THE MARCH 5, 1987, ECUADOR EARTHQUAKES:

Mass Wasting and Socioeconomic Effects

Executive Summary

The two earthquakes of magnitude 6.1 and 6.9 on March 5, 1987, occurred along the eastern slopes of the Andes Mountains in northeastern Ecuador. The epicenters were located in Napo Province, approximately 100 km ENE of Quito and 25 km N of Reventador Volcano. Ground shaking caused a number of moderate structural damages, primarily in areas near the epicenters. The occurrence of the earthquakes in an area of steep slopes covered by unstable volcanic and residual soils with high water contents, caused by heavy rainfall immediately prior to the earthquake, resulted in massive slope failures of high fluidity. Comparatively speaking, the economic and social losses directly due to earthquake shaking were small compared with the effects of catastrophic earthquake-triggered mass wasting (i.e., slumps and slides, debris flows, and debris avalanches) and flooding in the area adjacent to Reventador Volcano. Rock and earth slides, debris avalanches, and debris and mud flows east of the Andes resulted in the destruction or local severing of nearly 70 km of the Trans-Ecuadorian oil pipeline and the only highway from Quito to Ecuador's eastern rain forests and oil fields. Nearly all of the estimated 1,000 deaths from the earthquakes were a consequence of mass wasting and flooding. Economic losses were estimated at $1.0 billion; the effects of widespread denudation on the agricultural and hydroelectric development of the region are difficult to evaluate, but undoubtedly were very large.

General Geology of Northeastern Ecuador The geology of northeastern Ecuador and present-day physical processes related to geology are greatly influenced by the tectonic mechanisms responsible for the development of the Andes Mountains. The Andes have created three geologic and geomorphic zones: (1) the coastal plains (Costa) to the west, (2) the central mountainous area—the Andes (Sierra), and (3) the eastern lowlands (Oriente).

Seismicity and Tectonics Ecuador is exposed continually to earthquakes and other geologic hazards. The earthquake potential has always been a threat to the inhabitants of Ecuador, and thus coexisting with earthquake activity has become part of the Ecuadorian culture. In the past 80 years several large earthquakes (interplate events) have occurred in Ecuador's subduction zone. The March 1987 earthquakes, which occurred in the Andes, were not located in an active subduction zone along the plate boundaries. These intraplate earthquakes are shallow (10 to 14 km) events. Studies of earthquake potential, using conditional probability estimates, have shown a 66 percent probability for a great earthquake ($M_s \geq 7.7$) to take place along the subduction zone in the recurrence period of 1989-1999. The conditional probability estimates were evaluated using the historical and instrumental seismicity catalogue of the region; however, the historical record is poorly known for this region. A number of recommendations are made in this report to meet the urgent need to better evaluate the earthquake hazards in Ecuador. Among others, they include compilation of a more extensive and detailed historical earthquake catalogue for interplate and intraplate earthquakes, compilation of a historical earthquake catalogue for events that are associated with and have their origin in volcanism, deployment of sensitive seismological instruments in the region for ascertaining the level of seismicity and studying the joint focal mechanisms, and development of a working model of the tectonic regime of the region.

Intensity and Damage Distribution The areas of maximum Modified Mercalli Intensity (MMI) are concentrated in the meizoseismal area, attaining an Io = IX. However, much of the damage in this area should be classed as intensities VII and VIII. The problem encountered in the process of evaluating the intensity is that of "inconsistencies" in the MMI. For example, large landslides, such as were abundant in the high mountainous region near and around Reventador Volcano, as well as in other unstable regions in the high Andes, suggest an intensity greater than IX. Another factor that indicates high intensities (>IX) is surface faulting, such as that in areas near the epicentral region. Still another factor that yields higher intensities (X), as given in the intensity scale, is landslides from river banks and steep slopes due in some cases to water-saturated soils, shifted sand and mud, and water splashed over banks. In the MMI scale, "bridges destroyed" implies an intensity of XI. Yet in other cases in this event, although a bridge was indeed destroyed (but by flooding), wooden structures nearby sustained no damage. Other factors that may enter into the intensity-distribution pattern are seismic amplification effects, topographic seismic-wave amplification, influence of surficial soil conditions, and depth of the water table. Making the intensity assessment even more complicated are the highly mixed construction practices in this part of the country and the small and scattered population settlements in the mountainous areas.

Mass Wasting and Flooding Mass wasting and flooding account for the largest amount of destruction and number of deaths induced by the March 5, 1987, earthquakes. The area around Reventador Volcano includes the greatest intensity of landsliding triggered by the earthquakes. The earthquake epicenters lie a few kilometers to the N and W of the Reventador area. In this area, rainfall occurs throughout the year, but increases in intensity from March to July. Significantly, anomalously high precipitation occurred in the area in January and particularly in February 1987. On February 3 and 20, the gaging station just upstream from San Rafael Falls on the Coca River registered flow rates of 2,600 and 3,400 m^3/sec, respectively, which were 8 to 12 times higher than the average flow of the Coca River. More than 90 percent of the observed landslides began as shallow slips or slides of residual soils and highly weathered rock on the uppermost parts of the slopes of the main valleys or on the slopes of the lower-order tributaries. Average thicknesses of these slips were from 1.5 to 2.0 m, with a thickness range of a few decimeters to 5 m. The failing masses either were transformed into debris avalanches and then into debris flows or, in some cases, were reworked almost immediately into debris flows with high fluidity. A large number of the landslide scars displayed unweathered bedrock, attesting to the shallowness of the residual soil mantle.

The increase in denudation near Reventador Volcano was caused not only by its nearness to the epicenters, but also by other factors, namely relief, moisture conditions, elevation, and soil composition. The areas of near total denudation on the SW slope of the ancient cone correspond to an area of deep and dense dissection by parallel gullies. Here almost all the surfaces have slopes greater than 35 to 40°. Near total denudation in areas of dissection by gullies also has occurred along the walls of the deep canyons of several nearby rivers. In contrast, the slope on the north side of the ancient cone, which is not deeply dissected, is far less affected by landslides, even though it is closer to the epicenters and is less than 2 km from the area of almost total denudation.

One of the more striking characteristics of the mass wasting caused by the earthquakes was the effectiveness of the transport of materials and the volume of the materials from the slopes of the lowest-order tributaries to the flood plains of major streams. Two factors may have contributed to this characteristic. The first is the nature of the soils involved in the slope failures, and the second is the general morphology of the Reventador area.

Interruption of flow of the Coca River was witnessed immediately following the earthquakes, which indicates a strong possibility of natural damming of the river and/or its tributaries as the result of the earthquakes. Short-lived damming occurred in two ways: (1) "hydraulic" damming, in which stream flow, highly charged with debris, was impeded in passing through narrow bedrock constrictions in the stream channels, and (2) blockage of streams by debris flows issuing into the main stream from its tributaries.

Effects on Lifelines Damage to lifelines was severe in areas near the earthquake epicenters. Specifically, there was major damage to the Trans-Ecuadorian (crude oil) and Poliducto (propane) pipelines, as well as the principal highway linking Quito and Lago Agrio, the main town of the oil-producing region of Ecuador. Damage to lifelines in other areas was relatively light. The damage to these pipelines was so severe and widespread that it had a devastating economic impact on the nation, with possible repercussions felt worldwide. Approximately 40 km of the 498-km-long Trans-Ecuadorian pipeline had to be reconstructed, making this the single largest pipeline failure in history.

The Trans-Ecuadorian pipeline, commissioned in 1972, is composed primarily of 660-mm-diameter line pipe and associated pump and pressure-reducing stations. The pipeline is the main crude-oil transportation facility in Ecuador, conveying virtually all the oil from the eastern oil fields to a marine terminal port near Esmeraldas on the Pacific Ocean. The Poliducto pipeline is composed of 150-mm-diameter line pipe and associated compressor, pressure regulation, and pumping equipment. The line was built after the Trans-Ecuadorian pipeline was commissioned, and closely follows the right of way for the crude-oil line. The line is a multiproduct facility. It conveys different types of hydrocarbons at different times, including propane gas. It extends from Lago Agrio in the eastern oil field to Quito. It was destroyed and damaged at the same locations as the Trans-Ecuadorian pipeline, since the line was constructed following approximately the same route as the Trans-Ecuadorian pipeline.

The road parallel to the pipelines is the main transportation artery from Quito to the eastern oil field. Flooding destroyed the highway bridges on the Salado and Aguarico rivers, as well as large portions of the road between the Salado and Malo rivers. The Salado River bridge was replaced in 1988 by a Bailey bridge, which is still in use.

Loss of the Trans-Ecuadorian pipeline deprived Ecuador of 60 percent of its export revenue. As a consequence, the loss of this single lifeline had a dramatic effect on the country's economy. The total loss of revenue before the reconstructed line began its service in August 1987 was estimated at nearly $800 million. Added to that was the pipeline reconstruction cost of about $50 million.

The price of West Texas intermediate crude oil is often used as an index of the world price. News of the earthquakes and associated loss of the Trans-Ecuadorian pipeline was followed by a 6.25 percent increase in this index over the four trading days immediately following the earthquakes. Although oil prices had been climbing at the time of the earthquakes, market analysts claim that the news of Ecuador's suspension of oil exports encouraged trading at escalating prices. That is, the economic effects of the lifeline failure were not confined to a single country, but perhaps were felt on a worldwide basis by market speculation.

Local-Level Economic and Social Consequences The country's already deteriorating economy suffered a major blow when Ecuadorian oil production was disrupted by earthquake-related damage to the Trans-Ecuadorian pipeline. Since the oil fields had accounted for about 60 percent of the nation's export earnings, Ecuador's ability to meet its internal operating costs and to make interest payments on its foreign debt were severely impaired as the result of the pipeline failures. Within a week after the earthquakes, the national government instituted several extreme economic measures, including suspension of the external debt payment to private banks, increased fuel prices, a national austerity plan, and a price freeze on selected essential goods.

Both the emergency period after the earthquakes and the recovery process from the earthquakes were observed. One interesting point emerging from the observations is how people viewed their communities during the crisis. Aside from the original indigenous inhabitants, the populations in the towns and on the plantations of the Oriente were fairly recently arrived, and typically had left some other part of the country to seek economic opportunity as colonists to this area. These residents were not likely as yet to have long-term attachment to the land nor to have extensive and strong social ties to others in the area. One local storekeeper remarked that, right after the earthquake, the people had helped each other, but now things were "back to normal."

Another notable aspect of the earthquakes' effects on the Oriente was the impacts in Napo Province created by the loss of the Salado and Aguarico river bridges. First, the inaccessibility of the land along the approximately 67-km stretch of road between these two bridges prevented the return of the surviving farmers and plantation owners who had been evacuated from the area. Second, a large proportion of the 75,000 inhabitants of Napo Province were effectively cut off from the rest of Ecuador by the damage to the road between Baeza and Lago Agrio. Agricultural producers in the town of Lago Agrio and of the areas to the N and E in Napo Province suffered significant economic impacts as a result of not being able to transport their crops to market. It was estimated that the postearthquake production losses from abandonment of land or lack of access to markets amounted to about $7 million, based on the assumption that land access would be reestablished by the end of June, which it was not.

Another commonly observed issue during the recovery period of past natural disasters was again noted in this event, i.e., the dilemma of reconstructing communities in a timely manner versus taking the time and resources to provide safer housing and other facilities. On one hand, there is always concern that many families continue to live in houses that are even more vulnerable to future earthquakes than they were before the earthquakes. On the other hand, the reconstruction period also always provides one of the best opportunities for upgrading housing and making it safer, because interest in and awareness of earthquake threats are high.

Various interviews indicated that there was some controversy about what approach to reconstruction had the fewest drawbacks. Governmental officials claimed that the Indians, even though they are primarily farmers, had sufficient time to also work on the reconstruction of housing in their communities. They believe that the use of residents to provide construction labor makes the projects less costly and supposedly gives the residents a stronger sense of ownership for reconstruction activities. Others felt that the construction work was detrimental to the farming work and that this might lead to problems in the future if food production was inadequate. Another argument was given by some that it was not the best idea to have the villagers do the construction, since houses not properly designed and constructed will be likely to suffer damage during future earthquakes.

In the Sierra, special attention was given to the preservation of various damaged buildings that were felt to have historical and cultural value to the country. These buildings were considered important both for the citizens of Ecuador and for tourism. National funds were used for their repair.

A number of areas for further research are recommended from the assessment of economic and societal impacts on local communities as a result of the March 5, 1987, earthquakes. They include the extent to which technical assistance for construction, both in person and in the form of written materials, reaches the affected population, and what factors contribute to its effectiveness; the extent to which active efforts are made to distribute special instructional materials on handling the housing and health needs of disaster victims to persons at the local level who can assume responsibility for emergency programs; and the relationship between various types of recovery assistance and the promotion of local or national economic development, and policy development for this issue. Other recommendations are listed in Chapter 7.

Organizational Interaction in Response and Recovery The organizational interaction is particularly interesting in this event, given the multiple geographic locations of damage from the disaster, the multiple jurisdictional levels involved in disaster response and recovery activities, and the multiple perspectives required for timely and appropriate disaster assistance to the affected populations.

The earthquakes generated consequences of differing types and magnitudes in three geographic locations of Ecuador. The zone of primary impact, which included the epicenters of the earthquakes near Reventador Volcano, was located in western Napo Province. In this zone, major loss of life was caused by flash floods generated by massive landslides and debris flows. Major damage also occurred to the infrastructure systems. In the small towns affected by the disaster, the first response of the local organizations was directed toward meeting the human needs of the victims. The next major problems driving organizational interactions centered on destruction of the infrastructure. These problems included (1) reconstruction of the oil pipeline in geologically unstable territory, (2) loss of oil revenues and its consequent impact upon the national economy, (3) loss of the highway, bridges, and secondary roads for safe travel and economic activity of the resident population, and (4) reorientation and resettlement of local residents, severely shaken emotionally and economically by the disaster and struggling to cope with questions regarding an uncertain future in a zone of high seismic risk.

The zone of secondary impact from the disaster was the Sierra, where the principal problem was housing. Approximately 60,000 homes were damaged or rendered uninhabitable. Worse yet, what appeared to be a moderately severe event to other economic groups in this zone proved to be a disaster for those at the lowest economic level, whose homes were much more vulnerable to seismic risk and who had few resources for rebuilding. The third zone of impact from the disaster included the town of Lago Agrio and adjacent communities in eastern Napo Province. These communities suffered little structural damage and had no loss of life. The major problem generated by the earthquakes in this zone was isolation and economic deprivation, resulting from the destruction of the oil pipeline and the major route of land transportation. The cumulative effects of long-term isolation, unemployment, and lack of access to markets and supplies worsened with the prolonged period required for reconstruction of the infrastructure needed for the local economy, based upon oil production and agriculture.

Especially vulnerable were Indian communities along the Coca, Aguarico, Dué, Salado, and Papallacta rivers. Dependent upon the rivers for drinking water, food, and transportation, these communities suffered serious deprivation in the loss of these vital resources due to pollution and obstruction of the rivers. It was an interactive set of conditions that, unresolved, steadily worsened and overwhelmed the local resources of the residents and communities of this zone.

Differing consequences generated in three disaster zones required particular kinds of organizational actions for appropriate and timely response. As a result, the President of Ecuador established a national emergency committee, headed by the secretary of the National Security Council and an officer of the Ecuadorian Army, to direct the national disaster operation. However, the simultaneous needs of the populations in the three zones and the massive impact on the national economy from the combined loss of oil export revenues and cost of rebuilding the pipeline and transportation routes required resources beyond Ecuador's own capacity. As a result, some 22 nations responded to its needs. Yet the requirements for coordination and communication between participating nations and between the Ecuadorian levels of governmental jurisdiction in the simultaneous delivery of services to the three disaster zones elevated the complexity of organizational interaction.

The national emergency committee was also given the responsibility to coordinate activities by the international and voluntary organizations that participated in the disaster operation. In reality, the complexity of the operations and lack of communications facilities between national offices and the local governments necessitated that much of the actual work be done locally, with limited contribution from the national level.

As a result, voluntary charitable organizations played an important role in this disaster, particularly at the community level. These organizations, linked to the international community, provided resources that were not immediately available within Ecuador and initiated the design and implementation of disaster-assistance activities. The resulting pattern of organizational network performance, at times overlapping, at times operating independently, or uncoordinated, appears to be a function of at least four factors: (1) overall complexity of the disaster environment, (2) differing requirements of technology and resources for the problems addressed, (3) number and diversity of participating organizations, and (4) limited facilities, staff, and training for communication/coordination in disaster management.

Several needs were identified in this field study. They include the need (1) for improved communications, (2) for better coordination of action between the multiple organizations for improving performance in disaster operations, (3) to develop and disseminate more complete and systematic information for the wider set of organizations involved in disaster management, (4) to be especially sensitive when allocating disaster assistance to victims in communities with marginal economic standards, and (5) to evaluate performance in disaster operations and provide constructive feedback to participating organizations for improvement of their performance in future disasters.

The study also recommends several topics that warrant future research effort: (1) design and development of an interactive information system for decision support in disaster management, (2) design of interorganizational and interjurisdictional simulated postdisaster operations as a means of exploring the limits and capacities of human decision-making processes in disaster environments, (3) inquiry into the design and development of networks as appropriate organizational forms for the rapid mobilization, implementation, and evaluation of action in disaster management, and (4) inquiry into economies of resource management that will facilitate interorganizational participation.