface values are much lower, thus the possibility for site effects must be considered.

SITE EFFECTS

Damage surveys in the conjoined cities of Colima and Villa de Álvarez clearly indicated locations of damage concentration. Damage surveys were carried out using PQuake software (Georgia Institute of Technology; dataforensics, L.L.C.) to document damage to manmade structures. PQuake directly integrates digital photography and handheld GPS technology to facilitate documenting, mapping, analyzing and visualizing damage data. The use of PQuake permitted a digital data set of the earthquake effects to be created in a timely manner. Damage surveys were performed either by assigning an average damage index (D0 = no damage, D5 = collapse) to a whole block (Block Survey) or by assigning damage indices to individual buildings. Figure 3 shows the results of the damage surveys, clearly indicating locations of damage concentration around the neighborhoods of San Isidro (Villa de Álvarez) and Lomas de Circunvalación (Colima). In addition, damage to adobe housing in downtown Colima was extensive.

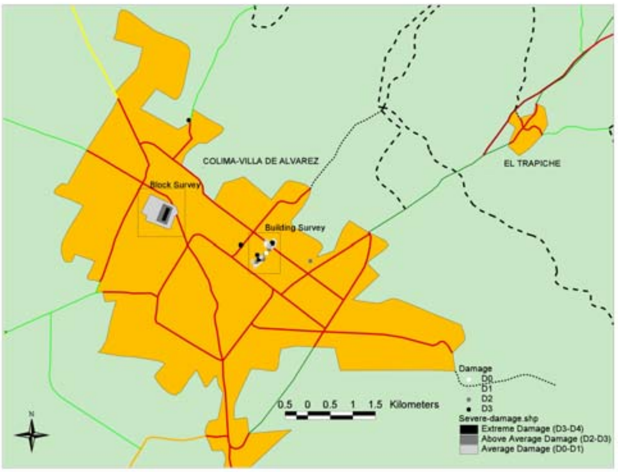

Fig. 3. Damage survey map of the city of Colima indicating areas of high damage concentration.

The San Isidro neighborhood is located near the *Arroyo de Pereira*, a small creek running north to south across Colima/Villa de Álvarez. Most of the damaged area overlies highly heterogeneous fill. Evidence of liquefaction was found in areas having high damage concentrations. Significant ground settlement was observed at various locations (Figure 4). Although construction quality in the San Isidro neighborhood is poor, other neighborhoods with similar construction did not suffer as much damage.

The Lomas de Circunvalación neighborhood is underlain by volcanic debris avalanche deposits that also underlie most of the north-central section of Colima. While this unit is highly heterogeneous, it is reportedly stiff and performs well as a foundation material. Intense damage in the Lomas de Circunvalación neighborhood is limited to a few city blocks. Construction patterns do not vary in this neighborhood, suggesting that localized damage is due to localized ground motion amplification.

Fig. 4. Ground settlement along at street in San Isidro.

SOIL LIQUEFACTION

Soil liquefaction caused damage in the coastal city of Manzanillo and the inland cities of neighboring Villa de Álvarez and Colima, located approximately 80 km from the coast. Liquefaction was also observed along a river valley south of Tecomán. Damage in various irrigation channels in the coastal area south and southeast of Tecomán was also attributed to liquefaction. In Manzanillo, home to one of the largest ports in Mexico, liquefaction was generally limited to waterfront sites, including several locations at the commercial shipping port, a public walk near the center of town, and a promenade located off a major boulevard. Liquefaction-related damage at the port occurred principally at undeveloped or non-critical areas, and it appeared that port operations were not significantly affected by liquefaction.

During the 1995 M_w 8.0 Manzanillo Earthquake, the Port of Manzanillo suffered considerable damage due to liquefaction. Since then, various ground-improvement techniques including stone columns and vibro-compaction have been used during repairs of new construction at the port to increase liquefaction resistance of the ground at critical locations. These ground improvement efforts were undertaken in response to the significant liquefaction that occurred at the port in the 1995 earthquake. It appeared that these improved sites generally performed well and no significant liquefaction-related ground deformation features were observed during the reconnaissance visit. Quantitative assessment of the performance of these improved areas will provide valuable information about performance of the ground improvement techniques used at the port. Other areas of the port where ground improvement had not been performed apparently suffered lateral spreading or seismic compression (i.e., earthquake-induced densification of unsaturated soil; see Figure 5).

Fig. 5. Strong shaking densified the unsaturated fill soils below the paving blocks (left), resulting in differential settlement of about 27 cm..

Observed ground distortions (ground cracking and lateral spreading) in a residential district located about 3 km northeast of Manzanillo's city center suggest that liquefaction may have also occurred in this neighborhood, though this was not confirmed. This portion of town was reportedly underlain by miscellaneous fill. A majority of the waterfront liquefaction sites in Manzanillo were marked by lateral spreading of the ground toward the free face. The horizontal displacements varied between sites, but were often in the range of 1-3 m. Figure 6 shows lateral spread of a pedestrian promenade located off an undamaged major boulevard. The promenade surface consisted of paving blocks, whose post-earthquake positions preserve deformation caused by lateral spreading. Investigation at the site indicated that a 0.2-0.5 m thick crust of silty sand moved over an unknown thickness of liquefied ground. The ground slope was about 3% and maximum lateral spread displacements at the site were on the order of 2 m.

In the city of Villa de Álvarez, just northwest of Colima, liquefaction and resulting lateral spread and shallow foundation failures damaged a number of residences in the San Isidro neighborhood. Portions of this neighborhood were reportedly built on reclaimed land adjacent to a small creek. Shallow subsurface materials at the site consisted of uncompacted or poorly compacted, miscellaneous fill. Local residents reported that immediately after the earthquake, muddy water was ejected from cracks in pavement surfaces and concrete floor slabs. In one structure in the neighborhood, a shallow foundation-supported concrete column experienced a liquefaction-related loss of bearing capacity and dropped about 30 cm, causing significant structural damage to the building. Liquefaction and consequent loss of strength, ground settlement, and lateral spreading are suspected causes of other damage to the neighborhood, including uplifted, sunken, or cracked concrete floor slabs; cracked and distorted pavements and sidewalks (Figure 7); and laterally displaced residential structures (Figure 8).

Fig. 6. Lateral spread at a promenade in Manzanillo.

Fig. 7. Damaged street and sidewalk in the City of Colima.

Fig. 8. Lateral spread caused this house to displace about 20 cm in the down slope direction.

LANDSLIDES

It is estimated that the earthquake triggered thousands of landslides in the region. As classified according to the system of Keefer (1984), the vast majority of these landslides were disrupted landslides, specifically rock falls, rock slides, soil falls, and disrupted soil slides. Several liquefaction-induced soil lateral spreads were also observed, as was a single embankment failure that has been classified as a coherent slide.

Especially high landslide concentrations were noted in two areas. The first area is located along the steep walls of the Armería River canyon and along its tributary, the Remate River, north of Colima in the vicinity of the town of Zacualpán. Along each river, a stretch of 6 to 8 km was subjected to such intense landsliding that material was removed from stretches of slope hundreds of meters to more than a kilometer long in each of several localities (Figure 9). Most or all of these areas were on the outside of meander bends. The vegetated cliffs where the landslide occurred were typically 150-200 m high and had slope inclinations estimated as ranging from about 70º to vertical. They were composed of very well graded volcanic debris-avalanche material reworked by fluvial action and interbedded with fluvial deposits. These materials had little or no matrix cementation. When this area was inspected on the ground about 10 days after the earthquake, the cliffs were so unstable that together they were still producing several falls each minute (Figure 10). These falls were typically small, ranging from a few cubic meters to perhaps 50 m^3 of material each. The continuing instability of these cliffs, exacerbated by the ongoing removal of material by falls, indicates a possible continuing hazard to villages, dwellings, and other infrastructure in the areas located close to the cliffs.

Fig. 9. . Stretch of cliff along Rio Armería northwest of Colima denuded by landslides during the earthquake.

The other area of high landslide concentration was along a 6-km stretch of the Barranca de Atenquique watershed, a deep, steep-sided canyon cut into the eastern flank of Nevado de Colima, an inactive volcano. At this location, numerous rock falls, soil falls, rock slides, and debris slides occurred in volcanic materials exposed on canyon walls, typically consisting of an upper fine-grained pyroclastic deposit, a middle unit consisting of well-indurated lava, and a lower unit consisting of a pyroclastic block-and-ash flow deposit (Figure 11). Volumes of the individual landslides typically ranged from a few cubic meters to a few hundreds of cubic meters each, and the highest landslide concentrations ranged up to about 40 landslides per linear kilometer of canyon wall. Slopes were near vertical and ranged up to about 500 m high.

Fig. 10. .One of the larger falls observed from the Rio Armería cliffs on the afternoon of January 28, 2003. A plume of dust accompanied the fall, which had an estimated volume of 20 m^3.

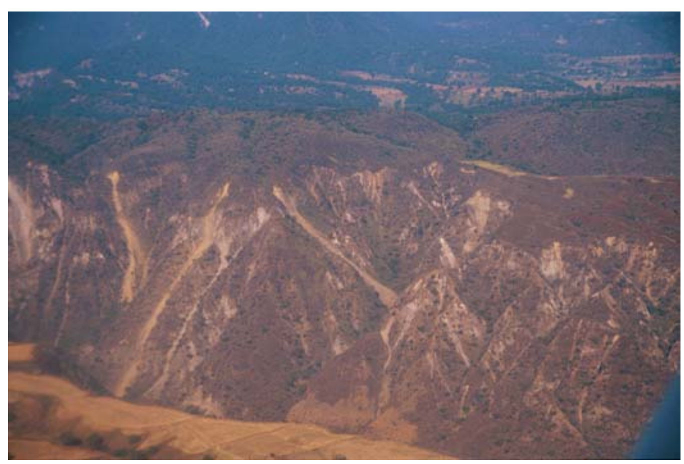

Fig. 11. Landslides along one stretch of canyon wall in the Barranca de Atenquique, on the east flank of Nevado de Colima volcano.

Three smaller areas with moderate landslide concentrations were also observed. Two of these, on the south flank of Volcán de Fuego and along several smaller canyons south of the Barranca de Atenquique, evidently involved similar materials to those along the Barranca de Atenquique. The third area, along the lower valley of the Armería River near the coast, produced a moderate number of landslides along highway and railroad cuts as well as along the bedrock valley walls. Outside of the areas discussed above, a large majority of the disrupted landslides that occurred were along artificial cuts. Fewer than 20 landslides from natural, unaltered slopes were observed outside those areas during either aerial or ground-based reconnaissance. The largest cut-slopes failures were along the Colima to Minatitlán road, between the Armería River and the village of Platanarillos. Cut-slope failures had reportedly blocked the main highway from Colima to Manzanillo and the road from Colima to Minatitlán, but these blockages had been removed by the time these areas were observed during the reconnaissance.

CONCLUSIONS

The 2003 Tecomán earthquake provides the geotechnical earthquake engineering profession with an important database of case histories of site response, ground failure, and performance of improved ground. In addition, the ground motion recorded at the Manzanillo power plant is one of only a few strong ground motion recordings of subduction earthquakes at a close distance from the causative fault. Ground failure, including landslides and liquefaction-related ground deformations, was a significant feature of the earthquake. These failures damaged structures and closed roads and impeded traffic flow after the earthquake. Geotechnical Engineering researchers from Mexico and the U.S. continue to study these failures with the hope of improving their understanding of the mechanisms controlling ground failure.

ACKNOWLEDGEMENTS

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