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Liquefaction during the 1977 San Juan Province, Argentina earthquake ($M_s = 7.4$)

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Abstract

Liquefaction effects generated by the 1977 San Juan Province, Argentina, earthquake ($M_s = 7.4$) are described. The larger and more abundant effects were concentrated in the 60-km long band of the lowlands in the Valle del Bermejo and in an equally long band along the Rio San Juan in the Valle de Tulum. Fissures in the Valle del Bermejo were up to several hundred meters long and up to several meters wide. Sand deposits, from boils that erupted through the fissures, covered areas up to tens of square meters. Fissures generally parallelled nearby stream channels. Because the Valle del Bermejo is undeveloped, these large features caused no damage. Liquefaction in the Valle del Tulum caused important or unusual damage at several localities, including the following five sites: (1) At the Barrio Justo P. Castro, a subdivision of Caucete, liquefaction of subsurface sediments decoupled overlying, unliquefied stiff sediments, producing a form of ground failure called "ground oscillation". The associated differential ground movements pulled apart houses and pavements in extension, while shearing curbs and buckling canal linings in compression at the same locality. (2) At the Escuela Normal, in Caucete, the roof of a 30-m long single-story classroom building shifted westward relative to the foundation. That displacement fractured and tilted columns supporting the roof. The foundation was fractured at several places, leaving open cracks, as wide as 15 mm. The cumulative width of the open cracks was 48 mm, an amount roughly equivalent to the 63 mm of offset between the roof and foundation at the east end of the building. The ground and foundation beneath the building extended (or spread) laterally opening cracks and lengthening the foundation while the roof remained in place. (3) The most spectacular damage to structures at the community of San Martin was the tilting of a 6-m high water tower and the toppling of a nearby pump house into a 1-m deep crater. Similarly, a small crater developed beneath a hand-pump in an open area and a large, 6-m diameter crater formed nearby. The following sequence of events created the craters and toppled the pump structures: During the earthquake, ground shaking generated excess pore pressures which were dissipated by upward flow of groundwater. Free drainage was restricted by an impermeable plastic-silt layer. Water apparently accumulated below the plastic-silt layer and then burst to the surface through several holes and cracks, including holes around well casings. (4) At the San Isidro winery, nine storage tanks tilted 2 to 5°. Five reinforced-concrete tanks were dismantled but four steel tanks were repaired by placing new footings and jacking the structures into an upright position. (5) At Escuela J.J. Pasos, differential settlement beneath buildings fractured several columns and walls. The largest settlements were about 60 mm and the maximum settlement of footings supporting columns was about 40 mm. In spite of the damage, the buildings were in no danger of collapse.

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1. Introduction

At 6:36 a.m. (local time), 23 November 1977, a major earthquake ($M_s = 7.4$) struck San Juan Province, Argentina, killing about 70 people, collapsing or severely damaging several hundred buildings, primarily adobe, and liquefying sediments in a widespread area. Kadinsky-Cade et al. (1985) report the following information concerning the earthquake. The earthquake was composed of a foreshock and a larger shock, both occurring at depths of 17 km. The epicenters for these two events are plotted on Fig. 1. The larger shock occurred 21 seconds after the foreshock and 65 km to the south, indicating a southward propagation of the fault rupture. The earthquake was generated by reverse slip (up to 4 m) on a buried westward dipping reverse fault. Although surface faulting has not been detected, the extent of the source zone could be rather well defined by the aftershock epicenters. That zone extends from a few kilometers north of the foreshock epicenter to a few kilometers south of the larger shock epicenter. The width of the zone is about 40 km, centered along a line connecting the two main epicenters. This zone lies in a remote unpopulated region 60 km east of the provincial capital of San Juan (Fig. 1).

Liquefaction was widely distributed and caused some of the more striking and damaging effects of the earthquake. Those effects included fissures, as much as several hundred meters long and several meters wide, accompanied by sand boils that vented water and sediment covering areas up to tens of square meters in extent. In developed areas, fissures and ground displacements disrupted fields, roadways, canals, pipelines, buildings, tanks and other constructed works. This investigation documents occurrences of liquefaction and examines some of the more spectacular and unusual effects.

Our investigation consisted of two parts. First, we conducted a reconnaissance study in which we located and described liquefaction effects, mapped their general distribution and documented the damage caused. Second, we conducted detailed site studies at five localities where liquefaction effects were either unusually spectacular or damaged important works. All these studies were conducted during January 1978, six weeks after the earthquake.

2. Regional setting and distribution of liquefaction effects

San Juan and Mendoza Provinces lie in western Argentina, adjacent to the Chilean border (Fig. 1). The western parts of these provinces lie in the Andean Cordillera and the eastern parts (where the 1977 earthquake and ensuing liquefaction occurred) lie in the Andean foothills. The foothill region is characterized by basin and range topography and active tectonism. The areas affected by liquefaction lie in two parallel north–south trending valleys, the Valle del Bermejo east of the large insular mountain range named Sierra Pie de Palo, and the Valle de Tulum west of that range. Most of the epicentral region, including the Valle del Bermejo, is undeveloped, unpopulated and unaccessible for land-based vehicles. Only the Valle del Tulum, which has been developed for agriculture and associated industries and which contains the provincial capital of San Juan, was accessible for a ground reconnaissance.

3. Valle del Bermejo

3.1. *Geologic and hydrologic setting*

The Valle del Bermejo is a broad, flat, fault-bounded structure that is traversed by two main rivers or the Rio Jachal in the north and the Rio Bermejo in the south (Fig. 1). The Rio Jachal, which originates in the Andes, carries substantial flows of water and sediment into the valley during the wet seasons. When the river enters the northwestern margin of the valley northwest of Mogna, the gradient decreases from a rather steep descent in the mountains to the almost flat surface of the valley floor. This sudden change of gradient causes rapid deposition of sediment which, in turn, is redistributed across the valley floor through a broad system of distributary channels and playas. Nearly all of the riverine water infiltrates into the valley floor through the distributary channel

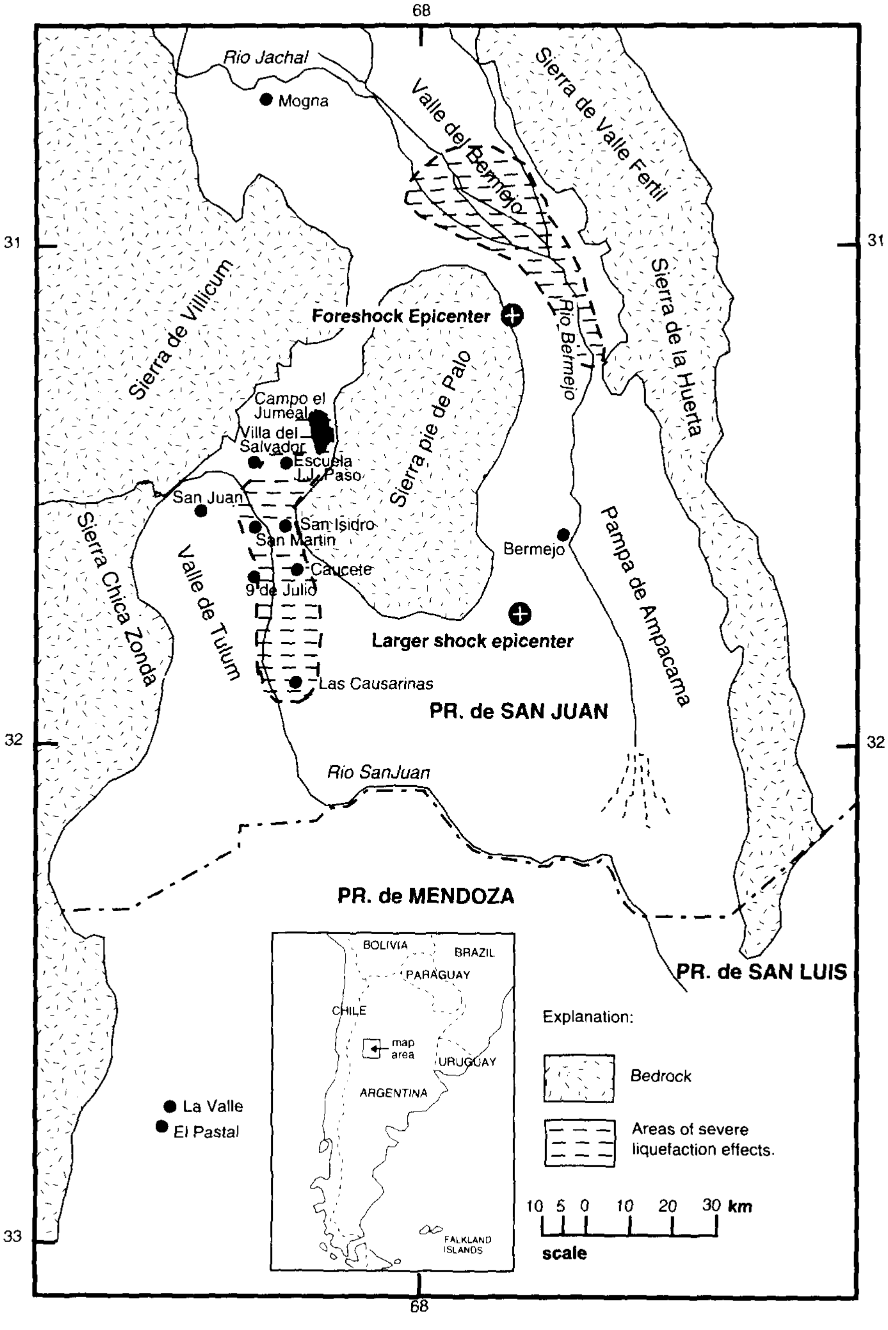

Fig. 1. Map of parts of the San Juan and Mendoza Provinces, Argentina, showing geologic and topographic features of the region, epicenters of the 1977 earthquake, areas where liquefaction was observed, and localities where specific site investigations were made.

systems; the remainder of the water flows overland into the Rio Bermejo through an adjunct pattern of intermittent streams and rivulets that meander southeastward through the valley.

The deposition and redistribution of sediment carried into the Valle del Bermejo by the Rio Jachal has led to the accumulation of thick deposits of late Holocene unconsolidated sediment in the lower parts of the valley. Because of the rapid and rather dynamic sedimentation processes, the sediments range from well to poorly sorted and are generally loosely compacted. Even though the region is in an arid environment, groundwater levels in the lower parts of the valley appear to be generally shallow (within a few meters of the ground surface) primarily due to the large volumes of water that flow beneath the valley floor and to natural barriers that apparently obstruct deep penetration of the flow. Both the recent rapid deposition of sediments and high groundwater levels generate a condition favorable for the occurrence of liquefaction.

The Rio Bermejo arises from intercepted subsurface flow and from an amalgamation of several intermittent streams connected to the Rio Jachal. The tributary streams of the Rio Bermejo coalesce into a broad system of channels that trend southward along the eastern margin of the valley. These channels carry the collected water southward through a broad plain called the Pampa de Ampacama. Infiltration through the Pampa de Ampacama, however, again depletes the flow to a few small rivulets and intermittent streams. In some areas, the rivers and rivulets meander across broad floodplains; in other areas they are incised within rather narrow channels.

3.2. Liquefaction effects

From an aerial reconnaissance of the Valle del Bermejo, the general distribution of ground fissures and sand boils on the valley floor are surveyed. The longest and widest fissures, and the largest sand boils were concentrated in a 60-km long northwest-trending segment of the Valle de Bermejo extending to distances of up to 40 km north of the foreshock epicenter (Fig. 1). Fissures in that area ranged up to several hundred meters long and up to several meters wide. Many large sand boils, with deposits up to tens of meters in extent, erupted through these fissures and also at several isolated locations. Most of the fissures were within one kilometer of and generally parallel to one of the many river channels that traverse the valley floor. The fissures and sand boils shown in Fig. 2 are typical of the larger liquefaction features formed in that area.

Beyond 40 km from the foreshock epicenter, ground fissures and sand boils were generally smaller and more scattered, and many areas were devoid of these features. The northernmost observed sand boils were near Mogna, 60 km northwest of the foreshock epicenter (G.E. Brogan and D.B. Slemmons, oral commun., 1978). The southernmost observed fissures and sand boils in the Valle del Bermejo were at a locality about 40 km southwest of that epicenter and about 25 km north of Bermejo (Fig. 1). Farther to the south, a few sand boils were reported near the Rio Desaguadero on the border between Mendoza and San Luis Provinces, 200 km southeast of the larger shock epicenter. These sand boils were the most

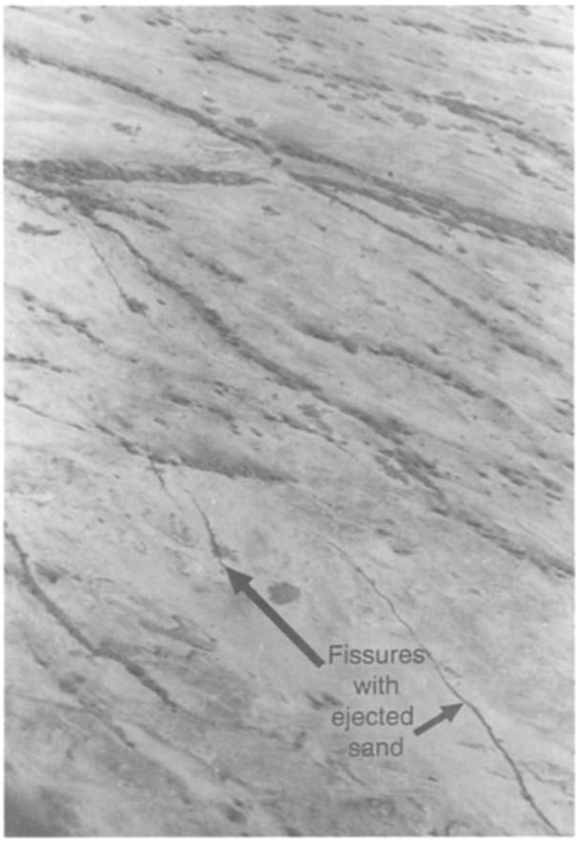

Fig. 2. Typical large fissures and sand boil deposits observed on the floor of the Valle del Bermejo. Fissures are several hundred meters long and several meters wide.

distant (from the seismic source zone) liquefaction effects reported for this event. The description of these sand boils, freely translated from Spanish, is as follows: "The eruption of cones of sand brought up large quantities of water (INPRES, 1977)."

Liquefaction in the Valle del Bermejo occurred primarily beneath active floodplains and other low-lying areas characterized by relatively recent deposition (presumably late Holocene) and shallow groundwater levels. Very few fissures or sand boils were observed on terraces, where groundwater levels are lower and deposits are older.

From an aerial reconnaissance similar to ours, Brogan and Slemmons (written commun., 1978) noted patches of light-colored sand and vegetation lineaments at several localities in the epicentral area. They suggest that these features may be remnants of sand boil and fissures generated by older earthquakes.

Because of the undeveloped nature of the epicentral area, the large and spectacular liquefaction effects caused no damage to works of man. Also, because of the remoteness of the region, we were unable to gain surface access to closely examine liquefaction features.

4. Valle del Tulum

4.1. Geologic and hydrologic setting

The Valle del Tulum lies west of Sierra Pie de Palo and extends southward past Sierra Pie de Palo into Mendoza Province. One large city, the provincial capital of San Juan (population about 250,000), and several smaller communities and villages lie in that area. The more fertile parts of the valley are cultivated, with citrus and grapes being the principal crops. Because the region is arid, all of the crops are irrigated with water diverted from rivers flowing from the Andes, primarily the Rio San Juan. Many industrial facilities, such as wineries, have been constructed to process the agricultural products produced in the region.

The geologic and hydrologic setting of the Valle del Tulum is generally similar to that of the Valle del Bermejo. Sediments are transported into the valley from the west by the Rio San Juan draining a large segment of the Andes Mountains. The gradient decreases abruptly when the river enters the valley, causing deposition of most of the sediment. Fluvial actions over time have segregated and spread the sediments across the valley floor. Closed depressions commonly form during the redistribution process; those depressions are then filled with marsh and playa deposits. The sediment column beneath any locality may consist of both fluvial and marsh/playa deposits.

Groundwater levels are permanently shallow in the lower parts of the valley (within a few meters of the ground surface). These high groundwater levels are maintained by infiltration of water directly from the Rio San Juan augmented by large quantities of irrigation water.

4.2. Liquefaction effects

Ground fissures and sand boils were the most widely distributed permanent surface effects generated by the earthquake in the Valle del Tulum. Although most of the liquefaction effects occurred in San Juan Province, a few scattered effects also developed in northern Mendoza Province.

4.3. Mendoza Province

A few liquefaction effects were identified in the vicinity of two small rural communities, Lavalle and El Pastal, in northern Mendoza Province, about 140 km south of the larger shock epicenter (Fig. 1). These effects included local differential settlements up to 0.3 m, scattered sand boils with craters up to 0.7 m in diameter, and bearing capacity failure beneath a heavily-loaded wine storage tank. Near El Pastal, a zone of ground settlement, 4 m wide and 50 m long, bounded by 0.1-m high scarps, disrupted the pavement of Highway 40 at the 22 km point. Most likely, this settlement was caused by liquefaction-enhanced compaction of underlying sandy deposits filling a buried channel. A more thorough investigation of these features, including subsurface drilling, was reported by Idriss et al. (1979).

4.4. San Juan Province

Liquefaction effects in the Valle del Tulum in San Juan Province consisted of fissures, sand boils and various forms of ground failure. The liquefaction effects were mostly restricted to the flat valley floor east of the Rio San Juan. Fissures and sand boils were most abundant in the area extending from the northern limits of the cultivated area near Campo el Jumeal south to Las Casuarinas (Fig. 1). Ground fissures and sand boils were discovered during each of 15 east–west flights over the area between Campo el Jumeal and Caucete, and Brogan and Slemmons (written commun., 1978) observed equally abundant effects between Caucete and Las Casuarinas.

Very few liquefaction effects were reported from areas south of Las Casuarinas, north of Angaco, or west of the Rio San Juan. No sand boils or fissures were observed or reported along the west bank of the Rio San Juan. However, any sand boils and fissures in that area would have been obliterated by flood waters from the Rio San Juan that covered the area shortly after the earthquake.

Damage caused by liquefaction in the Valle del Tulum included disrupted highways, railroads and canals (Fig. 3); fractured and differentially settled buildings; tilted tanks and water towers; and differentially settled fields. Examples of these types of damage are described and illustrated in the following sections on specific site studies.

5. Site studies

Detailed studies were conducted at five sites where damage caused by liquefaction was particularly disruptive or unusual. These studies included mapping of the locality, measurement of displacements, and hand-auguring or drilling to sample subsurface sediments. The site localities are: (1) Barrio Justo P. Castro in Caucete, (2) Escuela Normal in Caucete, (3) San Martin community center, (4) San Isidro Winery near San Martin, and (5) Escuela Juan J. Pasos northeast of Villa del Salvador. The locations of these communities are shown on Fig. 1.

6. Barrio Justo P. Castro

The Barrio Justo P. Castro is a subdivision of single-story duplex houses with unreinforced-concrete slab floors, lightly-reinforced masonry block walls and tile roofs. The houses were newly built and many were unoccupied at the time of the earthquake. The houses withstood the earthquake shaking very well except for a few that were severely damaged by differential ground displacements or eruption of sand boils. Ground displacements and sand boils were restricted to the southeastern part of the barrio, the only area beneath which liquefaction occurred (Fig. 4). The affected part of the Barrio was bounded on the southwest by an arcuate belt of open fissures (extensional features) accompanied by buckled concrete curbs and drainage channel linings (compressional features). The house shown in Fig. 5, for example, straddled the belt of open fissures and was pulled apart and fractured by fissures as wide as 220 mm with scarps as high as 200 mm. Just south of these open fissures, however, curbs and canal linings were buckled in compression.

The northern margin of the ground failure zone was bounded by a diffuse band of compressional effects including buckled, sheared and thrust curbs and crinkled channel linings. Fig. 6 shows buckled channel linings and a sheared curb. These disruptions are typical of compressional features that marked both margins of the disturbed zone. The maximum compression displacement measured across a single thrust feature was about 60 mm.

Sand boils erupted at several localities along the margins of the ground failure zone, including eruptions within two houses as noted on Fig. 4. The sand boils within houses provided an opportunity to estimate the quantities of sand and water that were erupted. Fig. 7 shows deposited sand along with high-water marks on the walls of one of the houses (the house near Hole JC-2). That house was unoccupied and the doors were closed at the time of the earthquake. The marks on the wall show that water ponded as high as 230 mm above the floor level during the eruption and sand deposits were as thick as 150 mm.

To estimate the quantities of sand and water that erupted into the house, the heights of the

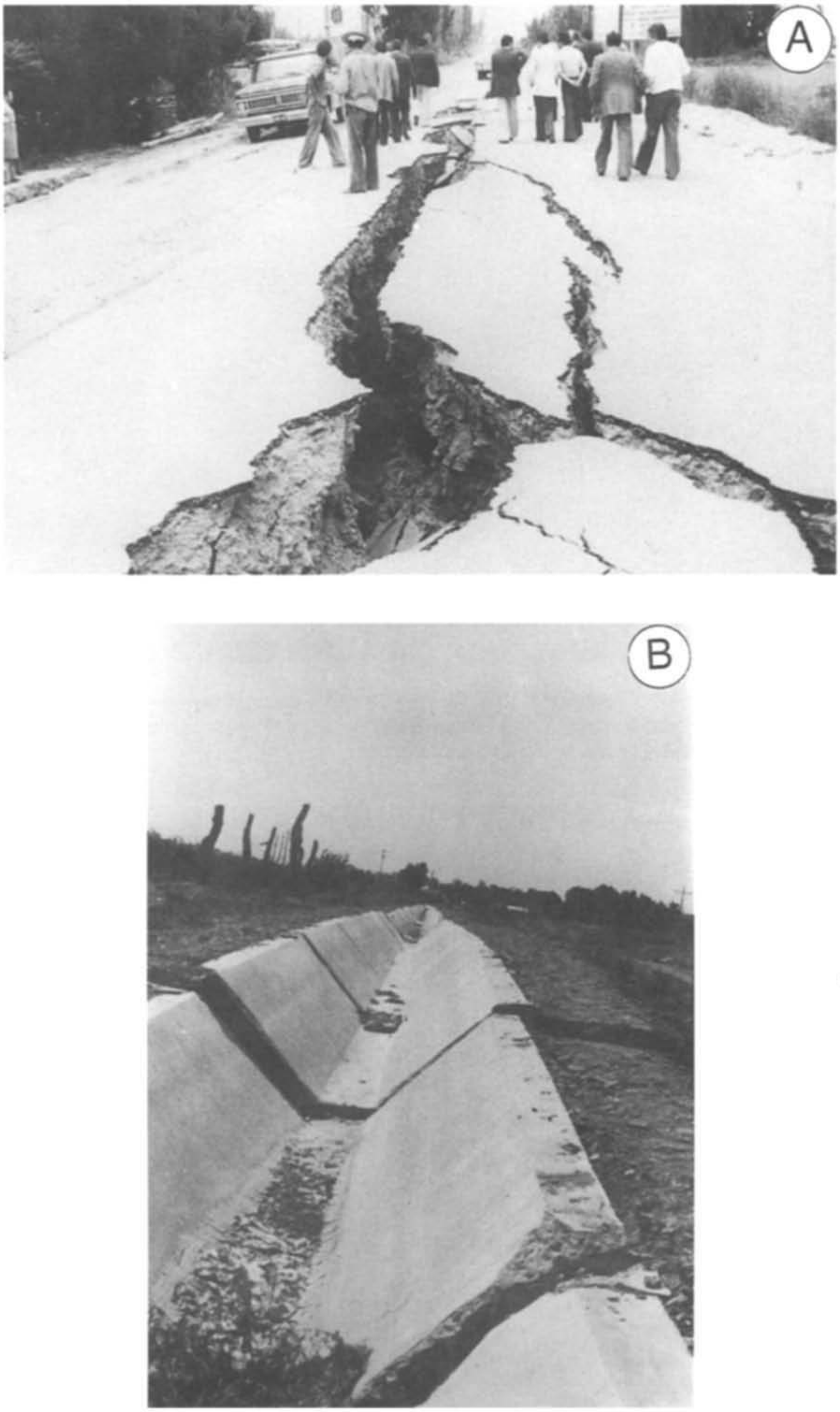

Fig. 3(A). Highway embankment settled and split due to liquefaction of subsurface soils (courtesy of INPRES). (B) Canal lining pulled apart by liquefaction-induced lateral spread (courtesy of K.L. Logani, Harza Engineering).

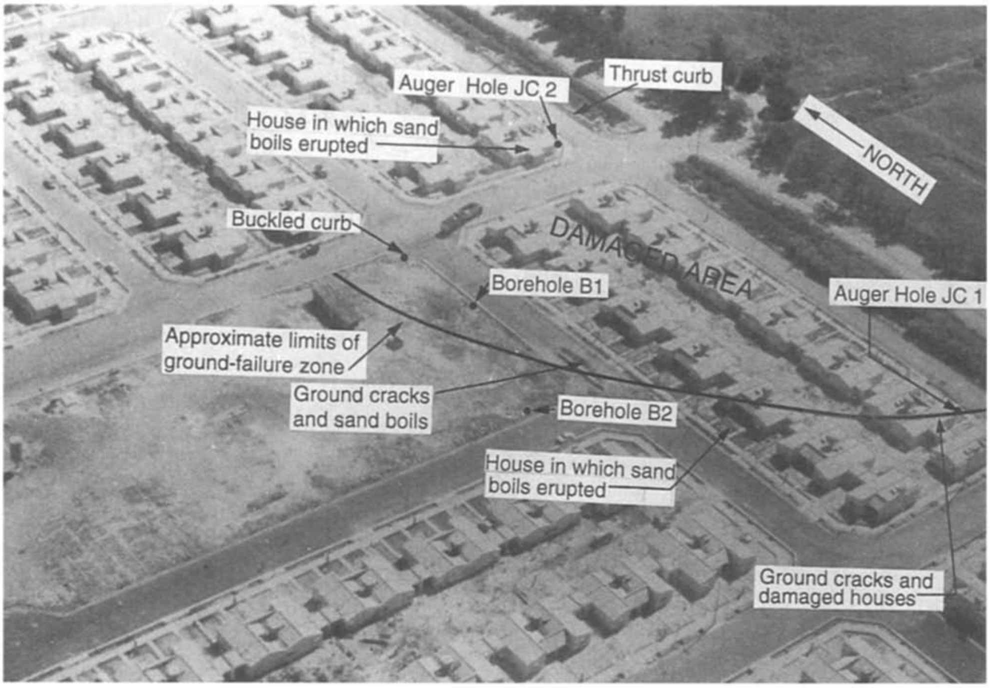

Fig. 4. Aerial photograph of Barrio J.P. Castro in Caucete showing the area where liquefaction and ground oscillation occurred and drill hole locations and houses within which sand boils erupted. The arcuate southern bound of the ground-failure zone is characterized by open fissures and buckled concrete curbs and walls.

Fig. 5. House in Barrio J.C. Castro intersected by a ground fissure that pulled apart and vertically offset the slab foundation and cracked or collapsed exterior and interior walls. Note the cracked and tilted walks and curbs in the foreground and the collapsed wall of the house in the background.

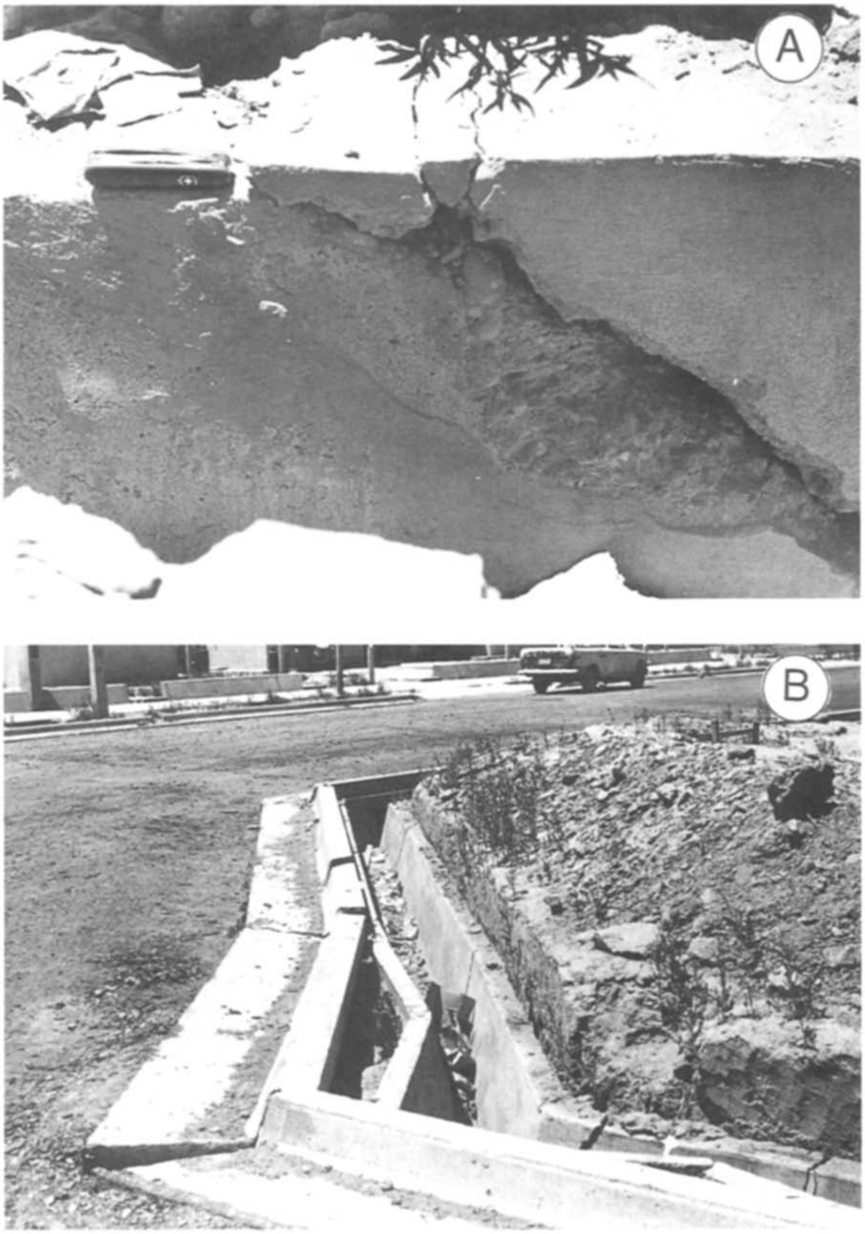

Fig. 6(A). Curb that was sheared and (B) canal linings that buckled due to compressional forces generated by liquefaction-induced ground oscillation and consequent impacts between mobile and immobile soil segments.

high-water marks above floor level were measured in the corners and at several places along the walls of each room. Also, a 1-m square grid was laid out on the deposited sand and the depth of the sand was measured at each grid intersection. Two minimally disturbed samples were taken from the deposited sediment with a 47-mm diameter thin-walled tube to estimate the bulk density of the sand.

Calculations from these measurements indicate that 11.99 m^3 of sand and water erupted into the house. The bulk volume of the sand on the floor

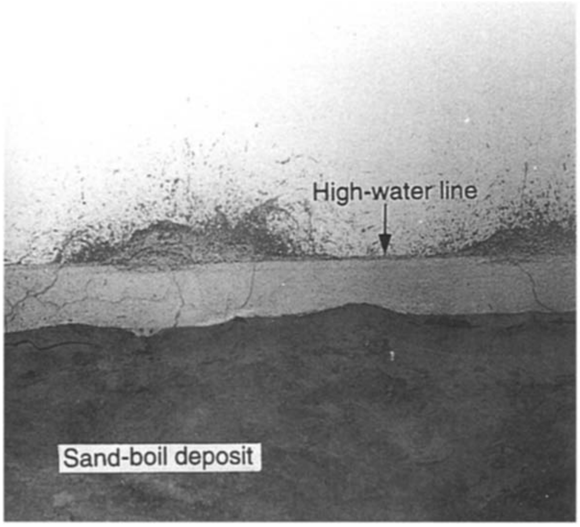

Fig. 7. Sand boil which erupted in a house in the Barrio J.P. Castro and deposited 12 m^3 of water and sediment on the floor. Stains on the walls show the height to which water rose during the sand boil eruption.

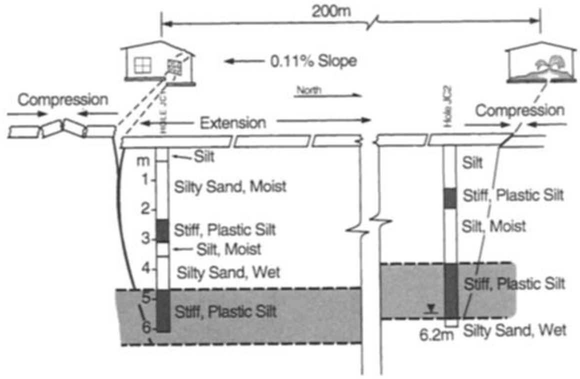

Fig. 8. Diagrammatic cross-section depicting sediment layers beneath that part of Barrio J.P Castro where liquefaction-induced ground oscillation and consequent damage occurred.

was 5.14 m^3. Assuming a specific gravity of 2.65 for the sand grains and an average bulk dry density of 1.43 g/cm^3 (the average of the two tube samples), the volumes of the granular solids and water were 2.77 m^3 and 9.22 m^3, respectively. These values yield a ratio of 3.33 parts water to 1 part solids, by volume, for this sand boil. The core samples of sediment contained 70% by weight sand, 27% silt and 3% clay with a mean grain size of 0.12 mm.

To investigate the shallow subsurface stratigraphy beneath the ground failure zone, two holes, JC1 and JC2, were hand augured to a depth of 6.1 m. The locations of these holes are noted on Fig. 4. Samples of the penetrated sediments were visually classified in the field, and bag samples were taken to the laboratory for further testing and classification. Logs of the two holes and an inferred cross-section of the sediment layers beneath the site are shown on Fig. 8. Also noted on the cross-section are the ground slope of 0.11%, downward to the south, and the relative locations of extensional and compressional surface features at the margins of the ground failure zone. The sediment section consists of a 4.0 to 4.7-m thick surficial sequence of silts and silty sands with minor amounts of clay. Beneath this sequence is a 1.9-m thick layer of very stiff plastic silt, which was difficult to penetrate with a hand auger. That silt contained intermittent zones of mottling and roots indicative of deposition in a marshy environment. The water table, at a depth of 5.7 m, lay near the base of the stiff plastic silt layer. With the available auger rod, we only were able to penetrate 0.3 m into a wet silty sand layer that lies beneath the stiff clay. The silty sand appears to be the upper part of the sediment unit that liquefied, as noted below.

A second subsurface investigation was performed at the site by Idriss et al. (1979). In January 1979, they drilled two holes, B1 and B2 (locations marked on Fig. 4) to explore the subsurface stratigraphy and conduct standard penetration tests. The logs of those two holes are reproduced in Fig. 9. The upper 6 m of the profile for hole B1, which was located within the ground failure zone, is similar to that of the auger holes with a 3.7-m thick layer of sandy silt underlain by a 2.7-m thick layer of medium stiff plastic silt, overlying a 0.6-m thick layer of silty sand. The top of the silty sand layer is at a depth of 6.4 m in hole B1 compared to 5.9 m in hole JC2. (Hole JC1, which was augured to a depth of 6.1 m, did not reach this silty sand layer.) The 0.6-m thick layer of silty sand and the two underlying similar layers of loose to medium dense sand are apparently the materials that liquefied during the earthquake.

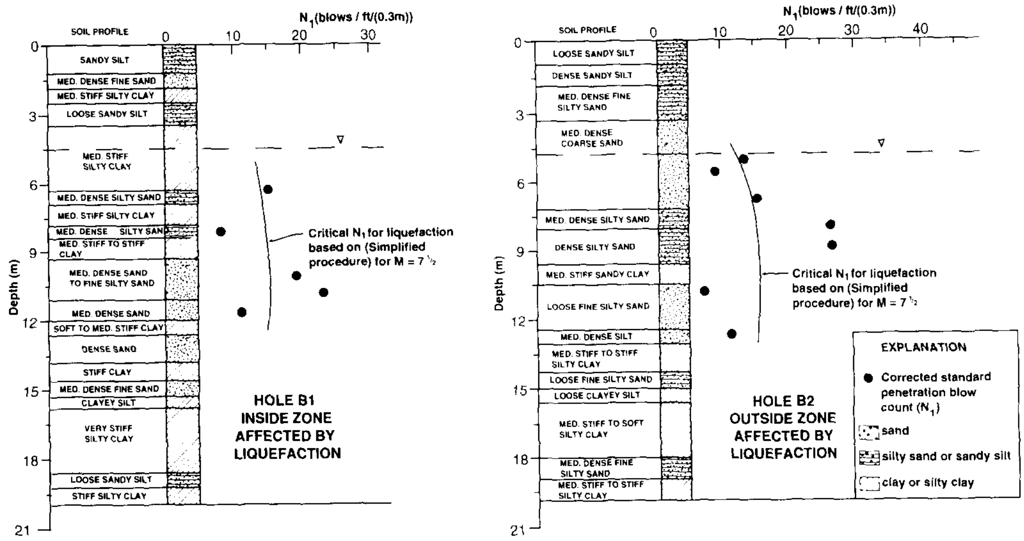

Fig. 9. Borehole logs showing subsurface sediment units where liquefaction effects were observed (Hole B1) and where they were not (Hole B2). Liquefaction occurred in an 0.6-m thick medium dense silty sand layer at a depth between 6 and 8 m (and perhaps in some underlying granular layers as well). Where the silty sand is capped by an impermeable clay layer, surface liquefaction effects were observed; where the silty sand is capped by a coarse sand layer (allowing upward drainage) liquefaction effects were not observed. (Borehole data from Idriss et al., 1979).

The principal difference between the soil profiles developed from holes B1, JC1, JC2 (within the ground failure zone) and B2 (outside the ground failure zone) is the absence of the 2.7-m thick clay layer above the 0.6-m thick silty sand layer. Hole B2 shows that that specific layer is replaced by a similarly thick layer of medium dense coarse sand. Idriss et al. (1979) suggest that excess pore pressures generated in the silty sand at the latter location may have readily dissipated upward into the partly saturated coarse sand, preventing liquefaction in that area.

While the authors were at the site at 8:25 a.m., January 17, 1978, the area was shaken by a magnitude 6.0 aftershock, yielding an intensity of ground shaking at the site of about MMI V. Hole JC2 was standing open at that time; the water level was measured on January 13 and 14. The water level in the hole was remeasured 5 min after the aftershock and several times thereafter. The water level in the hole initially rose and then slowly declined as shown in Fig. 10. On June 14, before the earthquake, the water level was at a depth of 5.73 m. Five minutes after the shock, the water level was at a depth of 5.66 m. Interpolation between this and subsequent measurements indicates that the water level rose to a maximum level of 5.64 m about 10 min after the aftershock, and then slowly declined over the next two hours. The rise of water level in Hole JC2 confirms the generation of excess pore pressures in the silty sand during the aftershock; those pressures gradually dissipated, in part by drainage into the open auger hole. Greater pore pressures leading to liquefaction apparently developed during the much stronger mainshock.

Liquefaction of subsurface sediment was the cause of ground failure in the Barrio Justo P. Castro. Here, the liquefied layer decoupled the overlying stiff sediments from the underlying deposits which allowed the upper non-liquefied sediment layers to transiently shift back and forth in a form of ground failure called "ground oscillation" (Youd, 1984; NRC, 1985). These upper layers broke into large blocks that oscillated independently of surrounding and underlying soils, alternately impacting one margin of the failure zone and then the other. The impacts produced compressional effects, such as the buckled curbs along both margins of the zone (Fig. 6). The final

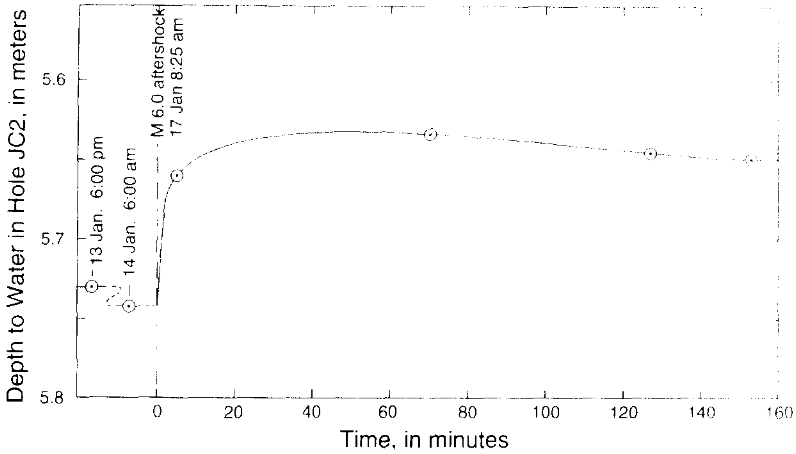

Fig. 10. Water depth in hole JC2 before and after the January 17, 1978 aftershock ($M = 6.0$).

excursion was in a northerly, up-slope direction, leaving open fissures along the southwest margin of the zone (Youd and Keefer, 1978). The maximum horizontal excursion during ground oscillation appears to have been more than 200 mm, based on the cumulative opening of residual ground fissures.

Settlements within the ground failure zone were caused by compaction of the liquefied layer augmented by removal of water and sand through sand boils. Observed differential settlements were as great as 220 mm.

The 1.9 to 2.7-m thick plastic-silt layer that capped the silty sand layer apparently contributed to the liquefied condition by preventing rapid upward drainage, except through fissures that developed along the margins of the ground failure zone.

7. Escuela Normal

The Escuela Normal was a 10-year-old secondary school located on a flat site in the east-central part of Caucete. The principal structures at the school were two east-west-trending, single-story, reinforced-concrete buildings (Figs. 11 and 12). The two buildings were 12 m wide, and 130 and 160 m long, respectively. The buildings were founded on unreinforced perimeter wall footings that extended upward to the floor level, one meter

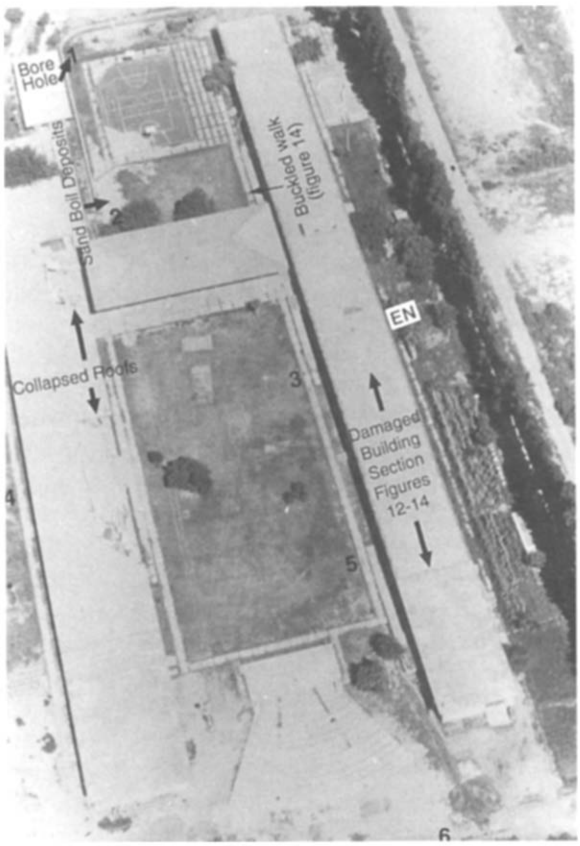

Fig. 11. Aerial view of Escuela Normal, Caucete, showing damaged building section, bore hole locations and other pertinent features. View looking west.

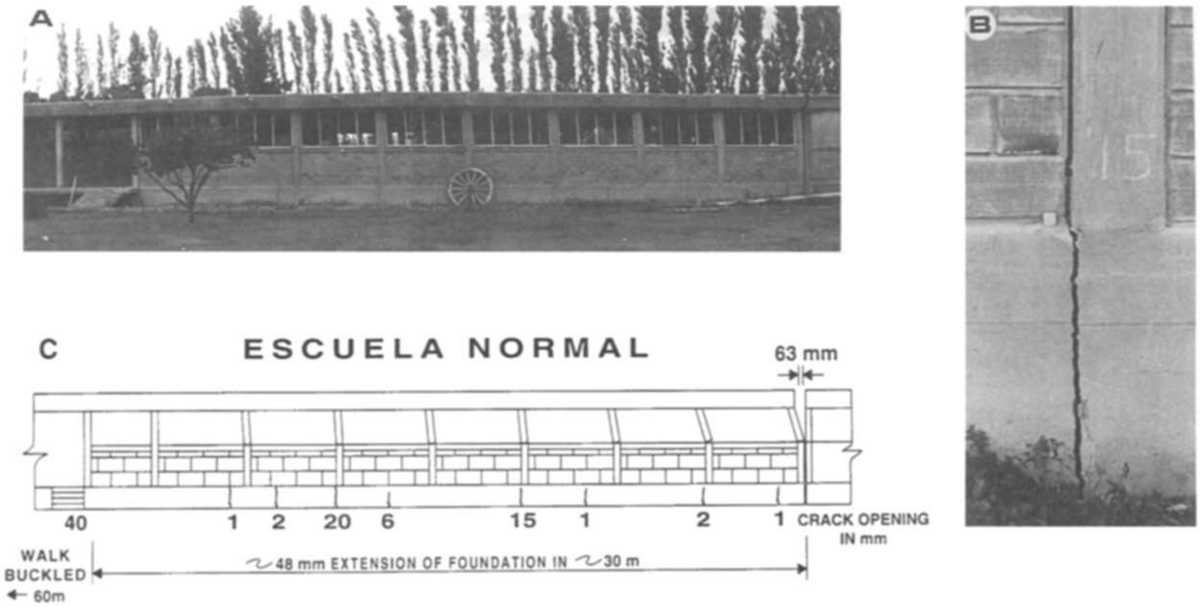

Fig. 12(A). Section of building damaged by extensional ground displacement at Escuela Normal. (B) Extensional crack in foundation with 20-mm opening. (C) Diagram of damaged section of building showing observed offset columns and foundation cracks. (After Youd, 1989.)

above grade. Reinforced-concrete columns rose upward from the footings to support the concrete roof section. Concrete block curtain walls filled the lower half of the sections between columns and windows filled the upper half (Fig. 12).

Both long buildings suffered severe damage. Ground shaking caused collapse of the heavy roof section at two localities in the 130-m long southern building (locations marked on Fig. 11). A 30-m long segment of the northern building suffered damage, with the roof of the building being shifted westward relative to the foundation. That displacement caused fracture of the columns at the top and bottom of the window level and column tilt between those two points.

The column with the largest tilt was located at the eastern end of the damaged section (Fig. 13). A 63-mm offset was measured in that column between the top of the block wall (bottom of the window) and the roof. The columns west of that locality were cracked and similarly offset, but the amount of offset decreased with each column until the eighth column, which was undamaged (Fig. 12).

Upon examination of the foundation of the building, several recent fractures were found in the perimeter wall, most of which were left open from a few to as much as 20 mm. The localities and widths of these cracks are noted on Fig. 12C. In the 30-m long section of the foundation wall beneath the fractured and tilted columns, the cumulative width of the cracks was 48 mm, which is roughly comparable to the 63 mm of maximum offset between the roof and foundation at the eastern end of the structure. (Additional separation may have occurred at foundation joints or in fractures beyond the 30-m section.) These measurements indicate that the ground and foundation beneath the damaged building extended (or spread) laterally by at least 48 mm, opening the cracks in the foundation wall. This action pulled the eastern end of the foundation and infilled walls relatively eastward while the roof remained attached to the western end of the building. This action caused fractions and tilting of the columns as illustrated in Fig. 12 (Youd, 1989).

Ground extension beneath the foundation was apparently compensated by compression in other

Fig. 13. Fractured and tilted column at the end of the damaged section of Escuela Normal building.

parts of the site. Evidence of such compression included a buckled sidewalk 30 m west of the damaged section of building (Fig. 14). The buckling shortened the sidewalk by about 130 mm.

Liquefaction of subsurface sediment was the apparent cause of ground displacement beneath the Escuela Normal. Evidence of liquefaction included numerous small fissures scattered throughout the site, and several large sand boils that erupted in the western part of the campus. Sediment ejected by those boils covered part of an outdoor basketball court (Fig. 11). The small fissures caused slight extension of sidewalk joints at several localities.

Other evidence of liquefaction in the vicinity of the school included a large north south-trending fissure that transsected a nearby football field. The fissure was 0.5 m wide and 3 m deep. Sand boils, which erupted through the fissure, deposited aprons of sand more than a meter wide on either side of the fissure.

In July of 1979, Ing. Raul Suarez, Universidad Nacional de San Juan, Argentina (written commun., 1979) drilled boreholes at the localities marked on Fig. 11. Logs from these borings are plotted on Fig. 15. The logs show a 6- to 8-m thick surficial layer of low to high plasticity silt (ML and MH). The silt is underlain by a layer of silty sand (SM) with some sublayers of poorly graded sand (SP). The sand layer is approximately 6 m thick beneath the eastern and western extension of the campus, but thins to about 3.5 m beneath the central part. Standard-penetration blow-counts in the silty sand and sand range from 5 to 23 with an average of 13.3. The fines content of the silty sand ranges from 14 to 34% by weight with an average of about 20%. The water table at the time of drilling (July 13, 1979, 20 months after the earthquake) was 3.2 m below ground surface; the groundwater level was much deeper, however, at the time of the field study described here. On January 18, 1978, a hole was hand augured to a depth of 6.0 m without encountering free groundwater. We believe that the groundwater level at the time of the investigation of the authors, 56 days after the earthquake, was probably closer to the level effective during the earthquake than the level reported 20 months later when deeper borings were drilled.

Using a groundwater depth of 6 m and the borehole data reported by Ing. Suarez, the liquefaction susceptibility is analyzed at the site using the "simplified procedure" of Seed et al. (1985). For this analysis, a peak acceleration, a_{max}, of 0.56 g is used, as reported by INPRES (1977) for Caucete. The results of the analysis indicate that the silty sand layer should have liquefied during the earthquake a result that is corroborated by the eruption of sand boils and the development of differential ground displacements that occurred at the site.

8. San Martin community center

The community center of the village of San Martin consists of an administration building, a

Fig. 14. Concrete side-walk buckled and shortened by about 130 mm due to compressional ground displacement on the Escuela Normal campus. (Location noted on Fig. 11.)

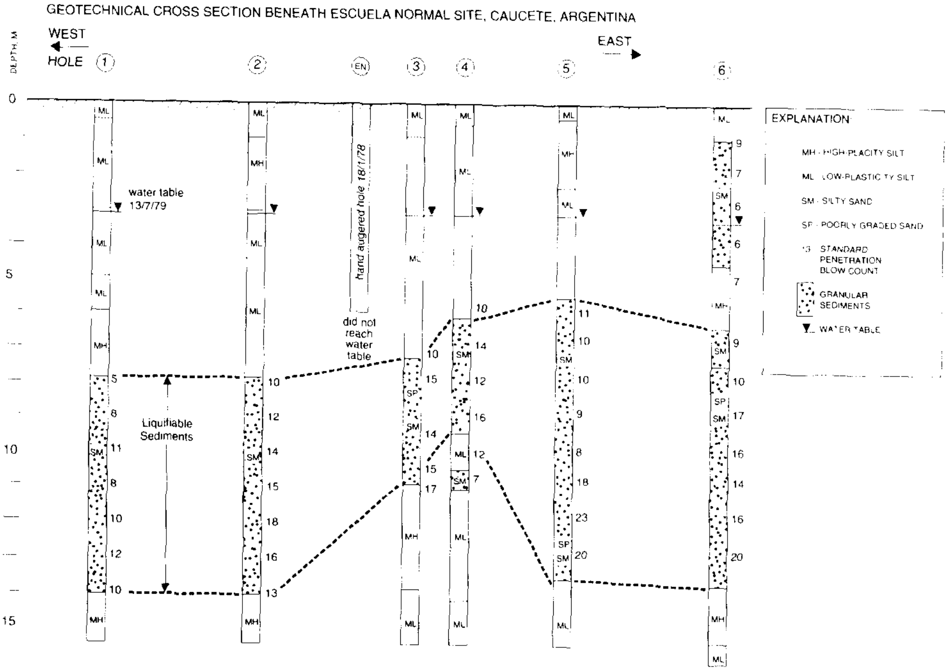

Fig. 15. Cross-section showing sediment layers beneath Escuela Normal campus. Borehole data from Ing. Raul Suarez, Universidad Nacional de San Juan, Argentina (written communication).

police station, a school, two towers, a pump house, several other small structures and several open areas (Fig. 16). Two modern, two-story reinforced-concrete buildings, an administration facility and a police station, suffered differential settlement of a few centimeters, but the only resultant damage we observed were a few very minor cracks in the exterior building walls. Also, an ornamental tower, about 10 m high, between the police station and the administration building, tilted about one degree to the east; the sidewalk between the buildings suffered minor differential settlement and buckling.

The most spectacular damage to structures at San Martin was the tilting of a 6-m high water tower and the toppling of a nearby pump house into a 1-m deep crater (Fig. 17). Similarly, a smaller crater developed beneath a small hand-pump structure in one of the open areas, and a large crater, 6 m in diameter and 1 m deep, formed in an open area about 100 m north of the small pump (Figs. 18A,B). Several residents reported that the area was flooded with water shortly after the earthquake, indicating that large quantities of water were generated and expelled upward from the underlying liquefied layer.

An exploratory hole was hand augured to a depth of 2.7 m near the toppled pump house. The hole penetrated interlayered fine sand and silty sand to a depth of 2.36 m and then penetrated a moderately stiff brown plastic silt that was very "sticky". We were able to penetrate only about 0.3 m into the plastic silt because its sticky consistency plugged our auger and because the overlying sand continually sloughed into the hole. The water table was at a depth of 1.4 m. Although we were unable to penetrate the plastic silt, the widespread liquefaction in that area indicates that a thick bed of liquefiable sand lies beneath the clay as depicted in Fig. 19. Evidence for the deeper sand layer includes wells drilled into that layer to supply water for the community and the large volume of water ejected through sand boils during the earthquake.

The apparent sequence of events that created the craters and caused tilting of the water tower

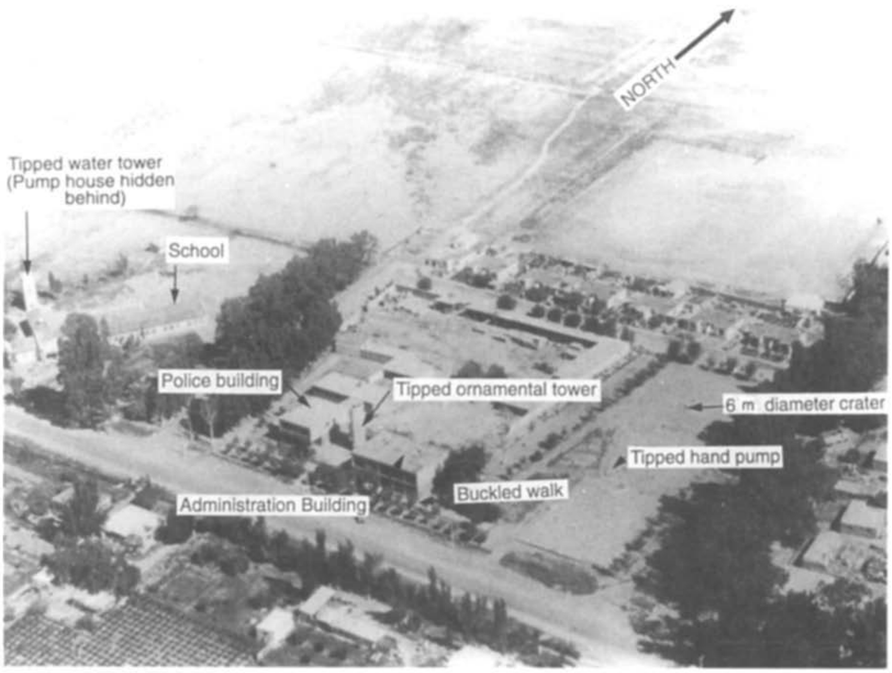

Fig. 16. Aerial view of municipal center at San Martin showing major buildings and localities of damage caused by liquefaction. View looking north.

Fig. 17. Photograph of the water-storage tower that tilted due to loss of bearing strength and nearby pump house that toppled into an eroded crater.

and toppling of the pump house are diagrammed in Fig. 19. During the earthquake, ground shaking caused compaction of sand, which disrupted grain-to-grain contacts. These disruptions led to a transfer of loads from granular contacts to the pore water, generating excess pore-water pressures. The excess pressures caused upward flow of pore water, but free drainage was restricted by the plastic-silt layer. The excess pore water accumulated and probably formed a transient layer of free groundwater immediately beneath the plastic-silt layer. That water was under sufficient pressure to generate dynamic expulsions of a large volumes of water through holes and cracks in the impermeable strata. The well casings that perforated the clay layer provided two such conduits. The large quantities of water that vented to the surface around those casings eroded cavities beneath the overlying structures. The structures then toppled into the cavities. Similarly, a hole or crack must have developed beneath the 6-m diameter crater (Fig. 18B) which led to the erosion of that feature.

The tilting of the ornamental tower and differential settlements beneath the police station and administration building were probably caused by compaction of underlying sand layers perhaps enhanced by transient loss of bearing strength. The walks likely buckled as a consequence of liquefaction-induced differential ground displacements.

9. San Isidro Winery

The San Isidro Winery, typical of the many wineries in the Valle del Tulum, consists of several single story buildings and a dozen or more large storage tanks founded on circular reinforced-concrete mat foundations (Fig. 20). The most important damage to the winery was tilting of nine tanks in a row behind the main processing facility (Fig. 21). Tilt of those tanks ranged from 2 to 5°. At the time of the visit of the authors, five of the tanks, those with the greatest rotation, had been dismantled, leaving only the tilted footings. These tanks were constructed of reinforced concrete. The four remaining tanks, all fabricated with steel, were repaired by constructing new perimeter-wall footings and then jacking the tanks back into an upright position.

Other damage to the winery included a slight differential settlement beneath some of the larger buildings and the collapse of a single-story garage structure (Fig. 20). A band of ground fissures passed beneath that garage; transient and permanent displacements associated with these fissures probably led to the collapse.

A hole to a depth of 2.8 m was augured near the tilted steel wine storage tanks. This hole penetrated gravelly fill to a depth of 1 m, followed by alternating layers of soft plastic silt and sand or silty sand to the bottom of the hole. Sloughing of sediment prevented deeper auguring. The water table was at a depth of 1.74 m.

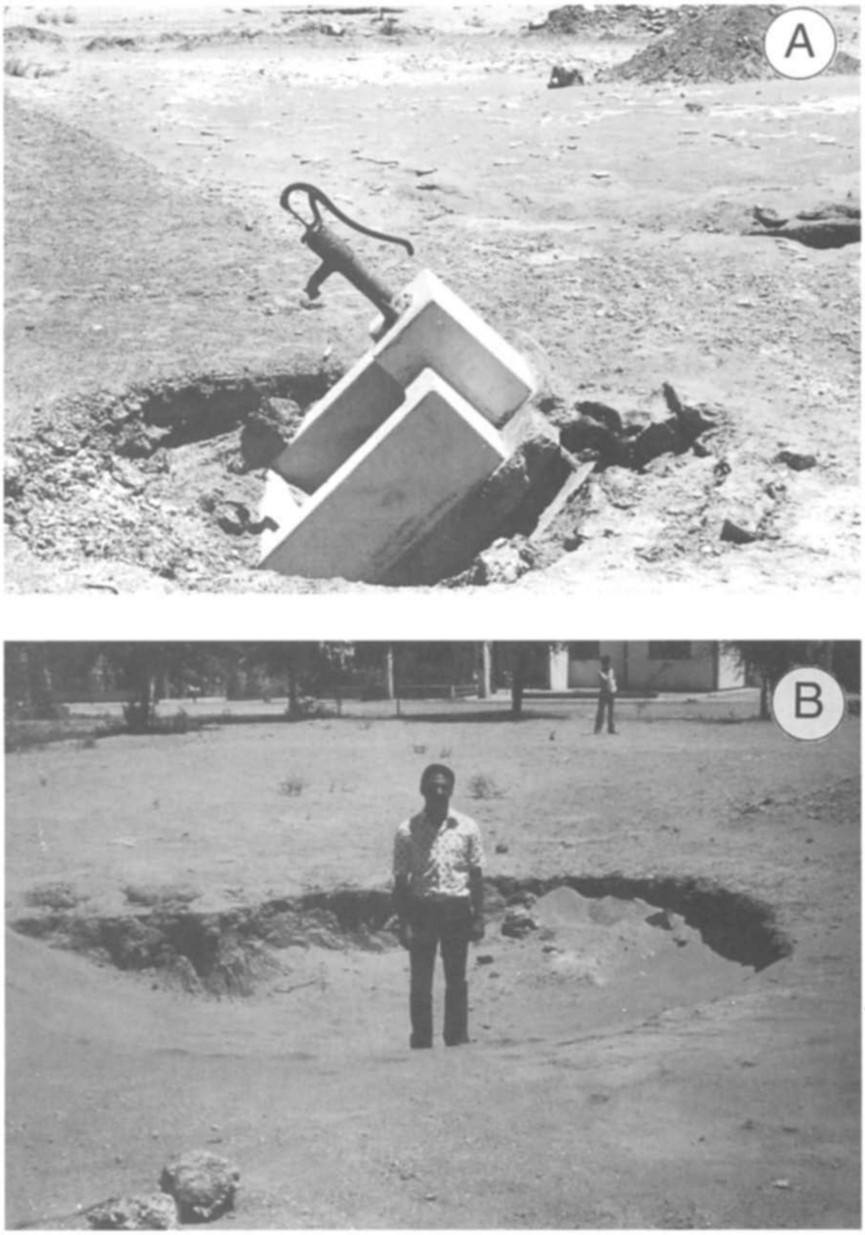

Fig. 18(A). Small crater that developed beneath a hand pump and (B) large (6-m diameter) crater that developed in a nearby open area.

Liquefaction of subsurface sands and silts led to the damage at the winery site. Liquefaction-induced loss of bearing strength allowed the nine tanks to tilt. The amount of tilting appears to have been a function of load. For example, several foundation slabs without tanks were unaffected while footings of filled tanks tilted substantially. Compaction of subsurface sediments and ground oscillation led to the other damage at the winery.

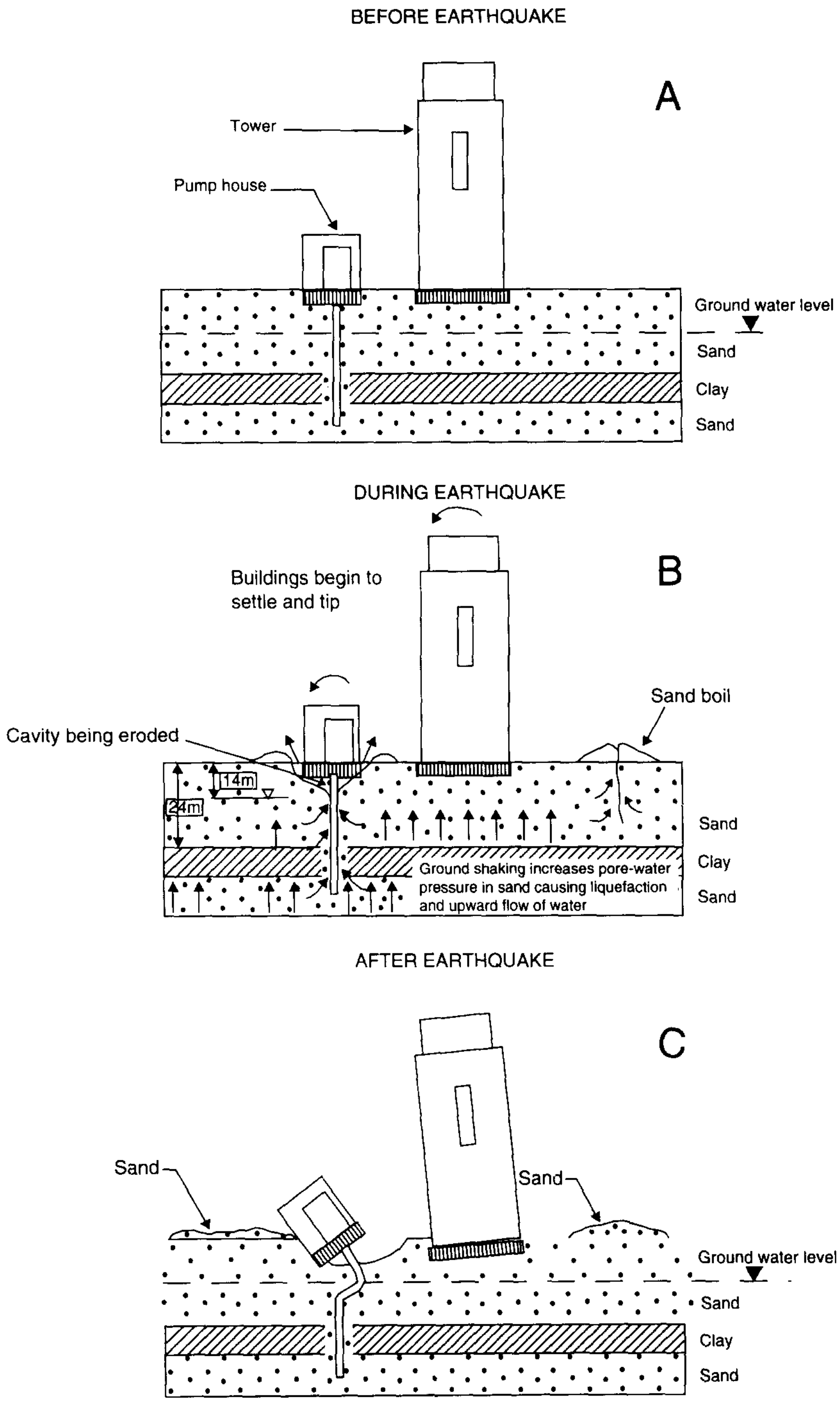

Fig. 19. Diagrams showing the processes that led to tilting of the water-storage tower and toppling of the pump house (see Fig. 16). (A) Setting before earthquake; (B) liquefaction during earthquake causes upward flow of water which found a ready drainage path around the well casing; (C) Setting after the earthquake with leaning tower and toppled pump house. (Drawings not to scale.)

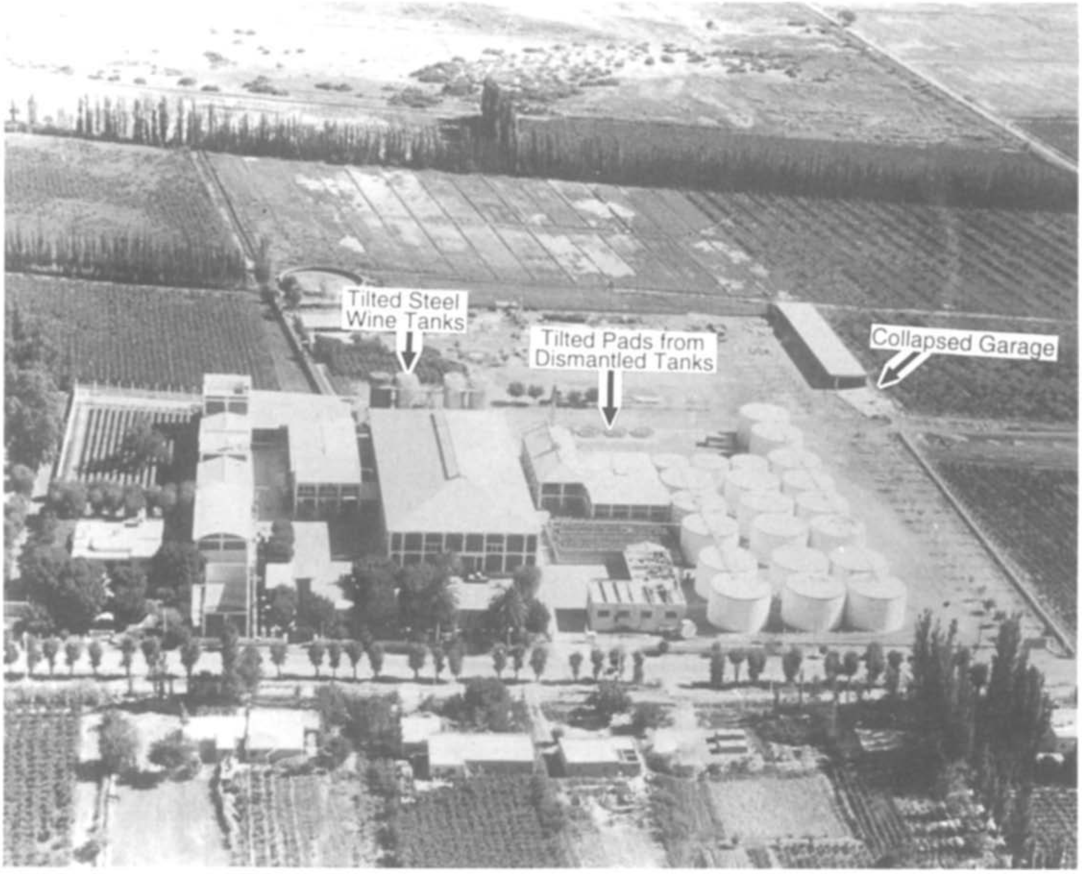

Fig. 20. Aerial photo of San Isidro Winery showing locations of tilted tanks and other damaged facilities. View looking north.

10. Escuela Juan J. Pasos

The Escuela Juan J. Pasos consists of several reinforced-concrete single-story classroom buildings founded on shallow spread and perimeter-wall footings. Wide verandas extend from the main structures to partially cover an interior court yard (Fig. 22). The school was constructed in 1948.

During the earthquake, sand boils erupted in fields surrounding the school and several large boils erupted within the courtyard, venting large quantities of water and sand. The vented sand deposits covered much of the area and extended under the verandas. Differential ground settlement beneath the buildings caused numerous cracks in columns and walls (Fig. 23). The largest differential settlement was about 60 mm, and the maximum settlement of footings supporting columns was about 40 mm. In spite of the differential settlements and the numerous cracks in walls and columns, the buildings were in no danger of collapse. At the time of the visit of the authors, the buildings were being repaired.

One hole was hand augured to a depth of 4.3 m near the most severely damaged building. This hole penetrated alternating thin layers of sand, silty sand and plastic silt to a depth of 2.1 m. From 2.1 m to 4.3 m, the sediment was composed of fine sand or silty sand with occasional thin clay layers. The water table was 1.88 m below ground surface.

Liquefaction-induced soil compaction and loss of bearing strength, combined with soil-structure interaction generated the differential settlements that disrupted the school buildings. Evidences of liquefaction included large sand boils that erupted

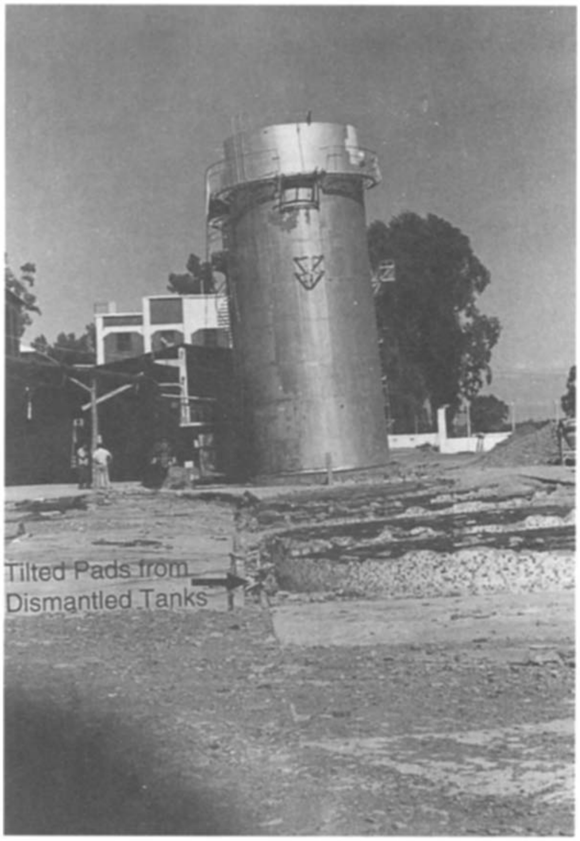

Fig. 21. Tilted steel tanks (4 units) and tilted foundation slabs (5 units) for concrete tanks that have been dismantled. Foundations and tanks tilted between 2 and 5°.

within the school courtyard and in the surrounding fields, and the existence of loose, saturated sand deposits at shallow depth.

11. Summary

(1) The 23 November, 1977 earthquake in western Argentina generated liquefaction effects over a wide area extending discontinuously as far as 200 km from the epicenter of the larger shock. The larger and more abundant effects were concentrated in a 60-km long band in the lowlands of the Valle del Bermejo and in an equally long band of lowlands along the Rio San Juan in the Valle de Tulum.

(2) Fissures in the Valle del Bermejo ranged up to several hundred meters long and up to several meters wide. Many large sand boils, with deposits covering areas up to tens of square meters in extent, erupted through these fissures; additional sand boils erupted at isolated locations. Most of the fissures and sand boils were within one kilometer of one of the many small river channels that traverse the valley floor. Orientation of the fissures was generally parallel to a nearby channel.

(3) Liquefaction-induced ground displacements in the Valle del Tulum disrupted highways, railroads and canals, fractured building foundations, tilted tanks and towers, and produced differential settlements in fields. Some of the more important or unusual damages are summarized below:

(4) In the Barrio Justo P. Castro, a subdivision of Caucete, liquefaction of a subsurface granular layer decoupled the overlying, unliquefied stiff sediments from the underlying ground. This decoupling allowed the upper sediments to shift back and forth in a form of ground failure called "ground oscillation". The decoupled sediment layers broke into large blocks that alternately impacted one margin of the failure zone and then the other. These impacts produced compressional effects along both margins. Pull-away of the blocks during the last oscillation left open cracks along the southwestern margin of the zone. Sand boils erupted through fissures at the margins of the zone, several of which vented water and sediments into houses permitting a rare opportunity to measure volumes of erupted sand and water. One such sand boil deposited 11.99 m^3 of water and sediment into an unoccupied home; that deposit had a ratio (by volume) of 3.33 parts water to 1 part solids.

(5) A 30-m long segment of a single-story class room building at the Escuela Normal in Caucete suffered damage with part of the roof shifting westward relative to the foundation. That displacement caused fractures of the columns at the top and bottom of the window level and column tilt between these points. Upon examination of the foundation, a number of recent fractures were found in the perimeter wall, some of which were left open by as much as 20 mm. In the 30-m long section, the cumulative width of the cracks in the foundation was 48 mm. That extension roughly

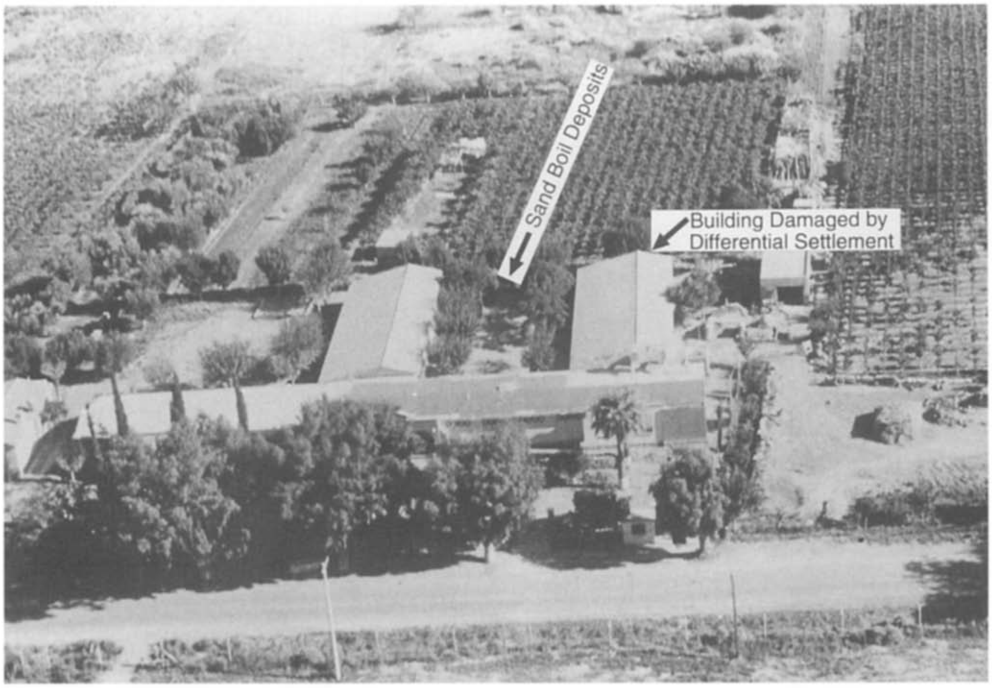

Fig. 22. Aerial view of Escuela J.J. Pasos showing buildings and areas where liquefaction effects were observed. View looking north.

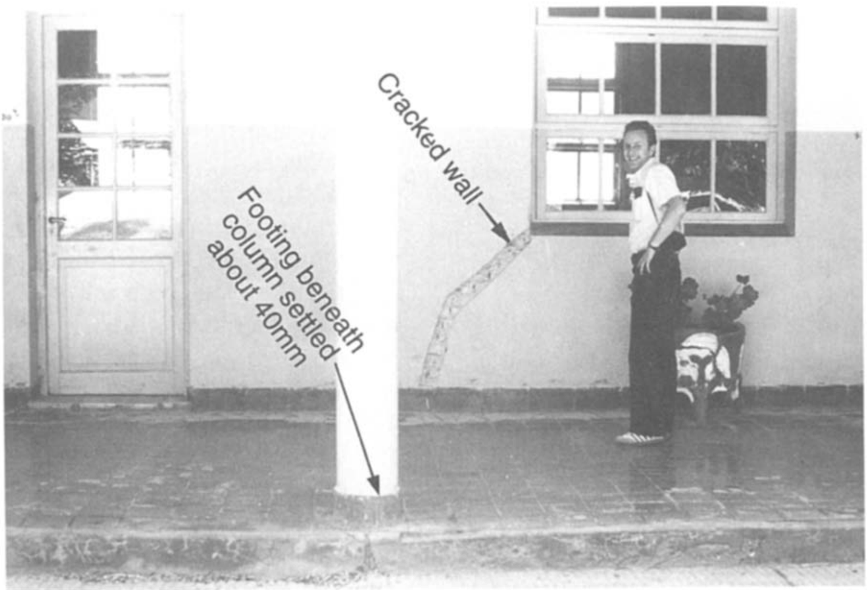

Fig. 23. Building at Escuela J.J. Pasos with cracked wall and differentially settled columns due to ground settlement and loss of bearing strength caused by liquefaction of subsurface sediments.

matches the 63 mm of maximum offset between the roof and foundation at the eastern end of the structure. These measurements indicate that the ground and foundation beneath the building extended (or spread) laterally, opening the cracks in the foundation wall. This action pulled the roof relatively westward, fracturing and tilting the columns.

(6) The most spectacular damage to structures in the community center of San Martin was the tilting of a 6-m high water tower and the toppling of a nearby pump house into a 1-m deep crater (Fig. 17). Similarly, a small crater developed beneath a hand-pump structure in an open area and a large crater of 6 m diameter and 1 m depth formed nearby. The apparent sequence of events that created the craters and caused tilting of the water tower and toppling of the pump house are as follows: During the earthquake, ground shaking caused compaction of subsurface sand layers, which generated excess pore-water pressures. The excess pressures caused upward migration of pore water, but free drainage was restricted by an impermeable plastic-silt layer. Apparently, water accumulated below the impermeable layer, and then burst to the surface through several vents and cracks, causing several large craters. Two well casings perforated the clay layer and provided vent holes through which water gushed, eroding cavities into which the overlying structures toppled. Similarly, a hole or crack must have punctured the clay beneath the 6-m diameter crater which led to the erosion of this feature.

(7) At the San Isidro winery, nine storage tanks tilted 2 to 5°. Liquefaction-induced loss of bearing strength caused the tilting. Five tanks, constructed of reinforced concrete, were damaged beyond repair and were dismantled. Four additional steel tanks were repaired by placing new footings and then jacking the superstructures into an upright position with support provided by the new foundations.

(8) At the Escuela J.J. Pasos, a small country school, differential ground settlement beneath the buildings fractured several columns and walls. The largest settlements were about 60 mm and the maximum settlement of footings supporting columns was about 40 mm. In spite of these settlements and fractures in walls and columns, the buildings were in no danger of collapse. Liquefaction-induced soil compaction and loss of bearing strength, combined with soil-structure interaction effects generated the observed differential settlements beneath those buildings.

Acknowledgements

The cooperation of the Instituto Nacional de Prevencion Sismica (INPRES), San Juan, Argentina is greatly appreciated. INPRES provided logistical support and surface and air transportation for the field study. In particular, field assistance by Engineers Alejandro Giuliano and Juan Carlos Rosas was instrumental to the success of the project. Borehole logs were generously provided by Ing. Raul Suarez, Universidad Nacional de San Juan, Argentina, and Dr. I.M. Idriss, Woodward Clyde Consultants, Santa Ana, California. Funding for the field work was provided by the US Geological Survey.

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