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FIELD RECONNAISSANCE OF THE EFFECTS OF THE EARTHQUAKE OF APRIL 13, 1973, NEAR LAGUNA DE ARENAL, COSTA RICA

By

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INTRODUCTION

At about 3:34 a.m. on April 13, 1973, a moderate-sized, but widely-felt, earthquake caused extensive damage with loss of 23 lives in a rural area of about 150 km^2 centered just south of Laguna de Arenal in northwestern Costa Rica (fig. 1).

Figure 1 near here

According to the National Oceanic and Atmospheric Administration the main shock, with surface wave magnitude of 6.5, occurred at 08:33:56.9 GMT at latitude 10.675 N., longitude 84.871 W. (personal commun., May 10, 1973). The epicenter, which is roughly 18 km due north of the east end of Laguna de Arenal, is well outside the area of most intense surface damage (fig. 1). This relationship suggests that the instrumentally-located epicenter is biased to the northeast just as it was for the Managua, Nicaragua, earthquake of December 23, 1972 (Brown, Ward, and Plafker, 1973). The hypocentral depth is given as 29 km $\pm$ 10 km, but is poorly constrained because the closest recording station is in San Salvador.

Eyewitness accounts indicate that the main shock began without warning foreshocks and that the shaking was so violent within the meizoseismal area that it was difficult or impossible to stand during the earthquake. Reliable evaluations of the duration and nature of ground motion naturally could not be made by people who were suddenly awakened by the shaking while it was still dark. Residents were in complete agreement that, although felt earthquakes are not uncommon, this was by far the most severe earthquake to affect the Laguna de Arenal area during their lifetimes. Available historic data on Costa Rican seismicity, which date back to the 17th century, do not contain references to destructive earthquakes in northern

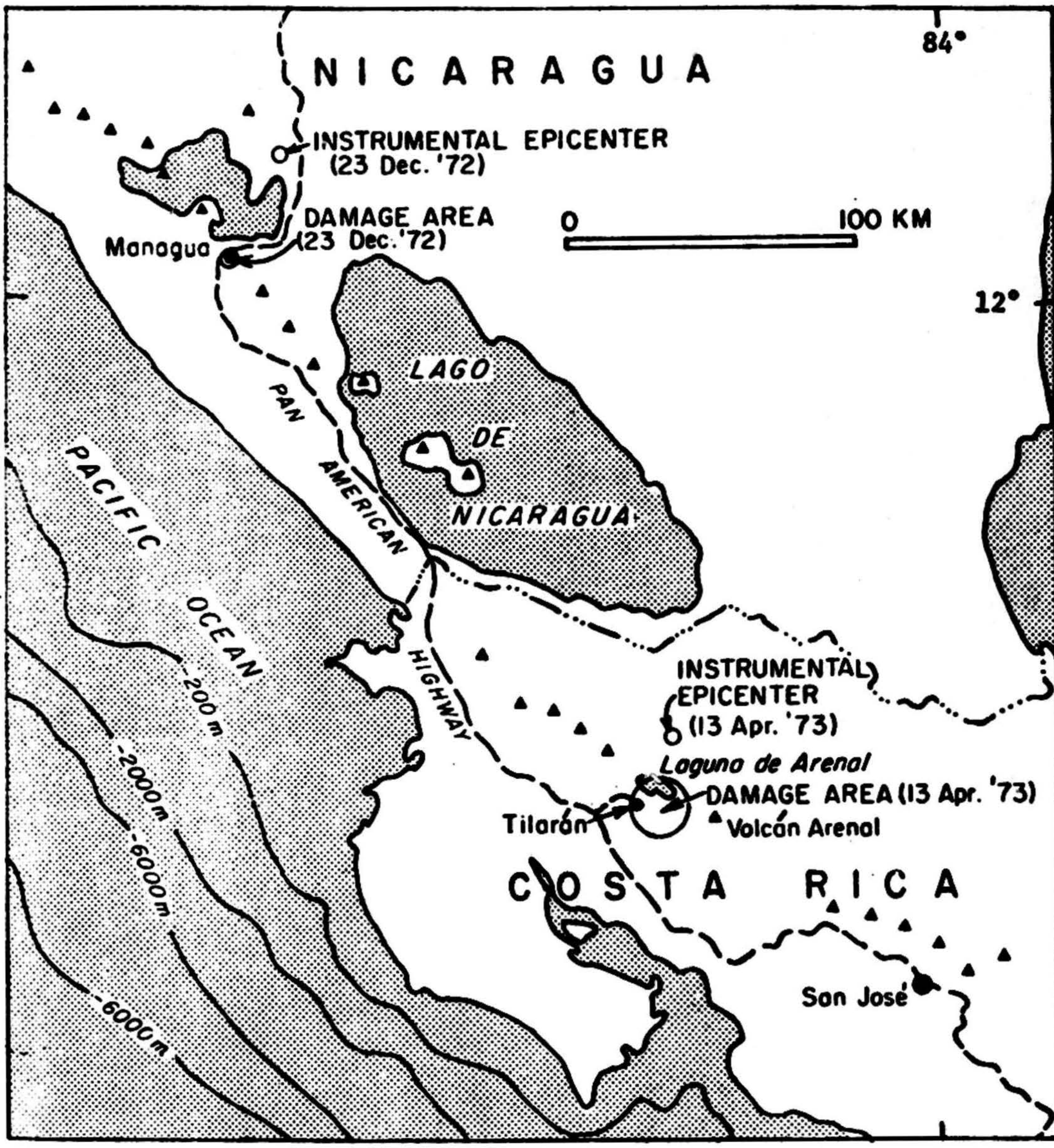

Figure 1. Index map showing locations of the epicenters and damage areas for the April 13, 1973 Costa Rica and December 23, 1972 Managua, Nicaragua earthquakes.

Costa Rica (Sieberg, 1932).

Based on the kind and amount of shaking damage to man-made structures whose foundations did not fail, the maximum intensity is judged to be about VIII on the Modified Mercalli Scale. However, if other criteria of the Mercalli Scale are used, such as ground effects, pipeline breaks, and the reaction of the populace, the intensity could be rated as high as X.

A large number of felt aftershocks were experienced during the weeks following the earthquake. As many as 53 aftershocks per day were counted by the local police during the first 3 days throughout the meizoseismal area. Several earthquakes were being felt daily at Tilarán even 18 days after the main shock (Edwin Olivares Aguilar, personal commun., Apr. 30, 1973). Some of the aftershocks were strong enough to topple objects from shelves or rattle windows and walls, but none is known to have caused additional damage. Nevertheless, the continuous aftershock activity and the fear of another destructive earthquake, or even a volcanic eruption, were so unnerving to many of the local residents that they abandoned homes and property to flee the area. Some of them had not yet returned at the time of my visit more than 2 weeks after the event.

This report summarizes the results of the writer's reconnaissance investigation of the area that was affected by the earthquake of April 13, 1973. A 4-day field study of the meizoseismal area was carried out during the period from April 28 through May 1 under the auspices of the U. S. Geological Survey. The primary objective of this study was to evaluate geologic factors that contributed to the damage and loss of life. The earthquake was also of special interest because of the possibility that it was accompanied by surface faulting comparable to that which occurred at Managua, Nicaragua, during the disastrous earthquake of December 23, 1972

(Brown, Ward, and Plafker, 1973). Such earthquake-related surface faulting can provide scientifically valuable information on active tectonic processes at shallow depths within the Middle America arc. Also, identification of active faults in this area is of considerable practical importance because of the planned construction of a major hydroelectric facility within the meizoseismal area by the Instituto Costarricense de Electricidad (I.C.E.). The project would involve creation of a storage reservoir within the Laguna de Arenal basin and part of the Río Arenal valley with a 75 m-high earthfill dam across Río Arenal at a point about 10 km east of the outlet of Laguna de Arenal.

I am indebted to numerous people in Costa Rica whose assistance and cooperation greatly facilitated this study. Ing. Jorge Umaña, Chief Geologist of I.C.E., generously provided information obtained by him and the I.C.E. staff shortly after the earthquake and greatly expedited the field work by making a jeep and driver available for 2 days. Dr. Jelle de Boer of Wesleyan College, who is in Costa Rica on a United Nations grant, shared with me the detailed observations he made in the earthquake-affected area shortly after the event as well as his interpretations of the regional structure as derived from a broad synthesis of geologic and geophysical data. Mr. Robert Senter, Interamerican Geodetic Survey representative in Costa Rica, kindly assisted with logistic arrangements and furnished base maps for use in the field. Dr. Tosimata Matumoto, of the University of Texas, furnished preliminary results obtained from a 3-station seismograph array that he deployed to monitor the aftershock sequence. Finally, I wish to express my appreciation to my good friends Gabriel Dengo and Gregorio Escalante who freely gave me the benefit of their intimate knowledge of Costa Rica and its geology and who helped make my stay in that country a

pleasant experience.

GEOGRAPHIC AND GEOLOGIC SETTING

As indicated on figure 2, the principal area affected by the earthquake

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Figure 2 near here

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of April 13, 1973, is crudely circular in shape, about 14 km in diameter, and is centered just south of Laguna de Arenal. It includes the towns of Tilarán, Tronadora, and Arenal as well as a large number of small villages and scattered farm houses; total population is estimated to be several thousand persons.

Most of the land has been cleared for cattle grazing, the principal industry in the area. There is also a modest amount of coffee, sugar, and vegetable farming along the margins of Laguna de Arenal and in some of the stream valleys. Remnants of the dense forest growth that originally covered the area are now largely restricted to ridge tops, some relatively inaccessible valleys, and steeper slopes.

The communities and larger farms are connected by a fairly dense network of roads which are shown by very short dashes on figure 2. Highway 19, which extends northwestward from Tilarán to the Interamerican Highway, is the only paved road in the map area; all others are dirt or are surfaced with crushed rock. All roads shown on the map were traversed during this study.

The topography within the earthquake-affected area is characteristically hilly to mountainous with local relief of 200-300 meters and extreme elevations ranging between 512 m and 1380 m. The basin including the flat-floored Laguna de Arenal and the valley of Río Arenal are the only sizeable areas of gentle topography. Slopes along the larger valleys average 15°-30° although locally they may be up to 45° where undercut by streams. Road cuts

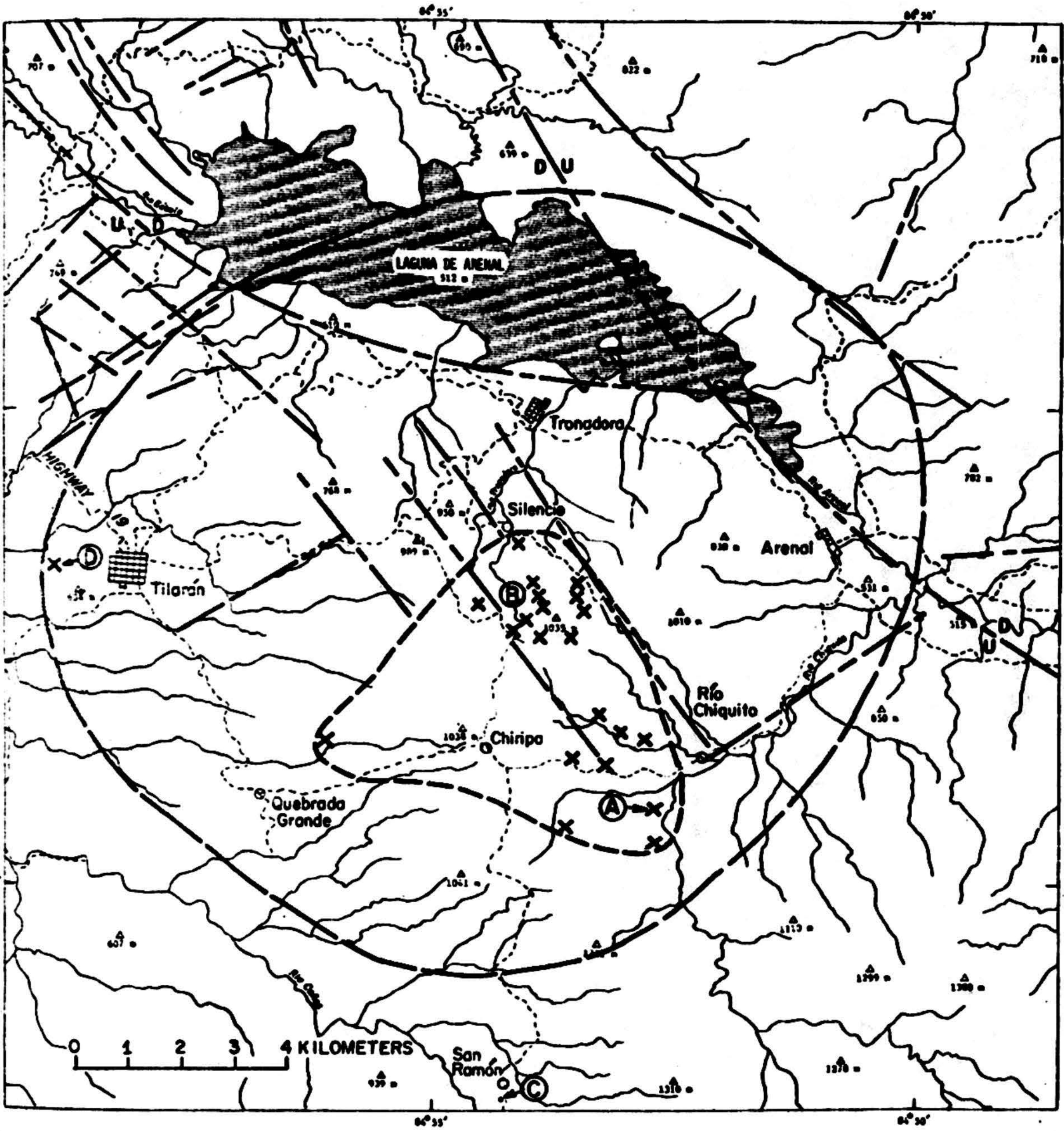

Figure 2. Damage area of the April 13, 1973 earthquake. Long dashed line outlines main zone of structural damage, landslides, and ground cracks. Short dashed line outlines zone characterized by severe ground effects and destructive landslides; crosses indicate larger landslides. Letters indicate locations referred to in text. Lineaments shown are from Dengo (1968) and unpublished map of I. C. E. (1972).

are commonly near-vertical where cut in the thick layer of lateritic soil and pyroclastic deposits which mantles most of the area. Rainfall is normally around 250 cm/year, with almost all the precipitation from late April through October. Because of abnormally sparse precipitation during the 1972 rainfall year, Laguna de Arenal was essentially dry and most streams contained little or no water at the time of the earthquake.

The earthquake-affected area is situated along the Middle America chain of active volcanoes that extends discontinuously from Guatemala to northern Panama (fig. 1). Bedrock consists of andesitic or basaltic andesitic flows with subordinate agglomerate of late Tertiary age (Dengo, 1968). These rocks are rarely well-exposed because they are mantled by a thick lateritic soil commonly 3-7 m thick and ash in layers generally a few tens of centimeters thick. Quaternary andesitic volcanic rocks underlie Tilarán and the area to the north and west (I.C.E., unpublished geologic map of Proyecto Arenal y Santa Rosa), and an andesitic volcanic cone, Volcán Arenal, lies just south of Río Arenal about 15 km east of the eastern end of Laguna de Arenal (fig. 1). In 1968, an explosive glowing avalanche eruption from Volcán Arenal killed 78 people and devastated 12 square kilometers in a period of 3 days (Melson and Saenz, 1968). A flank eruption of lava, which first emitted from Arenal in 1968, is still continuing to advance slowly.

It appears likely that the anomalously broad and flat-floored valley, in which the Río Arenal and Laguna de Arenal are situated, is a fundamental tectonic feature that is controlled by faulting, probably by movement on the two major faults shown on figure 2 that bound part of the basin. The thick sediment fill in this basin developed between natural dams of Quaternary volcanics that are located in the Tilarán area and north of Volcán Arenal (fig. 1). It should be emphasized, however, that these faults were inferred entirely on the basis of topography, and their existence has yet to be demonstrated conclusively from geologic relationships across them or by seismic activity along them (Gabriel Dengo, 1973, pers. commun.). In addition to the two major inferred faults shown on figure 2, there are a number of crudely linear stream valleys in the area that were mapped as faults on an unpublished map of the I.C.E. (1972). Dr. Jelle de Boer (oral commun., April 1973) has pointed out that these lineaments and many other topographic features throughout much of this area fall into two fairly well-defined sets trending northwest and northeast. Because of the prevailing deep surficial weathered zone, it is not known if any of the lineaments are fault controlled and, if so, if any of the faults are presently active.

EARTHQUAKE EFFECTS

Damage from the earthquake of April 13, 1973, resulted from: 1) direct seismic shaking of structures, 2) a variety of earthquake-triggered landslides, and 3) earthquake-induced lateral spreading and cracking of unconsolidated deposits. All of the significant damage observed appeared to be confined to the area of about 150 km^2 that is outlined by the long dashed line on figure 2. The deaths and injuries resulted entirely from burial by landslides, the larger of which were concentrated within an area of about 20 km^2 which is outlined by a short dashed line on figure 2.

No evidence was found for movement on surface faults during the earthquake. All of the ground cracks that were seen during my reconnaissance appeared to be readily related to gravitational movements of surficial deposits and to failure of roadway fills. None of the cracks could be traced as continuous linear zones for more than a few tens of meters cross-country. Because my field investigation was begun more than 2 weeks after the earthquake, many of the cracks in roads and in the towns had been obliterated or subdued by traffic and by repair work. Nevertheless, because of the fairly dense road network, intensive land use, and a large rural population, it seems improbable that a surface fault several kilometers or more in length could go undetected. Judging from a comparison with seismic events of the same magnitude elsewhere in the world, surface faulting on the order of 20-30 km is a reasonable possibility for a shallow 6.5 magnitude earthquake (Bonilla and Buchanan, 1970). For example, during the December 23, 1972, Managua earthquake ($M_s = 6.2$) sinistral displacement of about 60 cm occurred on two subparallel faults about 15 km long, and displacements of a few centimeters occurred on two other faults 1.6 and 2.7 km in length (Brown, Ward, and Plafker, 1973).

Structural damage

With few exceptions, most of the structures in the damage area are reasonably well built for resistance to lateral forces imposed by seismic shaking. The majority of them are small single-story wood frame homes on post or concrete foundations and with corrugated sheet metal roofs, although there are some two-story wood frame houses in Tilarán. Perhaps 20 to 30 percent of the homes are of concrete block, usually with minimal reinforcing steel rods on slab or perimeter foundations of concrete and with corrugated sheet metal roofs. Because of the equitable climate, heating is not required and there are no fireplaces or chimneys. Cooking stoves are usually vented with metal stovepipes. Larger commercial and public buildings in the towns are mainly of single-story frame construction. Exceptions are the churches which are all built of reinforced concrete, and a schoolhouse at Tronadora which is made of a steel frame with unreinforced concrete block end and partition walls. The few road bridges are small and built of reinforced concrete except for one across Río Arenal near Arenal, which is a steel Bailey bridge about 40 m long.

The earthquake was severe enough to cause extensive damage to the contents of buildings, mainly through objects falling from shelves, and to cause considerable window breakage in flexible wood frame houses. However, only a small percentage of buildings sustained significant damage solely by shaking. Most of the damage to structures involved varying degrees of collapse of unreinforced concrete block walls in homes and at the Tronadora school. A few frame houses were either partly or entirely shifted off their foundations. None of these failures involved total collapse of the buildings or caused injury to occupants.

Churches are the largest buildings in the area. Of these, the large modernistic cathedral at Tilarán sustained superficial damage involving cracking of walls, breakage of windows, and falling of decorative tile. A moderate-sized church at Arenal and another small one at Quebrada Grande were not visibly damaged by the earthquake. The only non-dwelling structure seen that was seriously damaged is the small church at Tronadora where the bell tower collapsed and fell through the church roof. However, as is discussed in a later section, the Tronadora church damage may have been, in part at least, the result of foundation failure. No bridges in the area showed damage either to the abutments or spans.

Landslides

Horizontal and vertical accelerations during the earthquake triggered numerous landslides and created many incipient slides throughout the area outlined on figure 2. As used herein, "landslide" denotes downward and outward movement of slope-forming materials composed of natural rock, soils, artificial fills, or combinations thereof. This definition and other terminology for landsliding generally follows Varnes (1958). All of the 23 deaths from the earthquake were due to burial beneath landslides. In addition, landslides caused extensive damage to roads resulting in the temporary isolation of some communities. The landslides included a wide variety of debris falls, slides, and flows primarily involving the regolith of unconsolidated lateritic soil and volcanic ash that everywhere mantles the older volcanic rocks of the area. Landslides involving bedrock were rare. No slump block r rotational slumps of large masses of coherent material were seen in the earthquake-affected area although some of the debris flows and falls may have been initiated in this way.

Debris slides and flows

The largest and most destructive landslides involved poorly consolidated soil and debris along steep slopes, some of which developed into fluid, high-velocity debris flows. One of these, near the village of Río Chiquito (location "A" on fig. 2), buried the farm home of Mr. Lindor Chavez. Mr. Chavez was rescued with severe injuries but 13 members of his family who were also in the house perished. The landslide, which developed at the head of a small tributary of Río Chiquito, involved an estimated 75,000-125,000 m^3 of debris consisting mainly of lateritic soil with minor air-fall ash near the surface. The debris flow is roughly 500 m long with about 200 m vertical drop from the crown to the toe, which reaches almost to Río Chiquito. Rapid movement of the mass is indicated by the fact that at a bend along its course, the debris was banked up 10 to 15 m higher on the outside of the turn than it was on the inside. The lobe averages 3-5 m thick, and its steep-sided, leveed margins suggest that the debris had considerable viscosity in the lower part of its course where it spread out over the flood plain of Río Chiquito.

Many other large debris slides and flows, several of which are probably larger than the Río Chiquito debris flow, originated along steep valley walls and ridge slopes, mainly in the area outlined by short dashes on figure 2. Most of these occurred in the headwaters of Río Chiquito and Río Tronadora; one large slide is located along Quebrada Grande. Approximate positions of some of the larger slides are shown by crosses on figure 2. Debris slides or flows along Río Tronadora in the area south of Silencio (near "B" on figure 2) caused the 10 other deaths attributable to the earthquake. Because I did not visit the site of the buried houses near Silencio, I do not know exactly which of the many slides buried them and the location shown on figure 2 indicates the general area where casualties occurred.

In addition to the casualties, the debris slides and flows locally caused major damage to roads either by taking out sections of roads that crossed the landslide areas or by covering roads with debris. Some of these roads had not yet been reopened for traffic more than 2 weeks after the earthquake.

Debris slides and flows have blocked the natural drainage in the headwaters of Río Tronadora and Río Chiquito. During periods of heavy rains lakes may form behind these natural dams and could overtop and rapidly erode the debris, thereby causing sudden inundation of downstream areas by floods or mud flows. The most critical period will be during the 1973 rainy season (April through October). The hazard is especially great to Tronadora because the shallow channel of the Río Tronadora through the town has little carrying capacity and most of the buildings in town are on the alluvial fan of the river where they are vulnerable to flooding. The hazard is less severe in the village of Río Chiquito but there are a number of farm houses in that area located on low ground that is susceptible to flooding or in the path of debris flows.

Failures of man-made cuts and fills

The overwhelming majority of landslides triggered by the earthquake are small falls or slides of poorly-consolidated debris along roadcuts. These occur throughout the area outlined on figure 2 and, less commonly, beyond the limits of the area shown. Roadcuts through the air-fall ash and deep lateritic soil in this area are commonly cut to angles between 45° and near-vertical. Because the roadcuts have much steeper inclinations than the natural slopes, it is not surprising that roadcut failures are more widely distributed than natural slope failures. Within the damage area outlined on figure 2, almost every large roadcut shows some sign of failure and many of them were completely collapsed. The greatest number and extent of such failures are in the area between Tronadora, Quebrada Grande, and Río Chiquito where some of the roads were virtually buried by debris slides and falls from roadcuts. In addition to damage to the roads, these roadcut failures resulted in incidental costly damage to many kilometers of barbed wire range fencing as well as to telephone and electric transmission lines along the right-of-way.

Slumping and cracking of roadway fills on the downhill shoulders were also common occurrences throughout the earthquake-affected area outlined on figure 2 but none of these slumps caused significant damage. The most extensive roadway fill failures seen were along a new segment of road just south of San Ramón at location "C" near the southern edge of figure 2 where exceptionally large fills were required because of the rugged nature of the terrain.

Rock falls

The one landslide involving rock that was seen in the earthquake-affected area is situated about 1 km west of Tilarán (location "D" on fig. 2). This was a fall of several thousand cubic meters of Quaternary andesite that is exposed on a steep, undercut valley wall. The locality is uninhabited and the rockfall caused no damage. Similar rockfalls may have occurred elsewhere, but were not observed during my brief reconnaissance study.

Soil slips and incipient landslides

Shallow soil slips of unconsolidated materials were observed throughout the area but were especially common on the steeper slopes. Typically these slips and incipient slides are manifested as a series of closely-spaced open cracks in the regolith that tend to parallel slope contours. This type of cracking was especially pervasive on the slope north of the Río Chiquito debris flow where open cracks were spaced a few meters apart over the entire hillside with as much as 15 cm separation of the walls. All gradations probably occur between ground cracks related to shallow soil slips and those that result from incipient sliding of larger relatively coherent masses. Such features, where situated above inhabited areas or roads, are potential hazards because they could develop into destructive debris slides or flows when they become water-saturated during the rainy season. In a few places, such as at Silencio, an incipient slide along a small creek bank has resulted in cracking of the foundation of the adjacent schoolhouse and slight rotational tilting of part of the structure.

Surficial effects in unconsolidated deposits

In areas of gentle slope vibratory loading of noncohesive granular deposits resulted in local mass downslope movement, lateral spreading, and differential compaction. Ground cracking and surficial subsidence were surface manifestations of such movements. At a few places where the water table is near the surface, lateral spreading and subsidence were accompanied by ejection of water or water-sand mixtures.

Most of the surficial effects were concentrated around the margins of the dry Laguna de Arenal and along the flood plains of streams and rivers. The resulting damage included 1) breakage of underground water distribution pipes; 2) failure of foundations beneath structures at Tronadora, and 3) cracking of roadfills resulting from compaction of unconsolidated deposits beneath the fills at stream and swamp crossings.

In all the localities where underground water pipe breakage occurred, the ruptures involved pulling apart of galvanized pipe at the joints. Such pull-aparts, which occurred at Tilarán, Tronadora, and Arenal, are clearly the result of lateral spreading of the surficial sediments in a downslope direction with resultant extension within the spreading mass. Where a 2-inch water pipe crosses the Río Arenal 1/2 km east of Arenal, lateral spreading of alluvium towards the river caused the pipe to fail in extension where it was buried on the east bank of the river, and caused slight compressive buckling of the pipe where it crossed the river above the ground on the bridge. At this locality, and at Tronadora, some degree of liquefaction within the sediment mass is suggested by the ejection of some water and the formation of small sand-boils towards the lower parts of the mobilized sediment mass.

Mass downslope movement of unconsolidated deposits was locally accompanied by ground cracking, most notably in the central part of Tronadora. Here discontinuous cracks extended about 75 m from Río Tronadora through the church grounds on the upslope side of the church, beneath a small wood frame house, across a road, and through a concrete home. Within a few meters of the church entrance, there are three cracks across which the aggregate extension is 5 cm and the downslope side is stepped down about 2 cm. The location of the church on the slide mass close to these fractures may have been a contributing factor that resulted in toppling of the steeple with extensive damage to the church.

Throughout the area road fills are commonly cracked and displaced downslope where they cross saturated alluvial deposits or swampy areas along the streams and rivers. Such failures may have resulted from lateral spreading and (or) compaction of the natural materials beneath the road embankments. Near the ford that crosses Río Chiquito about 1 1/2 km southeast of Arenal, cracking in the roadway extends 75 m back from the river with large extensional and vertical displacements, stepped down towards the river. As in all of the road systems of the area, however, the crack displacement could not be measured because traffic and road construction had greatly modified these features by the time of my field investigation.

Conclusions

1) Damage distribution related to the earthquake of April 13, 1973, suggests that the epicenter was situated south of Laguna de Arenal at least 18 km south of the instrumentally located epicenter.

2) The earthquake apparently was not accompanied by movement on surface faults. If any faulting did occur, the surface trace must have been masked by the thick mantle of loose surficial material and by pervasive gravitational movement of near-surface materials on slopes.

3) Both the location of the epicentral region and the decay characteristics of the aftershock sequence suggest that the earthquake was of tectonic, rather than volcanic, origin.

4) The limited extent of the damage area indicates that the earthquake source was shallow. However, the damage distribution, the extensive felt area, and the apparent absence of surface faulting are all suggestive of a source at least several kilometers in depth.

5) The main cause of damage and loss of life was widespread landsliding and lateral spreading including some high-velocity debris flows in areas of steep unstable slopes.

6) There is a potential hazard during the 1973 rainy season that destructive debris flows or floods could develop along some streams that are partially or wholly blocked by landslides or that have incipient slides. The most serious threat of this type to inhabited areas is at Tronadora and, to a lesser extent, at Río Chiquito.

7) As is often the case, general fear and panic, with abandonment of the area by many people, were among the more serious consequences of the April 13, 1973, earthquake. The numerous felt aftershocks and the memory of a disastrous 1968 eruption of nearby Volcán Arenal kept people in a constant state of agitation and apprehension. In such circumstances, prompt and thorough coordinated geologic and seismologic investigations can be invaluable for the following important reasons: a) to recover data on the aftershocks and surface deformation critical to understanding of the earthquake mechanism and assessment of earthquake-related geologic hazards; and b) to use these data to provide professional advice to the populace and governmental officials in a realistic evaluation of the hazards of additional damage from aftershocks, landslides, flooding, volcanic eruptions and related phenomena in the earthquake-affected area.

8) To ensure the safety of the planned Arenal hydroelectric development it is essential to determine whether active faults occur within the project area and to consider the possibility that filling of the storage reservoir could trigger potentially destructive earthquakes by raising pore water pressures in fault zones (Rothé, 1968).

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