NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH

State University of New York at Buffalo

Observations on Water System and Pipeline Performance in the Limon Area of Costa Rica Due to the April 22, 1991 Earthquake

by

M. J. O'Rourke
Department of Civil Engineering
Rensselaer Polytechnic University
Troy, New York 12180-3590

and

D. Ballantyne
Kennedy/Jenks/Chilton Consultants
530 South 336th Street
Federal Way, Washington 98003

Technical Report NCEER-92-0017

June 30, 1992

This research was conducted at Rensselaer Polytechnic Institute and Kennedy/Jenks/Chilton Consultants and was partially supported by the National Science Foundation under Grant No. BCS 90-25010 and the New York State Science and Technology Foundation under Grant No. NEC-91029.

NOTICE

Observations on Water System and Pipeline Performance in the Limon Area of Costa Rica Due to the April 22, 1991 Earthquake

by

M.J. O'Rourke[1] and D. Ballantyne[2]

June 30, 1992

Technical Report NCEER-92-0017

NCEER Project Number 90-3003

NSF Master Contract Number BCS 90-25010
and
NYSSTF Grant Number NEC-91029

1 Professor, Department of Civil and Environmental Engineering, Rensselaer Polytechnic Institute
2 Manager of Municipal Services, Kennedy/Jenks/Chilton

NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
State University of New York at Buffalo
Red Jacket Quadrangle, Buffalo, NY 14261

ABSTRACT

This document focuses on earthquake damage to water and oil pipelines, water supply, and water treatment following the 22 April 1991 Costa Rica Earthquake. The moment magnitude 7.5 earthquake occurred approximately 40 km south–southwest of Limón, and resulted in a coseismic uplift of up to 1.5 meters along Costa Rica's east coast. This report also provides an overview of the engineering aspects of the event and recovery activities.

Turbidity in the watershed which provides Limón's primary water supply increased to as high as 2.4 percent solids, making it extremely difficult to treat. In addition, the water treatment plant was damaged by the earthquake.

Cast iron, ductile iron and reinforced concrete cylinder pipe water transmission lines were damaged by both wave propagation and permanent ground deformation. Water distribution piping, also including PVC and galvanized iron, was similarly impacted. Documentation and evaluation of that damage is described, and compared with empirical estimates from previous earthquakes.

Twin 150 mm (6 in), 100 km long, oil transmission lines suffered only a single failure from wrinkling. A description of the pipelines and the failure is provided.

ACKNOWLEDGEMENTS

The authors would like to thank Dr.Guilleromo Santana, Mr. William Vargas and Mr. Adolfo Matamoras of the University of Costa Rica Earthquake Engineering Laboratory for their invaluable assistance during the authors' visit to Costa Rica. Water system information was provided by Mr. Herbert Ferer and Mr. Jose Carlos Solano of the Instituto Costarricense De Acueducto Y Alcantarillados, (AyA), in San Jose; Mr. Rodrigo Acuna, Regional Director, Atlantic Coast, AyA, in Limón; and Mr. Castillo Martinez, the water treatment plant operator. All are greatfully acknowledge for these assistance during a very busy period. Special thanks is also due to Ing. José Luis Arguedas of AyA who showed the first author damaged transmission pipe in the field. The authors also gratefully acknowledges the financial support for this trip from the National Center for Earthquake Engineering Research (O'Rourke) and the American Society of Civil Engineers (Ballantyne)

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF TABLES

SECTION 1

ENGINEERING DESCRIPTION OF EARTHQUAKE

This section presents various engineering characteristics of the April 22, 1991 earthquake in Costa Rica. These include the size, intensity, observed coseismic uplift along the Caribbean coast, and recorded peak ground motions primarily in the central valley of Costa Rica. In addition, attenuation relations for subduction events are compared to the observed ground motion and used to estimate peak ground velocity in the epicentral region.

1.1 Size, Intensity and Coseismic Uplift

The Costa Rica earthquake was caused by reverse or thrust faulting between the Caribbean Plate and the Cocos (Continental) Plate, resulting in uplifting of the Cocos Plate. As reported by Quintanar et al. [1], the size of the event as measured by the seismic moment (Mo) was 1.9×10^{20} N–m. This corresponds to a moment magnitude M= 7.5 and a surface wave magnitude Ms = 7.5. Figure 1–1 shows the epicenter of the April 22 event. Note that the epicenter is roughly 40 km South–Southwest of Limón which is located on the Caribbean Coast.

Shortly after the earthquake, the Vulcanological and Seismological Observatory of Costa Rica – National University (OVSICORI–UNA)[2] prepared a map of Modified Mercalli Intensity (MMI) for the event. These intensities resulted from field observations and interviews of about 250 people. The maximum MMI value of IX near the Caribbean Coast was based on sand boils, ground cracks and other evidence of liquefaction, as well as structural damage and collapse of bridges, buildings and highways.

A somewhat more refined isoseismal map, shown in Figure 1–3 is contained in the Earthquake Spectra reconnaissance report on the event [3]. Note that the Earthquake Spectra map assigns a MMI of VIII to be Caribbean coast region with isolated pockets of MMI IX.

As noted previously, the Cocos (continental) Plate overrode the Caribbean Plate, and resulted in uplifting along the Caribbean coast. Figure 1–4 is a map of the costal region near Limón, Figure 1–5 is a graph of coseismic uplift as a function of distance along the coast, as taken from the OVSICORI–UNA report [2]. Note that the maximum uplift of about 1.5 m occurred at Limón. It drops off sharply to the Northwest (being zero about 4.5 km Northwest of Moin) and decreases somewhat less rapidly to the Southeast (being about 0.7 m at Westfalia and 0.45 m at Cahuita). Plafka and Ward [4] use a uniform slip, planar (USP) dislocation model in a half space which matches fairly well the observed uplift along the coast. Their model suggests that the coseismic uplift decreases as one moves inland from the coast. The estimated uplift at Bomba on the Banano River is about 0.55 m, that is lower than that at Limón and Westfalia but somewhat higher than that at Cahuita.

1.2 Observed Peak Ground Acceleration

Prior to the earthquake, the University of Costa Rica (UCR) Earthquake Engineering Laboratory maintained a set of accelerometers primarily in the central valley of Costa Rica. The location of these accelerometers is shown in Figure 1–1. Note that all of the accelerometer stations are West of the epicenter. Table 1–I present the stations, structure type, soil type, epicentral distance Δ in km, and the maximum value of ground acceleration for three orthogonal directions. The information in Table 1–I is based upon the April 26, 1991 preliminary report by the UCR Earthquake Engineering Laboratory [5] and the Earthquake Spectra reconnaissance report [3]. The epicentral distances ranged from 73 to 161 km, and the peak horizontal ground acceleration, A_{max}, ranged from 270 to 40 gals (1000 gals = 1 g = 981cm/sec^2). As one would expect, A_{max} is generally a decreasing function of Δ.

1.3 Comparison of Recorded Ground Motion with Existing Attenuation Relations

The technical literature contains a number of empirical formulae which related various ground motion parameters such as peak ground acceleration or peak ground velocity, to earthquake size and source to site distance. In this subsection, the attenuation relation developed by Kawashima et al. [6] is compared to the peak ground acceleration recorded during the April 22, 1991 Costa Rica earthquake. The Kawashima et al. relation was chosen for a number of reasons. First of all, the Costa Rica event was a subduction zone earthquake and the Kawashima et al relation was developed from data recorded in Japanese earthquakes with local depths less than 60 km, most of which were presumably subduction zone events. Most of the other available attenuation relations are based upon California and other West coast events which are mainly strike–slip earthquakes. In addition, Kawashima et al. [6] provide relations for both peak ground acceleration and velocity and distinguish between values recorded on rock and various other sites. Finally, and most importantly, the Kawashima et al. relationship appears to provide the reasonable fit to the Costa Rica data. One drawback with the Kawashima et al. relations is that they use epicentral distance to characterize source–site separation. Since different parts of the fault rupture produce peak motion at different sites, the closest distance to the rupture may be a better source–site separation measure. The Kawashima et al. relation has the form:

$$Y = a\, 10^{bM} (\Delta + 30)^{d} \tag{1.1}$$

where Y is the peak ground acceleration (gals) or velocity (cm/sec), M is Japanese Meteorological Agency (JMA) magnitude and Δ is the epicentral distance (km). The coefficients a,b and d are empirical constants which are functions of the local soil conditions. Table 1–II describes the three site classifications established by Kawashima et al. Table 1–III presents the empirical constants a,b and d for peak ground acceleration and velocity for each of the three site groups. Figures 1–6 through 1–8 compare the peak ground accelerations recorded in the April 22 event with predicted values from the Kawashima et al. relationship. Note that a JMA magnitude of 7.38 corresponds to a seismic moment of 1.9 x 20^{20} N–m (Moment magnitude M = 7.5).

Figure 1–6 compares ground accelerations for Rock sites from Table 1–I with the Kawashima et al. relation for Group #1 site conditions. The recorded ground motion at CCH and GTS are roughly 10% higher than that predicted by Kawashima, while the value at QPS is half the predicted value. Figure 1–7 presents a similar comparison for Hard Sites from Table 1–I with the Kawashima relationship for Group #2 soils. All recorded values are within about 35% of the Kawashima value of each epicentral distance. Figure 1–8 compares peak horizontal accelerations recorded at Soft Sites in Table 1–I with predicted values for Group #3 soils from Kawashima et al. All of these sites with the exception of GLF have recorded values larger than those predicted by Kawashima et al. Of particular interest are values at CMA and CTG, which were roughly 2.5 time higher than the Kawashima values.

1.4 Estimated Peak Ground Velocity in Limón

Peak velocity, V_{max}, is the ground motion parameters of interest for seismic wave propagation effects on buried pipelines since ground strain and hence buried pipe strain are theoretically proportional to V_{max}. In this subsection, we will estimate V_{max} for the area in and around Limón.

Figure 1–9 is a plot of peak ground velocity, V_{max}, for a Moment magnitude M = 7.5 (JMA magnitude = 7.38) using the Kawashima et al. relationship. Note that for epicentral distances of 25 and 40 km (corresponding to the Banano River water treatment plant and the Port of Limón respectively) Kawashima et al. predict V_{max} values of 37 and 27 cm/sec for Group #3 site conditions with an average of 32 cm/sec. For the same epicentral distances, Kawashima et al predict 31 and 23 cm/sec for Group #2 site conditions, with an average of 27 cm/sec. These values, predicted by the Kawashima et al. relationships, will be modified based on data presented in Figures 1–7 and 1–8. In Figure 1–7, most of the observed Hard Site ground acceleration data points fall below the Kawashima et al line for Group #2 site conditions. The average value of the observed/predicted ratio is roughly 0.8. We assume herein that the acceleration ratio 0.8 also applies to ground velocity yielding V_{max} = 0.8(32) = 22 cm/sec for Hard Sites in and around Limón. Similarly, most of the observed Soft Site ground acceleration data points in Figure 1–8 lay above the Kawashima et al. line for Group #3 site conditions. The average value of the observed/predicted ratio is roughly 1.6. Again assuming that the acceleration ratio also applies to ground velocity, yields V_{max} = 1.6(32) = 51 cm/sec as the estimated peak ground velocity for Soft Sites in and around Limón.

Station Name	Code	Structural Type	Soil Type	Epicentral Distance (km)	Maximum Acceleration (%g)	Comp.
San Isidro (ground level)	ISD	L	H	73	0.20 0.17 0.15	0° Vertical 270°
Cachi (exploration tunnel)	CCH	F	R	80	0.15 0.06 0.09	0° Vertical 270°
Cartago (Central Park)	CTG	F	S	94	0.27 0.13 0.22	0° Vertical 270°
Guatuso (ground level)	GTS	L	R	106	0.11 0.04 0.06	0° Vertical 270°
San Pedro Main Library UCR (ground level)	CMA	H	S	109	0.16 0.12 0.20	92.5° Vertical 2.5°
Golfito (ground level)	GLF	L	S	111	0.06 0.02 0.04	0° Vertical 270°
San Jose Aurola Hotel (basement)	AUR	H	H	112	0.07 0.04 0.06	0° Vertical 270°
San Jose Banco Nacional Building (basement)	BNC	H	H	113	0.08 0.07 0.07	262° Vertical 172°
San Jose Hatillo (ground level)	HTO	L	S	114	0.12 0.06 0.09	0° Vertical 270°
San Jose ICE Central Building (basement)	ICE	H	H	115	0.08 0.06 0.09	285° Vertical 195°
Quepos (ground level)	QPS	L	R	119	0.04 0.03 0.03	0° Vertical 270°
Alajuela CIPET (ground level)	ALJ	L	S	129	0.11 0.05 0.09	0° Vertical 270°
Puriscal (ground level)	PCL	L	S	137	0.09 0.07 0.07	0° Vertical 270°
San Ramon UCR (ground level)	SRM	L	S	161	0.09 0.08 0.08	0° Vertical 270°

TYPE OF STRUCTURE
H: High rise (3 or more stories)
L: Low rise (fewer than 3 stories)
F: Free field installation

TYPE OF SOIL
R: Rock
H: Hard soil
S: Soft soil

Table 1–I Recorded Ground Acceleration due to the April 22, 1991 Earthquake

Group	Geological Definition	Natural Period Definition
1	Tertiary or older rock diluvium less than 10 m thick	Period less than 0.2 s
2	Diluvium with thickness 10 m or more or alluvium less than 25 m thick including soft layer less than 5 m thick	Period between 0.2 and 0.6 s
3	Other than the above, usually soft alluvium or reclaimed land	Period more than 0.6 s

Table 1–II Site Classifications for Kawashima et al. Attenuation Relationship

Ground motion Parameter	Group #	a	b	d
Acceleration (gals)	1	987	0.216	–1.218
	2	233	0.313	–1.218
	3	404	0.265	–1.218
Velocity (cm/sec)	1	20.8	0.263	–1.222
	2	2.81	0.430	–1.222
	3	5.11	0.404	–1.222

Table 1–III Empirical Constants for Kawashima et al. Attenuation Relationship

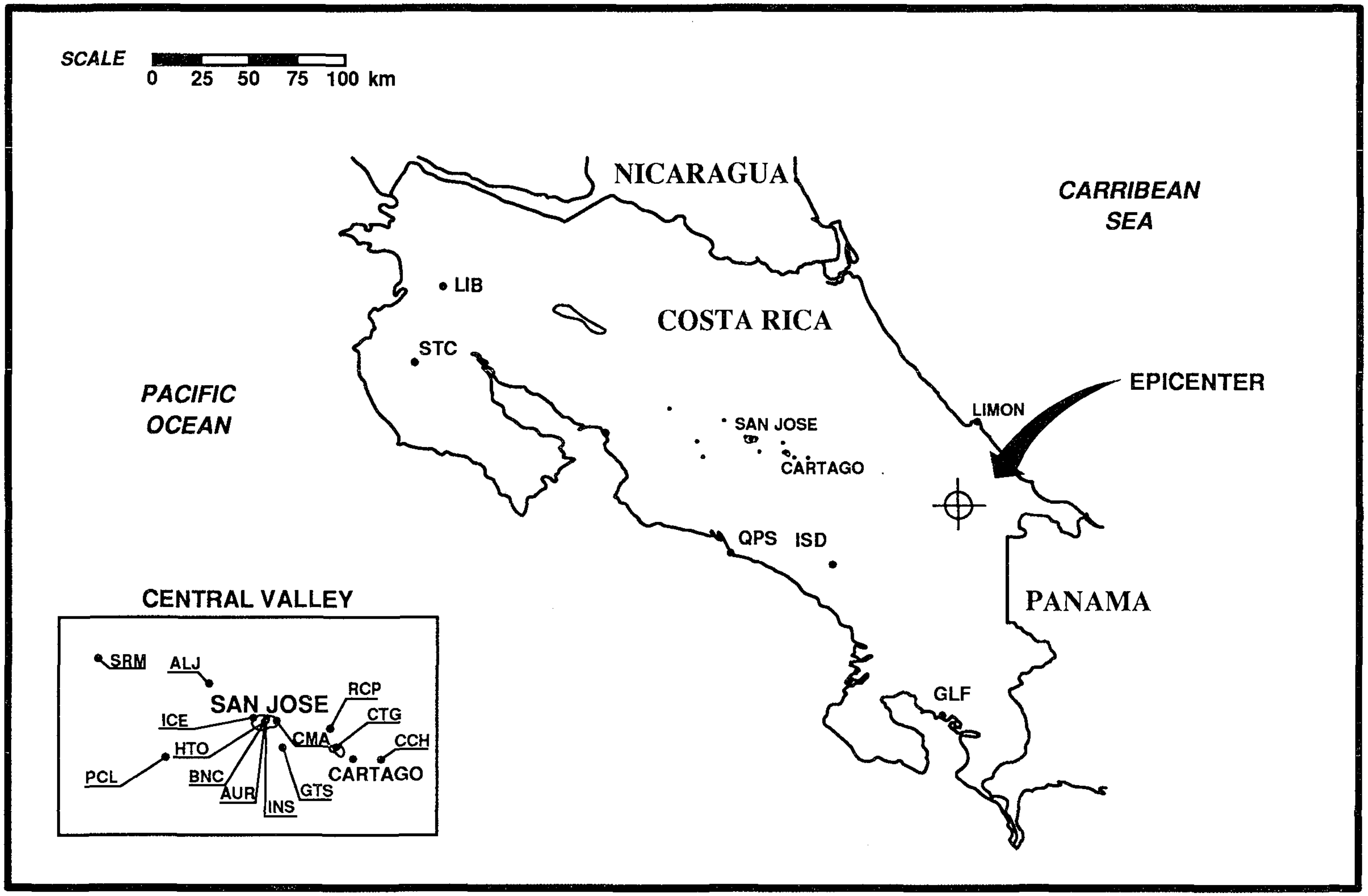

FIGURE 1–1 Map of Costa Rica Showing April 22, 1991 Epicenter, Limón on Caribbean Coast and Accelerograph Stations (after UCR Earthquake Engineering Lab. Report, 1991)

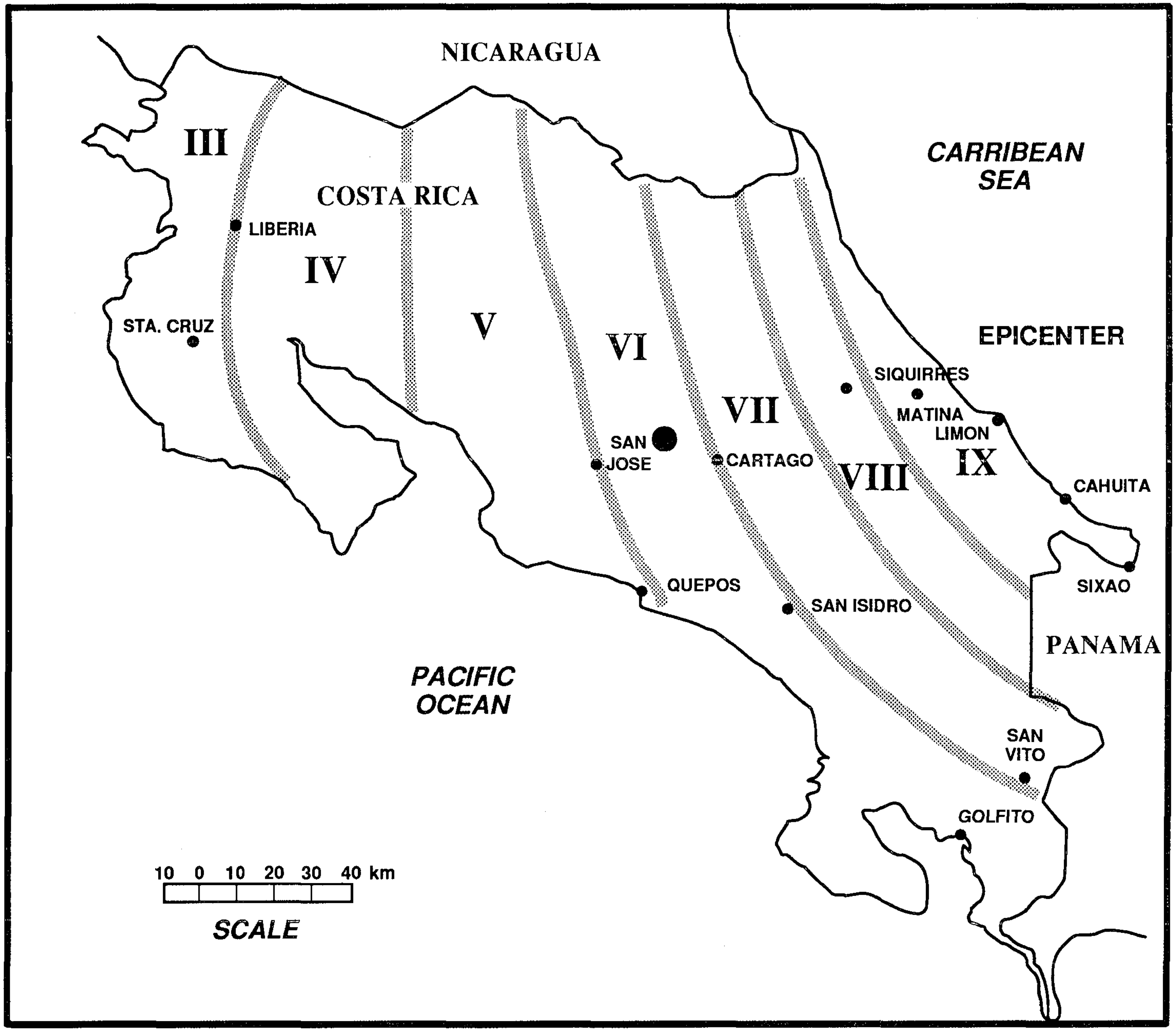

FIGURE 1–2 Isoseismal Map for April 22, 1991 Earthquake (after OVSICORI–UNA Report, 1991)

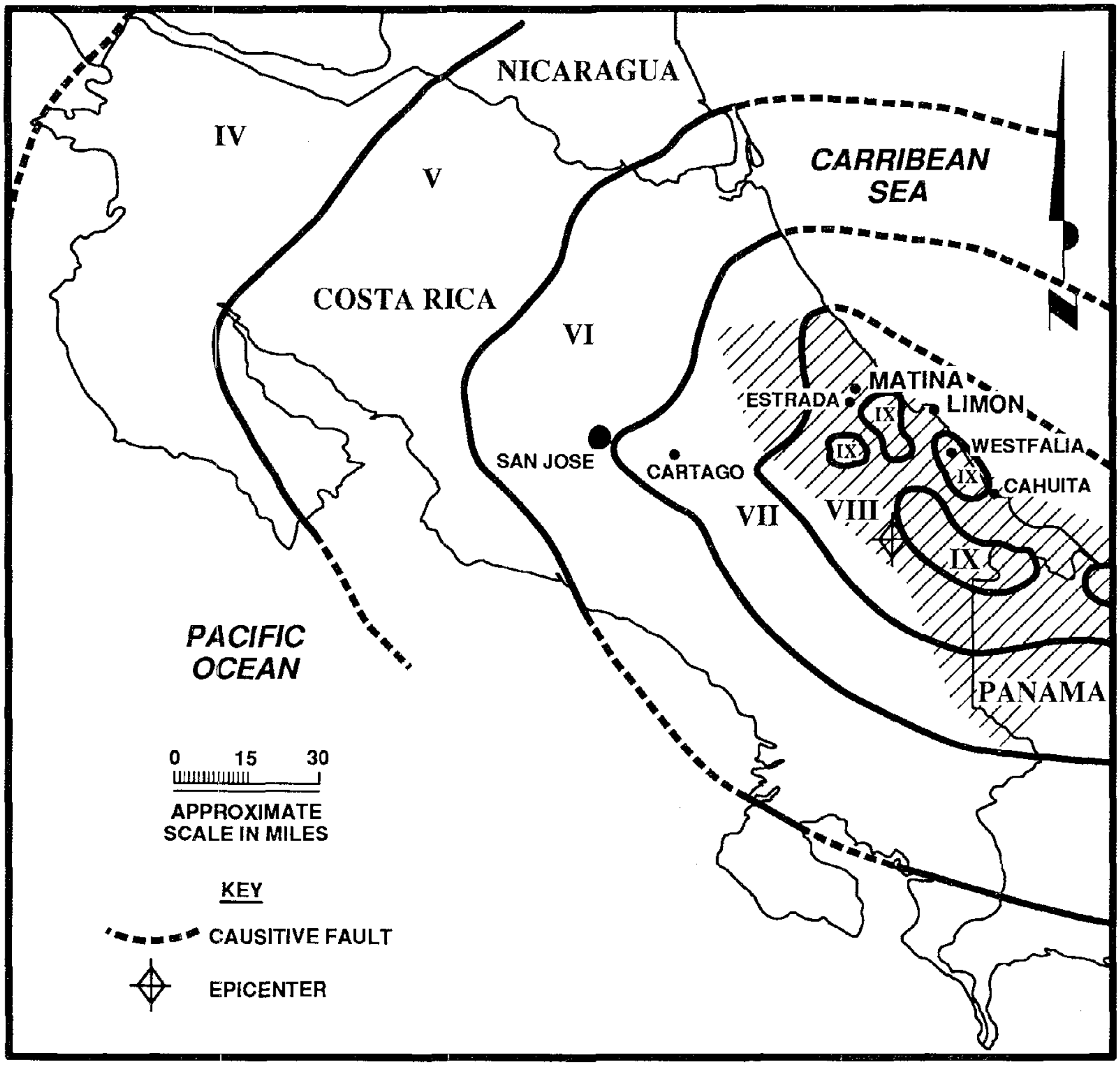

FIGURE 1–3 **Isoseismal Map for April 22, 1991 Earthquake (after Earthquake Spectra Report, 1991)**

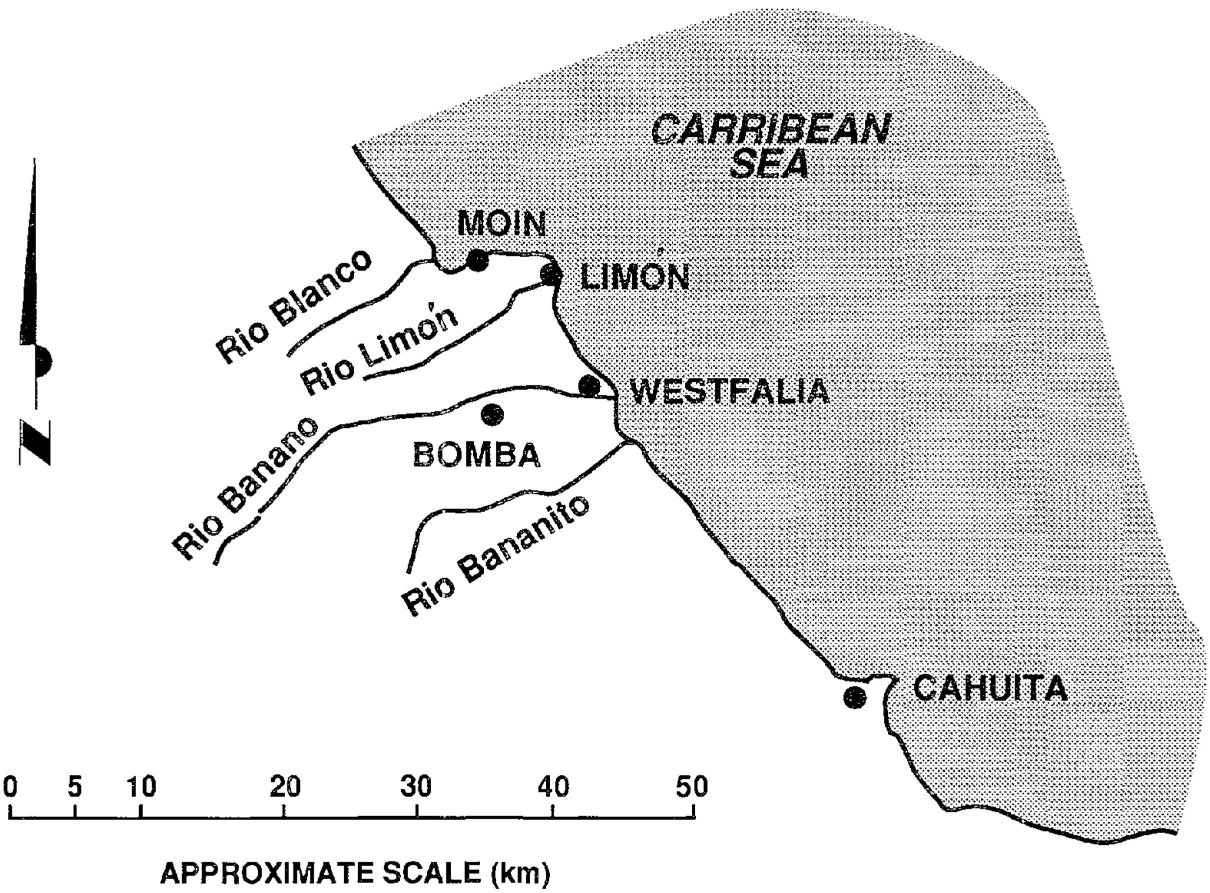

FIGURE 1–4 Map of Coastal Region near Limón, Costa Rica

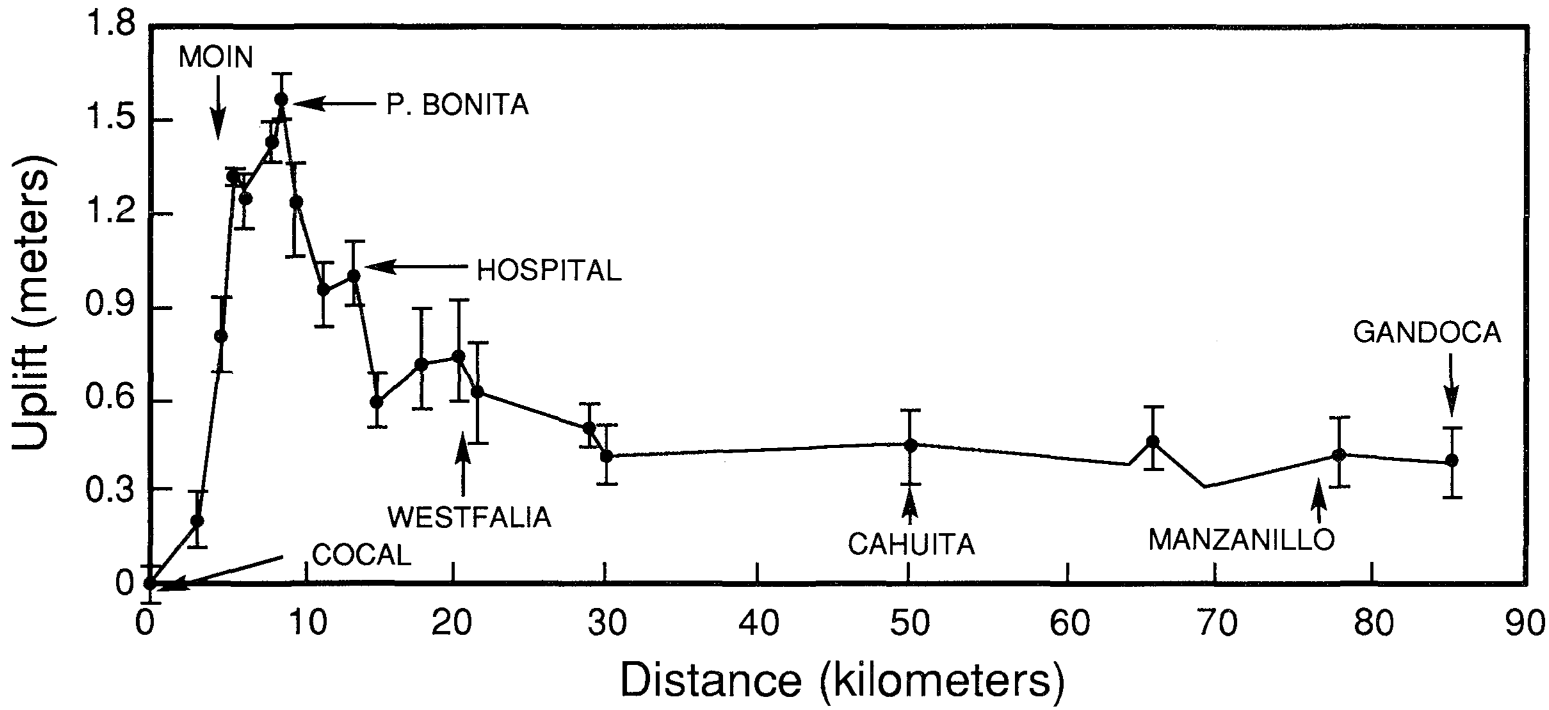

FIGURE 1–5 Coseismic Uplift along Caribbean Coast for April 22, 1991 Earthquake (after OVSICORI–UNA Report, 1991)

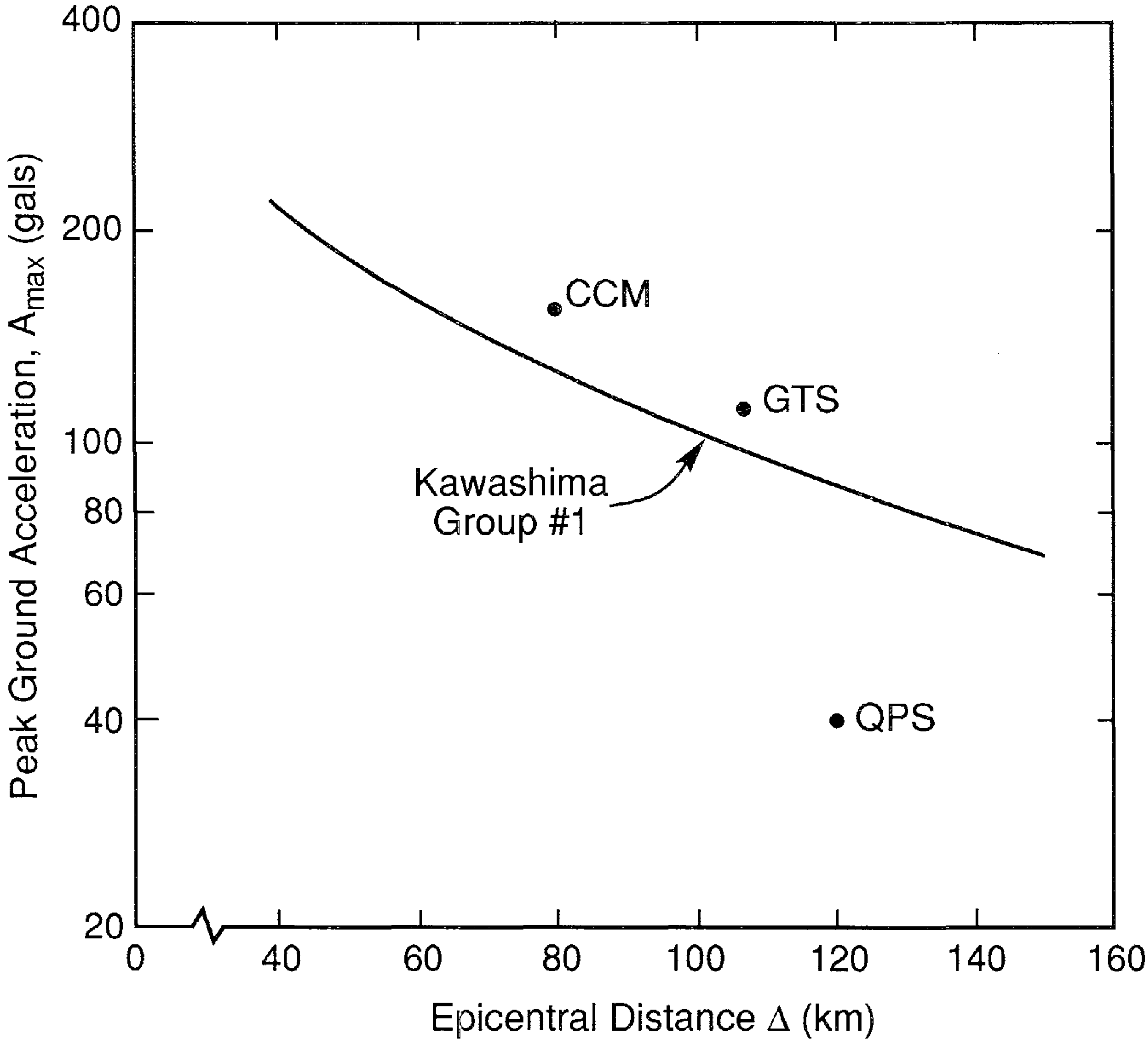

FIGURE 1–6 **Peak Horizontal Ground Acceleration for Rock Sites in Table 1–I and Kawashima et al. Relation for Site Group #1**

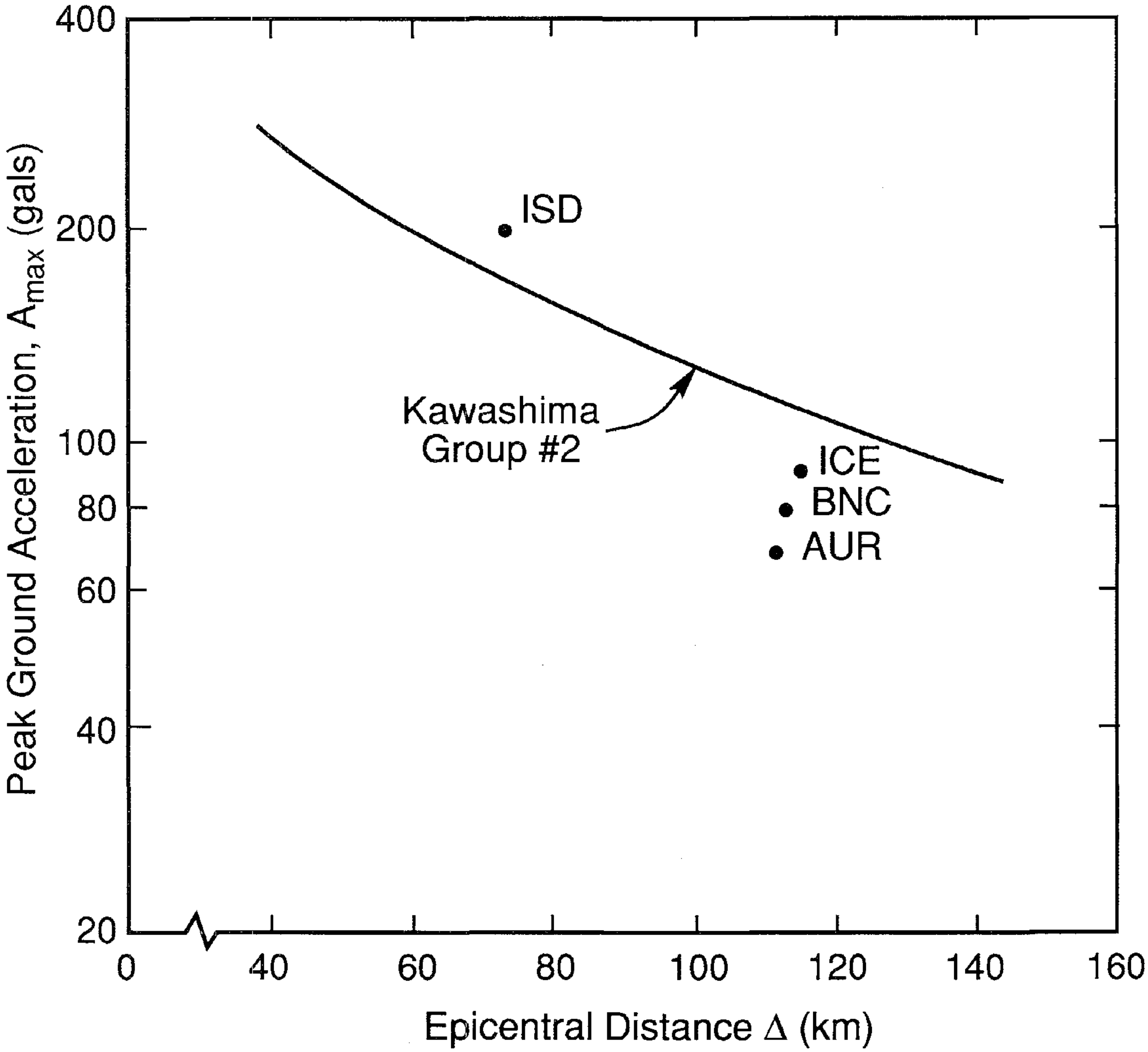

FIGURE 1–7 **Peak Horizontal Ground Acceleration for Hard Sites in Table 1–I and Kawashima et al. Relation for Site Group #2.**

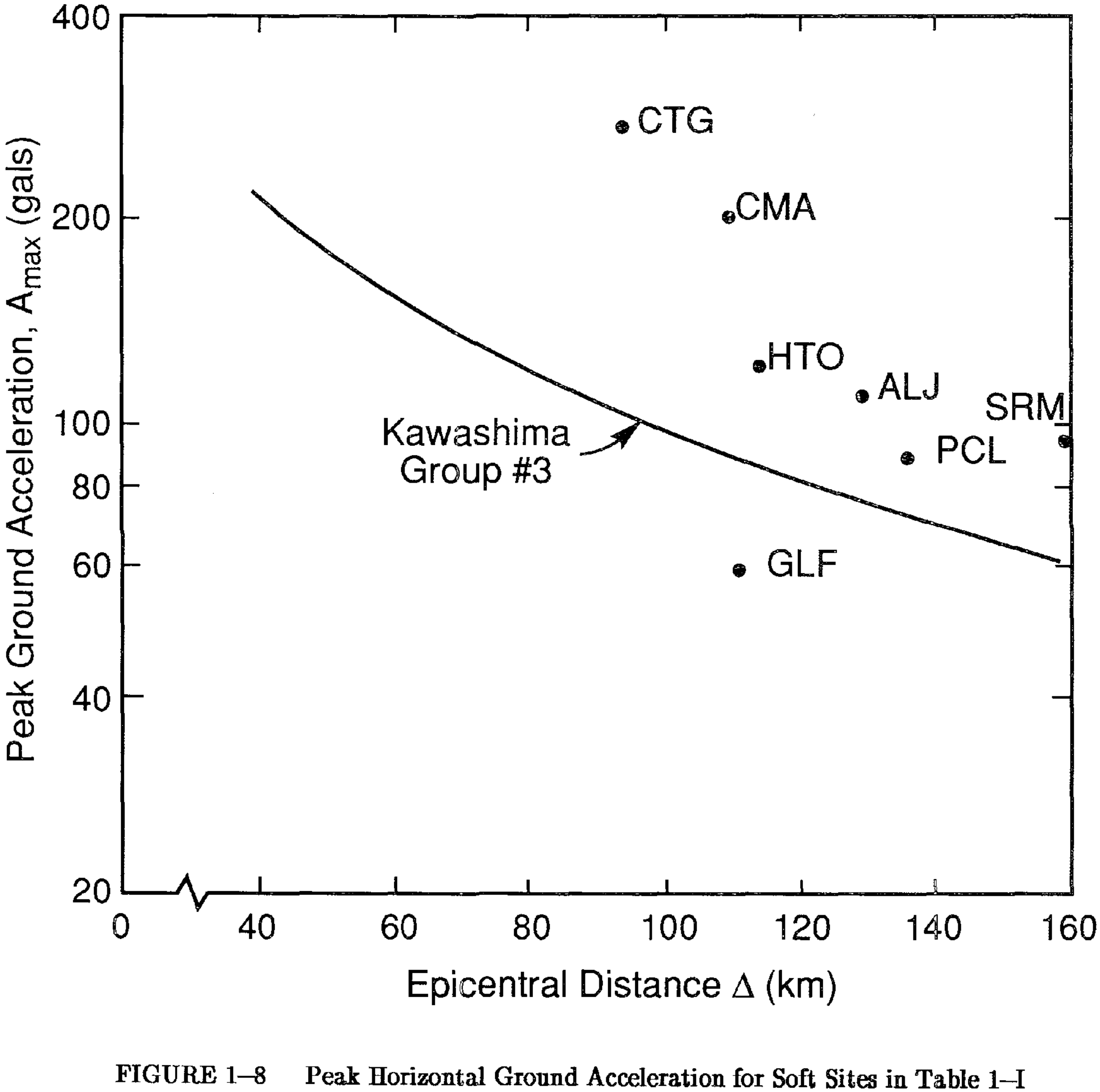

FIGURE 1–8 Peak Horizontal Ground Acceleration for Soft Sites in Table 1–I and Kawashima et al. Relation for Site Group #3.

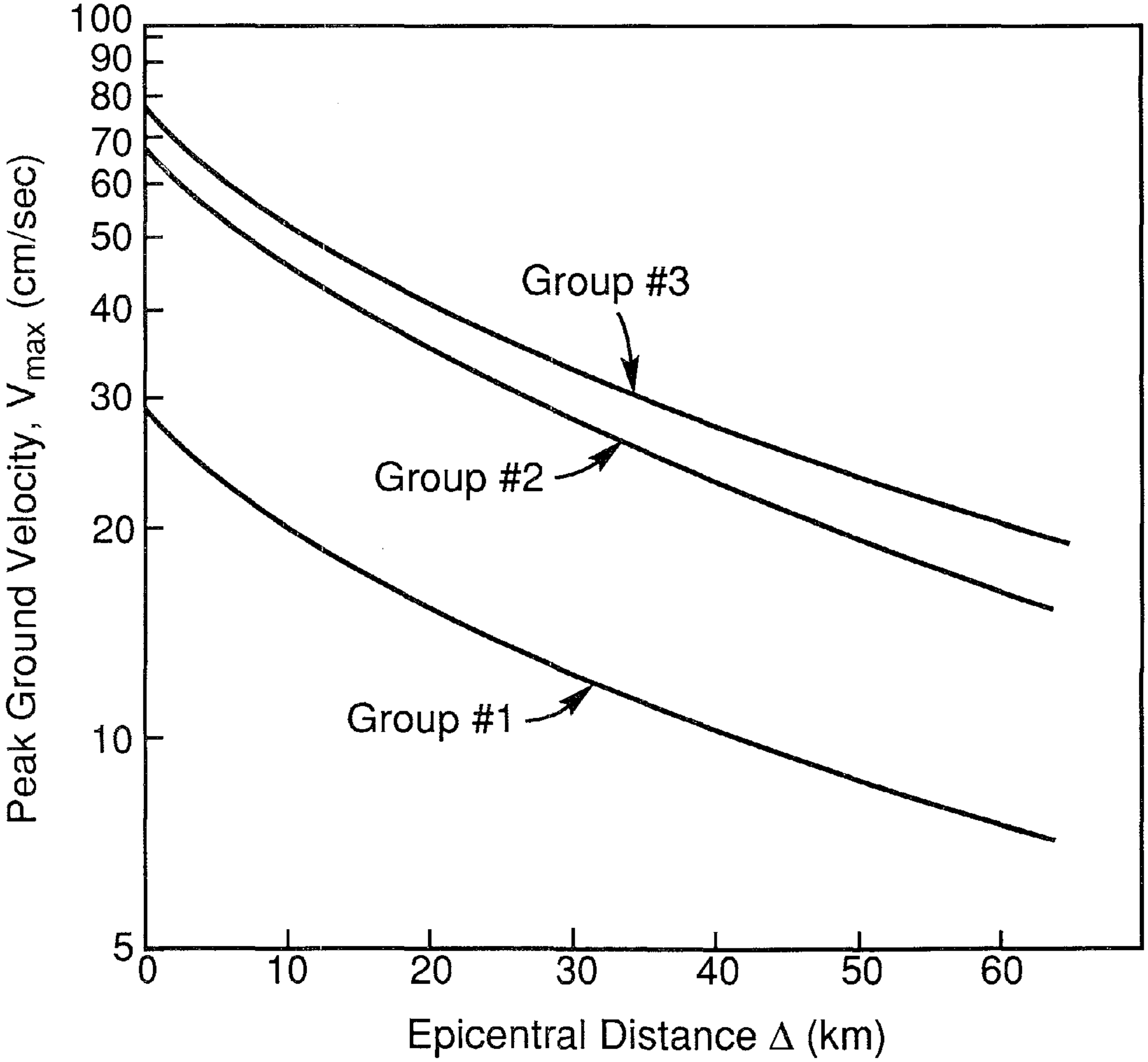

FIGURE 1–9 **Peak Ground Velocity Predicted by Kawashima et al. for moment magnitude M = 7.5 (Site Groups #1, #2, and #3)**

SECTION 2

WATER SUPPLIES AND TREATMENT PLANT

This section describes the water supply and water treatment facilities serving Limón and Moin, and earthquake damage to the treatment facilities. Water transmission and distribution pipelines are described in Section 3. Post–earthquake recovery of the water system, including the water treatment plant is described in Section 5.

2.1 System Description

The Limón and Moin areas have a population of about 60,000 people. The overall system demand is 350 liters per second (lps). The primary water supply, approximately 250 lps, is pumped from the Rio Banano to a water treatment plant in Bomba. The Rio Banano rises in the rugged foothills of the jungle covered Cordillera de Talamanca. Access to most of the watershed can be achieved only on foot. An estimated 250 families live in the watershed.

The raw water pump station shown in Figure 2–1 consists of three split case pumps as shown for example in Fig. 2–2, taking suction from a pipe hung in the Banano River, protected by gabions. The treatment plant, built in 1982, has a capacity of 350 lps. It is located on a hill which appeared to be geotechnically stable. Treatment tankage is reinforced concrete.

The water treatment process consists of pre–chlorination, alum addition for flocculation, clarification, filtration through dual media filters, and post chlorination. There is no provision for presettling. Alum is fed through one of two dry chemical feeders. Flocculation is achieved through static mixing in tanks with asbestos cement baffles. Clarification is achieved using plate clarifiers also constructed of asbestos cement. Chlorine is supplied in 68 kg cylinders. The plant is equipped with a small laboratory. The facility normally sees maximum turbidities of approximately 1,600 milligrams/liter, mg/l. Prior to construction of the plant, water was pumped directly out of the river, into the system with no treatment.

The Siguerres water treatment plant, approximately 50 km west–northwest from Limón, had a design very similar to the Limón water treatment facility.

After treatment, the water flows by gravity to Limón and Moin through 300 mm (12 inch) and 500 mm (20 inch) pipelines. These transmission lines connect into the southeast side of the distribution system.

Seven wells are located along the pipeline alignment from Bomba to Limón. These wells provided a standby supply prior to the earthquake. Two of the wells were dry prior to the earthquake. The remaining five wells have a capacity of approximately 100 lps. It appeared that these wells were relied on more heavily prior to construction of the treatment plant.

The second water supply, approximately 100 lps, comes from a spring source in Moin, and is connected to Limón through an independent 300 mm (12 inch) ductile iron transmission line connecting into the northwest side of the distribution system.

2.2 Earthquake Damage

Earthquake Modified Mercalli Intensity, MMI, at the treatment plant site in the Bomba watershed is estimated from Section 1 and Figures 1–2 and 1–3 to be VIII. Peak ground acceleration at Bomba, based on Figure 1–7, and correlation with MMI is estimated to be approximately 300 gal.

In the watershed, 27 landslides were identified, one creating a lake. Several of these landslides are shown in Figure 2–3. A high percentage of the resulting steep barren slopes would have normally been jungle. Turbidity in the Rio Banano increased to as high as 24,000 mg/l, (2.4 percent solids) on 2 May 1991, one of the first major rain storms of the rainy season. The rainy season was only two weeks old, and would be expected to last into November.

The high solids content water clogged the raw water pump suction. Otherwise, the raw water pump station was undamaged.

Even at lower turbidities, water treatment was very difficult and reduced the plant capacity. There was hope that the extremely high turbidity was a transient condition, and that the loose soil would be flushed away with further rain.

At the treatment plant, an unrestricted chlorine cylinder shown in Figure 2–4 toppled, breaking connecting piping and releasing chlorine. One worker was injured by the chlorine. One unanchored dry chemical feeder shown in Figure 2–5 used for feeding alum toppled, breaking connecting piping and puncturing the bottom.

Asbestos cement baffles in the flocculators and asbestos cement clarifier plates were broken as shown in Figure 2–6 through 2–9. One concrete channel cracked. Glassware in the lab and the portable radio, sitting on the shelf, were undamaged. There was no reported damage to the filters.

For comparison, the Siquerres water treatment plant, located in an area with intensities estimated to be between VII and VIII was undamaged. The peak ground acceleration at this point, based on Figure 1–7, and correlation with the MMIs is estimated to be 190 gal.

There was no earthquake damage reported to the seven wells adjacent to the pipeline between Bomba and Limón. In addition there was no earthquake damage to the Moin spring supply.

2.3 Evaluation and Recommendations

2.3.1 Elevated Turbidity

There is no previous record of earthquake induced landslides occurring in water sheds which have resulted in elevated turbidities. However, in two earthquake vulnerability projects involving water sheds, landslides resulting in elevated turbidity were an identified concern. The City of Portland, Oregon's primary water supply comes from the Bull Run water shed. In 1972, a flood induced landslide exposed a deposit of volcanic ash in the water shed. Until it was stabilized, water with elevated turbidities entered the distribution system. Landslides continue to be a threat to Portland's primary water supply. Partially as a result of the impact of the slide, Portland developed an alternative groundwater supply that could be used in the event of disfunction of the primary surface water supply. Additional system operation flexibility was provided.

The City of Everest, Washington relies on water from the Sultan River water shed. Originally, water was taken directly from the Sultan River. More recently a concrete diversion dam and tunnel to Lake Chaplain, a manmade impoundment, was completed. Operators still have the capability to withdraw water directly from the Sultan River, bypassing the lake. Today, landslides resulting in increased turbidity may occur in either the Sultan River water shed or in Lake Chaplain. In either case, the city has the ability to select the source of raw water from either the Sultan River or Lake Chaplain, until turbidity problems are mitigated. Again, system operational flexibility seems to be the solution.

2.3.2 Chlorine Cylinders

This is the third significant earthquake in the past years where chlorine leaks have resulted from earthquake damage [9, 10]. In both the 1989 Loma Prieta earthquake and the 1990 Philippine earthquake, vertical chlorine cylinders without lateral restraint also toppled, breaking connecting piping.

Chlorine, in cylinders, is used extensively throughout the world as a disinfectant for potable water supplies. Few installations adequately anchor the cylinders. The solution is simple. Restrain each cylinder at both the top and bottom.

The Uniform Building Code [11] now requires that structures housing gaseous chlorine systems be designed to automatically contain and neutralize any chlorine leak. These systems require air scrubbers with emergency generators so they are operable when power supply is lost. As a result of the cost for these facilities, many small chlorination systems are being designed using sodium hypochlorite, chlorine bleach. Although the chemical cost is approximately twice that of gaseous chlorine, the capital cost of the system including life safety components, is much less.

2.3.3 Flocculators and Plate Clarifiers

Flocculators are provided in water treatment plants following addition of coagulants, to allow agglomeration of small particles so that they will settle out. One means of providing flocculation is by hydraulic movement of the water through baffles to slowly provide mixing.

Plate clarifiers, structurally similar to baffles, are installed in clarifier tanks to enhance clarification. The increased efficiency of clarification results from an increased projected horizontal surface area. Other processes in water treatment may also depend on baffles in tanks such as clarifiers and chlorine contact tanks with serpentine flow.

Depending on the configuration, these baffles are subjected to both impulsive and convective loads from water during an earthquake [12]. Closely spaced baffles are loaded with essentially 100 percent of the effective mass times the lateral earthquake acceleration of the water between them. Baffles spaced further apart are loaded to a lesser degree by the impulsive loads, but to a greater degree by convective or "sloshing" loads.

These extreme loads shattered the non–ductile asbestos cement baffles in the flocculators at the water treatment plant in Bomba. Extensive baffle damage occurred in the Loma Prieta earthquake at water and wastewater treatment plants. Examples include racking of the reactor clarifiers at the Rinconada Water Treatment Plant, breaking up of the wooden baffles in the flocculator at the Montevina Water Treatment Plant, and bending of the baffles structural supports in the chlorine contact tank at the San Mateo Wastewater Treatment Plant [12].

Operationally, water treatment plants can be kept on line at lower treatment rates when the flocculators and clarifiers are not operational. The Rinconada Water Treatment Plant initiated direct filtration at less than half the treatment rate available when the flocculators and clarifiers are operable.

To minimize earthquake damage, baffles must be designed to either resist these significant hydraulic loads, or to break away with a design for easy repair. Design to resist loads, depending on the configuration, become cumbersome. Break away designs are encouraged. Break away designs should provide a restraint to keep the baffle from falling to the tank bottom.

2.3.4. Concrete Tank and Channel Cracking

Reinforced concrete tanks have resisted damaged from earthquakes very well. This may be a result of the conservative tank design employed to minimize cracking for water–tightness. The only significant concrete tank or channel cracking reported in the Loma Prieta earthquake was at the Santa Cruz Wastewater Treatment Plant [12]. In that instance, the crack occurred at a construction joint between two segments constructed at different times. A secondary concern associated with undermining by leaking water may be a problem. At the water treatment plant in Bomba, there was inadequate information available to evaluate the likely cause of the cracking.

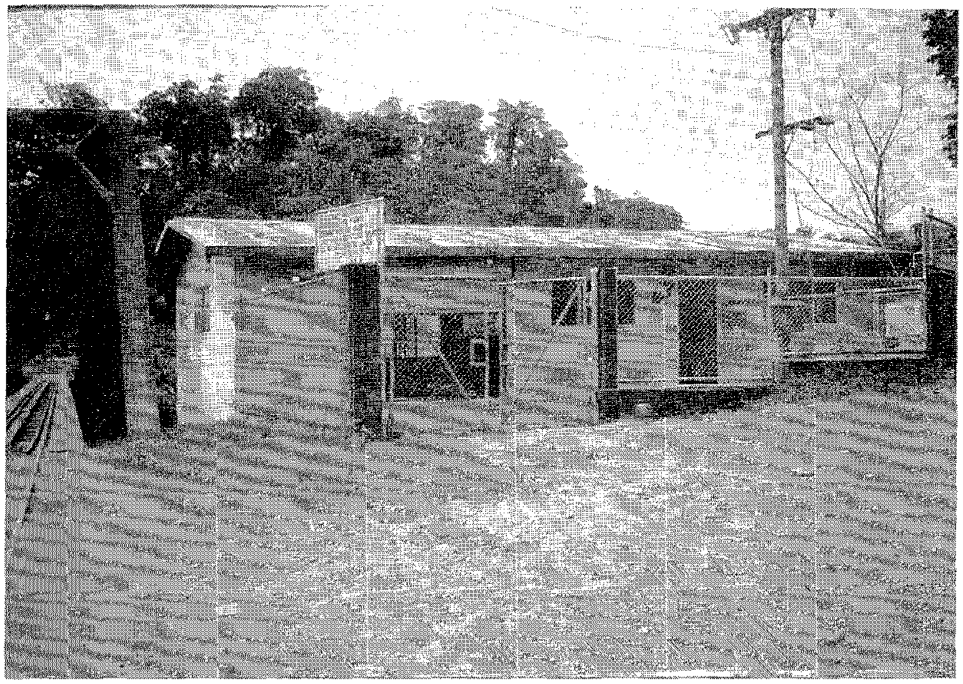

FIGURE 2–1 Undamaged Raw Water Pump Station on the Banano River

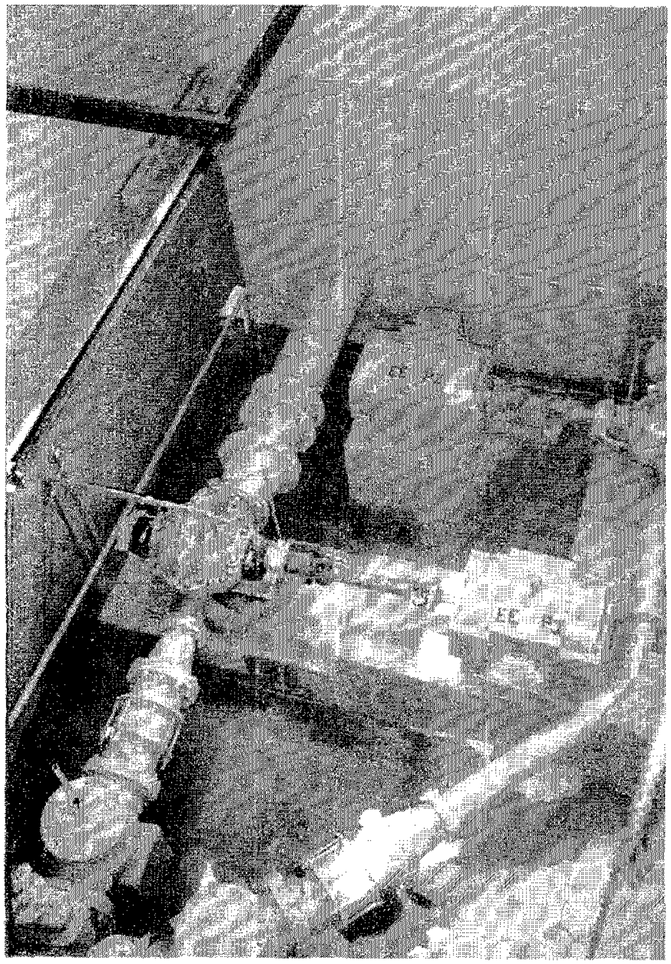

FIGURE 2–2 Split Case Pump in Raw Water Station on the Banano River

FIGURE 2–3 Air Photo Showing Landslides in Banano River Water Shed

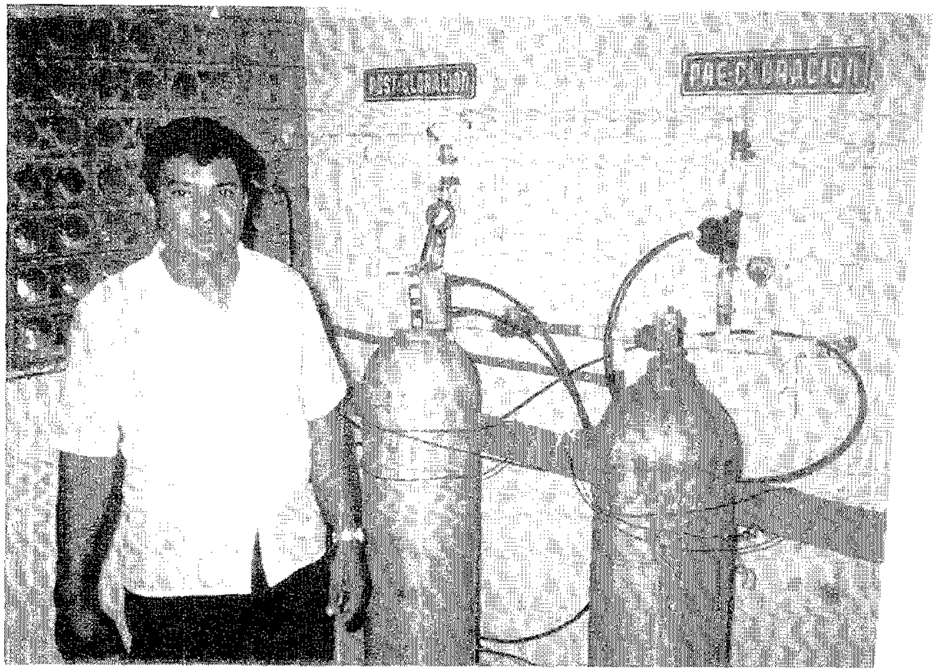

FIGURE 2–4 Chlorine Cylinder which Toppled Breaking Connection Pipe and Rcleasing Chlorine

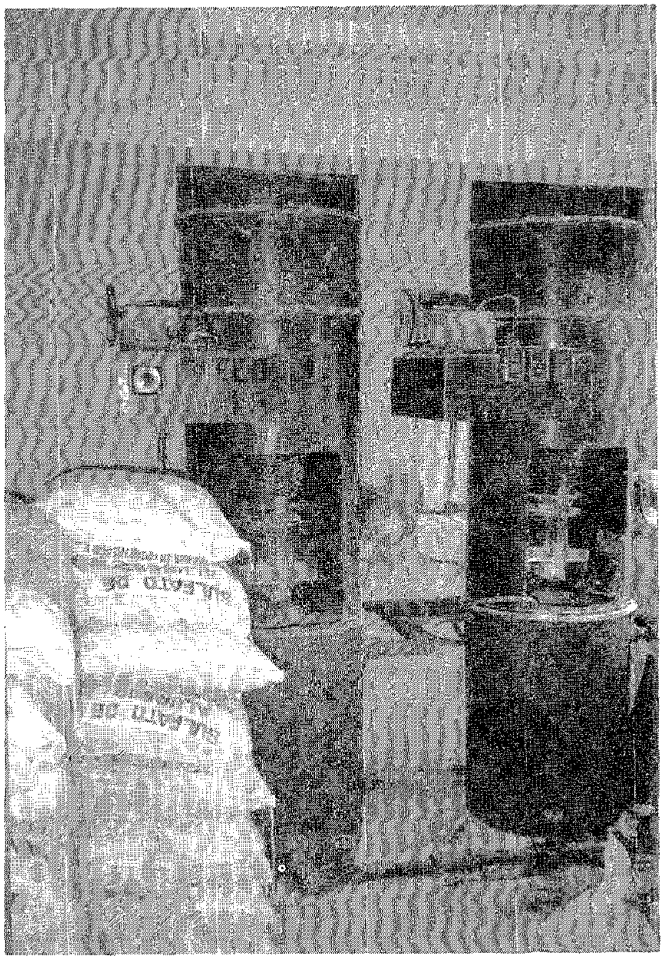

FIGURE 2–5 One of the Two Unanchored Dry Chemical Feeders Fell over and was Reinstalled after Repairs

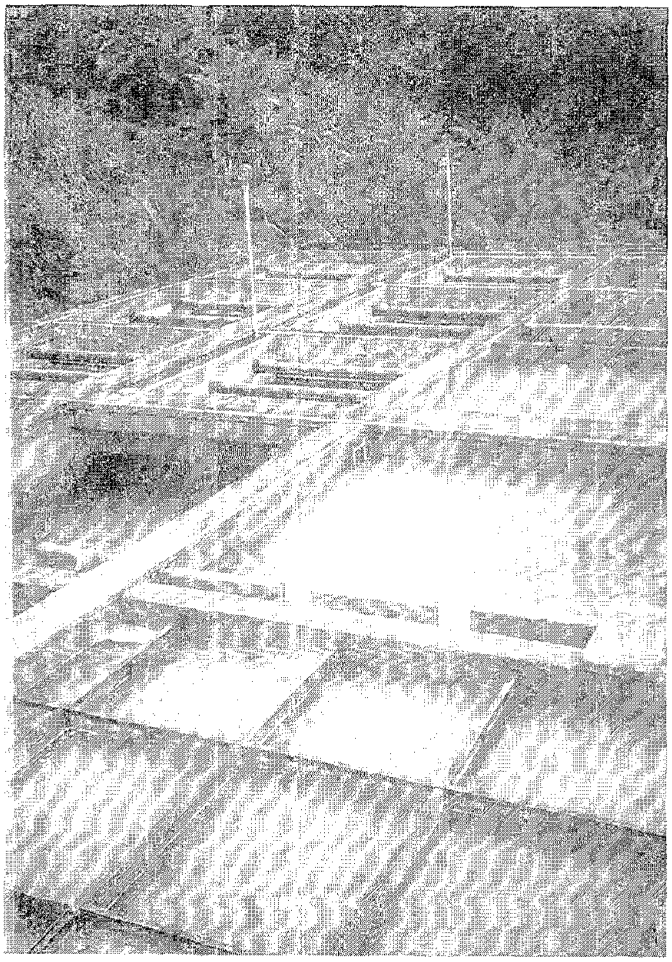

FIGURE 2–6 Operating Flocculators in Foreground with Clarifiers Beyond

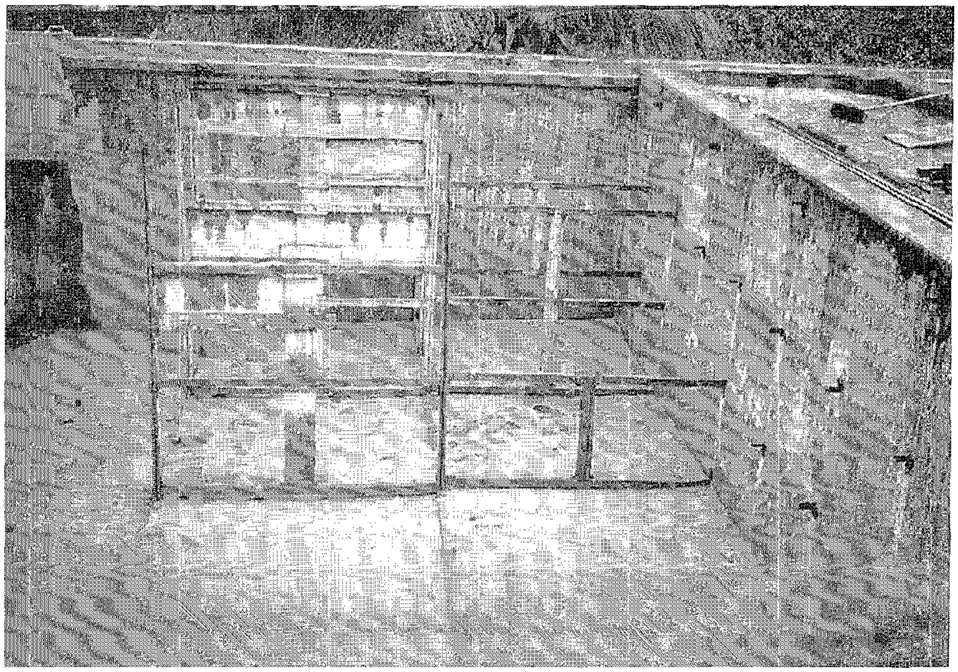

FIGURE 2–7 Flocculator Baffles Being Replaced after Earthquake Induced Hydraulic Load Damage

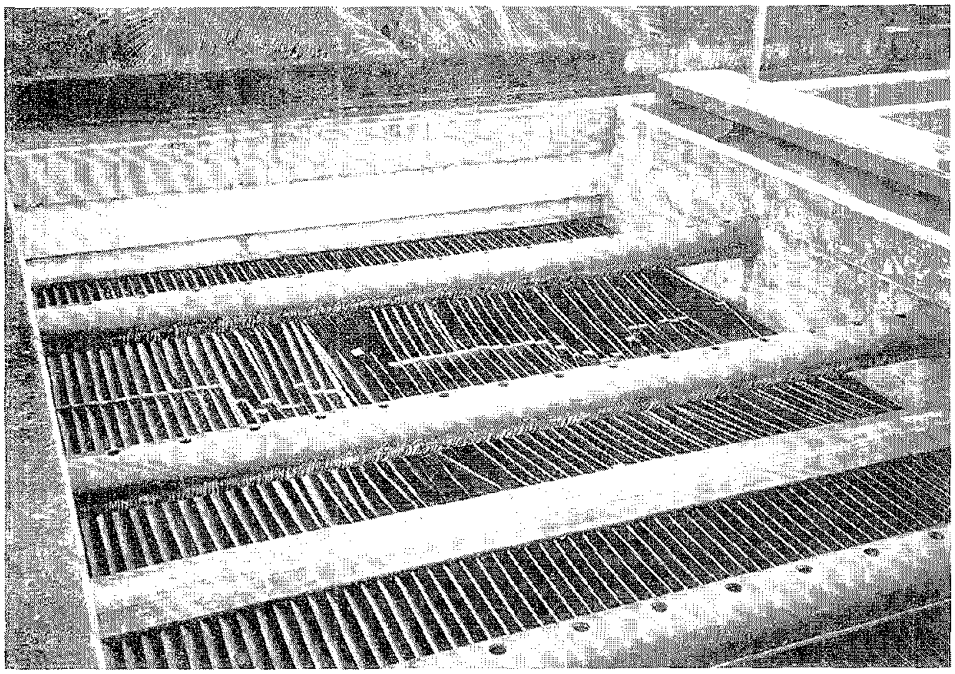

FIGURE 2–8 Broken Asbestos Cement Clarifier Plates, Similar Plates at Siquerres Water Treatment Plant (~ 190 gal) Were Undamaged

FIGURE 2–9 Piles of Broken and Removed Asbestos Cement Flocculator and Clarifier Plates

SECTION 3
SEISMIC DAMAGE TO PIPELINES

As noted previously Instituto Costarricense de Acueductos y Alcantarillados (AyA), the national water and sewer company, provides potable water to the Limón area. In addition Refinadora Costarricense de Petroleo (RECOPE) operates a liquid fuel pipeline between Limón and San Jose to the West as well as a coding water line which was damaged in the earthquake. In this section, seismic damage to AyA water transmission and distribution pipelines and the RECOPE liquid fuel pipeline, occasional by the April 22, 1991 earthquake, will be described in detail. In the following section the damage ratio (repairs per kilometer) to the AyA pipelines will be compared to existing empirical relations.

3.1 Water Transmission Pipeline

Potable water for the Limón area comes from two sources; the Banano River treatment plant and pump station located about 14 km south of Limón, and the Moin well field located about 5 km northwest of Limón. The Transmission line from the Moin wells is 300 mm (12 inch) nominal diameter Ductile Iron (DI) pipe constructed in 1970. Two pipelines transport water from the Banano River source. They are a 300 mm (12 inch) diameter Cast Iron (CI) line constructed in the 1930's and a 500 mm (20 inch) diameter reinforced concrete cylinder pipe (RCCP) constructed in the 1980's. The Cast Iron pipe has primarily unbolted mechanical joints while the RCCP pipe (AWWA C303 – Reinforced Concrete Water Pipe – Steel Cylinder type, Pretensioned) manufactured by CANRON of Canada has rubber gasketed bell and spigot joints. As shown in Figure 3–1 the RCCP pipe consists of a 16 gauge steel "can", wire wrapped for structural integrity, with mortar lining and coating resulting in a total wall thickness of 4.76 cm (1.875 in). Steel bells and spigots were welded to the can on either end of the pipe. The joint has a bell depth of 8.3 cm (3.25 in). The nominal pipe length is 7.4 meters (24 feet). At some locations both pipelines follow the same right–of–way. Figure 3–2 shows the C.I. pipe on the ground surface (under the back wheel of the backhoe) and the buried concrete pipe being repaired about 4 meters to the right.

3.1.1 Aggregate Damage to Transmission Piping

As of October 2, 1991, AyA reported a total of 16 repairs to the 4.54 km length of D.I. pipe from the Moin well fields. For the two pipelines from the Banano River, AyA reported 41 repairs for the 12.5 km length of CI pipe and 120 repairs for the 14 km length of RCCP pipe. This results in aggregate damage ratios of 3.5, 3.3 and 8.6 repairs per kilometer respectively. This information is summarized in Table 3–I. As will be discussed in Section 4, experience from past earthquakes suggests that the expected seismic damage to DI pipe, particularily from wave propagation, is substantially less that that to CI pipe. The authors believe that the relatively large amount of DI transmissions pipe damage in the April 22 event, as compared to the CI transmission pipe damage, is attributed to the coseismal uplift discussed in Section 1. That is, the DI transmission line from the Moin well field was apparently subjected to larger coseismal uplift than the CI transmission line from the Banano River water treatment plant. Most of this damage was due to the April 22, 1991 main shock, but according to AyA engineer J. Arguedas [3], some damage particularly to the RCCP pipe line was due to subsequent aftershocks. Also note that some of the earthquake induced leaks were discovered only after other leaks were repaired and the line temporarily repressurized. In addition, a number of leaks to the DI line from the Moin well field had to be repaired more than once. However, the aggregate value of the repairs in table 3–I corresponds to individual leak locations where one or more repairs were required.

For the D.I. and C.I. transmission piping, AyA identified three types of damage mechanisms; a break in the pipe segment body (e.g. round crack), a break in a union piece connecting two pipes segments, and pullout joint separation. Figure 3–3 shows sketches of these three mechanisms, as well three others which will be discussed later in relation to distribution pipe damage. Table 3–II presents a breakdown of the repair data by damage mechanisms for the D.I. and C.I. transmission piping. Notice that roughly half of the C.I. and D.I. transmission damage was due to joint pull–out as shown in Figure 3–3f while the remaining half was due primarily to breaks in the pipe segments themselves as shown in Figure 3–3a.

The repairs in the RCCP transmission pipe were due primarily to joint failure, either compressive telescoping as shown in Figure 3–3e or joint pull–out as shown in Figure 3–3f. AyA noted that the RCCP pipes black rubber gasket was visible in many cases suggesting that the percentage of repairs occasioned by joint pull–out was larger than that due to compressive telescoping.

3.1.2 Details of Transmission Pipe Damage

Figure 3–4 shows a repaired portion of the 300 mm (12 inch) C.I. Banano River transmission pipe. In this case, the seismic damage occurred in the barrel portion between joints corresponding to Figure 3–3a. Figure 3–5 shows what appears to be a pin hole in the damaged portion immediately to the right of the tree branch. Hence it appears that pipe corrosion contributed to the failure shown in Figure 3–4. As noted by Isenberg and Taylor [14], seismic damage often occurs in buried pipelines previously weakened by corrosion. Also note that an old repair coupling was found on the line about 10 m away from the seismic damage shown in Figure 3–4. This is further evidence that this local area suffered damage prior to the April 22 earthquake.

The 500 mm (20 inch) diameter RCCP pipeline from the Banano River was the most heavily damaged,in terms of the number of repairs per unit length, of all pipelines in and around the Limón area. As mentioned previously, most of this damage to RCCP pipe was at joints, corresponding either to a compressive telescoping failure shown in Figure 3–3e or a joint pull–out failure shown in Figure 3–3f. Figures 3–6 through 3–13 described PGD which occurred along a 750 m section of the main road out of Limón, near Pueblo Nuevo. There were 20 repairs to the 500 mm (20 inch) RCCP pipe which parallels the road at this location. That is, a sixth of the 120 RCCP repairs occurred in this location, resulting in a damage ratio of 26.7 repairs per kilometer (8.1 repairs per 1000 ft.) for this 750 m length of pipe.

Figure 3–6 is a view from a railroad underpass looking East towards the Caribbean. At the center of this photograph there is a 12.8m (42 foot) length of severe road damage as measured along the road center line. As shown in Figure 3–7, a view looking West towards the railroad underpass, there was about a 0.4 m (16 in) lateral effect over this 12.8 m (42 foot) length of road damage. The block in the foreground moved to the left (i.e. to the South). There also appeared to be a vertical offset which could not be measured. To the immediate North of the road damage there was ground cracks measuring 15 cm to 30 cm (6 to 12 inches) in width and garbens as shown in Figure 3–8 through 3–10. Garbens to the North of the road are consistent with lateral movement of the road to the South. Figure 3–11 is a sketch of this area near the railroad underpass, showing the length and width of the garbens as well as the road offset.

About 500 meters to the East of the railroad underpass, there was an area of abrupt vertical PGD near a drainage culvert as shown in Figure 3–12. There was a total vertical offset of about 20 cm (8 inches) over a distance of roughly 15.8 m (52 feet). The individual vertical offsets were 2.54, 7.6, 7.6 and 2.5 cm (1, 3, 3 and 1 inch) separated by distances of 4.3, 6.4 and 5.2 m (14, 21 and 17 feet) respectively as shown in Figure 3–13.

Although much of the transmission pipe damage is attributed to PGD there were certain locations where it appears that damage was due to seismic wave propagation. For example, Figure 3–14 shows an area above a yet to be excavated pipeline leak. The ground was very wet, but no ejected sand was observed in the area. Also note that the fence line shown in Figure 3–15 is reasonably straight and there was no obvious settlement or lateral displacement to the dirt and gravel road shown in Figure 3–16. This leads one to suspect that this leak was due to seismic wave propagation.

3.2 Water Distribution Pipelines

The water distribution system for Limón consists of two storage standpipes, a in–ground reservoir and about 110 km of distribution piping. The steel storage standpipes, Pueblo Nuevo and Corrales both have height to diameter ratio, H/D, near one. The 4 million liter concrete reservoir is located at the operations yard in Limón. Except for cracking at the roof/wall intersection of the in–ground concrete reservoir, shown in Fig. 3–17, these three storage facilities were undamaged by the earthquake.

The distribution pipe is composed of Polyvinal Cloride (PVC), Cast Iron, (CI) Asbestos Cement (AC) and Galvanized Iron (GI) with diameters ranging from 18 mm (3/4 inch) to 350 mm (14 inch).

3.2.1 Aggregate Damage to Distribution Pipes

As of October 2, 1991, AyA reported a total of 246 repairs to the 50.3 km of PVC piping, 34 repairs to the 28.4 km of CI piping, 81 repairs to the 16.8 km of AC piping, and 39 repairs to the 10.2 km of GI piping. This results in aggregate damage ratios of 4.9, 1.2, 4.8 and 3.8 repairs per kilometer for PVC, CI, AC and GI piping respectively. This information is summarized in Table 3–III.

Table 3–IV presents a breakdown of distribution pipe damage by diameter range for each pipe material. Note there is no common trend when one compares the Damage Ratios for all diameters in Table 3–III with the breakdown by diameter range in Table 3–IV, That is, the damage ratio decreases with increasing diameter for PVC while the reverse occurs for AC. For both CI and GI, most all the pipe is in a single diameter range, hence a breakdown by diameter range is meaningless.

Figure 3–18 is a plot of Damage Ratio versus diameter range for both transmission and distribution piping. In this plot, data points corresponding to a diameter range with less than 10 percent of the total length for that material are excluded. For example, the length of PVC pipe in the 200 to 250 mm (8 to 10 inch) diameter range is only 1.02 km out of a total of 50.3 km and is not plotted on Figure 3–17. As shown in Figure 3–18, the damage ratio for all materials except RCCP fall in the range of 2 to 6 repairs per km and is not strongly influenced by diameter. For the 500 mm (20 inch) RCCP pipe, the damage ratio is above 8 repairs per km.

AyA identified six types of damage mechanisms for the PVC, CI, AC and GI distribution pipeline. These are: a break in the pipe segment (Figure 3–3a), break in union piece connection two pipe segments (Figure 3–3b), blowout at a Tee (Figure 3–3c), disconnection at a Tee (Figure 3–3d), compressive telescoping of a joint (Figure 3–3e), and tensile pull–out at a joint (in Figure 3–3f).

Table 3–V presents a breakdown of distribution pipe repair by damage mechanism. This Table indicates that essentially all the damage to AC piping was due to breaks in the pipe segment (Figure 3–3a) while for GI essentially all the damage was due to a break in the union piece (Figure 3–3b). For PVC about half the damage was due to pipe segment breaks (Figure 3–3a) while joint pullout (Figure 3–3f) was significant for larger diameters in the 75 to 150 mm (3 to 6 inch) range. For CI pipe, which was used for both transmission and distribution, Tables 3–II and 3–V indicate that pipe segment breaks (Fig. 3–3 a) and joint pull–out (Figure 3–3f) account for the majority of damage. As mentioned previously, damage to the RCCP transmissions pipe was due to telescoping (Figure 3–3e) or pullout (Figure 3–3f) at the joints.

3.2.2 Details of Distribution Pipe Damage

Figure 3–19 shows a repair to the barrel portion of a small diameter AC pipe. There was some street damage in this location as shown in Figure 3–20. However a local resident claimed that this street damage occurred after the earthquake as a result of large amounts of water running towards the gutter on the right. Undermining of the street surface seems possible in light of the fact that the road cracks extend only over the right hand side of the road and the cracks were shallow as shown in Figure 3–21. Hence it appears that this damage could very well have been due to seismic wave propagation.

3.3 Liquid Fuel Pipeline

Refinadora Costarricense de Petroleo (RECOPE) operates the liquid fuel pipeline system in Costa Rica. Crude oil and diesel fuel arrives by ship at the Port of Moin about 6 km (4 miles) up the coast from Limón. Some of this product is refined at a plant outside Limón and is pumped from the plant at a pressure of about 6.9 MPa (1000 psi) to San Jose and on to the Pacific Coast. On the nominally flat coastal plane adjacent to the Caribbean, the pipeline is located along the main road from Limón to San Jose, Route 240. This liquid fuel transmission system consists of twin 150 mm (6 in) nominal diameter, welded steel pipe with 6.4 mm (0.25 in) wall thickness (O.D. = 163 mm (6.5 in)).

Immediately after the earthquake, operators at the RECOPE refinery near Limón noticed a pressure drop in one of the two liquid fuel pipelines. The leak was eventually located near the small village of Estrada, close to the bridge over the Chirripo River. As shown in Figure 3–22, the road in this area, which is on fill, was heavily damaged, so much so that it was not possible to determine the amount of vertical or horizontal PGD. However there was evidence of liquefaction as indicated by ejected sand on the ground surface in the foreground of Figure 3–23.

Figures 3–24 and 3–25 show tensile cracks along the lower half of the pipe circumference (as situated on the repair truck) due to severe local buckling (wrinkling) caused by bending of the pipe through an angle of roughly 25°. Although tension cracks in a region of flexural compression appears somewhat odd, the high local curvatures at the wrinkles cause tearing of the pipe wall. This tearing of a welded steel pipe wall due to local buckling also occurred in the 1985 Michoacan Earthquake, as documented by O'Rourke and Ayala [15].

The only failure in the RECOPE liquid fuel pipeline is described above. There were, however, other areas of PGD along the RECOPE pipeline route which did not result in pipeline failure. A description of one such location with particular emphasis on the type of pipe support conditions which avoided failure follows. Figures 3–26 through 3–30 correspond to a 400 m length of sever damage to Route 240, adjacent to the RECOPE liquid fuel pipeline. The elevation of the road surface, built on fill, was roughly 2 to 3 m (7 to 10 feet) higher than that of the native soil. Figure 3–26 shows a vertical settlement of roughly 1 m (3.5 feet) at the western edge of this road damage area. Because of the extensive damage to the road surface, the amount, if any, of horizontal PDG could not be determined. However, there was liquefaction in the area as shown by the ejected sand in Figures 3–27 and 3–28. The deep ground crack towards the middle of Figure 3–27 was caused by the earthquake. The ejected dark gray–black sand had a depth of about 15 cm (6 in) near this fissure. There was also a pre–existing drainage ditch toward the background of Figure 3–27. Figure 3–28 shows ejected sand and a tilted steel support frame (goal post) for the undamaged RECOPE pipeline in the same general area.

The RECOPE pipelines were supported by short concrete railroad ties for part of this area and supported on steel frames (goal posts) in others. Although there were no pipeline leaks in this area, the pipe moved about 15 cm (6 in) with respect to the short concrete supports as shown in Figure 3–29, and were distorted as they snaked over the steel support frames as shown in Figure 3–30.

The flexible support conditions for the RECOPE line in this area, (i.e. ground level concrete supports and above ground steel frames) certainly contributed to the lack of pipeline damage.

Material	Diameter mm (in)	Length km	Repairs	Damage Ratio repairs/km
DI	300 (12)	4.54	16	3.5
CI	300 (12)	12.5	41	3.3
RCCP	500 (20)	14.0	120	8.6

Table 3–I Summary of Repairs to Water Transmission Pipelines for the Limón Area as of October, 1991 due to the April 22, 1991 Earthquake.

Material	Diameter mm (in)	Total Repairs	Breakdown by Damage Mechanism		
			Pipe Segment Fig.3–3a	Union Piece Fig.3–3b	Pull–out Fig.3–3f
DI	300 (12)	16	6 (38%)		10 (62%)
CI	300 (12)	41	19 (46%)	5 (12%)	17 (42%)

Table 3–II Summary of CI and DI Transmission Pipe Repairs by Mechanism Damage

Material	Diameter Range mm (in)	Length km	Repairs	Damage Ratio Repairs/km
PVC	18 to 200 (3/4 to 8)	50.3	246	4.9
CI	75 to 250 (3 to 10)	28.4	34	1.2
AC	75 to 350 (3 to 14)	16.8	81	4.8
GI	25 to 75 (1 to 3)	10.2	39	3.8

Table 3–III Summary of Repairs to Water Distribution Pipelines for the Limón Area as of October,1991, due to the April 22, 1991 Earthquake

Material	Diameter Range mm(in)	Length km	Repairs	Damage Ratio repairs/km
PVC	18 to 62 (3/4 to 2½)	20.4	121	5.9
	75 to 150 (3 to 6)	28.9	125	4.3
	200 to 250 (8 to 10)	1.02	–	–
CI	75 to 150 (3 to 6)	25.5	34	1.3
	200 to 250 (8 to 10)	2.9	–	–
AC	75 to 150 (3 to 6)	12.8	54	4.2
	200 to 250 (8 to 10)	3.9	26	6.6
	300 to 350 (12 to 14)	0.1	1	10.0
GI	18 to 62 (3/4 to 2½)	9.5	39	4.1
	75 to 150 (3 to 6)	0.7	–	–

Table 3–IV Summary of Water Distribution Repairs by Pipe Diameter Range.

Material	Diameter mm (in)	Total Repairs	Pipe Fig.3–3a	Union Fig.3–3b	Tee Blowout Fig.3–3a	Tee Disconnect Fig.3–3d	Telescoping Fig.3–3e	Pullout Fig.3–3f
PVC	18 to 62 (3/4 to 2½)	121	77(64%)	5(4%)	22(18%)	14(12%)	–(0%)	3(2%)
	75 to 150 (3 to 6)	125	35(28%)	–(0%)	6(5%)	31(25%)	6(5%)	47(37%)
CI	75 to 150 (3 to 6)	34	10(29%)	–(0%)	–(0%)	4(12%)	2(6%)	18(53%)
AC	75 to 150 (3 to 6)	54	54(100%)	–(0%)	–(0%)	–(0%)	–(0%)	–(0%)
	200 to 250 (8 to 10)	26	26(100%)	–(0%)	–(0%)	–(0%)	–(0%)	–(0%)
	300 to 350 (12 to 14)	1	–(0%)	–(0%)	–(0%)	1(100%)	–(0%)	–(0%)
GI	18 to 62 (3/4 to 2½)	39	1(3%)	34(87%)	–(0%)	4(10%)	–(0%)	–(0%)

Table 3–V Summary of PVC, CI, AC and GI Distribution Pipe Repairs by Damage Mechanism

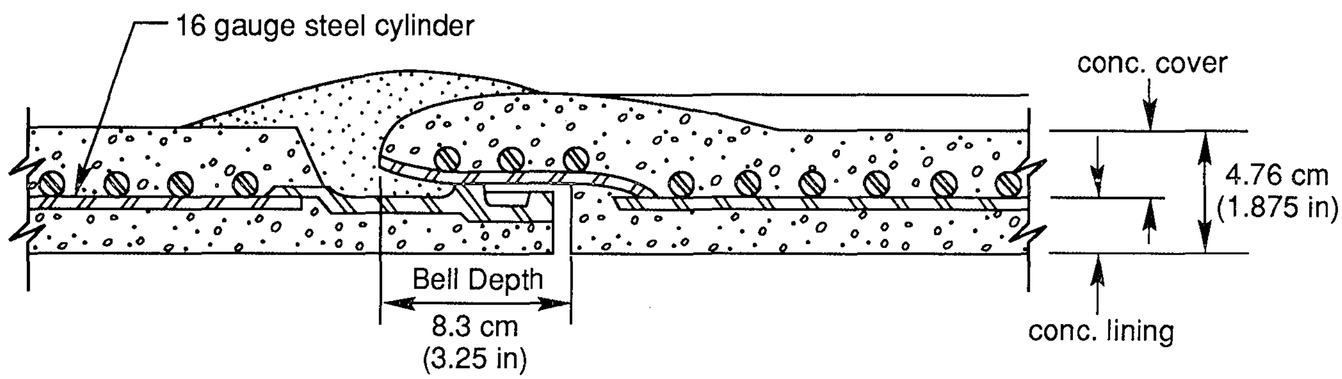

FIGURE 3–1 Longitudinal Section of RCCP Joint

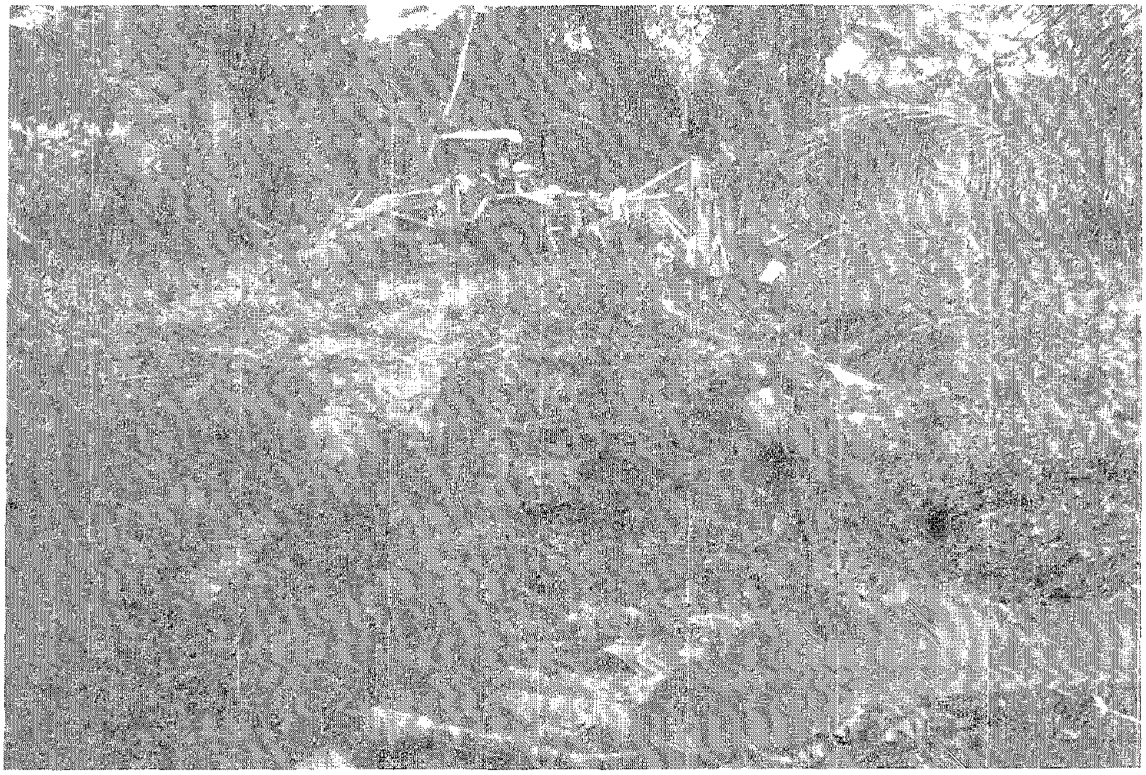

FIGURE 3–2 Transmission Pipelines from Banano River, 300 mm (12 in) Diameter Cast Iron (CI) Pipe under Backhoe Wheel, 500 mm (20 in) Reinforced Concrete Cylinder Pipe (RCCP) Being Repaired on Right.

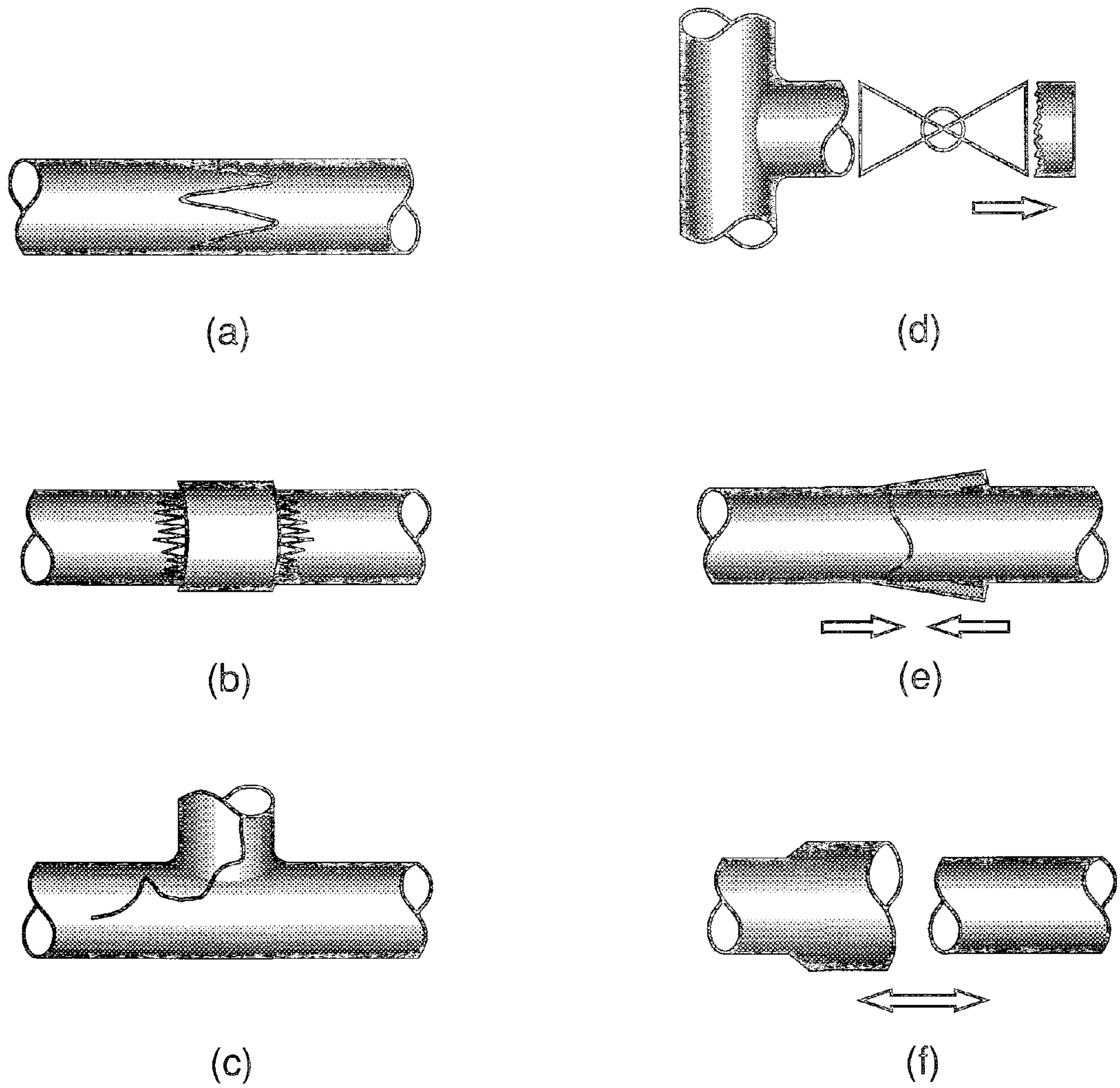

FIGURE 3–3 Damage Mechanisms; (a) pipe segment break, (b) break in union piece, (c) blowout at Tee, (d) disconnection at Tee, (e) compressive telescoping at joint, (f) tensile pull–out at joint

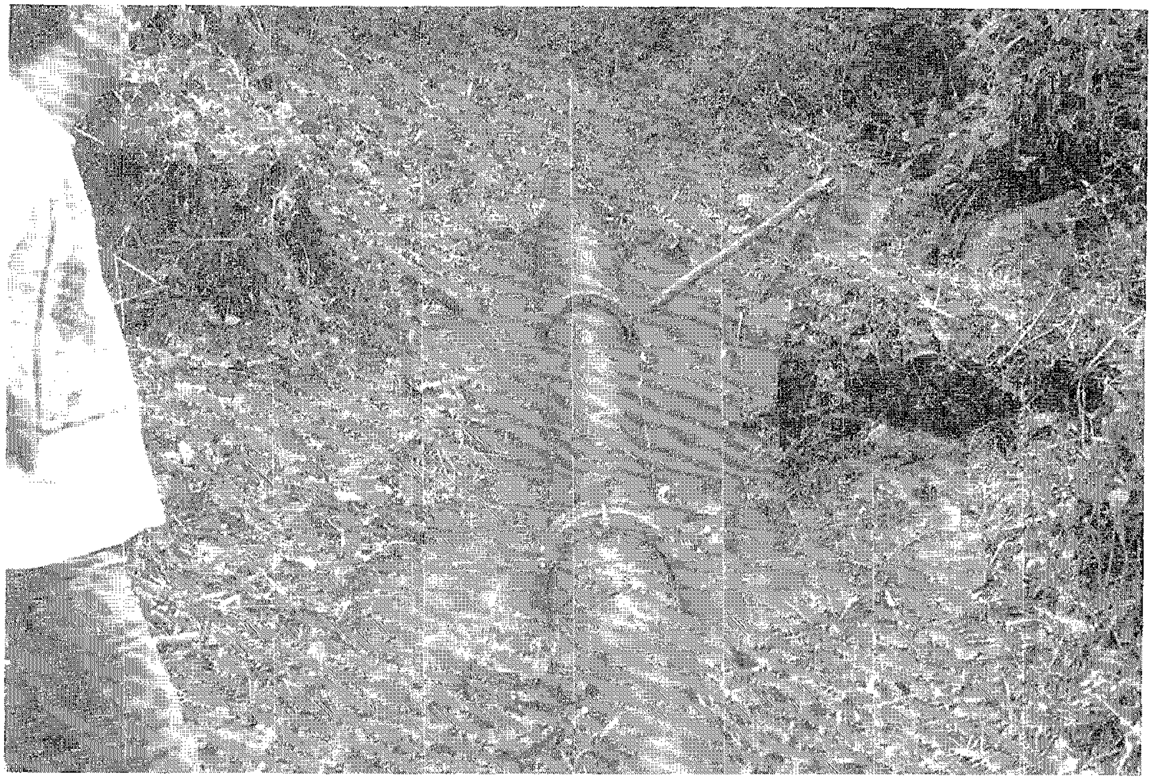

FIGURE 3–4 Repair of Pipe Segment Break (see Figure 3–3a) in 300 mm (12 in) CI Transmission Line from Banano River. AyA Engineer, José Arguedas, on the Left

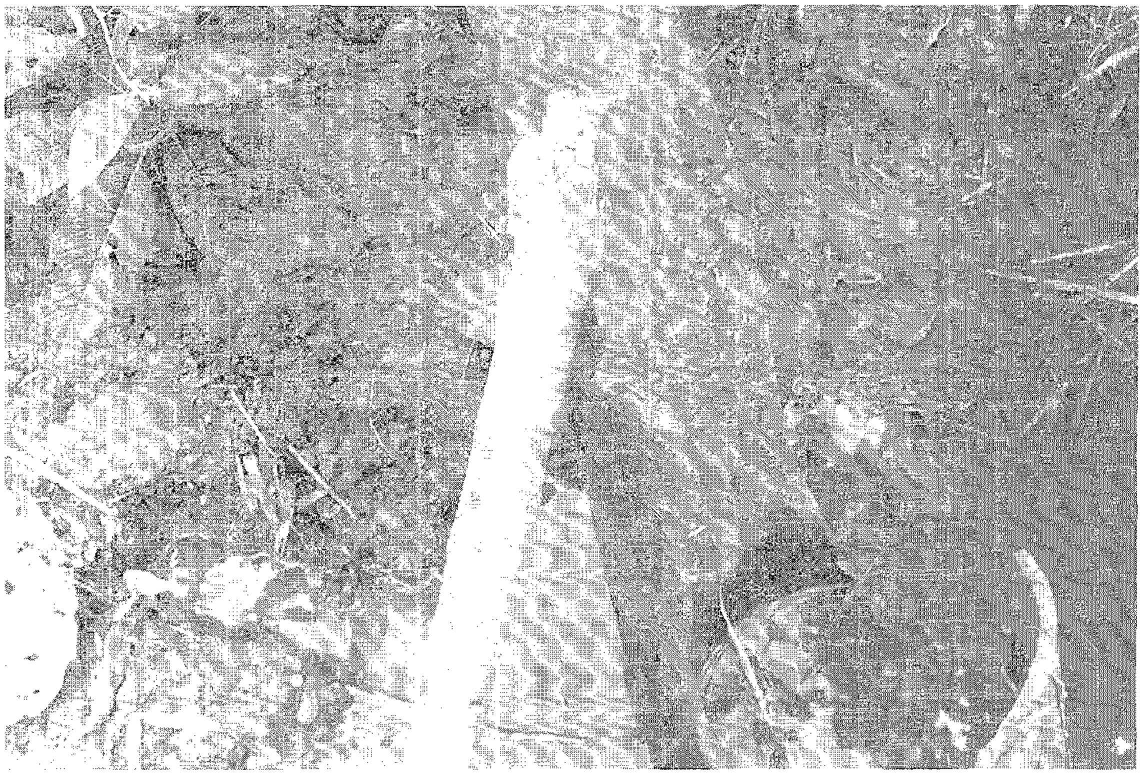

FIGURE 3–5 Close–up of Damaged 300 mm (12 inch) CI Transmission Line Shown in Figure 3–4. Note Apparent Corrosion Pin Hole to Right of Tree Limb.

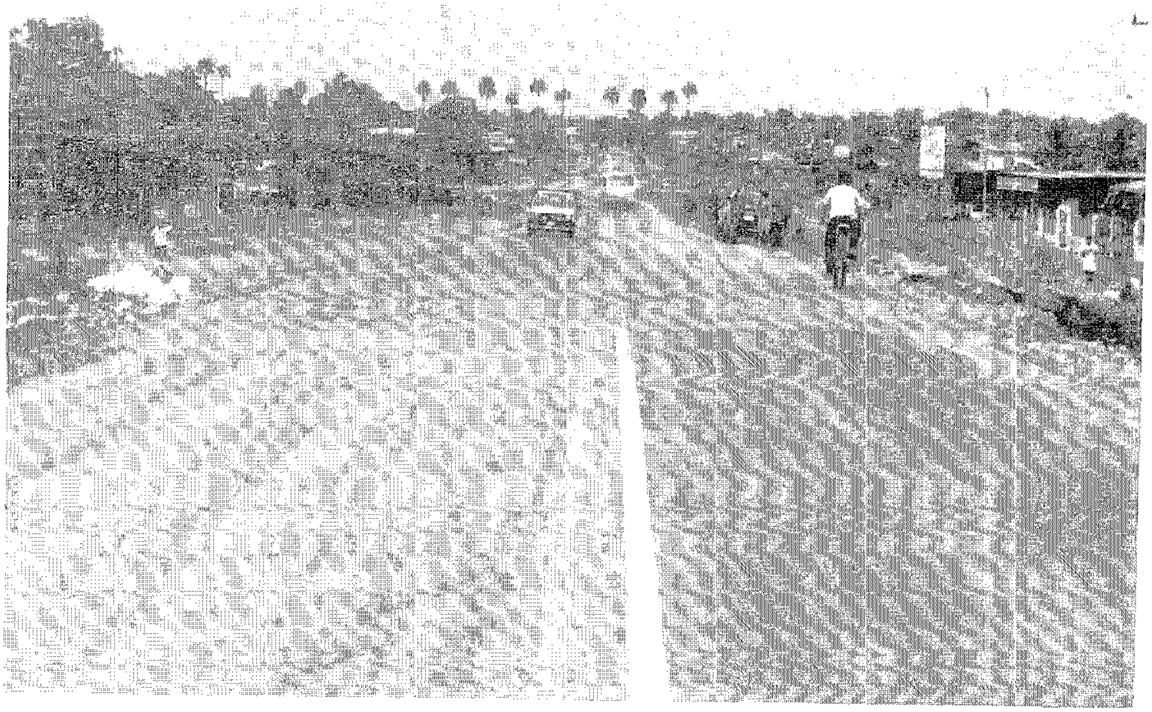

FIGURE 3–6 View Looking East Showing 13 m (42 feet) of Road Damage near Railroad Underpass. RCCP Transmission Line to Right.

FIGURE 3–7 View Looking West towards Railroad Underpass Showing 40 cm (16 inch) Lateral Offset of Road Centerlines. Cab of Flatbed Truck #89 over Railroad, Width of Road Stripping is 10 cm (4 inch).

FIGURE 3–8 View Looking West towards Railroad Underpass Showing Garbens at Center, in Front of Dirt Pile

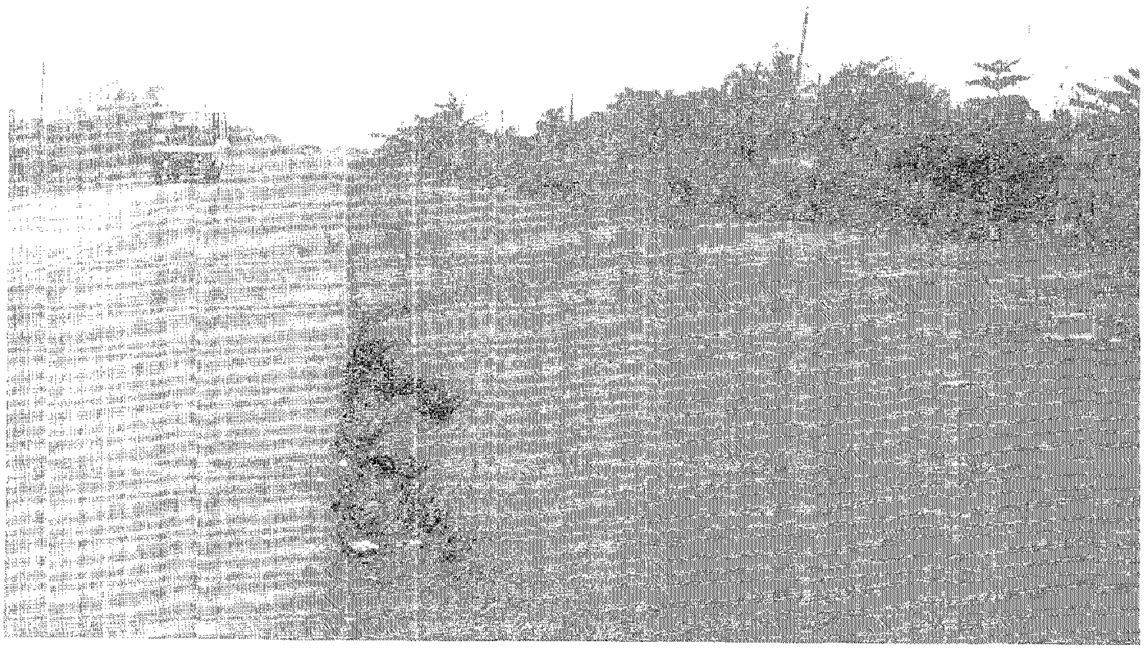

FIGURE 3–9 View Looking West towards Railroads Underpass Showing 15 to 30 cm (6 to 12 inch) Wide Ground Cracks at North Side of Road.

FIGURE 3–10 View Looking East from Railroad Underpass Showing Scarp at Side of Garbens.

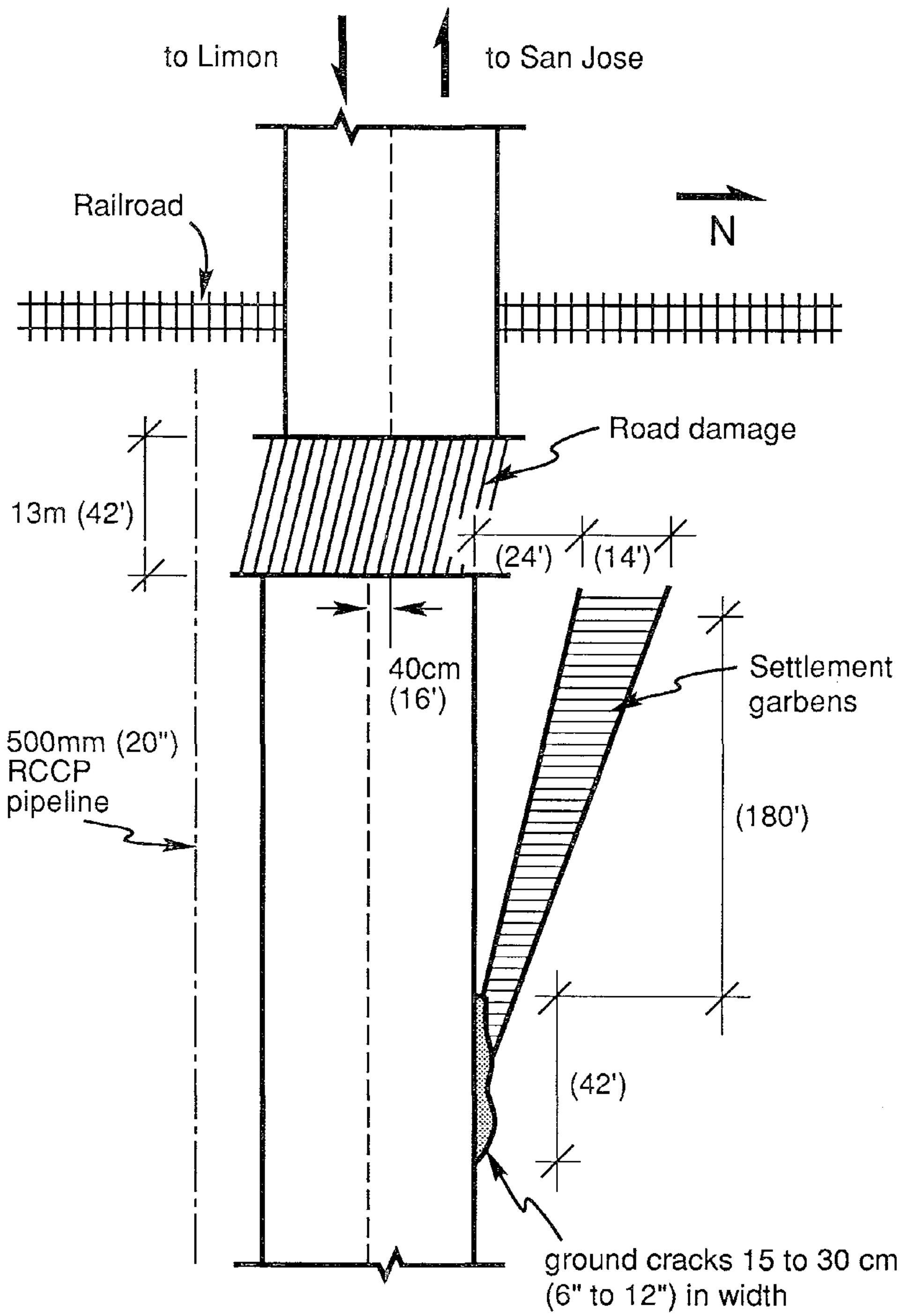

FIGURE 3–11 Plan View of Road Damage, Ground Cracks, Garbens and 500 mm (20 inch) RCCP Transmission Pipe Damage Immediately East of Railroad Underpass.

FIGURE 3–12 Vertical Settlement in Road near Pueblo Nuevo Entrance, about 500 m East of Railroad Underpass.

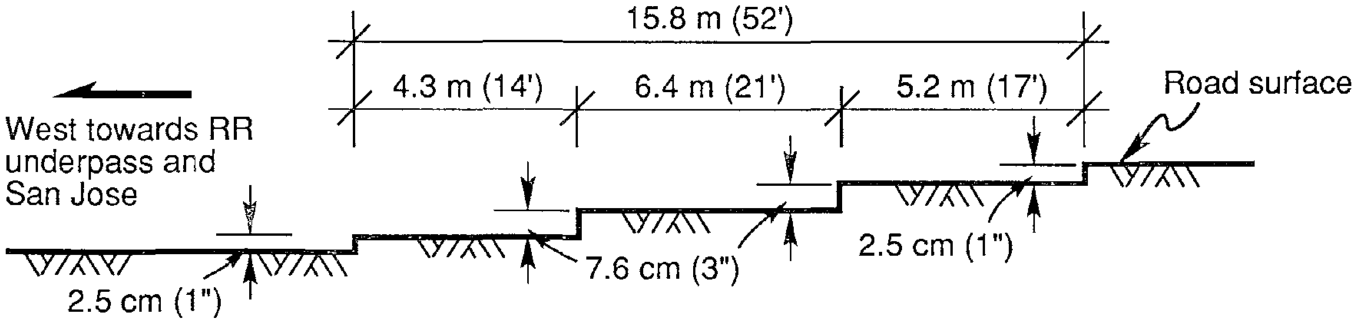

FIGURE 3–13 Elevation View of 20 cm (8 inch) Vertical Settlement over 16 m (52 feet) of Road Surface near Pueblo Nuevo Entrance.

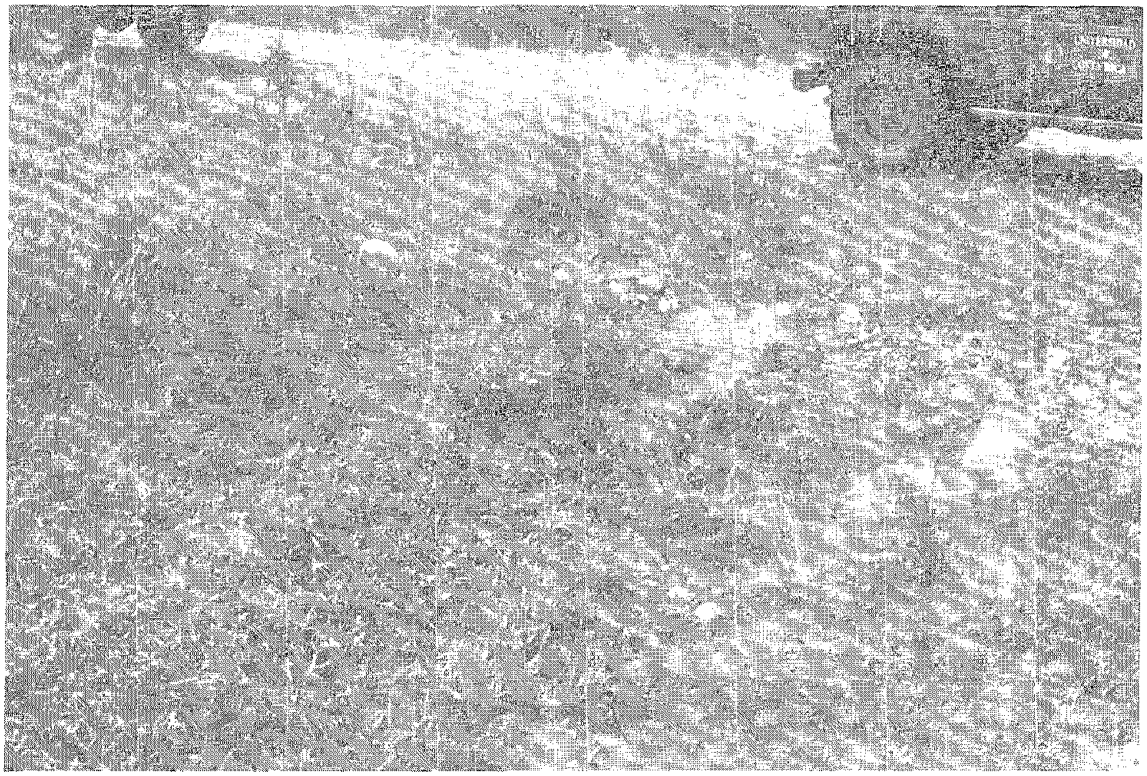

FIGURE 3–14 Water on Ground Surface above Unrepaired Transmission Pipe Leak.

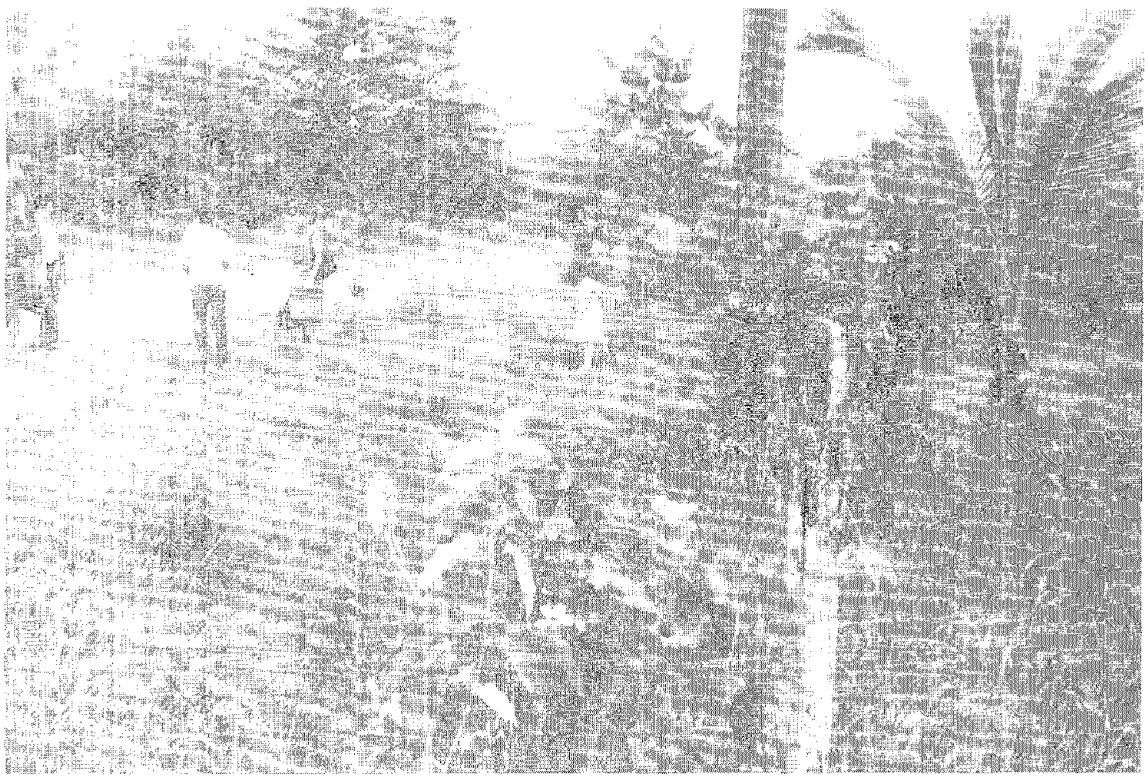

FIGURE 3–15 Reasonably Straight Fence Line Roughly 5 m (16 feet) to Right of Unrepaired Transmission Pipe Leak in Figure 3–14.

FIGURE 3–16 Dirt and Gravel Road Adjacent to Unrepaired Transmission Pipe Leak in Figure 3–14.

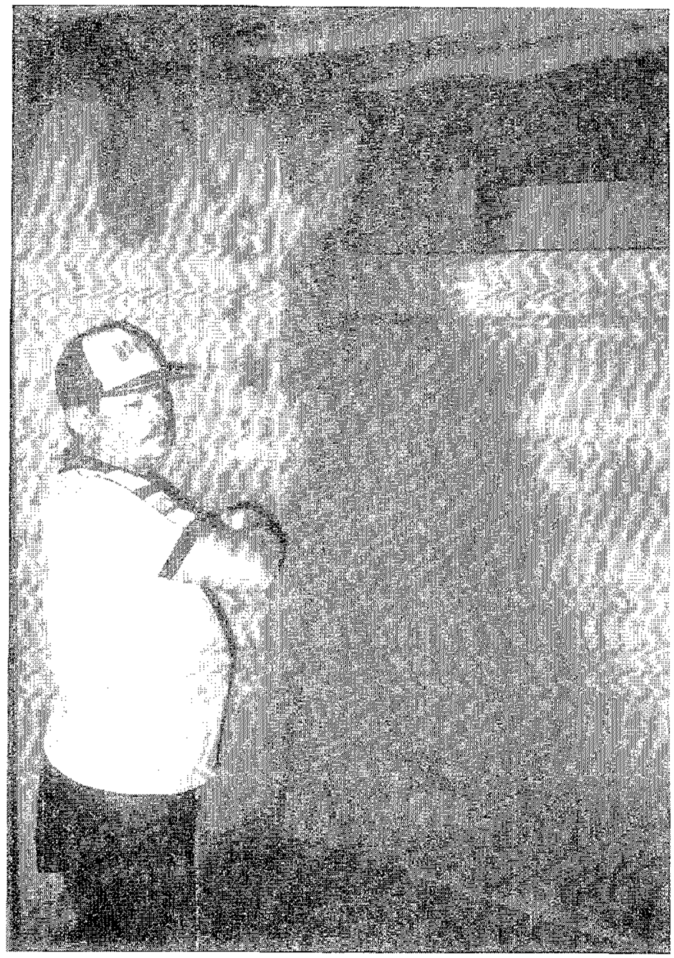

FIGURE 3–17 Repaired Cracking at Top and Corner of the 4 Million Liter Concrete Reservoir in Limón

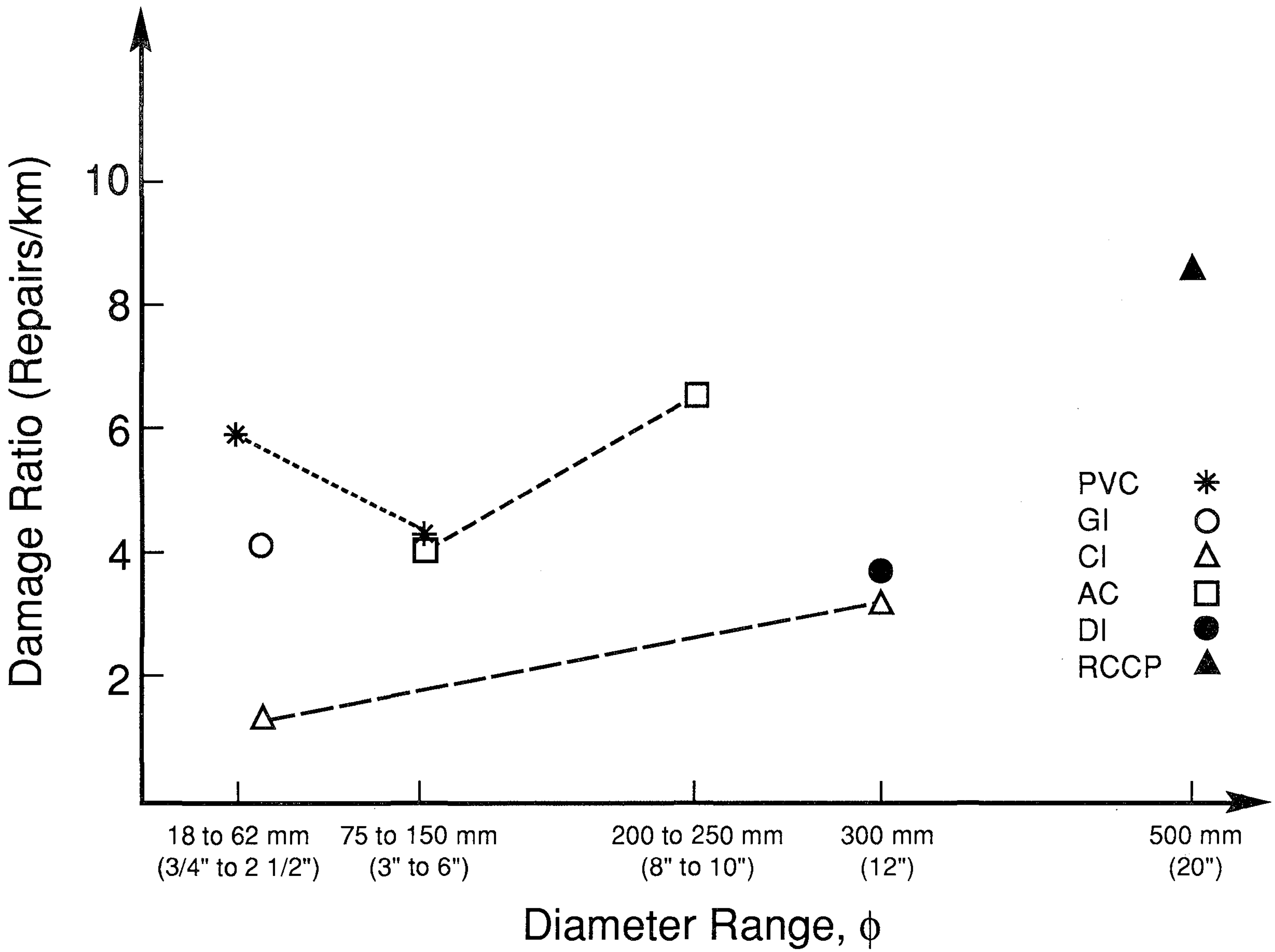

FIGURE 3–18 Damage Ratios for Distribution and Transmission Pipe Versus Diameter Range

FIGURE 3–19 Repaired Leak in Small Diameter AC Distribution Pipe in Limón, Repair Coupling at Right and Original AC Joint at Left.

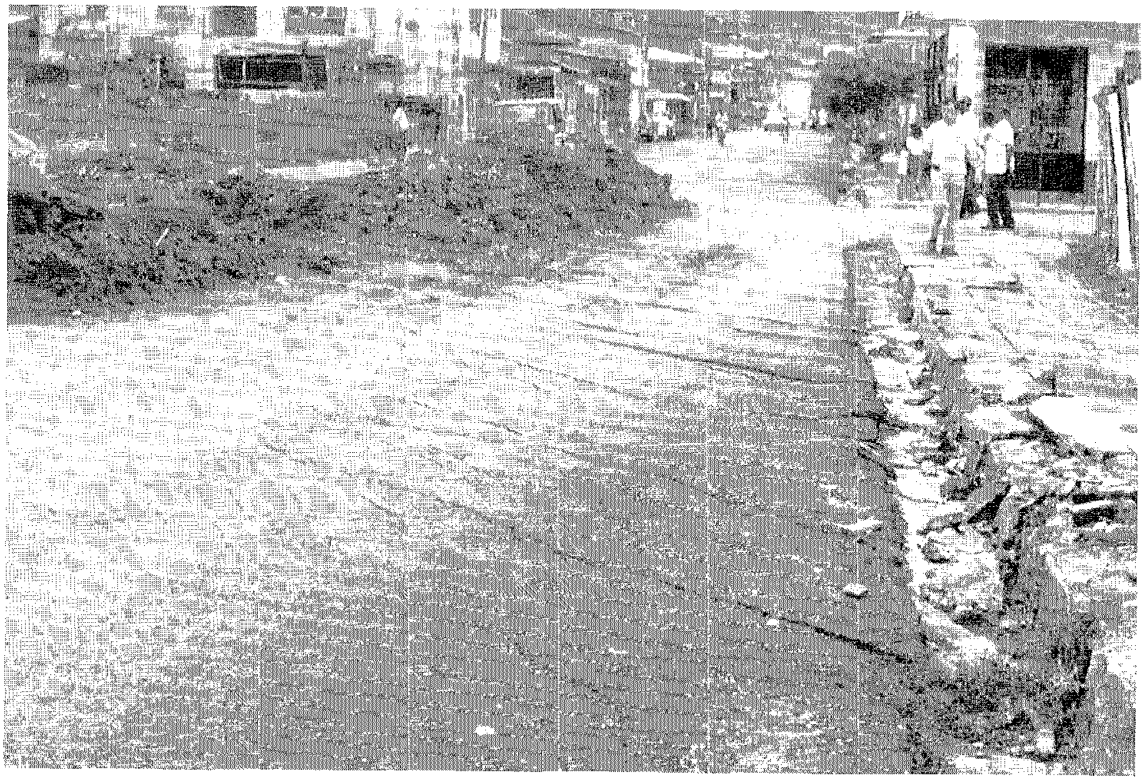

FIGURE 3–20 Road Surface Damage Adjacent to Distribution Pipe Break Shown in Figure 3–19

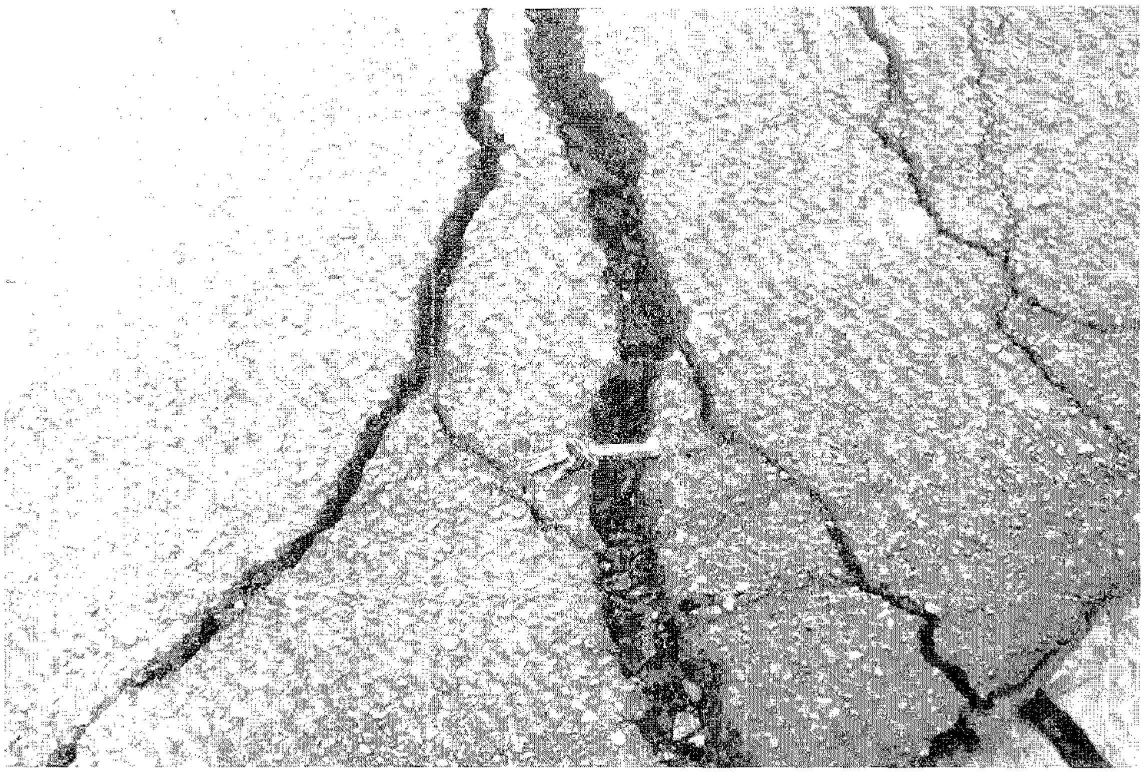

FIGURE 3–21 Close–Up of Superficial Road Cracks Shown in Figure 3–20

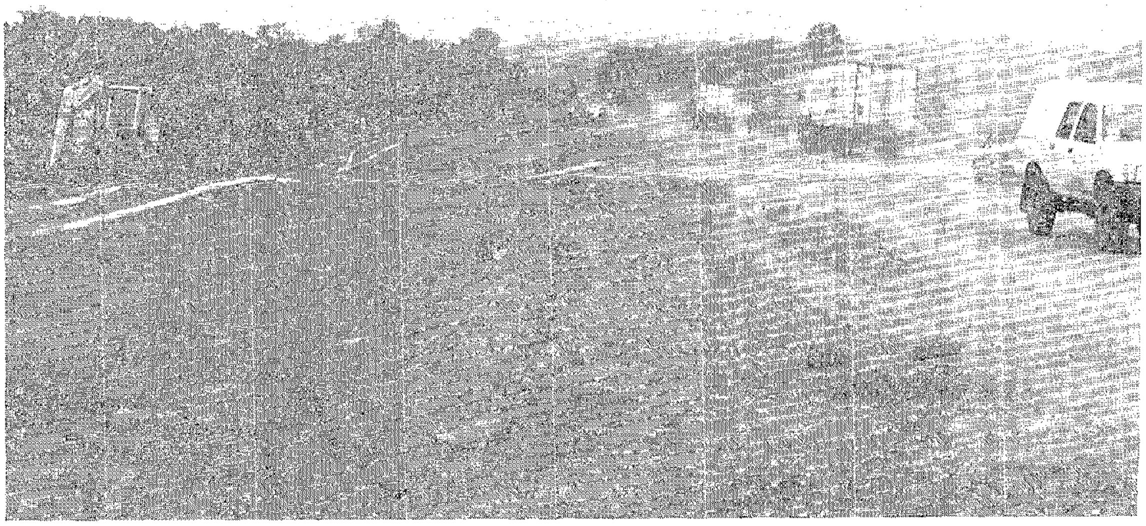

FIGURE 3–22 Heavy Road Damage near Village of Estrada in General Vicinity of RECOPE Pipe Leak, Note That Road Surface at Somewhat Higher Elevation Than Banana Plantation on Left.

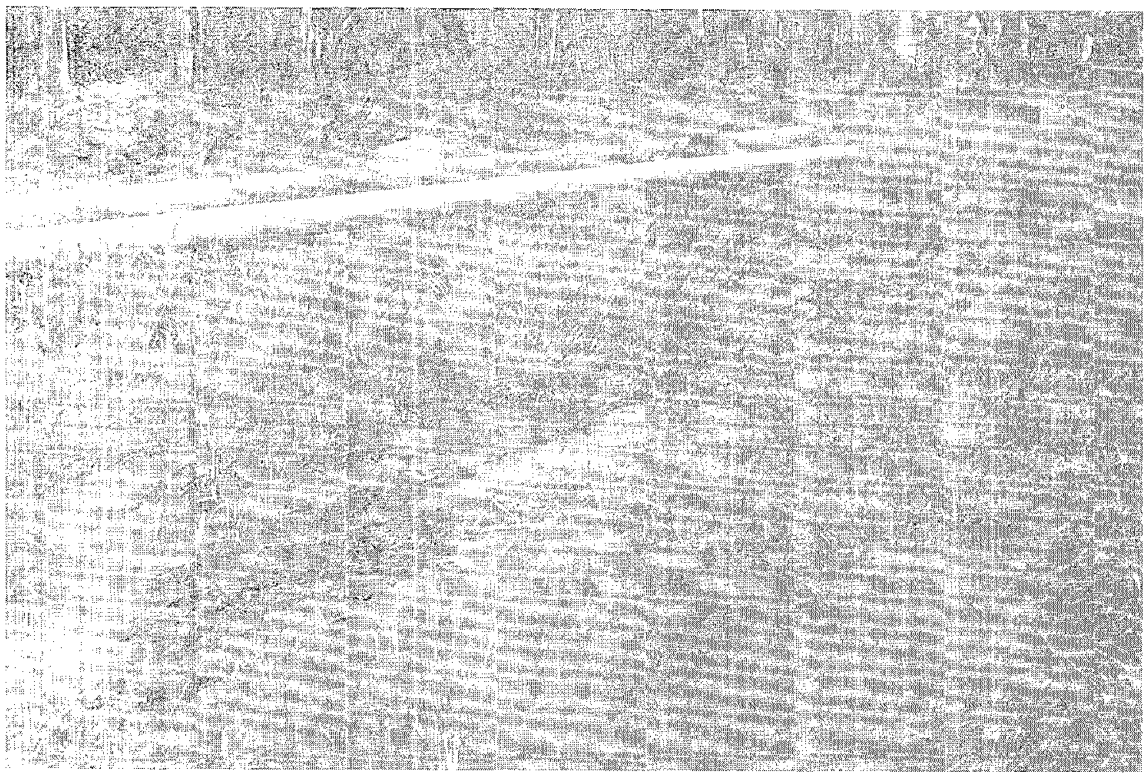

FIGURE 3–23 Ejected Sand on Ground Surface in General Vicinity of RECOPE Pipeline Leak.

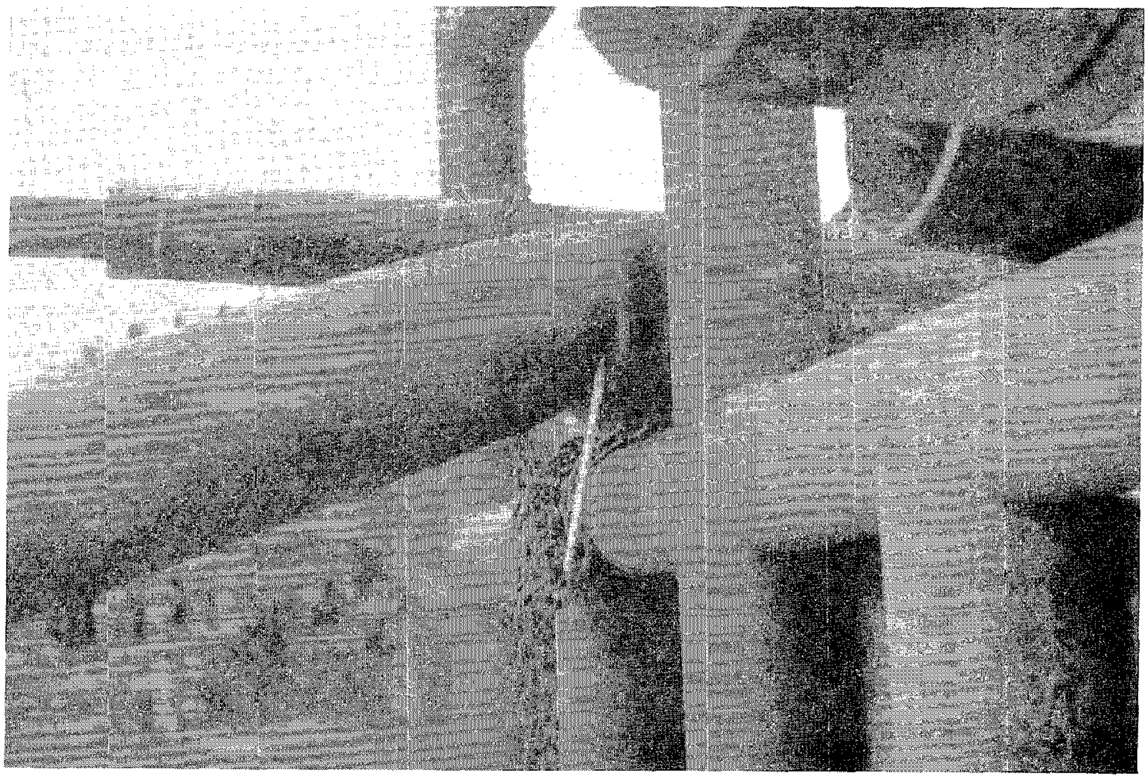

FIGURE 3–24 Damaged Portion of RECOPE Pipeline on Back of Repair Truck, Pencil Stuck in Tensile Crack Generated by Severe Local Buckling (Wrinkling) on Compression Side of This Flexural Failure.

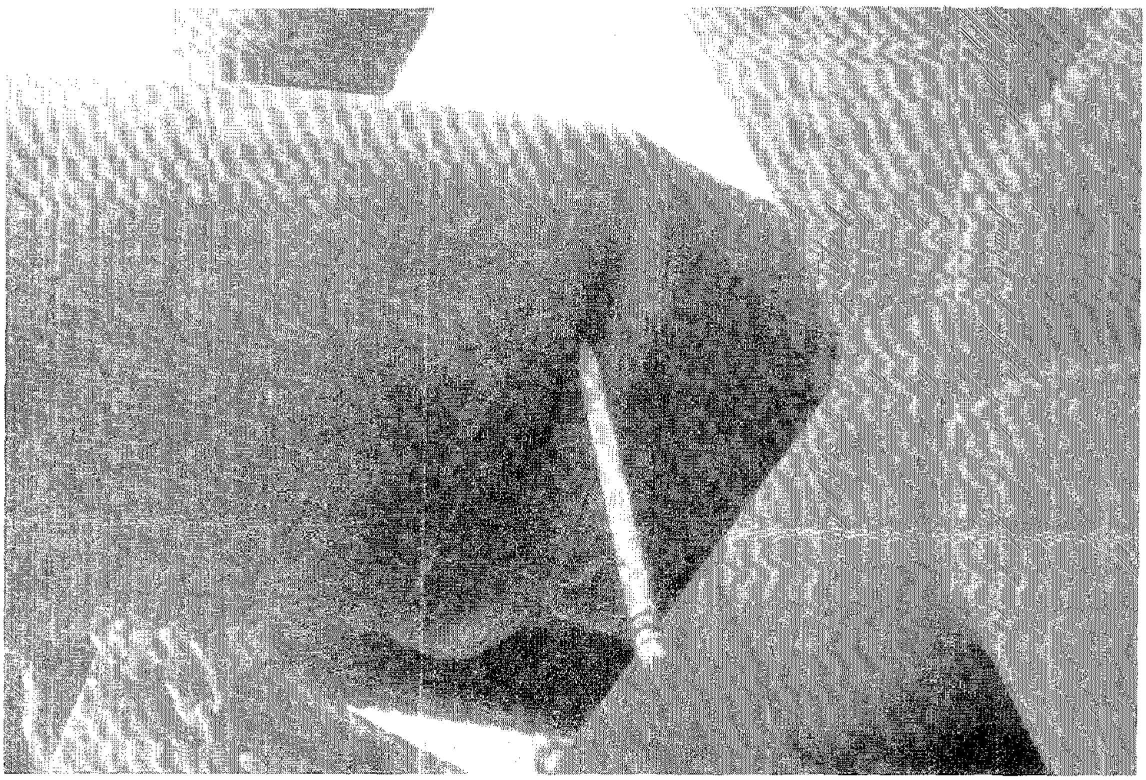

FIGURE 3–25 Close–Up View of Local Buckling (Wrinkling) of RECOPE Pipeline.

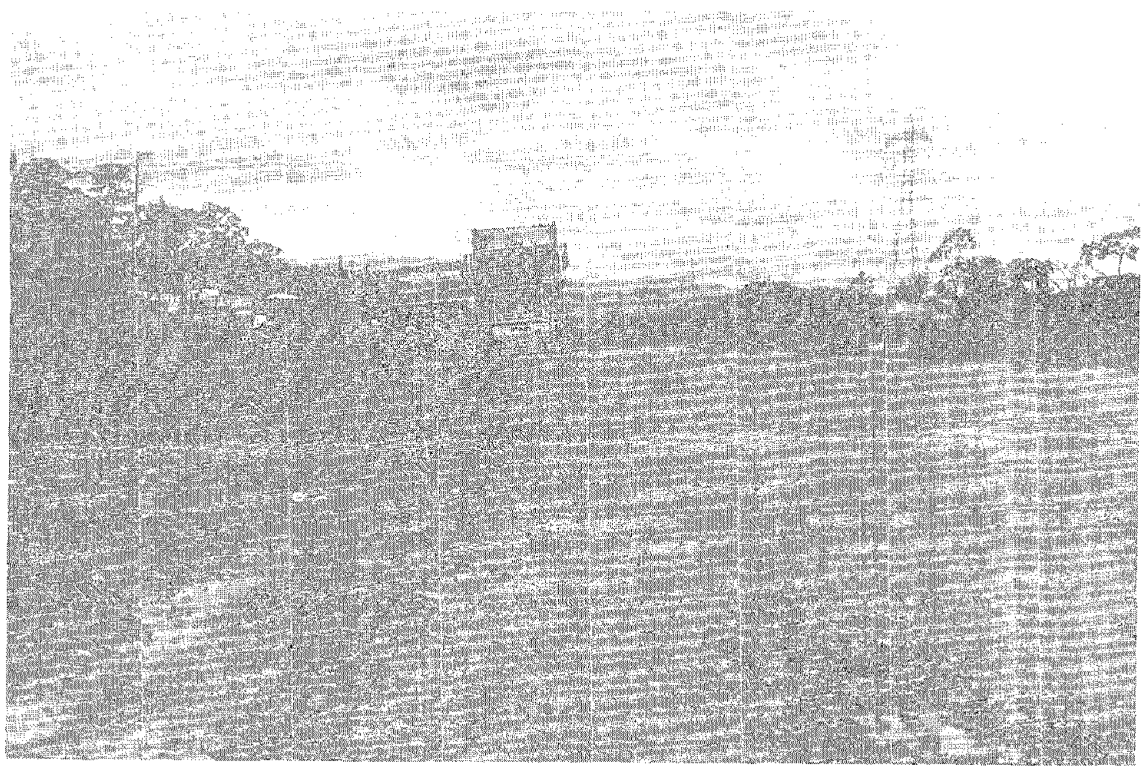

FIGURE 3–26 Road Settlement of Roughly 1 m (3.5 ft.) at Western Edge of 400 m Length of Severe Damage to Route 240. Photograph Taken while Kneeling on Temporary Road Surface with Undamaged Road Surface at Eye Level.

FIGURE 3–27 Ground Cracks and Ejected Sand at Ground Fissure Adjacent to 400 m Length of Severe Damage to Route 240. Note Water Drip Pattern Directly under Undamaged RECOPE Pipeline

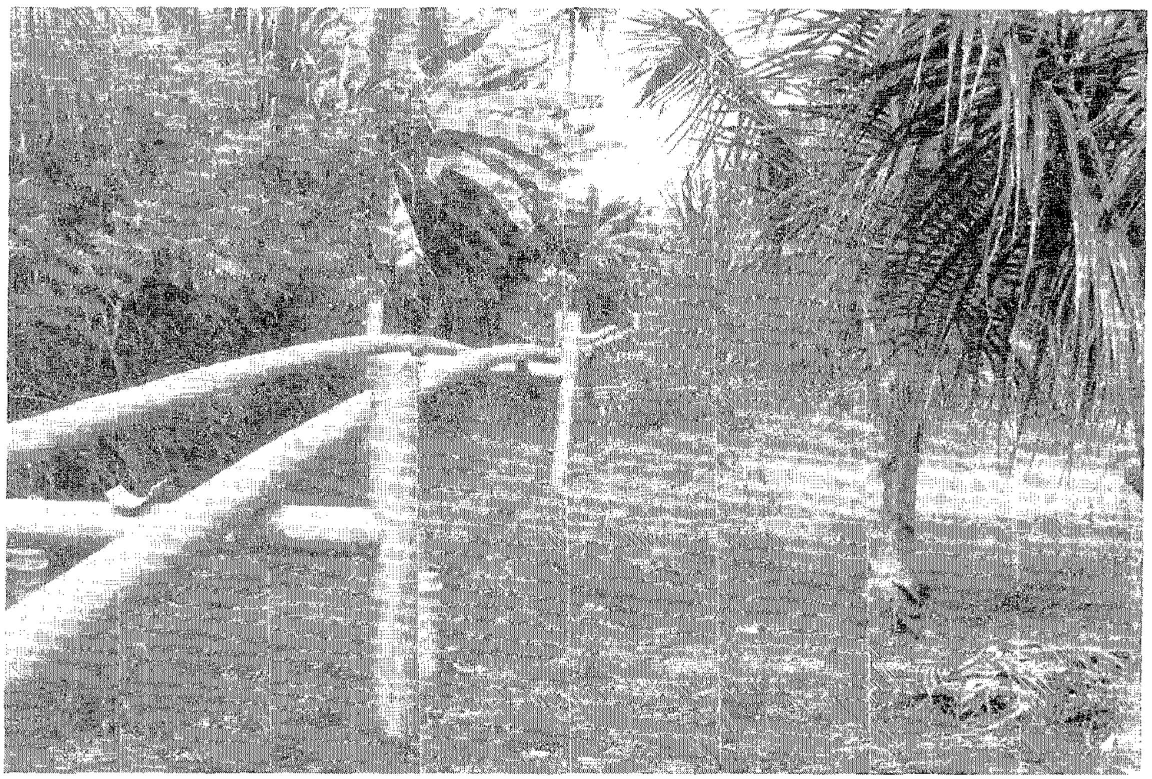

FIGURE 3–28 Ejected Sand at Base and to Right of Tilted Steel Support Frame for Undamaged RECOPE Pipeline.

FIGURE 3–29 15 cm (6 in) Relative Movement of Undamaged RECOPE Pipeline Adjacent to 400 m Length of Road Damage to Route 240.

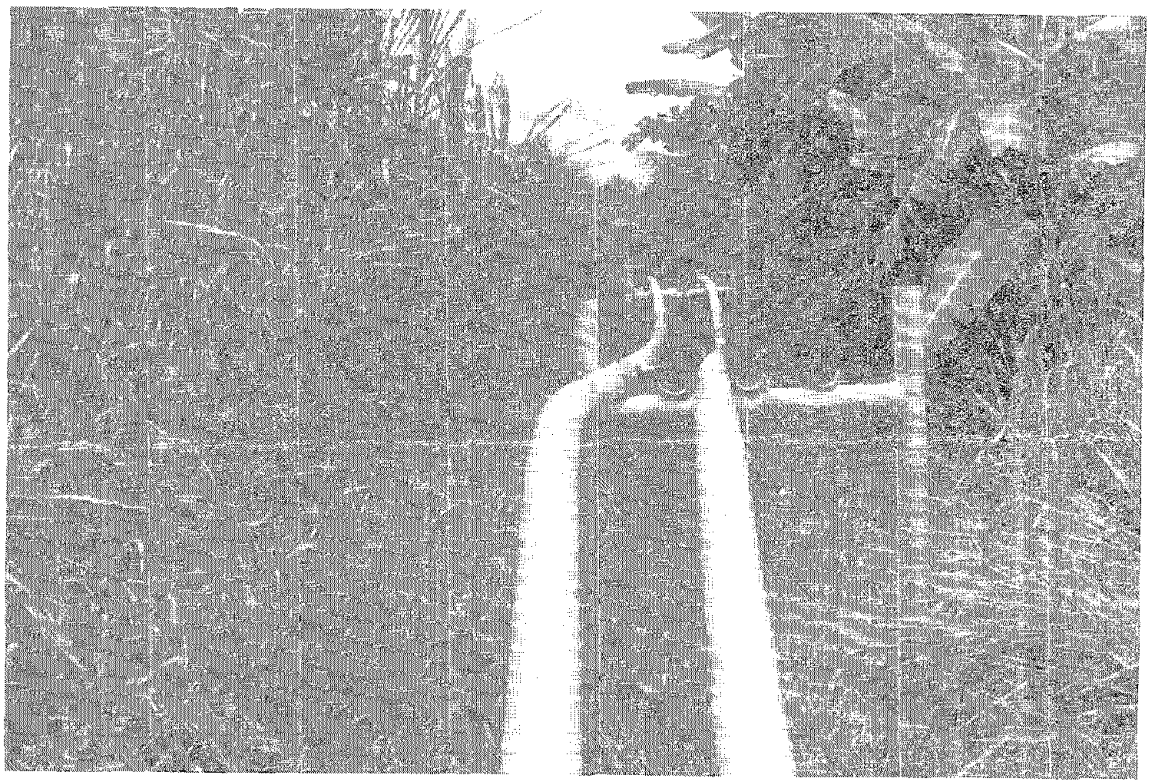

FIGURE 3–30 Severe Distortion of Undamaged RECOPE Pipeline Adjacent to 400 m Length of Road Damage to Route 240. Note Pipelines no Longer in Semicircular Steel Saddles.

SECTION 4

COMPARISON OF PIPELINE DAMAGE TO EXISTING EMPIRICAL ESTIMATES

In this section the observed damage to segmented pipelines in and around Limón occasioned by the April 22, 1991 Costa Rica earthquake will be compared to existing empirical damage estimates. The peak ground velocity V_{max} and earthquake intensity for the Limón area established in Section 1 will be used to estimate damage due to seismic wave propagation (WP). Estimated pipe damage due to a combination of WP and PGD effects will be based on the observed coseismic uplift and earthquake intensity.

4.1 Wave Propagation Damage Versus MMI

Seismic wave propagation refers to ground strain and curvature which results from seismic waves traversing the ground surface. It appears that Eguchi et al. [16] were the first to separate WP damage and PGD damage when developing empirical estimates of pipe damage. For seismic wave propagation they plot observed damage ratio for various pipe materials versus MMI. His most recent plot, Eguchi [17], is shown in Figure 4–1. Note for MMI < 8, the damage ratio increases by a factor of 10 for a unit increase in MMI. While a unit increase in MMI results in roughly doubling of the damage ratio for MMI > 8. Also note that for any given ground motion intensity the damage ratios for AC or are roughly 2.5 times that for CI.

As shown in Figures 1–2 and 1–3, the estimates MMI in the Limón area was VIII or IX. From Figure 4–1 for MMI of VIII one expects 0.37 repairs/km (.11 repairs per 1000ft) for AC and CONC. pipe while one expects 0.26, 0.18 and 0.04 repairs/km for PVC, CI and DI respectively. For MMI of IX one expects 0.82, 0.49, 0.36 and 0.09 repairs/km for AC/CONC, PVC, CI and DI respectively.

4.2 Wave Propagation Damage Versus V_{max}

Theoretically the relative axial strain in the pipe segments as well as the relative axial displacement at pipe joints are functions of the transient ground strain ϵ, which is given by

$$\epsilon = V_{max}/C \tag{4.1}$$

where V_{max} is the peak horizontal ground velocity and C is the effective propagation velocity of seismic waves with respect to the ground surface. With this as a theoretical background Barenberg [18] developed an empirical relation for WP damage to CI pipes as a function of peak ground velocity. O'Rourke and Ayala [19] extended the Barenberg relation by including information from additional earthquakes and other common pipe materials. The O'Rourke and Ayala relationship, shown in Figure 4–2, is based on damage in repairs per km from four U.S. earthquake and two Mexican earthquakes where PGD effects are not observed. The figure contains data for AC and CI pipes with diameters primarily in the 75 mm (3 in) to 1220 mm (48 in) range, RCCP pipes with diameters of 1830 mm (72 in) and concrete pipe with diameters primarily in the 500 mm (20 in) to 1220 mm (48 in) range.

Attempts by O'Rourke and Ayala to establish material specific relationship, from their data, proved unsuccessful. No attempts were made to establish diameter specific relationships. O'Rourke and Ayala [19] attribute the scatter to variations in C or unusual soil conditions, such as corrosive soils or variable subsurface conditions. A map showing soil conditions and the pipeline network in the Limón area is not currently available. Also, there was some PGD within the city as shown in Figure 4–3. However, for most of the pipe breaks we were unable to determine whether they are due to WP or PGD. Hence a more detailed estimate of wave propagation damage using Figure 4–2 is not possible.

4.3 Combined Damage Versus MMI

When an earthquake causes PGD such as lateral spreading due to liquefaction, settlement or landsliding, it is often difficult to separate WP damage from that due specifically to PGD. Hence empirical damage estimates for such earthquakes typically correlate combined damage, that is due to both WP and PGD, against some measure of earthquake size. One such relationship was developed by O'Rourke et al. [20]. As shown in Figure 4–4, combined damage in repairs per km in plotted versus MMI. The data points in Figure 4–4 are for CI pipe behavior in seven U.S. earthquake.

As noted in Section 1, the estimated MMI for the April 22, 1991 Costa Rica earthquake was VIII or IX in the Limón area. From Figure 4–4, one expects about 0.55 and 4.2 repairs per km in CI pipe for MMI of VIII and IX respectively.

4.4 Combined Damage Versus Uplift

Using data from the Northeast San Fernando Valley during its 1971 earthquake, Barenberg [18] correlated vertical PGD with damage to CI and steel pipe with semi–rigid or poorly welded joints. The relationship is shown in Figure 4–5, and as with Figure 4–4, both WP and PGD damage are combined. The PGD used by Barenberg is the average vertical uplift in a 1 square mile sector. One suspects that pipe damage is more directly related to differential movements or ground strain within an area, however the average uplift in an area may also be a rough measure of differential movements.

As noted in Section 1, the coseismic uplift in Limón was about 1.5 m while the uplift at Bomba on the Banano River was about 0.55 m. From Figure 4–5, one expects combined damage ratios of about 6.0 and 60.0 repairs/km for average vertical PGD of 55 cm and 150 cm respectively.

4.5 Comparisons with Greater Limón Damage

Figure 4–4 and 4–5 present expected damage to CI pipe due to both WP and PGD effects. Specifically the O'Rourke et al [20] relation predicts 0.55 and 4.2 repairs per km for the observed MMI of VIII or IX respectively, while the Barenberg [18] relation predicts 6.0 and 60.0 repairs per km for the observed uplifts of 0.55 and 1.5 m respectively. This information is summarized in Table 4–I.

The observed damage rates for the Limón area are presented in Tables 3–I and 3–III. For CI pipe there were 41 repairs to the 12.5 km of transmission pipe and 34 repairs to the 28.4 km of distribution pipe. This yield 75 repairs for the total 40.9 km length of CI pipe in the system and a aggregate damage ratio of 1.83 repairs per km, as shown in Table 4–I. Hence the observed damage to CI pipe, due to both WP and PGD effects, falls in range predicted by the O'Rourke et al. MMI relationship [20], while the Barenberg uplift relationship [18] predicts damage ratios significantly higher than that which was observed.

Figure 4–2 presents expected damage to AC, CI and RCCP due to WP effects only. Specifically the O'Rourke and Ayala [19] relation predicts 0.10 and 1.0 repairs per km for Hard and Soft site respectively in the Limón area as shown in Table 4–II. From Tables 3–I and 3–III, the number of repairs to AC, CI and RCCP pipe from both WP and PGD effects were 81, 75 and 120 over lengths of 16.8, 40.9 and 14.0 km respectively. This yields damage rates of 4.82, 1.83 and 8.57 repairs per km for AC, CI and RCCP respectively and 3.85 repairs per km for all three materials combined. These values are also presented in Table 4–II. Hence the O'Rourke and Ayala [19] V_{max} relation is consistent with the observed damage in the sense that the predicted WP damage was less than the observed total for both WP and PGD effects.

Figure 4–1 presents expected WP damage for a number of common pipe materials. For example one expects 0.37 and 0.82 repairs per km for AC or RCCP pipe subject to MMI of VIII and IX respectively. These and corresponding values for PVC, CI and DI are summarized in Table 4–III. Table 4–III also presents the observed WP and PGD damage for these materials from Tables 3–I and 3–III. As shown in Table 4–III, the Eguchi [17] MMI relation is consistent with the observed damage in the sense that the predicted WP damage was less than the observed total for both WP and PGD effects. However, although the Eguchi relationship suggests that WP damage to DI pipe would be less than 20% of that to PVC pipe, the observed WP and PGD damage to DI pipe was actually more than 70% of that to PVC pipe. As noted previously, the authors believe that the relatively high damage ratio for DI pipe, in comparison with CI or PVC, is due to the differential coseismic uplift in the region from Moin to Limón as shown in Figure 1–5. Note that this is the route for the 300 mm (12 in) DI transmission line.

Material	WP and PGD Damage Predicted by O'Rourke et al [20]		WP and PGD Damage Predicted by Barenberg [18]		Observed WP and PGD Damage
	MMI = VIII	MMI = IX	Uplift = 55 cm	Uplift = 150 cm	
CI	0.55	4.2	6.0	60.0	1.83

Table 4–I Comparison of Observed CI Pipe Damage due to both WP and PGD Effects, with Values Predicted by O'Rourke et al. [20] and Barenberg [18].

Material	WP Damage Predicted by O'Rourke and Ayala [19]		Observed WP and PGD Damage
	Hard Sites	Soft Sites	
AC	0.10	1.0	4.82
CI	0.10	1.0	1.83
RCCP	0.10	1.0	8.57
AC, CI, RCCP	0.10	1.0	3.85

Table 4–II Comparison of Observed AC, CI and RCCP Pipe Damage in repairs/km due to both WP and PGD effects with Values Predicted by O'Rourke and Ayala [19] for WP Damage only.

Material	WP Damage Predicted by Equchi [17]		Observed WP and PGD Damage
	MMI = VIII	MMI = IX	
AC/RCCP	0.37	0.82	6.5
PVC	0.26	0.49	4.9
CI	0.18	0.36	1.8
DI	0.04	0.09	3.5

Table 4–III Comparison of Observed AC/RCCP, PVC, CI and DI Pipe Damage in Repairs/km for both WP and PGD effects with Values Predicted by Eguchi [17] for WP Damage only.

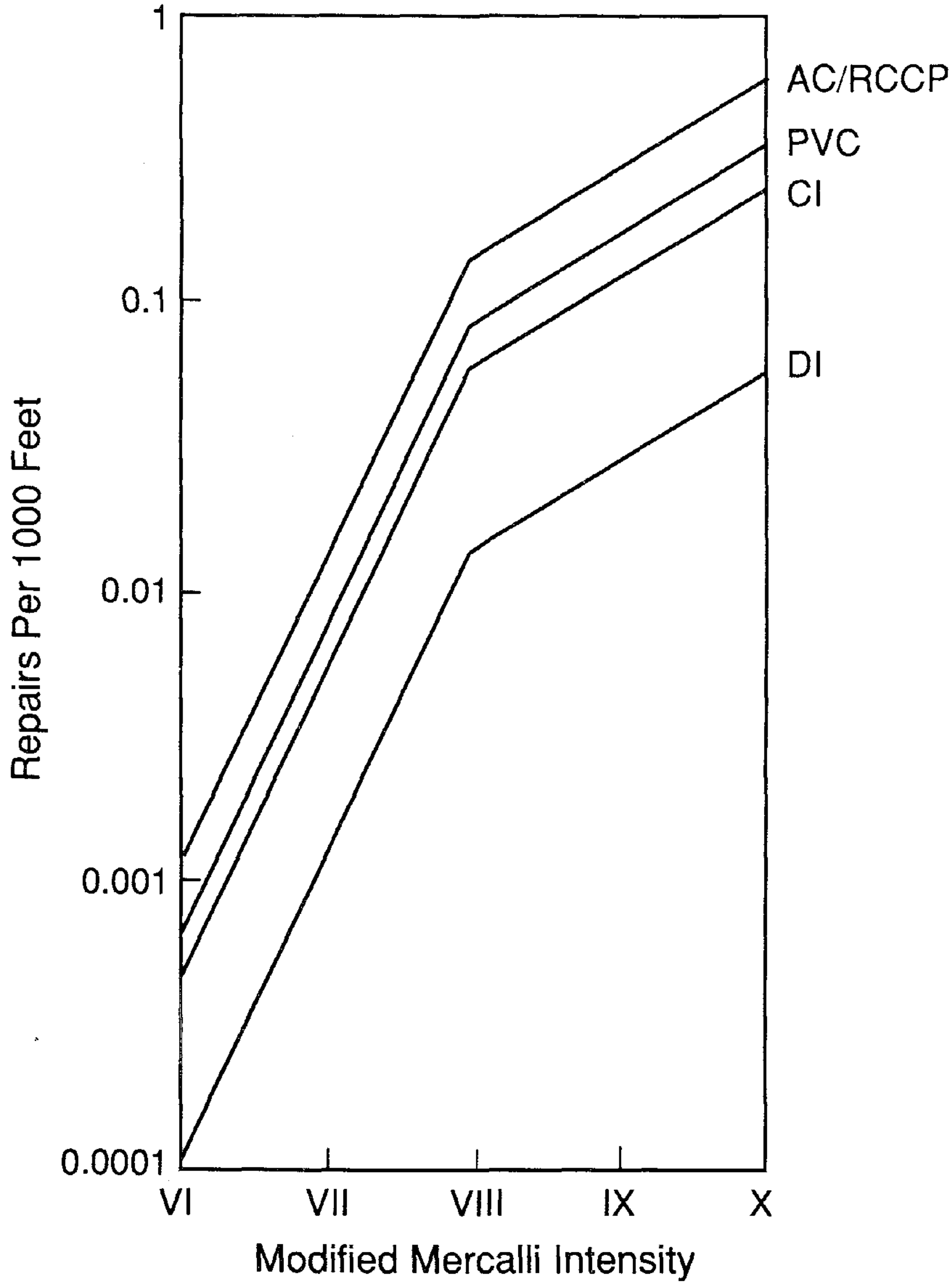

FIGURE 4–1 Wave Propagation Damage in Repairs per 1000 feet Versus Modified Mercalli Intensity, AC = Asbestos Cement, CI = Cast Iron, DI = Ductile Iron, PVC = Polyvinyl Chloride, RCCP = Reinforced Concrete Cylinder Pipe (after Eguchi, 1991).

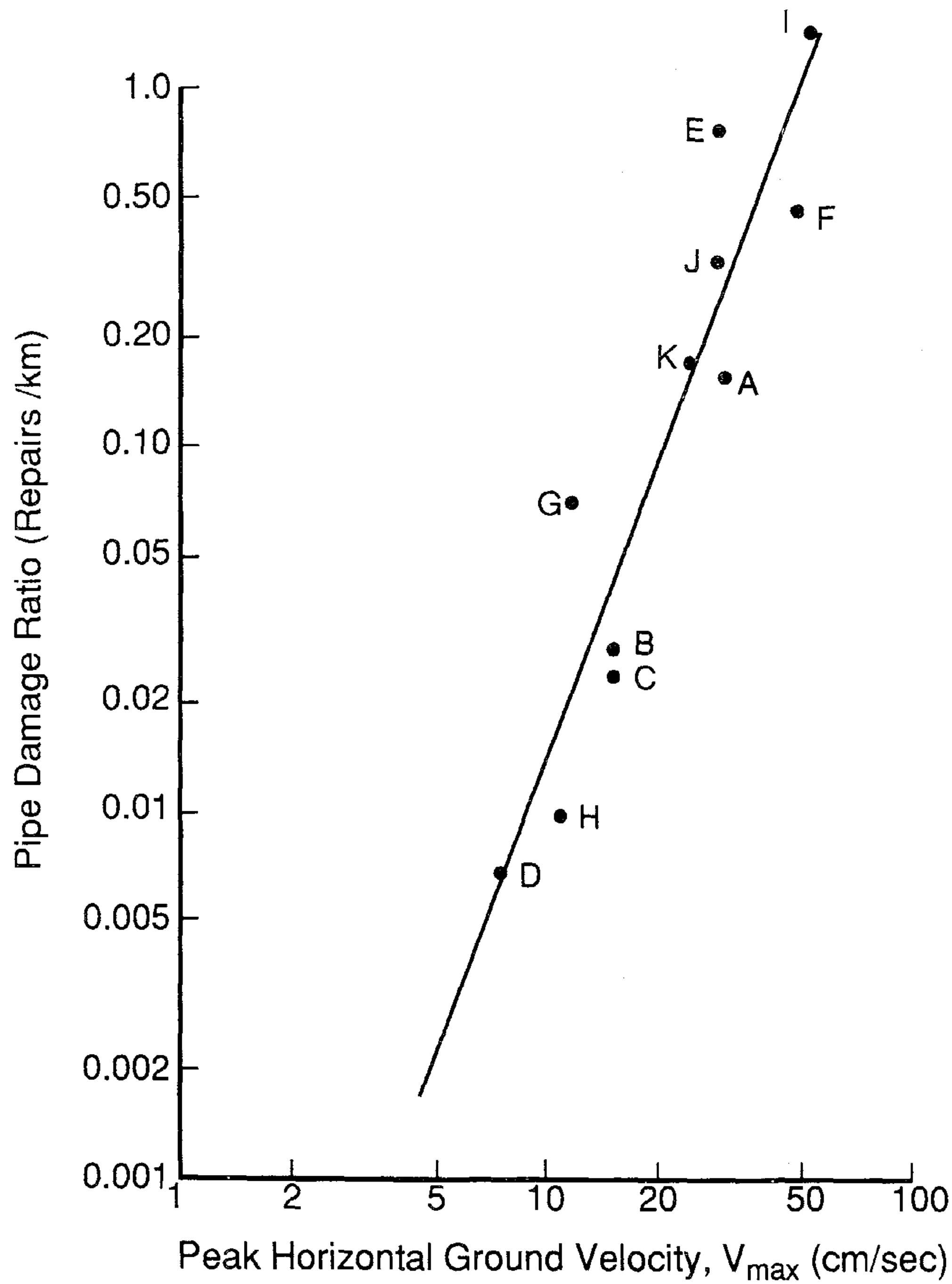

FIGURE 4–2 Wave Propagation Damage to Common Water System Pipe (after O'Rourke and Ayala, 1992)

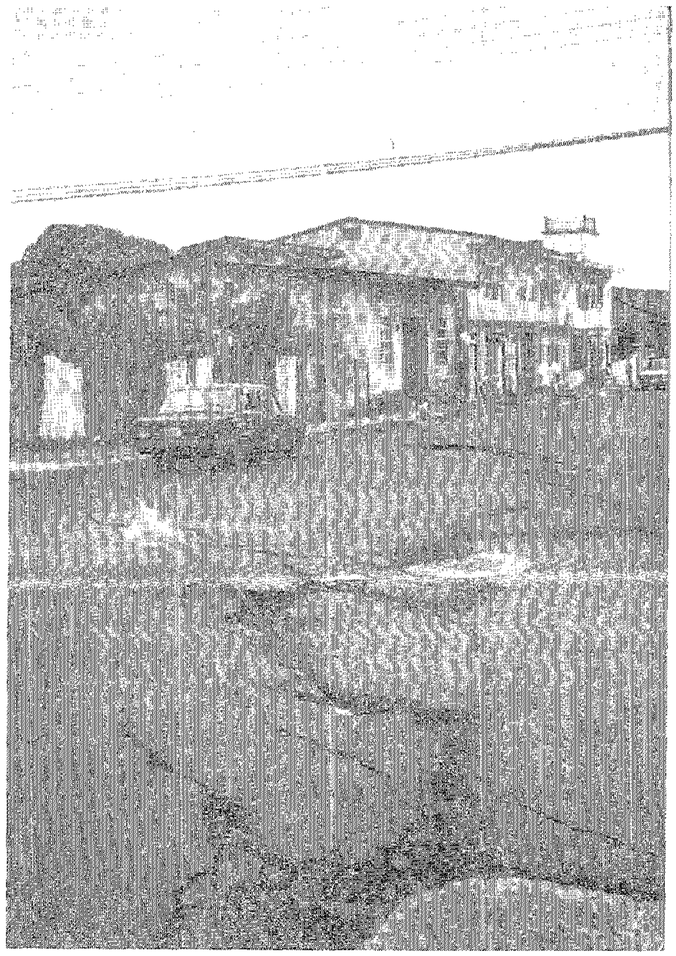

FIGURE 4–3 Ground Cracking Likely due to Lateral Spreading in Limón, which Caused Damage to Buried Pipelines

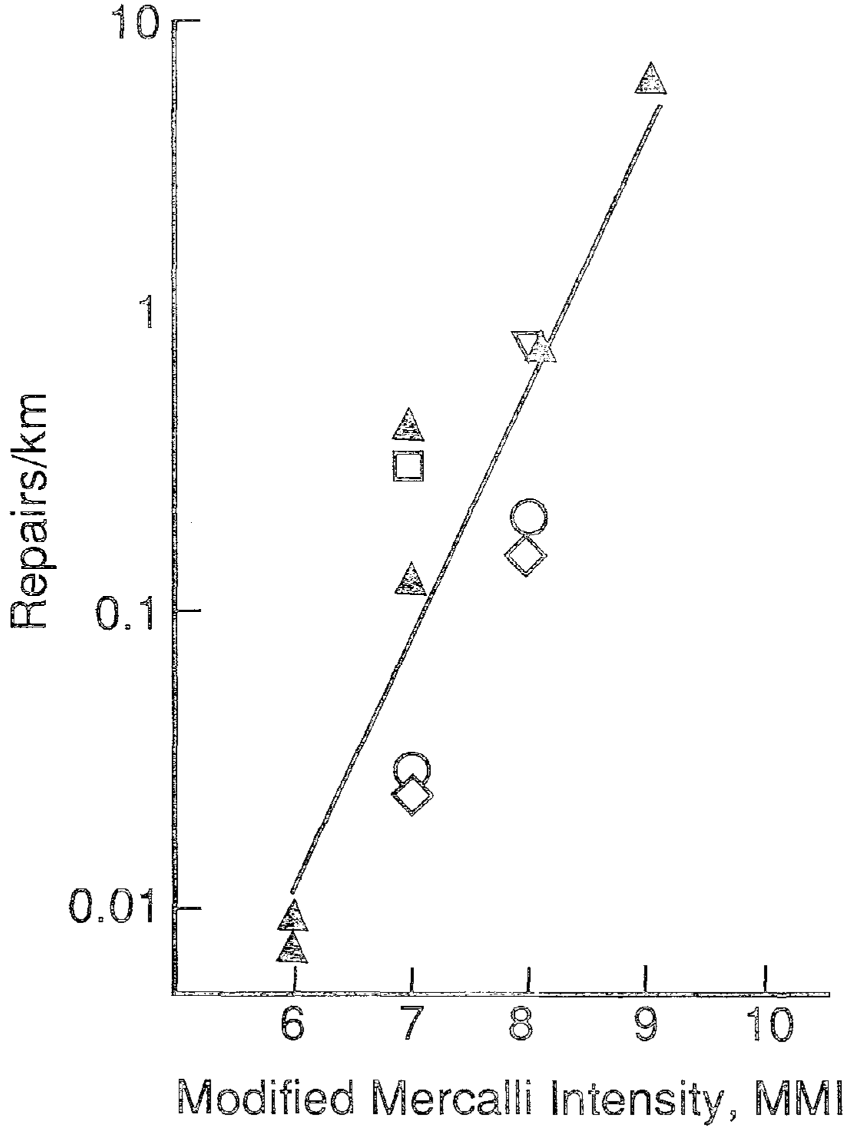

FIGURE 4–4 Combined Damage Rate for Cast Iron Pipe (after O'Rourke et al., [20])

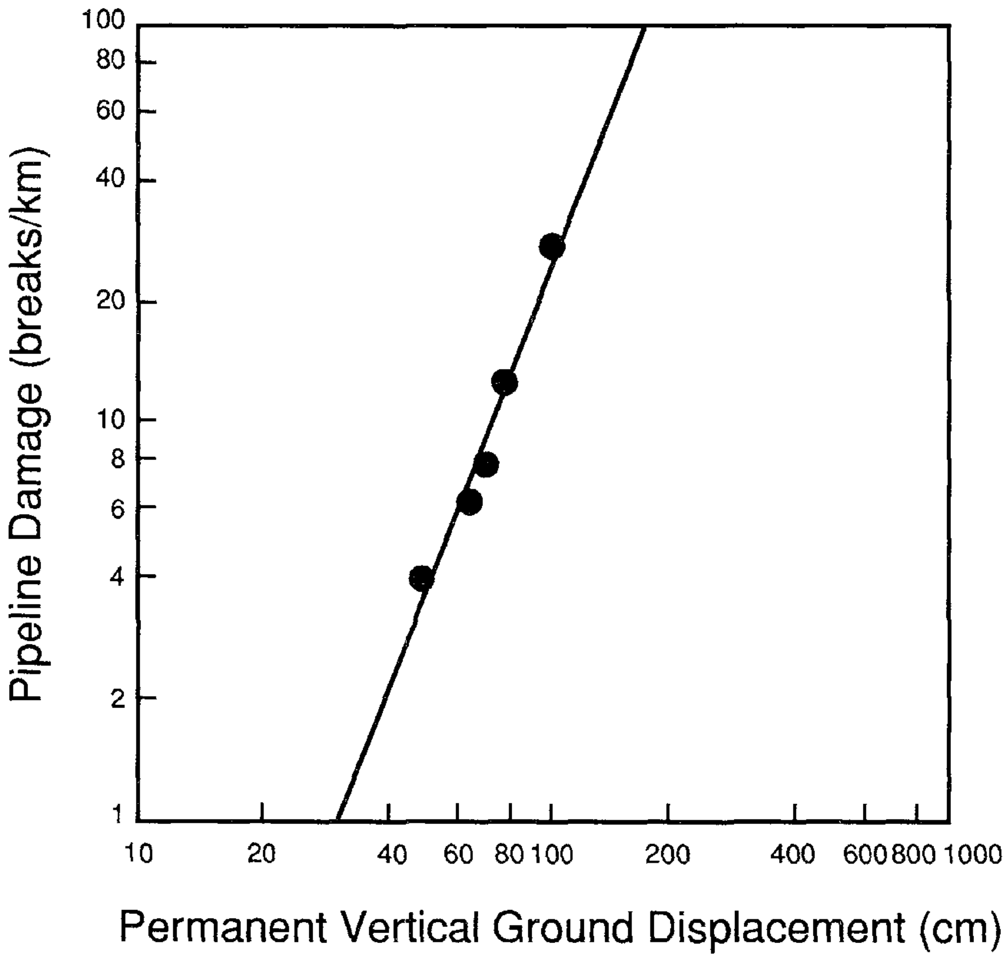

FIGURE 4–5 **Combined Damage Rates for Cast Iron and Steel Pipe (after Barenberg, [18])**

SECTION 5
POST–EARTHQUAKE WATER SUPPLY AND RECOVERY

This section presents information on the immediate post–earthquake status of the Limón water system and methods used for temporary distribution of potable water. In addition, the time required and the repair procedures used for the AyA transmission and distribution pipelines will be summarized. Finally, AyA plans for longer term improvements to the Limón water system will be discussed.

5.1. Post–Earthquake Status Of AyA System

The Limón water system was inoperable immediately following the April 22, earthquake, primarily due to pipeline damage. However as of May 1, nine days after the earthquake, service to approximately one–third of the service area was restored. In point of fact one of the hotels used by the inspection team (the Matama , located along the coast North of Limón) had potable water service on May 2. This localized service was due primarily to the fairly rapid repair of the 300 mm (12 inch) diameter DI line from the Moin well field.

The 300 mm (12 inch) diameter CI line from the Banano River water treatment plant was functioning as of April 29. However, it provided only minimal water pressure to some sections of Limón. Of the 135 lps flow into the line, 100 lps was coming out the other end, so there were some remaining leaks.

Towards the end of July, about three months after the earthquake, repairs to about 400 of the 465 leaks in the distribution piping in Limón had been completed and the 500 mm (20 inch) diameter RCCP transmission pipe from the Banano river treatment plant had been repaired.

In the immediate post–earthquake period, bottled and "bagged" potable water was flown in to Limón from San José, the nation's capital located about 120 km to the West. After the road from San José to Limón was made passable, potable water arrived by truck. Figure 5–1 shows workers unloading and storing potable water adjacent to the inground reservoir at the AyA operations yard on May 3. Figure 5–2 shows this potable water "aqua pura" in 2 liter plastic bottles supplied by the Coca Cola bottling plant in San José. As time progressed, small diameter hoses were connected to main distribution piping within the city to allow residents to get water. This was done because there was inadequate pressure to service the house plumbing. A "boil water" was put into effect. Note that during repair of pipelines within the city, trench dewatering was not being practiced, and open pipe was being submerged in muddy water as shown in Figure 3–18. On May 26, 1991, it was reported that five portable reservoirs had been set up in Limón to supply water.

At the treatment plant the chlorine cylinder was set back into place and tied–back with wire. The dry chemical feeder was repaired and put back into operation. The crack in the concrete channel was patched.

On 30 April, the plant had been restored to 135 lps of its original 350 lps capacity. This reduction was a result of the damaged baffles and clarifier plates coupled with the high raw water turbidity. Flocculator baffles were being replaced during the 30 April visit to the plant. The 135 lps was being achieved by operating the still functional flocculators and clarifiers, and by operating the filters in a direct filtration mode. The disadvantage of the direct filtration mode is the requirement for more frequent backwashing of the filters.

On 26 April, the plant operators began using a Cat–Floc polymer to enhance removal of the high turbidity. They could successfully treat turbidities up to 12,000 mg/l.

Two of the seven wells along the transmission line has been brought on line by the 30 April visit producing 43 and 11 lps respectively. A total of 100 lps from all five wells was expected when the remaining three productive wells were started the next week.

5.2 Water Pipeline Restoration

As noted previously, the 16 breaks in the DI transmission line from the Moin well field were repaired by May 1, at the latest. The CI transmission line from the Banano River, which required 37 repairs, was functioning by April 29, 7 days after the earthquake. Roughly 90 days after the earthquake the 120 repairs to the RCCP transmission line from the Banano River water treatment plant were completed as well as repairs to 400 of the distribution line leaks in Limón. This suggests gross restoration rates of roughly 3 to 5 repairs per day for the DI transmission line, the CI transmission line, and the distribution lines, and a gross restoration rate of roughly 1 repair per day for the RCCP transmission line. Only one significant figure is provided for the restoration rates because of imprecise information about required repair times and in some cases the comparatively small number of repairs. Also the gross restoration cited above rates do not take into account the size of the repair crews, the order in which the lines were repaired, nor the number of the repair crews assigned to each line.

Nevertheless, as noted by AyA engineers, the RCCP line repairs were much more difficult than those for CI, DI, and other pipe materials. This is primarily due to the fact that commercially available couplings were used for the CI, DI and AC lines while welding and pouring concrete encasement blocks were needed for the RCCP line. For example, Figure 3–4 shows repairs to 300 mm (12 inch) CI transmission line. The repairs were accompanied by simply cutting out the damage portion, in this case a portion of the barrel away from the joints, and replacing it with a new piece which is attached to the existing line with couplings. A similar repair procedure was used for DI pipe as well as the AC distribution pipe shown in Figure 3–19.

The repair technique for RCCP transmission pipe damage which occurred almost exclusively at joints involved cutting away portions of both the male and female ends near the damaged joint and welding a new steel cylinder to each adjoining pipe segment. After welding, the pipe is pressurized to test for leaks and then a reinforced concrete encasement block is poured around the new steel cylinder. For example, Figure 5–3 shows an unrepaired RCCP joint with its black rubber gasket visible on the top and right hand side of the pipe. Hence, this appears to be a joint pull–out failure as shown in Figure 3–3f. Figure 5–4 shows AyA workers preparing for the welding at a RCCP joint while Figure 5–5 shows the reinforcing bar cages around two partially repaired RCCP joints. Figure 5–6 shows completed RCCP joint repairs, awaiting the backfill operation.

5.3 Longer Term Improvements

There is a long term impact from earthquake–induced slides in the watershed, which caused extremely high turbidities in the raw water supply. As a result, AyA is developing alternative ground water sources to supplement the surface supply for Limón. Four additional wells, supplying 50 lps each are being considered for development to overcome the turbidity induced water shortage. These wells would be located along the Rio Blanco, west of Limón, and require construction of 15 km of pipeline to connect them to the main water system. Water from these wells would not be available for at least six months.

At the Banano River water treatment plant, construction of a pre–sedimentation basins is being considered to improve its handling capability. However, this would be available only in three to six months.

In general, providing potable water to the population while earthquake repairs are being completed requires ingenuity and regional cooperation. It is often desirable to have a plan for the temporary distribution of water established before the emergency. In this case, since AyA is the national water and sewer company, regional cooperation is a mute question. Except for the San José System, AyA has no pre–established plans for the temporary distributions of water. This is due to the fact that the rest of the countries water systems are relatively small with only one or two sources of water, and the relatively small size of the country as a whole. Note that after the roads were repaired, water delivery trucks from San José, roughly in the middle of the country, would take only two or three hours to reach Limón which is on the coast.

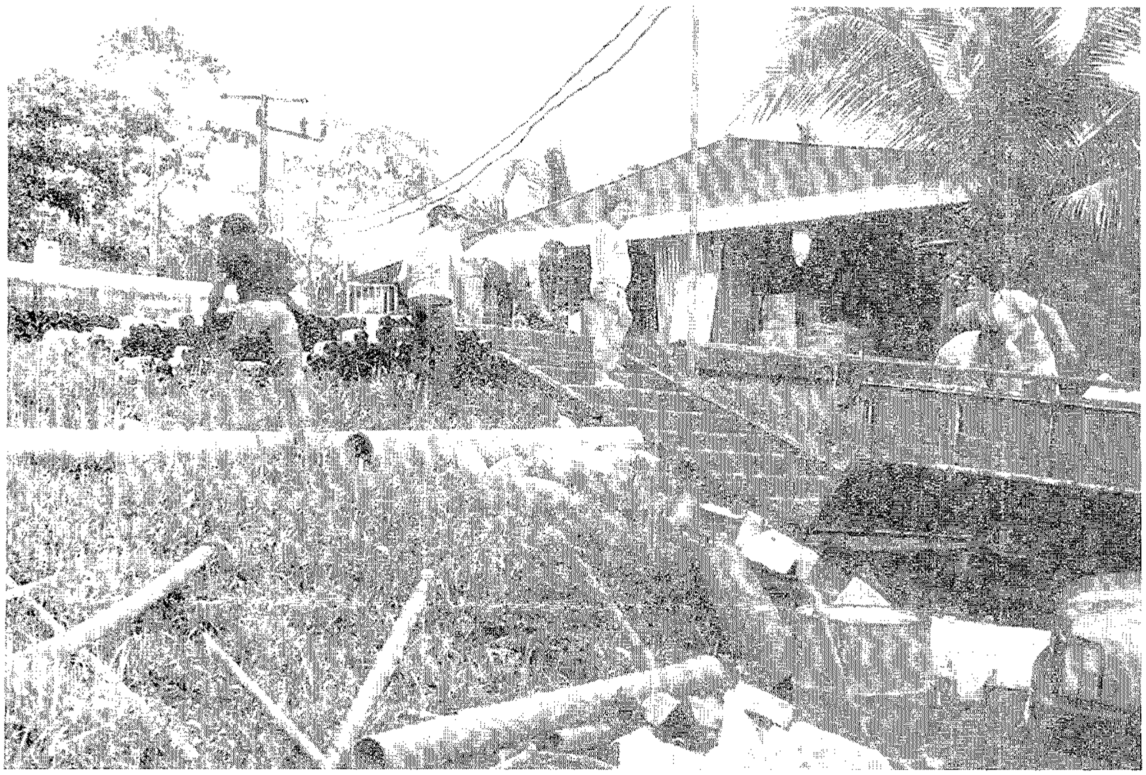

FIGURE 5–1 Workers Unloading Potable Water at the AyA Operations Yard in Limón, on May 3, 1991.

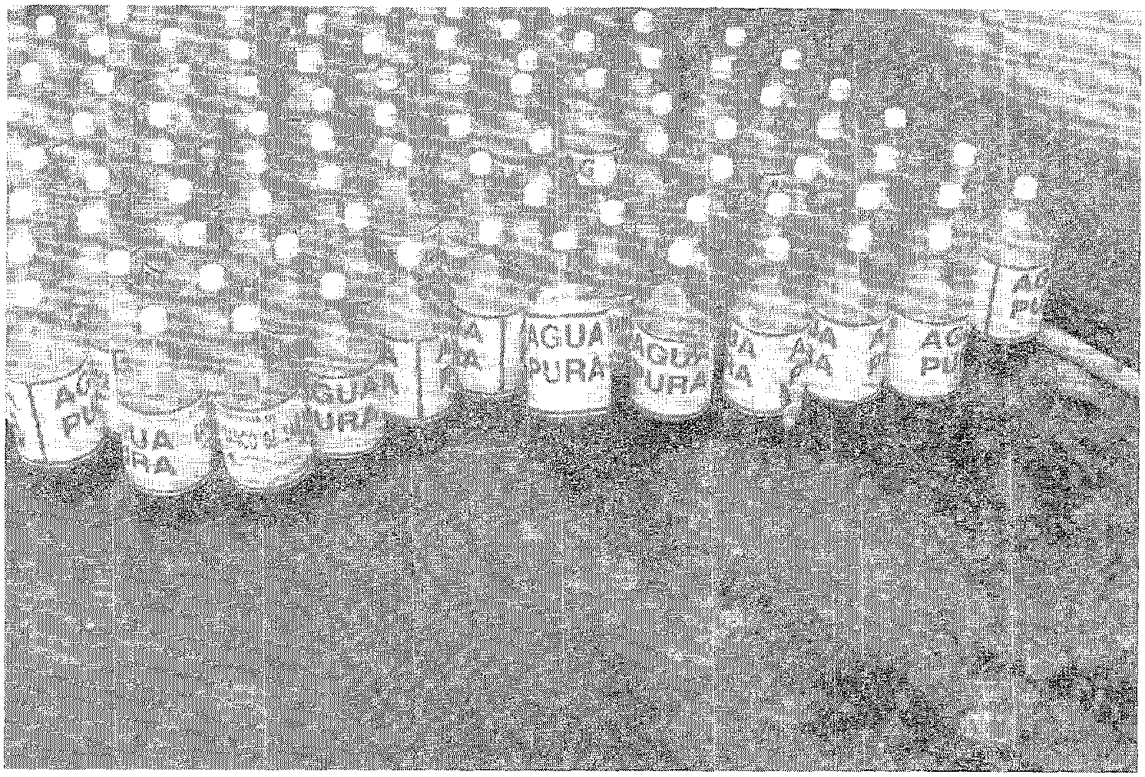

FIGURE 5–2 Two Liter Plastic Coca Cola Bottles Trucked to Limón from San José, Used for Temporary Potable Water Distribution.

FIGURE 5–3 Unrepaired Tensile Pull–out Failure at Joint (see Figure 3–3(f)) in 500 mm (20 inch) RCCP Transmission line from Banano River. Note Black Rubber Gasket at Top and Right Side of Joint.

FIGURE 5–4 AyA Workers Preparing to Weld 500 mm (20 inch) RCCP Transmission Line from Banano River.

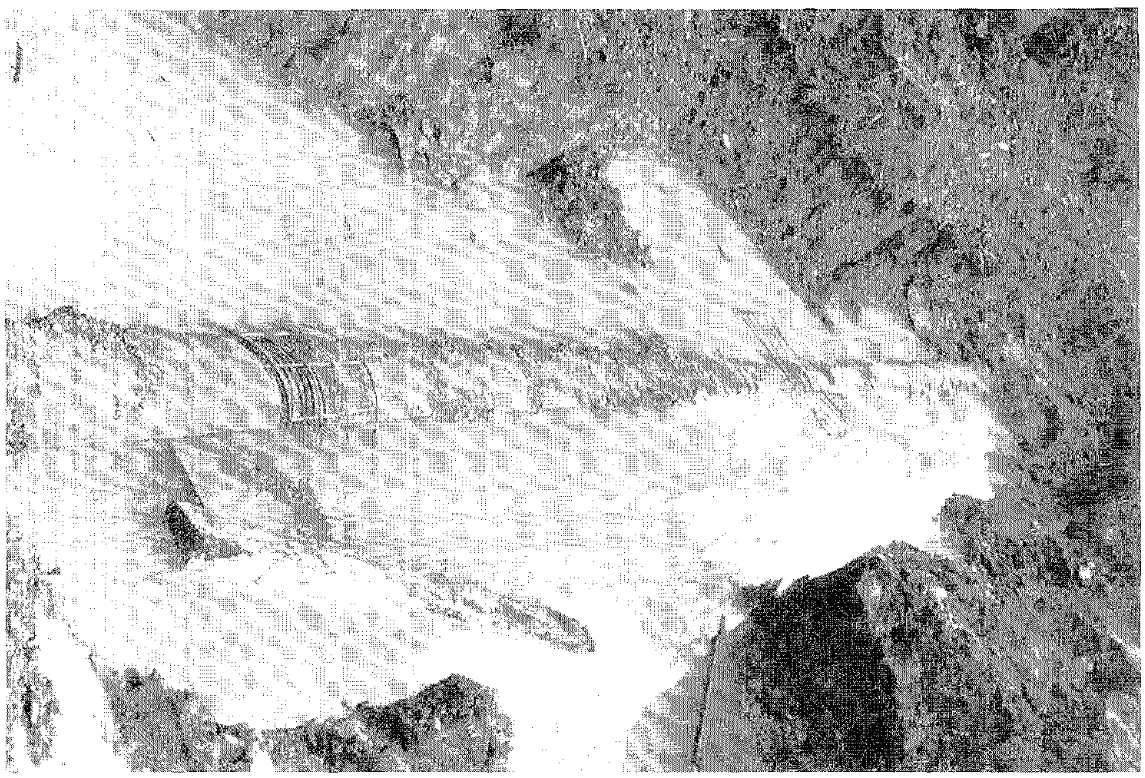

FIGURE 5–5 Partially Repaired Joint in 500 mm (20 inch) RCCP Transmission Line from Banano River. Steel Rebars Await Pour of Concrete.

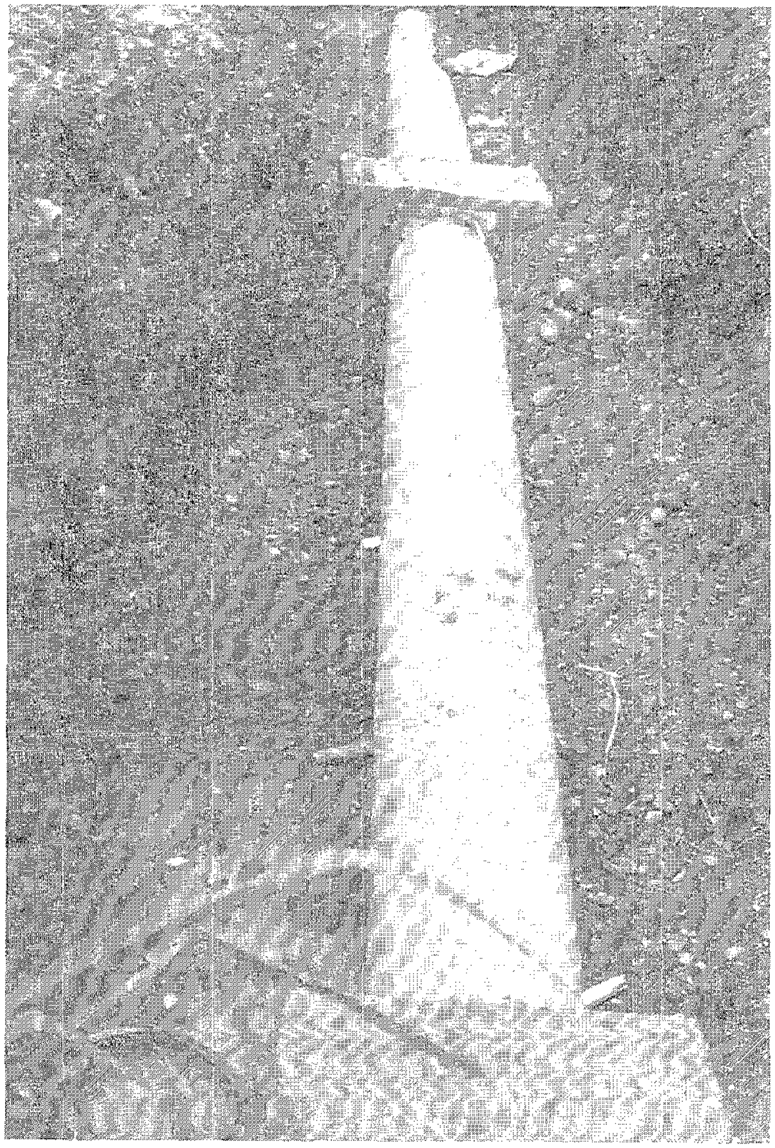

FIGURE 5–6 Repaired Joints in 500 mm (20 inch) RCCP Transmission Line from Banano River. Concrete Encasement Blocks at Joints Part of Repair Procedure.

SECTION 6

SUMMARY, CONCLUSIONS AND LESSONS LEARNED

This report presents information on the behavior and observed damage to water treatment facilities and pipelines occasioned by the April 22, 1991 earthquake in Costa Rica.

6.1 Summary and Conclusions

The April 22, 1991 earthquake had a surface wave magnitude $M_s = 7.5$ and resulted in significant damage in and around Limón on the Caribbean coast. The modified Mercalli Intensity (MMI) for the event was reported to be in the VIII to IX range. Coseismic uplifts in Limón were as large as 1.5 m.

Using the recorded peak ground accelerations primarily in the Central Valley of Costa Rica, and available attenuation relations, peak ground velocities in the Limón area were estimated to be roughly 20 cm/sec for Hard Sites and roughly 50 cm/sec for Soft Sites.

Extremely high raw water turbidities at the water treatment plant resulted from extensive landsliding in the Rio Banano water shed. A short term solution was to initiate the use of polymers to enhance turbidity removal. A long term solution under consideration is to add pre–sedimentation basins to the treatment plant. Putting standby wells back into operation helped allow restoration of water supply. Development of a new well field will help provide a long term solution.

At the treatment plant, a chloride tank toppled and released chlorine, injuring an operator. Seismically induced hydraulic loading on flocculator baffles and clarifier plates broke them making those unit processes partially dysfunctional. Plant operation at a reduced level was restored by initiating direct filtration.

There was only one leak to the welded steel RECOPE liquid fuel pipeline. It was caused by bending of the pipeline through an angle of roughly 25°. High curvature at compressional wrinkles caused tensile cracks in the pipe wall.

The amount of water distribution and transmission pipeline damage in the greater Limón area ranged from about 1.8 repairs per km for CI pipe up to about 8.6 repairs per km for one section of RCCP pipe. The values for AC, PVC, and DI pipe were 4.8, 4.9 and 3.5 respectively. Much of the pipeline damage, particularly to RCCP pipe, is attributed to Permanent Ground Deformation effects although what appeared to be wave propagation damage was also observed.

For PVC pipe there was a slight decrease in damage rate with increasing pipe diameter, while the opposite trend was observed for AC pipe. Considering all materials, the damage rate in repairs per km was not a function of diameter. For AC pipe essentially all the damage was due to a break, such as a round crack, in the pipe segments while for GI pipe most of the damage was due to fracture of the union piece connections two adjacent pipe segments. For RCCP pipe essentially all the damage occurred at joints either telescoping or pull–out. For CI, DI, and PVC most of the damage was due to either pipe segments breaks or joint pull–out.

The observed damage to CI pipe in the Limón area was consistent with the empirical relation between repairs/km from both wave propagation and permanent ground deformation damage and MMI developed by O'Rourke et al. [20]. However the Barenberg empirical relation [18], based upon vertical PGD, significantly overestimated the observed CI damage. Empirical estimates of wave propagation (WP) damage were consistent with the observed damaged. That is both the Eguchi relation [17] based upon MMI and the O'Rourke and Ayala relation [19], based on V_{max} both predicted WP damage which were less than the observed total for both WP and PGD effects.

The RCCP pipe damage was the most difficult to repair. AyA crews were able to make a little over one RCCP repair per day, while the rate for all other materials ranged from roughly 3 to 5 repairs per day. The difference in repair rate is due primarily to the lack of commercially available couplings for RCCP pipe.

6.2 Lessons Learned

The lesson learned or observations confirmed by the April 22, 1991 earthquake are presented below:

- Landslides, which may cause extremely high turbidity, can be catastrophic. Surface water supplies with watersheds vulnerable to slides should provide contingency planning for this potential problem.

- Chlorine cylinders should be anchored. This was the third major earthquake within the last 2 years where a chloride cylinder toppled, breaking connecting piping, and releasing chlorine gas.

- Submerged baffles are subject to substantial seismic loads due to hydrodynamic effects. While it may not be appropriate to design these elements to resist the loads, "break–away" designs which allow easy repair should be employed.

- By their nature, water distribution systems are usually highly redundant, which provides operational flexibility in an emergency. However, where possible, redundancy in supply sources and water transmission systems is also highly desirable. Note that a few days after the earthquake the Moin well field source was able to provide reduced service to Limón when the Banano River source was down due to turbidity problems and transmission line damage.

- Pipelines buried in fill or in areas susceptible to liquefaction are particularly vulnerable to seismic damage.

- The 150 mm (6 in) diameter welded steel pipe used for oil transmission performed extremely well with only one break in 200 km of pipe. The above grade installation in some locations limited soil loadings on the pipe. The one leak occurred in an area of severe PGD. The damage mechanism was tearing due to excessive compressional wrinkling (local buckling), common for welded steel pipe.

- The key to seismic design of buried segmented pipelines is flexibility. That is, the joints, backfill or support conditions, etc. should be such that the line can bend, extend or compress with the ground without failure or leakage.

- The repair procedure used for concrete cylinder pipe was very time–consuming. Ease of repair should be considered when selecting new pipe types. For existing pipelines, repair procedures and material inventories should be developed to allow quick repair following an earthquake.

SECTION 7

REFERENCES

[1] Quintanar L., Deschamps, A., and Madariagn, R., "Rupture Process of the Costa Rica Earthquake of April 22, 1991 by Teleseismic P–waves Inversion"., paper no. S12C–5, presented at Amer. Geophysical Union meeting San Francisco, CA, Dec. 1991.

[2] Montero, C., Segura, J., Malavassi, E., Güendel, F., Gonzales, V., Fernandez, E., De Obaldia, F., Rojas, D., Rodriguez, H., Mata, A., Van Der Laat, R., Barroza, V., Barrantes, O., Marino, T., and McNally, K., "Preliminary Information, 22 April 1991 Earthquake (Ms = 7.4) Valle de la Estrella, Limón, Costa Rica", Vulcanological and Seismological Observatory of Costa Rica – National Univ. Report, May 1991, 27 p. (in Spanish).

[3] "Costa Rica Earthquake of April 22, 1991 Reconnaissance Report", Supplement B to Vol. 7, Oct. 1991, Earthquake Spectra Publication 91–02, EERI, 127 p.

[4] Plafker, G., and Ward, S., "Thrust Faulting and Tectonic Uplift Along the Caribbean Sea Coast During the April 22, 1991 Costa Rica Earthquake", Submitted to Tectonics, July 1991.

[5] "Preliminary Report on Acceleration Records Obtained during the April 22, 1991 Earthquake", Earthquake Engineering Laboratory of the University of Costa Rica, April 26, 1991, 12 p., (in Spanish).

[6] Kawashima, K., Aizawa, K., and Takahashi, K., "Attenuation of Peak Ground Motions and Absolute Acceleration Response Spectra" Proc. Eight World Conf. on Earthquake Engineering, San Francisco, CA, Vol. II, p.257–264, 1984.

[7] Ballantyne, D., "Earthquake Loss Estimation of the Portland, Oregon Water and Sewage Systems – Evaluation of Concentrated Facilities," Kennedy/Jenks/Chilton Report No. 896015.00, Funded by the United States Geological Survey, Grant Number 14–08–0001–G1694, 1989.

[8] Ballantyne, D., "Earthquake Loss Estimation Modeling for the City of Everett, Washington's Lifelines" Kennedy/Jenks/Chilton Report No. 906014.00, Funded by the United States Geological Survey, Grant Number 14–08–0001–G1804, May 1991.

[9] Lund, LeVal; "Water and Sewage Systems", Loma Prieta Earthquake Reconnaissance Report, Earthquake Spectra, Supplement to Volume 6, May 1990.

[10] Ballantyne, D., "Water, Sewer, and Hydro Systems", in Philippines Earthquake Reconnaissance Report, Earthquake Spectra, Supplement A to Vol. 7, October 1991.

[11] International Conference of Building Officials, "Uniform Building Code", Whittier, California, 1991.

[12] Ballantyne, D., "1989 Loma Prieta Earthquake Damage Evaluation of Water and Waste Treatment Facility Nonstructural Tank Elements", Kennedy/Jenks/Chilton Report No. 896086.00, prepared for the National Science Foundation, Grant Number BCS–9002459, December 1990.

[13] Arguedas, J., personal communication, July 18, 1991.

[14] Isenberg, J., and Taylor, C., "Performance of Water and Sewer Lifelines in the May 2, 1983 Coalinga California Earthquake," Lifeline Earthquake Engineering: Performance Design and Construction, Proc. ASCE Symposium at San Francisco, CA, J. Cooper ed., pp. 176–189, 1984.

[15] O'Rourke, M., and Ayala, G., "Seismic Damage to Pipeline: Case Study," Journal of Transportation Engineering, ASCE, Vol. 116, No. 2, March/April, 1990, pp.123–134.

[16] Eguchi, R., Taylor, D., and Hasselman, T., "Seismic Component Vulnerability Models for Lifelines Risk Analysis," Technical Report No. 82–1396–2C, J.H. Wiggins Co., Redondo Beach, CA., 1983.

[17] Eguchi, R., "Early Post–Earthquake Damage Detection for Underground Lifelines," Final Report to National Science Foundation, Dames and Moore P.C., Los Angeles, CA., 1991.

[18] Barenberg, M., "Correlation of pipelines Damage with Ground Motion," Journal of Geotechnical Engineering, ASCE, Vol. 114, No. 6, pp. 706–711, 1988.

[19] O'Rourke, M., and Ayala, G., "Pipeline Damage Due to Wave Propagation", submitted to Journal of Geotechnical Engineering, ASCE.

[20] O'Rourke, T., Gowdy, T., Steward, H., and Pease, J., "Lifeline and Geotechnical Aspects of the 1989 Loma Prieta Earthquake," Proc. 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, March, 1991.

NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
LIST OF TECHNICAL REPORTS

The National Center for Earthquake Engineering Research (NCEER) publishes technical reports on a variety of subjects related to earthquake engineering written by authors funded through NCEER. These reports are available from both NCEER's Publications Department and the National Technical Information Service (NTIS). Requests for reports should be directed to the Publications Department, National Center for Earthquake Engineering Research, State University of New York at Buffalo, Red Jacket Quadrangle, Buffalo, New York 14261. Reports can also be requested through NTIS, 5285 Port Royal Road, Springfield, Virginia 22161. NTIS accession numbers are shown in parenthesis, if available.

NCEER-87-0001 "First-Year Program in Research, Education and Technology Transfer," 3/5/87, (PB88-134275/AS).

NCEER-87-0002 "Experimental Evaluation of Instantaneous Optimal Algorithms for Structural Control," by R.C. Lin, T.T. Soong and A.M. Reinhorn, 4/20/87, (PB88-134341/AS).

NCEER-87-0003 "Experimentation Using the Earthquake Simulation Facilities at University at Buffalo," by A.M. Reinhorn and R.L. Ketter, to be published.

NCEER-87-0004 "The System Characteristics and Performance of a Shaking Table," by J.S. Hwang, K.C. Chang and G.C. Lee, 6/1/87, (PB88-134259/AS). This report is available only through NTIS (see address given above).

NCEER-87-0005 "A Finite Element Formulation for Nonlinear Viscoplastic Material Using a Q Model," by O. Gyebi and G. Dasgupta, 11/2/87, (PB88-213764/AS).

NCEER-87-0006 "Symbolic Manipulation Program (SMP) - Algebraic Codes for Two and Three Dimensional Finite Element Formulations," by X. Lee and G. Dasgupta, 11/9/87, (PB88-219522/AS).

NCEER-87-0007 "Instantaneous Optimal Control Laws for Tall Buildings Under Seismic Excitations," by J.N. Yang, A. Akbarpour and P. Ghaemmaghami, 6/10/87, (PB88-134333/AS).

NCEER-87-0008 "IDARC: Inelastic Damage Analysis of Reinforced Concrete Frame - Shear-Wall Structures," by Y.J. Park, A.M. Reinhorn and S.K. Kunnath, 7/20/87, (PB88-134325/AS).

NCEER-87-0009 "Liquefaction Potential for New York State: A Preliminary Report on Sites in Manhattan and Buffalo," by M. Budhu, V. Vijayakumar, R.F. Giese and L. Baumgras, 8/31/87, (PB88-163704/AS). This report is available only through NTIS (see address given above).

NCEER-87-0010 "Vertical and Torsional Vibration of Foundations in Inhomogeneous Media," by A.S. Veletsos and K.W. Dotson, 6/1/87, (PB88-134291/AS).

NCEER-87-0011 "Seismic Probabilistic Risk Assessment and Seismic Margins Studies for Nuclear Power Plants," by Howard H.M. Hwang, 6/15/87, (PB88-134267/AS).

NCEER-87-0012 "Parametric Studies of Frequency Response of Secondary Systems Under Ground-Acceleration Excitations," by Y. Yong and Y.K. Lin, 6/10/87, (PB88-134309/AS).

NCEER-87-0013 "Frequency Response of Secondary Systems Under Seismic Excitation," by J.A. HoLung, J. Cai and Y.K. Lin, 7/31/87, (PB88-134317/AS).

NCEER-87-0014 "Modelling Earthquake Ground Motions in Seismically Active Regions Using Parametric Time Series Methods," by G.W. Ellis and A.S. Cakmak, 8/25/87, (PB88-134283/AS).

NCEER-87-0015 "Detection and Assessment of Seismic Structural Damage," by E. DiPasquale and A.S. Cakmak, 8/25/87, (PB88-163712/AS).

NCEER-87-0016 "Pipeline Experiment at Parkfield, California," by J. Isenberg and E. Richardson, 9/15/87, (PB88-163720/AS). This report is available only through NTIS (see address given above).

NCEER-87-0017 "Digital Simulation of Seismic Ground Motion," by M. Shinozuka, G. Deodatis and T. Harada, 8/31/87, (PB88-155197/AS). This report is available only through NTIS (see address given above).

NCEER-87-0018 "Practical Considerations for Structural Control: System Uncertainty, System Time Delay and Truncation of Small Control Forces," J.N. Yang and A. Akbarpour, 8/10/87, (PB88-163738/AS).

NCEER-87-0019 "Modal Analysis of Nonclassically Damped Structural Systems Using Canonical Transformation," by J.N. Yang, S. Sarkani and F.X. Long, 9/27/87, (PB88-187851/AS).

NCEER-87-0020 "A Nonstationary Solution in Random Vibration Theory," by J.R. Red-Horse and P.D. Spanos, 11/3/87, (PB88-163746/AS).

NCEER-87-0021 "Horizontal Impedances for Radially Inhomogeneous Viscoelastic Soil Layers," by A.S. Veletsos and K.W. Dotson, 10/15/87, (PB88-150859/AS).

NCEER-87-0022 "Seismic Damage Assessment of Reinforced Concrete Members," by Y.S. Chung, C. Meyer and M. Shinozuka, 10/9/87, (PB88-150867/AS). This report is available only through NTIS (see address given above).

NCEER-87-0023 "Active Structural Control in Civil Engineering," by T.T. Soong, 11/11/87, (PB88-187778/AS).

NCEER-87-0024 "Vertical and Torsional Impedances for Radially Inhomogeneous Viscoelastic Soil Layers," by K.W. Dotson and A.S. Veletsos, 12/87, (PB88-187786/AS).

NCEER-87-0025 "Proceedings from the Symposium on Seismic Hazards, Ground Motions, Soil-Liquefaction and Engineering Practice in Eastern North America," October 20-22, 1987, edited by K.H. Jacob, 12/87, (PB88-188115/AS).

NCEER-87-0026 "Report on the Whittier-Narrows, California, Earthquake of October 1, 1987," by J. Pantelic and A. Reinhorn, 11/87, (PB88-187752/AS). This report is available only through NTIS (see address given above).

NCEER-87-0027 "Design of a Modular Program for Transient Nonlinear Analysis of Large 3-D Building Structures," by S. Srivastav and J.F. Abel, 12/30/87, (PB88-187950/AS).

NCEER-87-0028 "Second-Year Program in Research, Education and Technology Transfer," 3/8/88, (PB88-219480/AS).

NCEER-88-0001 "Workshop on Seismic Computer Analysis and Design of Buildings With Interactive Graphics," by W. McGuire, J.F. Abel and C.H. Conley, 1/18/88, (PB88-187760/AS).

NCEER-88-0002 "Optimal Control of Nonlinear Flexible Structures," by J.N. Yang, F.X. Long and D. Wong, 1/22/88, (PB88-213772/AS).

NCEER-88-0003 "Substructuring Techniques in the Time Domain for Primary-Secondary Structural Systems," by G.D. Manolis and G. Juhn, 2/10/88, (PB88-213780/AS).

NCEER-88-0004 "Iterative Seismic Analysis of Primary-Secondary Systems," by A. Singhal, L.D. Lutes and P.D. Spanos, 2/23/88, (PB88-213798/AS).

NCEER-88-0005 "Stochastic Finite Element Expansion for Random Media," by P.D. Spanos and R. Ghanem, 3/14/88, (PB88-213806/AS).

NCEER-88-0006 "Combining Structural Optimization and Structural Control," by F.Y. Cheng and C.P. Pantelides, 1/10/88, (PB88-213814/AS).

NCEER-88-0007 "Seismic Performance Assessment of Code-Designed Structures," by H.H-M. Hwang, J-W. Jaw and H-J. Shau, 3/20/88, (PB88-219423/AS).

NCEER-88-0008 "Reliability Analysis of Code-Designed Structures Under Natural Hazards," by H.H-M. Hwang, H. Ushiba and M. Shinozuka, 2/29/88, (PB88-229471/AS).

NCEER-88-0009 "Seismic Fragility Analysis of Shear Wall Structures," by J-W Jaw and H.H-M. Hwang, 4/30/88, (PB89-102867/AS).

NCEER-88-0010 "Base Isolation of a Multi-Story Building Under a Harmonic Ground Motion - A Comparison of Performances of Various Systems," by F-G Fan, G. Ahmadi and I.G. Tadjbakhsh, 5/18/88, (PB89-122238/AS).

NCEER-88-0011 "Seismic Floor Response Spectra for a Combined System by Green's Functions," by F.M. Lavelle, L.A. Bergman and P.D. Spanos, 5/1/88, (PB89-102875/AS).

NCEER-88-0012 "A New Solution Technique for Randomly Excited Hysteretic Structures," by G.Q. Cai and Y.K. Lin, 5/16/88, (PB89-102883/AS).

NCEER-88-0013 "A Study of Radiation Damping and Soil-Structure Interaction Effects in the Centrifuge," by K. Weissman, supervised by J.H. Prevost, 5/24/88, (PB89-144703/AS).

NCEER-88-0014 "Parameter Identification and Implementation of a Kinematic Plasticity Model for Frictional Soils," by J.H. Prevost and D.V. Griffiths, to be published.

NCEER-88-0015 "Two- and Three- Dimensional Dynamic Finite Element Analyses of the Long Valley Dam," by D.V. Griffiths and J.H. Prevost, 6/17/88, (PB89-144711/AS).

NCEER-88-0016 "Damage Assessment of Reinforced Concrete Structures in Eastern United States," by A.M. Reinhorn, M.J. Seidel, S.K. Kunnath and Y.J. Park, 6/15/88, (PB89-122220/AS).

NCEER-88-0017 "Dynamic Compliance of Vertically Loaded Strip Foundations in Multilayered Viscoelastic Soils," by S. Ahmad and A.S.M. Israil, 6/17/88, (PB89-102891/AS).

NCEER-88-0018 "An Experimental Study of Seismic Structural Response With Added Viscoelastic Dampers," by R.C. Lin, Z. Liang, T.T. Soong and R.H. Zhang, 6/30/88, (PB89-122212/AS). This report is available only through NTIS (see address given above).

NCEER-88-0019 "Experimental Investigation of Primary - Secondary System Interaction," by G.D. Manolis, G. Juhn and A.M. Reinhorn, 5/27/88, (PB89-122204/AS).

NCEER-88-0020 "A Response Spectrum Approach For Analysis of Nonclassically Damped Structures," by J.N. Yang, S. Sarkani and F.X. Long, 4/22/88, (PB89-102909/AS).

NCEER-88-0021 "Seismic Interaction of Structures and Soils: Stochastic Approach," by A.S. Veletsos and A.M. Prasad, 7/21/88, (PB89-122196/AS).

NCEER-88-0022 "Identification of the Serviceability Limit State and Detection of Seismic Structural Damage," by E. DiPasquale and A.S. Cakmak, 6/15/88, (PB89-122188/AS). This report is available only through NTIS (see address given above).

NCEER-88-0023 "Multi-Hazard Risk Analysis: Case of a Simple Offshore Structure," by B.K. Bhartia and E.H. Vanmarcke, 7/21/88, (PB89-145213/AS).

NCEER-88-0024 "Automated Seismic Design of Reinforced Concrete Buildings," by Y.S. Chung, C. Meyer and M. Shinozuka, 7/5/88, (PB89-122170/AS). This report is available only through NTIS (see address given above).

NCEER-88-0025 "Experimental Study of Active Control of MDOF Structures Under Seismic Excitations," by L.L. Chung, R.C. Lin, T.T. Soong and A.M. Reinhorn, 7/10/88, (PB89-122600/AS).

NCEER-88-0026 "Earthquake Simulation Tests of a Low-Rise Metal Structure," by J.S. Hwang, K.C. Chang, G.C. Lee and R.L. Ketter, 8/1/88, (PB89-102917/AS).

NCEER-88-0027 "Systems Study of Urban Response and Reconstruction Due to Catastrophic Earthquakes," by F. Kozin and H.K. Zhou, 9/22/88, (PB90-162348/AS).

NCEER-88-0028 "Seismic Fragility Analysis of Plane Frame Structures," by H.H-M. Hwang and Y.K. Low, 7/31/88, (PB89-131445/AS).

NCEER-88-0029 "Response Analysis of Stochastic Structures," by A. Kardara, C. Bucher and M. Shinozuka, 9/22/88, (PB89-174429/AS).

NCEER-88-0030 "Nonnormal Accelerations Due to Yielding in a Primary Structure," by D.C.K. Chen and L.D. Lutes, 9/19/88, (PB89-131437/AS).

NCEER-88-0031 "Design Approaches for Soil-Structure Interaction," by A.S. Veletsos, A.M. Prasad and Y. Tang, 12/30/88, (PB89-174437/AS). This report is available only through NTIS (see address given above).

NCEER-88-0032 "A Re-evaluation of Design Spectra for Seismic Damage Control," by C.J. Turkstra and A.G. Tallin, 11/7/88, (PB89-145221/AS).

NCEER-88-0033 "The Behavior and Design of Noncontact Lap Splices Subjected to Repeated Inelastic Tensile Loading," by V.E. Sagan, P. Gergely and R.N. White, 12/8/88, (PB89-163737/AS).

NCEER-88-0034 "Seismic Response of Pile Foundations," by S.M. Mamoon, P.K. Banerjee and S. Ahmad, 11/1/88, (PB89-145239/AS).

NCEER-88-0035 "Modeling of R/C Building Structures With Flexible Floor Diaphragms (IDARC2)," by A.M. Reinhorn, S.K. Kunnath and N. Panahshahi, 9/7/88, (PB89-207153/AS).

NCEER-88-0036 "Solution of the Dam-Reservoir Interaction Problem Using a Combination of FEM, BEM with Particular Integrals, Modal Analysis, and Substructuring," by C-S. Tsai, G.C. Lee and R.L. Ketter, 12/31/88, (PB89-207146/AS).

NCEER-88-0037 "Optimal Placement of Actuators for Structural Control," by F.Y. Cheng and C.P. Pantelides, 8/15/88, (PB89-162846/AS).

NCEER-88-0038 "Teflon Bearings in Aseismic Base Isolation: Experimental Studies and Mathematical Modeling," by A. Mokha, M.C. Constantinou and A.M. Reinhorn, 12/5/88, (PB89-218457/AS). This report is available only through NTIS (see address given above).

NCEER-88-0039 "Seismic Behavior of Flat Slab High-Rise Buildings in the New York City Area," by P. Weidlinger and M. Ettouney, 10/15/88, (PB90-145681/AS).

NCEER-88-0040 "Evaluation of the Earthquake Resistance of Existing Buildings in New York City," by P. Weidlinger and M. Ettouney, 10/15/88, to be published.

NCEER-88-0041 "Small-Scale Modeling Techniques for Reinforced Concrete Structures Subjected to Seismic Loads," by W. Kim, A. El-Attar and R.N. White, 11/22/88, (PB89-189625/AS).

NCEER-88-0042 "Modeling Strong Ground Motion from Multiple Event Earthquakes," by G.W. Ellis and A.S. Cakmak, 10/15/88, (PB89-174445/AS).

NCEER-88-0043 "Nonstationary Models of Seismic Ground Acceleration," by M. Grigoriu, S.E. Ruiz and E. Rosenblueth, 7/15/88, (PB89-189617/AS).

NCEER-88-0044 "SARCF User's Guide: Seismic Analysis of Reinforced Concrete Frames," by Y.S. Chung, C. Meyer and M. Shinozuka, 11/9/88, (PB89-174452/AS).

NCEER-88-0045 "First Expert Panel Meeting on Disaster Research and Planning," edited by J. Pantelic and J. Stoyle, 9/15/88, (PB89-174460/AS).

NCEER-88-0046 "Preliminary Studies of the Effect of Degrading Infill Walls on the Nonlinear Seismic Response of Steel Frames," by C.Z. Chrysostomou, P. Gergely and J.F. Abel, 12/19/88, (PB89-208383/AS).

NCEER-88-0047 "Reinforced Concrete Frame Component Testing Facility - Design, Construction, Instrumentation and Operation," by S.P. Pessiki, C. Conley, T. Bond, P. Gergely and R.N. White, 12/16/88, (PB89-174478/AS).

NCEER-89-0001 "Effects of Protective Cushion and Soil Compliancy on the Response of Equipment Within a Seismically Excited Building," by J.A. HoLung, 2/16/89, (PB89-207179/AS).

NCEER-89-0002 "Statistical Evaluation of Response Modification Factors for Reinforced Concrete Structures," by H.H-M. Hwang and J-W. Jaw, 2/17/89, (PB89-207187/AS).

NCEER-89-0003 "Hysteretic Columns Under Random Excitation," by G-Q. Cai and Y.K. Lin, 1/9/89, (PB89-196513/AS).

NCEER-89-0004 "Experimental Study of 'Elephant Foot Bulge' Instability of Thin-Walled Metal Tanks," by Z-H. Jia and R.L. Ketter, 2/22/89, (PB89-207195/AS).

NCEER-89-0005 "Experiment on Performance of Buried Pipelines Across San Andreas Fault," by J. Isenberg, E. Richardson and T.D. O'Rourke, 3/10/89, (PB89-218440/AS).

NCEER-89-0006 "A Knowledge-Based Approach to Structural Design of Earthquake-Resistant Buildings," by M. Subramani, P. Gergely, C.H. Conley, J.F. Abel and A.H. Zaghw, 1/15/89, (PB89-218465/AS).

NCEER-89-0007 "Liquefaction Hazards and Their Effects on Buried Pipelines," by T.D. O'Rourke and P.A. Lane, 2/1/89, (PB89-218481).

NCEER-89-0008 "Fundamentals of System Identification in Structural Dynamics," by H. Imai, C-B. Yun, O. Maruyama and M. Shinozuka, 1/26/89, (PB89-207211/AS).

NCEER-89-0009 "Effects of the 1985 Michoacan Earthquake on Water Systems and Other Buried Lifelines in Mexico," by A.G. Ayala and M.J. O'Rourke, 3/8/89, (PB89-207229/AS).

NCEER-89-R010 "NCEER Bibliography of Earthquake Education Materials," by K.E.K. Ross, Second Revision, 9/1/89, (PB90-125352/AS).

NCEER-89-0011 "Inelastic Three-Dimensional Response Analysis of Reinforced Concrete Building Structures (IDARC-3D), Part I - Modeling," by S.K. Kunnath and A.M. Reinhorn, 4/17/89, (PB90-114612/AS).

NCEER-89-0012 "Recommended Modifications to ATC-14," by C.D. Poland and J.O. Malley, 4/12/89, (PB90-108648/AS).

NCEER-89-0013 "Repair and Strengthening of Beam-to-Column Connections Subjected to Earthquake Loading," by M. Corazao and A.J. Durrani, 2/28/89, (PB90-109885/AS).

NCEER-89-0014 "Program EXKAL2 for Identification of Structural Dynamic Systems," by O. Maruyama, C-B. Yun, M. Hoshiya and M. Shinozuka, 5/19/89, (PB90-109877/AS).

NCEER-89-0015 "Response of Frames With Bolted Semi-Rigid Connections, Part I - Experimental Study and Analytical Predictions," by P.J. DiCorso, A.M. Reinhorn, J.R. Dickerson, J.B. Radziminski and W.L. Harper, 6/1/89, to be published.

NCEER-89-0016 "ARMA Monte Carlo Simulation in Probabilistic Structural Analysis," by P.D. Spanos and M.P. Mignolet, 7/10/89, (PB90-109893/AS).

NCEER-89-P017 "Preliminary Proceedings from the Conference on Disaster Preparedness - The Place of Earthquake Education in Our Schools," Edited by K.E.K. Ross, 6/23/89.

NCEER-89-0017 "Proceedings from the Conference on Disaster Preparedness - The Place of Earthquake Education in Our Schools," Edited by K.E.K. Ross, 12/31/89, (PB90-207895). This report is available only through NTIS (see address given above).

NCEER-89-0018 "Multidimensional Models of Hysteretic Material Behavior for Vibration Analysis of Shape Memory Energy Absorbing Devices, by E.J. Graesser and F.A. Cozzarelli, 6/7/89, (PB90-164146/AS).

NCEER-89-0019 "Nonlinear Dynamic Analysis of Three-Dimensional Base Isolated Structures (3D-BASIS)," by S. Nagarajaiah, A.M. Reinhorn and M.C. Constantinou, 8/3/89, (PB90-161936/AS). This report is available only through NTIS (see address given above).

NCEER-89-0020 "Structural Control Considering Time-Rate of Control Forces and Control Rate Constraints," by F.Y. Cheng and C.P. Pantelides, 8/3/89, (PB90-120445/AS).

NCEER-89-0021 "Subsurface Conditions of Memphis and Shelby County," by K.W. Ng, T-S. Chang and H-H.M. Hwang, 7/26/89, (PB90-120437/AS).

NCEER-89-0022 "Seismic Wave Propagation Effects on Straight Jointed Buried Pipelines," by K. Elhmadi and M.J. O'Rourke, 8/24/89, (PB90-162322/AS).

NCEER-89-0023 "Workshop on Serviceability Analysis of Water Delivery Systems," edited by M. Grigoriu, 3/6/89, (PB90-127424/AS).

NCEER-89-0024 "Shaking Table Study of a 1/5 Scale Steel Frame Composed of Tapered Members," by K.C. Chang, J.S. Hwang and G.C. Lee, 9/18/89, (PB90-160169/AS).

NCEER-89-0025 "DYNA1D: A Computer Program for Nonlinear Seismic Site Response Analysis - Technical Documentation," by Jean H. Prevost, 9/14/89, (PB90-161944/AS). This report is available only through NTIS (see address given above).

NCEER-89-0026 "1:4 Scale Model Studies of Active Tendon Systems and Active Mass Dampers for Aseismic Protection," by A.M. Reinhorn, T.T. Soong, R.C. Lin, Y.P. Yang, Y. Fukao, H. Abe and M. Nakai, 9/15/89, (PB90-173246/AS).

NCEER-89-0027 "Scattering of Waves by Inclusions in a Nonhomogeneous Elastic Half Space Solved by Boundary Element Methods," by P.K. Hadley, A. Askar and A.S. Cakmak, 6/15/89, (PB90-145699/AS).

NCEER-89-0028 "Statistical Evaluation of Deflection Amplification Factors for Reinforced Concrete Structures," by H.H.M. Hwang, J-W. Jaw and A.L. Ch'ng, 8/31/89, (PB90-164633/AS).

NCEER-89-0029 "Bedrock Accelerations in Memphis Area Due to Large New Madrid Earthquakes," by H.H.M. Hwang, C.H.S. Chen and G. Yu, 11/7/89, (PB90-162330/AS).

NCEER-89-0030 "Seismic Behavior and Response Sensitivity of Secondary Structural Systems," by Y.Q. Chen and T.T. Soong, 10/23/89, (PB90-164658/AS).

NCEER-89-0031 "Random Vibration and Reliability Analysis of Primary-Secondary Structural Systems," by Y. Ibrahim, M. Grigoriu and T.T. Soong, 11/10/89, (PB90-161951/AS).

NCEER-89-0032 "Proceedings from the Second U.S. - Japan Workshop on Liquefaction, Large Ground Deformation and Their Effects on Lifelines, September 26-29, 1989," Edited by T.D. O'Rourke and M. Hamada, 12/1/89, (PB90-209388/AS).

NCEER-89-0033 "Deterministic Model for Seismic Damage Evaluation of Reinforced Concrete Structures," by J.M. Bracci, A.M. Reinhorn, J.B. Mander and S.K. Kunnath, 9/27/89.

NCEER-89-0034 "On the Relation Between Local and Global Damage Indices," by E. DiPasquale and A.S. Cakmak, 8/15/89, (PB90-173865).

NCEER-89-0035 "Cyclic Undrained Behavior of Nonplastic and Low Plasticity Silts," by A.J. Walker and H.E. Stewart, 7/26/89, (PB90-183518/AS).

NCEER-89-0036 "Liquefaction Potential of Surficial Deposits in the City of Buffalo, New York," by M. Budhu, R. Giese and L. Baumgrass, 1/17/89, (PB90-208455/AS).

NCEER-89-0037 "A Determinstic Assessment of Effects of Ground Motion Incoherence," by A.S. Veletsos and Y. Tang, 7/15/89, (PB90-164294/AS).

NCEER-89-0038 "Workshop on Ground Motion Parameters for Seismic Hazard Mapping," July 17-18, 1989, edited by R.V. Whitman, 12/1/89, (PB90-173923/AS).

NCEER-89-0039 "Seismic Effects on Elevated Transit Lines of the New York City Transit Authority," by C.J. Costantino, C.A. Miller and E. Heymsfield, 12/26/89, (PB90-207887/AS).

NCEER-89-0040 "Centrifugal Modeling of Dynamic Soil-Structure Interaction," by K. Weissman, Supervised by J.H. Prevost, 5/10/89, (PB90-207879/AS).

NCEER-89-0041 "Linearized Identification of Buildings With Cores for Seismic Vulnerability Assessment," by I-K. Ho and A.E. Aktan, 11/1/89, (PB90-251943/AS).

NCEER-90-0001 "Geotechnical and Lifeline Aspects of the October 17, 1989 Loma Prieta Earthquake in San Francisco," by T.D. O'Rourke, H.E. Stewart, F.T. Blackburn and T.S. Dickerman, 1/90, (PB90-208596/AS).

NCEER-90-0002 "Nonnormal Secondary Response Due to Yielding in a Primary Structure," by D.C.K. Chen and L.D. Lutes, 2/28/90, (PB90-251976/AS).

NCEER-90-0003 "Earthquake Education Materials for Grades K-12," by K.E.K. Ross, 4/16/90, (PB91-113415/AS).

NCEER-90-0004 "Catalog of Strong Motion Stations in Eastern North America," by R.W. Busby, 4/3/90, (PB90-251984)/AS.

NCEER-90-0005 "NCEER Strong-Motion Data Base: A User Manuel for the GeoBase Release (Version 1.0 for the Sun3)," by P. Friberg and K. Jacob, 3/31/90 (PB90-258062/AS).

NCEER-90-0006 "Seismic Hazard Along a Crude Oil Pipeline in the Event of an 1811-1812 Type New Madrid Earthquake," by H.H.M. Hwang and C-H.S. Chen, 4/16/90(PB90-258054).

NCEER-90-0007 "Site-Specific Response Spectra for Memphis Sheahan Pumping Station," by H.H.M. Hwang and C.S. Lee, 5/15/90, (PB91-108811/AS).

NCEER-90-0008 "Pilot Study on Seismic Vulnerability of Crude Oil Transmission Systems," by T. Ariman, R. Dobry, M. Grigoriu, F. Kozin, M. O'Rourke, T. O'Rourke and M. Shinozuka, 5/25/90, (PB91-108837/AS).

NCEER-90-0009 "A Program to Generate Site Dependent Time Histories: EQGEN," by G.W. Ellis, M. Srinivasan and A.S. Cakmak, 1/30/90, (PB91-108829/AS).

NCEER-90-0010 "Active Isolation for Seismic Protection of Operating Rooms," by M.E. Talbott, Supervised by M. Shinozuka, 6/8/9, (PB91-110205/AS).

NCEER-90-0011 "Program LINEARID for Identification of Linear Structural Dynamic Systems," by C-B. Yun and M. Shinozuka, 6/25/90, (PB91-110312/AS).

NCEER-90-0012 "Two-Dimensional Two-Phase Elasto-Plastic Seismic Response of Earth Dams," by A.N. Yiagos, Supervised by J.H. Prevost, 6/20/90, (PB91-110197/AS).

NCEER-90-0013 "Secondary Systems in Base-Isolated Structures: Experimental Investigation, Stochastic Response and Stochastic Sensitivity," by G.D. Manolis, G. Juhn, M.C. Constantinou and A.M. Reinhorn, 7/1/90, (PB91-110320/AS).

NCEER-90-0014 "Seismic Behavior of Lightly-Reinforced Concrete Column and Beam-Column Joint Details," by S.P. Pessiki, C.H. Conley, P. Gergely and R.N. White, 8/22/90, (PB91-108795/AS).

NCEER-90-0015 "Two Hybrid Control Systems for Building Structures Under Strong Earthquakes," by J.N. Yang and A. Danielians, 6/29/90, (PB91-125393/AS).

NCEER-90-0016 "Instantaneous Optimal Control with Acceleration and Velocity Feedback," by J.N. Yang and Z. Li, 6/29/90, (PB91-125401/AS).

NCEER-90-0017 "Reconnaissance Report on the Northern Iran Earthquake of June 21, 1990," by M. Mehrain, 10/4/90, (PB91-125377/AS).

NCEER-90-0018 "Evaluation of Liquefaction Potential in Memphis and Shelby County," by T.S. Chang, P.S. Tang, C.S. Lee and H. Hwang, 8/10/90, (PB91-125427/AS).

NCEER-90-0019 "Experimental and Analytical Study of a Combined Sliding Disc Bearing and Helical Steel Spring Isolation System," by M.C. Constantinou, A.S. Mokha and A.M. Reinhorn, 10/4/90, (PB91-125385/AS).

NCEER-90-0020 "Experimental Study and Analytical Prediction of Earthquake Response of a Sliding Isolation System with a Spherical Surface," by A.S. Mokha, M.C. Constantinou and A.M. Reinhorn, 10/11/90, (PB91-125419/AS).

NCEER-90-0021 "Dynamic Interaction Factors for Floating Pile Groups," by G. Gazetas, K. Fan, A. Kaynia and E. Kausel, 9/10/90, (PB91-170381/AS).

NCEER-90-0022 "Evaluation of Seismic Damage Indices for Reinforced Concrete Structures," by S. Rodriguez-Gomez and A.S. Cakmak, 9/30/90, PB91-171322/AS).

NCEER-90-0023 "Study of Site Response at a Selected Memphis Site," by H. Desai, S. Ahmad, E.S. Gazetas and M.R. Oh, 10/11/90, (PB91-196857/AS).

NCEER-90-0024 "A User's Guide to Strongmo: Version 1.0 of NCEER's Strong-Motion Data Access Tool for PCs and Terminals," by P.A. Friberg and C.A.T. Susch, 11/15/90, (PB91-171272/AS).

NCEER-90-0025 "A Three-Dimensional Analytical Study of Spatial Variability of Seismic Ground Motions," by L-L. Hong and A.H.-S. Ang, 10/30/90, (PB91-170399/AS).

NCEER-90-0026 "MUMOID User's Guide - A Program for the Identification of Modal Parameters," by S. Rodriguez-Gomez and E. DiPasquale, 9/30/90, (PB91-171298/AS).

NCEER-90-0027 "SARCF-II User's Guide - Seismic Analysis of Reinforced Concrete Frames," by S. Rodriguez-Gomez, Y.S. Chung and C. Meyer, 9/30/90, (PB91-171280/AS).

NCEER-90-0028 "Viscous Dampers: Testing, Modeling and Application in Vibration and Seismic Isolation," by N. Makris and M.C. Constantinou, 12/20/90 (PB91-190561/AS).

NCEER-90-0029 "Soil Effects on Earthquake Ground Motions in the Memphis Area," by H. Hwang, C.S. Lee, K.W. Ng and T.S. Chang, 8/2/90, (PB91-190751/AS).

NCEER-91-0001 "Proceedings from the Third Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures for Soil Liquefaction, December 17-19, 1990," edited by T.D. O'Rourke and M. Hamada, 2/1/91, (PB91-179259/AS).

NCEER-91-0002 "Physical Space Solutions of Non-Proportionally Damped Systems," by M. Tong, Z. Liang and G.C. Lee, 1/15/91, (PB91-179242/AS).

NCEER-91-0003 "Seismic Response of Single Piles and Pile Groups," by K. Fan and G. Gazetas, 1/10/91, (PB92-174994/AS).

NCEER-91-0004 "Damping of Structures: Part 1 - Theory of Complex Damping," by Z. Liang and G. Lee, 10/10/91, (PB92-197235/AS).

NCEER-91-0005 "3D-BASIS - Nonlinear Dynamic Analysis of Three Dimensional Base Isolated Structures: Part II," by S. Nagarajaiah, A.M. Reinhorn and M.C. Constantinou, 2/28/91, (PB91-190553/AS).

NCEER-91-0006 "A Multidimensional Hysteretic Model for Plasticity Deforming Metals in Energy Absorbing Devices," by E.J. Graesser and F.A. Cozzarelli, 4/9/91.

NCEER-91-0007 "A Framework for Customizable Knowledge-Based Expert Systems with an Application to a KBES for Evaluating the Seismic Resistance of Existing Buildings," by E.G. Ibarra-Anaya and S.J. Fenves, 4/9/91, (PB91-210930/AS).

NCEER-91-0008 "Nonlinear Analysis of Steel Frames with Semi-Rigid Connections Using the Capacity Spectrum Method," by G.G. Deierlein, S-H. Hsieh, Y-J. Shen and J.F. Abel, 7/2/91, (PB92-113828/AS).

NCEER-91-0009 "Earthquake Education Materials for Grades K-12," by K.E.K. Ross, 4/30/91, (PB91-212142/AS).

NCEER-91-0010 "Phase Wave Velocities and Displacement Phase Differences in a Harmonically Oscillating Pile," by N. Makris and G. Gazetas, 7/8/91, (PB92-108356/AS).

NCEER-91-0011 "Dynamic Characteristics of a Full-Size Five-Story Steel Structure and a 2/5 Scale Model," by K.C. Chang, G.C. Yao, G.C. Lee, D.S. Hao and Y.C. Yeh," 7/2/91.

NCEER-91-0012 "Seismic Response of a 2/5 Scale Steel Structure with Added Viscoelastic Dampers," by K.C. Chang, T.T. Soong, S-T. Oh and M.L. Lai, 5/17/91 (PB92-110816/AS).

NCEER-91-0013 "Earthquake Response of Retaining Walls; Full-Scale Testing and Computational Modeling," by S. Alampalli and A-W.M. Elgamal, 6/20/91, to be published.

NCEER-91-0014 "3D-BASIS-M: Nonlinear Dynamic Analysis of Multiple Building Base Isolated Structures," by P.C. Tsopelas, S. Nagarajaiah, M.C. Constantinou and A.M. Reinhorn, 5/28/91, (PB92-113885/AS).

NCEER-91-0015 "Evaluation of SEAOC Design Requirements for Sliding Isolated Structures," by D. Theodossiou and M.C. Constantinou, 6/10/91, (PB92-114602/AS).

NCEER-91-0016 "Closed-Loop Modal Testing of a 27-Story Reinforced Concrete Flat Plate-Core Building," by H.R. Somaprasad, T. Toksoy, H. Yoshiyuki and A.E. Aktan, 7/15/91, (PB92-129980/AS).

NCEER-91-0017 "Shake Table Test of a 1/6 Scale Two-Story Lightly Reinforced Concrete Building," by A.G. El-Attar, R.N. White and P. Gergely, 2/28/91.

NCEER-91-0018 "Shake Table Test of a 1/8 Scale Three-Story Lightly Reinforced Concrete Building," by A.G. El-Attar, R.N. White and P. Gergely, 2/28/91.

NCEER-91-0019 "Transfer Functions for Rigid Rectangular Foundations," by A.S. Veletsos, A.M. Prasad and W.H. Wu, 7/31/91, to be published.

NCEER-91-0020 "Hybrid Control of Seismic-Excited Nonlinear and Inelastic Structural Systems," by J.N. Yang, Z. Li and A. Danielians, 8/1/91.

NCEER-91-0021 "The NCEER-91 Earthquake Catalog: Improved Intensity-Based Magnitudes and Recurrence Relations for U.S. Earthquakes East of New Madrid," by L. Seeber and J.G. Armbruster, 8/28/91, (PB92-176742/AS).

NCEER-91-0022 "Proceedings from the Implementation of Earthquake Planning and Education in Schools: The Need for Change - The Roles of the Changemakers," by K.E.K. Ross and F. Winslow, 7/23/91, (PB92-129998/AS).

NCEER-91-0023 "A Study of Reliability-Based Criteria for Seismic Design of Reinforced Concrete Frame Buildings," by H.H.M. Hwang and H-M. Hsu, 8/10/91.

NCEER-91-0024 "Experimental Verification of a Number of Structural System Identification Algorithms," by R.G. Ghanem, H. Gavin and M. Shinozuka, 9/18/91, (PB92-176577/AS).

NCEER-91-0025 "Probabilistic Evaluation of Liquefaction Potential," by H.H.M. Hwang and C.S. Lee," 11/25/91.

NCEER-91-0026 "Instantaneous Optimal Control for Linear, Nonlinear and Hysteretic Structures - Stable Controllers," by J.N. Yang and Z. Li, 11/15/91, (PB92-163807/AS).

NCEER-91-0027 "Experimental and Theoretical Study of a Sliding Isolation System for Bridges," by M.C. Constantinou, A. Kartoum, A.M. Reinhorn and P. Bradford, 11/15/91, (PB92-176973/AS).

NCEER-92-0001 "Case Studies of Liquefaction and Lifeline Performance During Past Earthquakes, Volume 1: Japanese Case Studies," Edited by M. Hamada and T. O'Rourke, 2/17/92, (PB92-197243/AS).

NCEER-92-0002 "Case Studies of Liquefaction and Lifeline Performance During Past Earthquakes, Volume 2: United States Case Studies," Edited by T. O'Rourke and M. Hamada, 2/17/92, (PB92-197250/AS).

NCEER-92-0003 "Issues in Earthquake Education," Edited by K. Ross, 2/3/92.

NCEER-92-0004 "Proceedings from the First U.S. - Japan Workshop on Earthquake Protective Systems for Bridges," 2/4/92, to be published.

NCEER-92-0005 "Seismic Ground Motion from a Haskell-Type Source in a Multiple-Layered Half-Space," A.P. Theoharis, G. Deodatis and M. Shinozuka, 1/2/92, to be published.

NCEER-92-0006 "Proceedings from the Site Effects Workshop," Edited by R. Whitman, 2/29/92, (PB92-197201/AS).

NCEER-92-0007 "Engineering Evaluation of Permanent Ground Deformations Due to Seismically-Induced Liquefaction," by M.H. Baziar, R. Dobry and A-W.M. Elgamal, 3/24/92.

NCEER-92-0008 "A Procedure for the Seismic Evaluation of Buildings in the Central and Eastern United States," by C.D. Poland and J.O. Malley, 4/2/92.

NCEER-92-0009 "Experimental and Analytical Study of a Hybrid Isolation System Using Friction Controllable Sliding Bearings," by Q. Feng, S. Fujii and M. Shinozuka, 2/15/92, to be published.

NCEER-92-0010 "Seismic Resistance of Slab-Column Connections in Existing Non-Ductile Flat-Plate Buildings," by A.J. Durrani and Y. Du, 5/18/92.

NCEER-92-0011 "The Hysteretic and Dynamic Behavior of Brick Masonry Walls Upgraded by Ferrocement Coatings Under Cyclic Loading and Strong Simulated Ground Motion," by H. Lee and S.P. Prawel, 5/11/92, to be published.

NCEER-92-0012 "Study of Wire Rope Systems for Seismic Protection of Equipment in Buildings," by G.F. Demetriades, M.C. Constantinou and A.M. Reinhorn, 5/20/92.

NCEER-92-0013 "Shape Memory Structural Dampers: Material Properties, Design and Seismic Testing," by P.R. Witting and F.A. Cozzarelli, 5/26/92.

NCEER-92-0014 "Longitudinal Permanent Ground Deformation Effects on Buried Continuous Pipelines," by M.J. O'Rourke, and C. Nordberg, 6/15/92.

NCEER-92-0015 "A Simulation Method for Stationary Gaussian Random Functions Based on the Sampling Theorem," by M. Grigoriu and S. Balopoulou, 6/11/92.

NCEER-92-0016 "Gravity-Load-Designed Reinforced Concrete Buildings," by G.W. Hoffmann, S.K. Kunnath, J.B. Mander and A.M. Reinhorn, 7/15/92, to be published.

NCEER-92-0017 "Observations on Water System and Pipeline Performance in the Limón Area of Costa Rica Due to the April 22, 1991 Earthquake," by M. O'Rourke and D. Ballantyne, 6/30/92.