Learning from Earthquakes

Preliminary Observations on the Southern Peru Earthquake of June 23, 2001

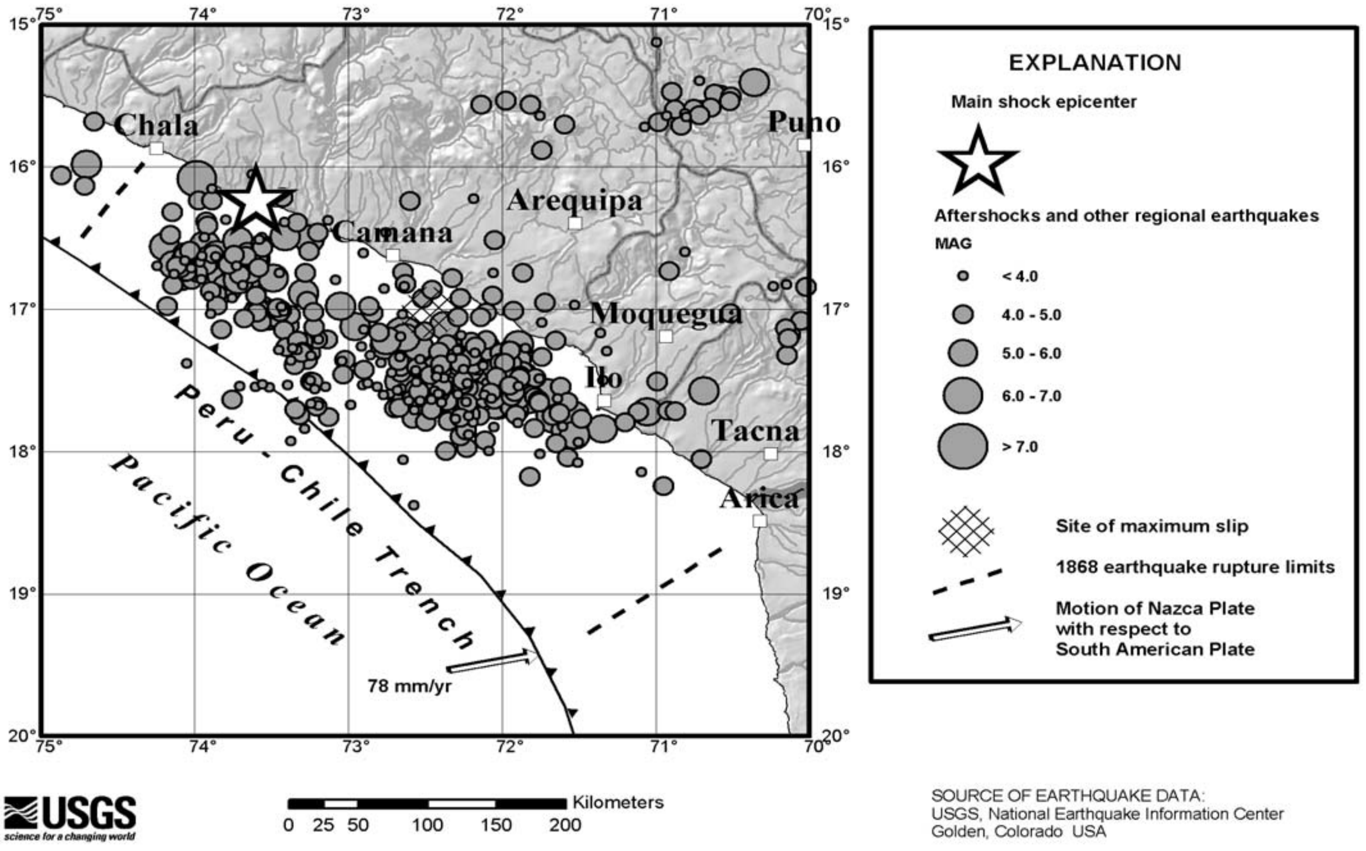
This report is condensed from the post-earthquake surveys of numerous individuals and teams, most of which traveled to Peru with their own funding. They contributed their findings to this report, one of a series in the Earthquake Engineering Research Institute's Learning from Earthquakes (LFE) Program. The publication and distribution of this report are funded by the National Science Foundation as part of EERI's LFE Program, under Grant #CMS 0131895.

Introduction

On June 23, 2001, at 8:33PM UTC, 3:33 PM local time, a Mw=8.3 (USGS) earthquake struck near the coast of south-central Peru along the subduction zone between the Nazca and South American plates, at coordinates 16.2 S, 73.75 W. The districts of Arequipa, Moquegua, Tacna, and Ayacucho sustained losses. There were dozens of strong aftershocks in the region. The southern coastline was affected by a tsunami following the main event; the coastal towns of Ocoña and Camana were particularly hard hit.

Only one strong-motion record of the main event has been recovered from a station in Moquegua. Field surveys and local reports indicate that the duration of ground motion was relatively long (45-60 seconds), with peak ground accelerations ranging from approximately 0.10g near Arequipa to 0.30g near Moquegua.

The National Institute for Civil Defense of Peru reports 77 dead, 68 missing, 2,713 injured, 213,430 people affected, 33,570 houses damaged, and 25,399 houses destroyed.



SOURCE OF EARTHQUAKE DATA:
USGS, National Earthquake Information Center
Golden, Colorado USA

Figure 1 *Southern Peru earthquake and associated seismicity, June 23–July 23, 2001. Offshore epicenters extending from the main-shock epicenter southeast to Ilo probably occurred on or near the main-shock rupture surface. Boundaries of the 1868 rupture are as proposed by Dorbath et al. (1990). Inland shocks occurred on different faults than the main shock and may have occurred independently of the main shock. (Dewey)*

The Earthquake and Aftershock Activity

James W. Dewey, U.S. Geological Survey, Denver, Colorado; Juan Bariola, JBB S.A.C., Peru

The earthquake resulted from thrust faulting on the boundary between the Nazca and South American plates. The locations of main-shock hypocenter, early aftershocks (Figure 1), and moment-tensor solutions of the earthquake imply that fault-rupture nucleated at a depth of approximately 30 km beneath the coastline between Chala and Camana, and propagated updip toward the Peru-Chile trench and to the southeast, terminating near Ilo. The causative fault-rupture had an along-strike length of about 300 km and a down-dip width of about 100 km.

The average fault displacement was several meters, but seismograms of the earthquake imply that slip varied greatly along the fault surface. For example, a moment-tensor analysis conducted by Kikuchi and Yamanaka (2001) shows maximum slip occurring approximately 150 km southeast of the main-shock hypocenter. The duration of the overall main-shock rupture was approximately 80 seconds (Harvard Centroid Moment Tensor solution).

The earthquake struck part of an approximately 1000-km long section of the western South American plate boundary that many seismologists believed had high potential for great earthquakes in upcoming decades (Dorbath et al, 1990). Most of the plate-interface thrust zone between Chala, Peru (15.9 S), and Mejillones, Chile (23 S), had been seismically quiescent (defining a so-called "seismic gap") since the great earthquakes in 1868 (Southern Peru) and 1877 (Northern Chile). The zone has been accumulating elastic strain as the Nazca plate subducts beneath the South American plate at a rate of approximately 78 mm per year. The June 23rd earthquake would have substantially reduced elastic strain in the 300-km zone ruptured, but much of the remaining 700 km of the plate interface that ruptured in 1868 and 1877 probably still remains in a condition of high elastic strain accumulated since the late nineteenth century.

One strong-motion record was obtained at Moquegua. Two other instruments in the epicentral area apparently malfunctioned. The strong-motion site is situated approximately 175 km from the source of maximum slip identified by Kikuchi and Yamanaka (2001), and 100 km from nearest part of the main-shock fault-plane, offshore Ilo, that is suggested by the earthquake's focal mechanism and aftershock distribution.

The Universidad Nacional de Ingenieria and the Centro Peruano Japones de Investigaciones Sismicas y Mitigacion de Desastres (CISMID) recovered and corrected the ground acceleration time histories (Figure 2) and the corresponding acceleration response spectra (Figure 3) from the Moqequa instrument recording in east-west, north-south, and vertical directions. PGA values were .295, .220 and .160g in the east-west, north-south and up directions, respectively. Larger accelerations were observed in the approximately normal-to-fault direction comparatively to the parallel-to-fault-direction. The ratio of peak-vertical to peak-horizontal acceleration was 54%, slightly larger than that in previous Peruvian events.

Aftershocks were predominantly south of the main shock. Fault rupture occurred following the same path shown by aftershocks — north to south directivity as has been common in previous earthquakes in Peru (Wyss et al., 2000) — so energy-focusing effects may have caused larger intensities in towns south of

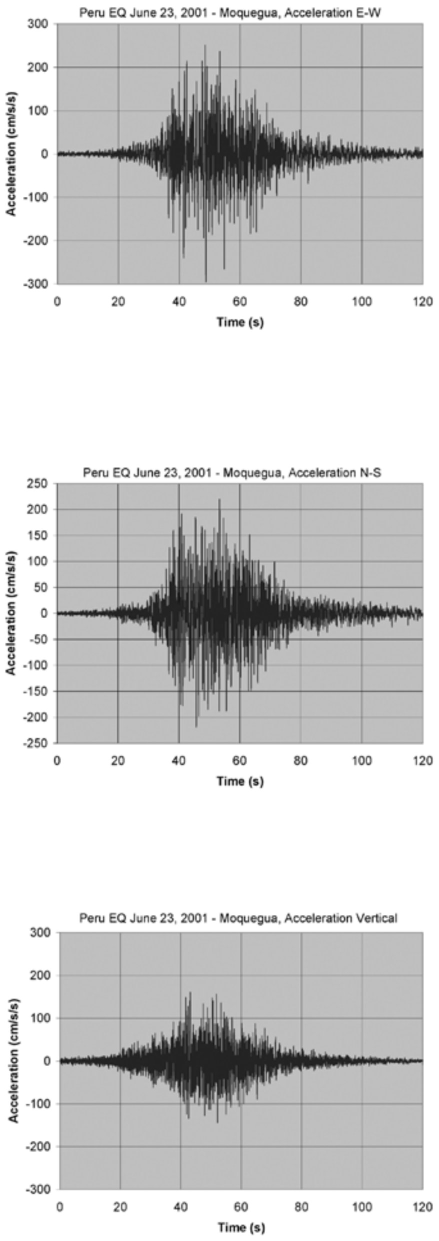


Figure 2 *Acceleration time histories of the east-west, north-south, and vertical components of the corrected ground-motion recording in the city of Moquegua. (The Universidad Nacional de Ingenieria and the Centro Peruano Japones de Investigaciones Sismicas y Mitigacion de Desastres [CISMID]).*

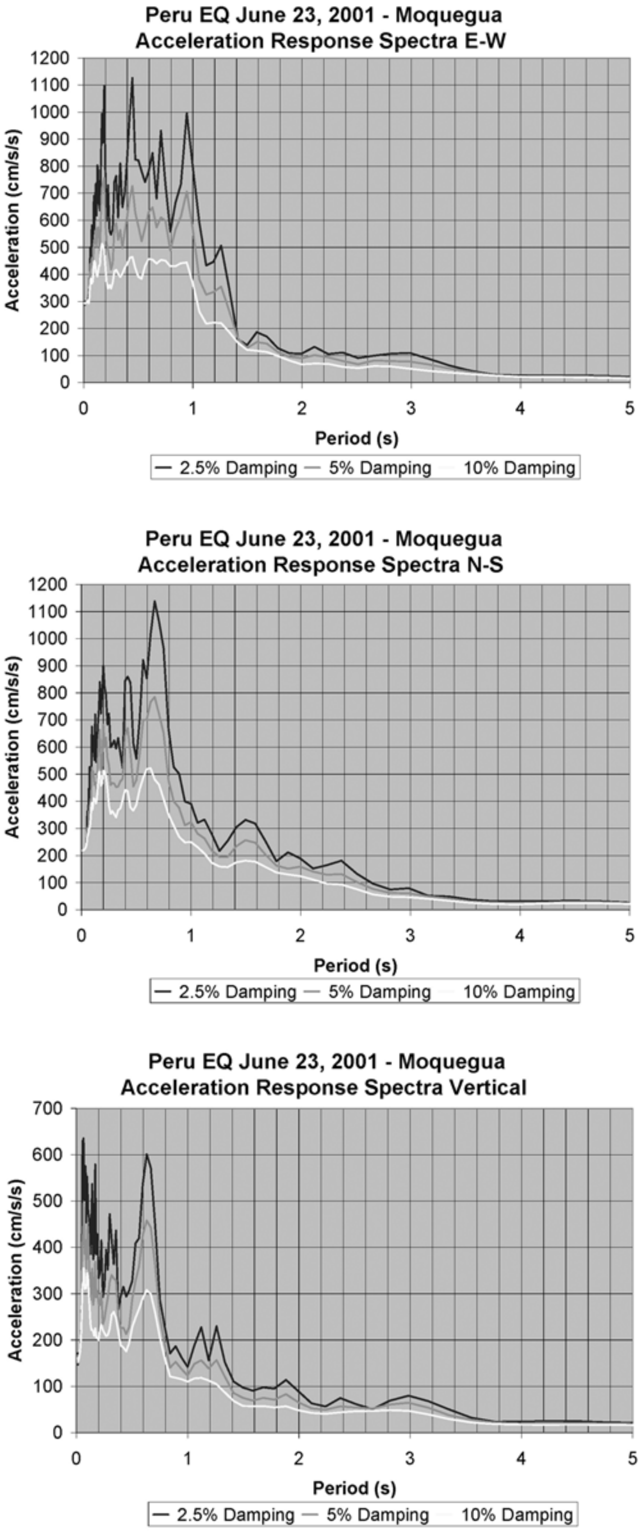


Figure 3 *Acceleration response spectra obtained from the corrected ground motion along the east-west, north-south, and vertical components of the recording in the city of Moquegua. (The Universidad Nacional de Ingenieria and the Centro Peruano Japones de Investigaciones Sismicas y Mitigacion de Desastres [CISMID])*

the epicenter such as Moquegua.

Geotechnical Observations

A. Rodriguez-Marek, Washington State University, Pullman; P. Repetto, URS Corporation, Denver, Colorado; J. Wartman, Drexel University, Philadelphia, Pennsylvania; D. Baures, URS Corporation, Denver; E. Rondinel, Pontificia Universidad Católica del Perú; J. Williams, URS Corporation, Denver; J. Zegarra-Pellane, Pontificia Universidad Católica del Perú. The National Science Foundation sponsored the reconnaissance team, with additional support from Washington State University, Drexel University, the Catholic University of Peru, and URS Corporation.

Ground Failure: Considerable damage was done to highways in the regions of Tacna, Moquegua, and Arequipa as a result of landslides, rockfalls, fill densification, and liquefaction. Observed ground failure was concentrated along Peru's primary north-south highway, the Pan-American Highway, and several of the other major roads connecting the cities of Atico, Camana, Arequipa, Ilo, Moquegua, and Tacna. Several instances of relatively minor ground failure were also observed in urban centers of the region.

Fill densification caused considerable damage to bridge abutments and approaches. Roadway damage also occurred at the location of valley fills. The fill soils typically consisted of poorly graded coarse to fine sands and non-plastic silts. Deformations were largest along the edges of highway fills.

Liquefaction was observed at three bridge sites located in alluvial valleys. In one instance, liquefaction-induced lateral spread severely damaged a concrete bridge and several residences located along the banks of a river (Figure 4). At another site, liquefaction caused a

Figure 4 *The offset in the corn rows (left to right near middle of photo) is due to localized displacement induced by lateral spread. (photo: geotechnical reconnaissance team)*

localized bearing-capacity failure of a concrete column supporting a large and relatively new bridge. A third site had about a meter of lateral spread, but no apparent damage to structures.

Landslides and slope stability failures occurred at localized cut and fill sections along highways (Figure 5). In most cases, slope movements in the fill section were due to fill densification. Rockfalls were observed along many of the steep road cuts in the region. Observed rockfalls ranged from single-block failures to raveling of both bedrock and the exposed colluvial material. Some planar and wedge failures within the bedrock were also observed. Natural slopes composed of bedrock or colluvium had very little observed failure, with the exception of displacements of a shallow veneer of soil in sandy slopes.

Site Effects: The concentration of damage in some areas of Tacna, Moquegua, and Ilo suggests the influence of site amplification in the resulting damage levels. Local engineers indicated the presence of sand deposits in areas of concentrated damage, while areas underlain by stiffer gravel deposits suffered less damage. It is noteworthy that public schools in Peru that were built in the same time period were generally constructed to a similar design and using similar construction practices throughout the country. Observations of the performance of school buildings in different locations permit a comparative evaluation of the ground motions experienced during the earthquake.

Some of the damage to houses and businesses located at or near the top of several steep ridges in the towns of Arequipa and Moquegua can possibly be attributed to topographic effects. The inclinations of the ridge slopes varied, but were on the order of 35 to 60 degrees.

Engineered Structures: Inspection of three large copper mines located in the region affected by the earthquake indicated relatively minor damage to mining facilities. The only notable exception is the liquefaction flow of a heap-leach pad. Local authorities reported no damage to dams in the region. A concrete-face rockfill dam at a mine suffered minor damage due to fill settlement at a sacrificial portion of the crest.

Landslides

David K. Keefer, U.S. Geological Survey (USGS), Menlo Park, California. This reconnaissance was carried out by personnel from the USGS (David Keefer, Robert Tilling, and James Smith, who is currently on assignment to the USAID Office of Foreign Disaster Assistance [OFDA]); the Instituto Geológico Minero y Metalúrgico del Perú (INGEMMET — Julio de la Cruz, Antonio Guzmán, Lionel Fídel, Segundo Nuñez, Marco Rivera, and Bilberto Zavala); and the Instituto Geofisico del Perú (IGP — Juan Carlos Gómez and Jersy Mariño). Funding for USGS participation was provided by OFDA, and coordination and logistical support were provided

Figure 5 *Slope failure along highway between Cuajone and Moqegua. (photo: geotechnical reconnaissance team)*

by INGEMMET.

The earthquake caused landslides throughout an estimated area of at least 25,000 km^2 stretching from the epicenter along the coast south to the region between Ilo and Tacna, and inland as far as Arequipa and Canderave. The immediate effects of landslides primarily concerned highways; repairs were underway at many localities, and roads were constricted to one traffic lane at several others. A longer-term hazard from these landslides derives from their transportation of large amounts of loose sediments into drainage channels; this sediment may exacerbate the damage due to post-earthquake flooding, brought on by such events as strong El Niños in coastal areas.

The largest landslides were observed along a 20-km stretch of the Pan-American Highway between the town of Atico and the village of Cerro de Arena, where a landslide damaged a dwelling and restaurant. Many landslides in this area were rock falls, and rock slides in rock that was well indurated but closely fissured. Other landslides were debris slides in colluvium and rotational slumps in unconsolidated dune sand and in highway fill. These landslides caused substantial local damage to the highway, and traffic was still being delayed at sites of repair more than a month after the earthquake.

There were also abundant earthquake-induced landslides inland from the southern end of the fault rupture, in the vicinity of the towns of Moquegua, Ilo, and Canderave. Around Moquegua, many small and moderate-sized falls and slides of rock and soil occurred along stream banks, roadcuts, and other steep slopes composed of material derived from the Moquegua formation, which consists largely of weakly cemented clays, sandstones, and conglomerates. The largest of these landslides is estimated to have a volume of about 5,000 m^3. Other landslides typically had volumes of a few to a few hundred cubic meters, and individual landslides are typically spaced a few tens to hundreds of meters apart along the susceptible slopes. Landslides in the better-indurated volcanic rocks to the northeast of Moquegua were typically smaller and spaced farther apart.

South of Moquegua, in the lower Ilo Valley, shallow landslides with sizes and spacing similar to those in the Moquegua formation occurred in the well-indurated but closely fissured bedrock of the coastal cordillera and in river-terrace materials (Figure 6). Landsliding was also severe around the town of Canderave, east of Moquegua, where the largest landslides were rock falls off the scarp of a large, pre-existing deep-seated landslide. Throughout this southern region, slumps in highway fill were also relatively common.

No landslides were observed along the Pan-American Highway north of the epicenter, while between Cerro de Arena and the Moquegua area, landslides were typically small and spaced far apart. Soil liquefaction effects, including lateral spreading landslides, occurred in the lower courses of some of the major rivers that cross the coastal plain south of the epicenter. Throughout this area most of the landslides were either small rock falls or rock slides or slumps in highway fill.

The types of landslides and types of materials that produced landslides in this earthquake are similar to those caused by the vast majority of other earthquakes worldwide (Keefer, 1984), but the absence of large landslides outside the small zone south of the epicenter contrasts significantly with findings from many other earthquakes of comparable magnitude.

Tsunami

Lori Dengler, Humboldt State University. International Tsunami Survey Team (ITST) members: Sebastian Araya, Lori Dengler, Humboldt State University; Jose Borrero, Matt Swensson, the University of Southern California; Emile Okal, Brandon Gomer, Northwestern University; Shunichi Koshimura, National Oceanic & Atmospheric Administration Pacific Marine Environmental Laboratory (NOAA PMEL); Gustavo Laos, Daniel Olcese, Fernando Vegas, Direccion de Hidrografia y Navegacion, Peru Navy; Modesto Ortiz, Centro de Investigación Científica y de Educación Superior de Ense-

Figure 6 *Typical rock fall from wall of lower Ilo Valley near Algarrobal. (photo: David K. Keefer)*

nada (CICESE), Encinitas, Mexico; Vasily Titov, NOAA PMEL and the University of Washington.

The tsunami produced by the earthquake was recorded throughout the Pacific basin. Maximum recorded wave heights (peak-to-trough) were 2.57 m in Arica, Chile; 0.7 m in Hilo, Hawaii; 0.4 m in Crescent City, California; 0.24 m in Sandpoint, Alaska; 0.55 m on Chatham Island, New Zealand; and 0.5 m at Hanasaki, Japan. A complete tabulation of recorded tsunami wave heights is posted at **http://wcatwc.gov/06-23-01.htm.** One hour after the earthquake, the Pacific Tsunami Warning Center declared a tsunami warning for Peru, Ecuador, northern Chile, and Southern Colombia. Later, that was expanded to include all of the west coast of South and Central America, Mexico, and French Polynesia. Mollendo and the adjacent port city of Matarani in Southern Peru organized evacuations of low-lying areas after the water was observed receding. Port authorities directed the Matarani evacuation, and local police directed the Mollendo evacuation.

The tsunami was observed by eyewitnesses from Tanaka, Peru, to Arika, Chile. Outside the municipality of Camana, the tsunami was described by observers as an initial draw-down that began 10 to 15 minutes after the earthquake extending 50 to 100 meters offshore. Most respondents, upon seeing the water recede, moved to higher ground. The water remained low for “a long time,” variously described as 15 to 20 or more minutes. Many expected a significant positive wave to follow, but the incoming wave did not significantly exceed the ambient high water level. Several observers described cracks opening in the exposed seafloor and dirty water with a distinctive odor bubbling up. Three or four more oscillations of the water were observed, the draw-down always apparently larger in amplitude. No structures were reported damaged by the tsunami in these areas.

The impacts were quite different within the municipality of Camana. It has eight districts that include coastal resort communities, farming regions, and fishing communities, with a total population of about 53,000 people. Damage was concentrated along a 20-km long flat coastal beach no higher than 5 m above sea level. The tsunami destroyed over 2,000 structures, damaged an additional 1,000, killed 22 people and left 52 missing, and flooded 2,000 hectares of farmland. Estimates of undamaged structures within the inundation zone were between 12 and 30. In Camana, the earthquake impacts were much less significant than the tsunami effects. The largest waves (5-8 m) and deepest penetration (1-1.2 km) (Figure 7) produced by this tsunami coincided with the most-developed beach resort area along the southern Peruvian coast. La Punta and the adjacent resort communities have many summer homes, occupied by about 5000 residents during the peak summer season.

Many people observing the water recede self-evacuated. No one responded to the ground shaking even though all felt the earthquake strongly. Eyewitnesses described an initial draw-down that lasted 15 minutes or more. The initial positive wave was small, but followed by two destructive waves of near identical size.

Buildings in the coastal area are of three general types. In the farming areas and fishing villages, weak adobe structures and shacks of bamboo and other light-weight materials predominate. In the resort area, most structures are built on concrete slab foundations with reinforced columns. Unreinforced bricks are filled in to form the walls between the columns. A number of hotels, some restaurants, and a few homes were built of reinforced concrete. There were no wood structures in the inundation zone. Adobe and infilled wall structures per-

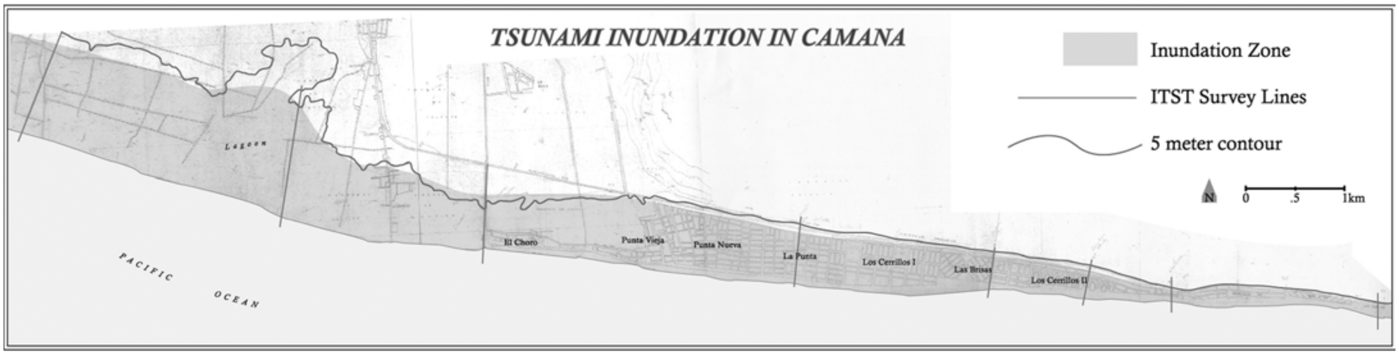


Figure 7 *Tsunami inundation and ITST survey lines in the Camana area. (Base map from the Planning Department of the Municipalidad Provincial de Camana, inundation by L. Dengler based on ITST data. Map compiled by Verena Kellner, Humboldt State University.)*

Figure 8 *Reinforced column/infilled brick wall structure in the La Punta area. Brick walls perpendicular to wave impact were typically blown out. (photo: Sebastian Araya)*

formed very poorly. No signs of adobe structures remained. Infilled walls were typically blown out on walls perpendicular to the wave direction (Figure 8). Significant scour occurred to structures at the corners, often undermining the slab foundations. Reinforced concrete structures with thicker foundations were most likely to survive.

Demographic information on earthquake victims compiled by the Instituto Nacional de Defensa Civil suggests that most of the victims of ground-shaking damage were the young or the elderly. However, about a third of the tsunami victims were between 30 and 50. No demographic information was available for the 52 persons listed as missing, but anecdotal evidence gathered by the reconnaissance team indicated that most were farmers working in the onion fields. The normal Saturday work shift ended at 4:00 pm, and people were reluctant to leave before their shift ended.

While the extent of inundation and the number of structures damaged or destroyed was significant, the number of lives lost was considerably reduced from several other recent tsunamis. The difference in casualties has several causes: 1) a tsunami-aware coastal population: most of the people interviewed knew what tsunamis were, recognized the water draw-down as a sign of danger, and self-evacuated; 2) time of year: the earthquake and tsunami occurred in winter, so the beach discotheques, hotels, and cafes were empty; 3) time of day: because the earthquake and tsunami occurred in mid-afternoon people could see the water recede; and 4) ambient tide level: the tsunami coincided with a minus-40-cm tide, one of the lowest tides of the year.

Structural Damage

Eduardo Fierro, Wiss, Janney, Elstner Associates, Inc. (WJE), Emeryville, California. Assembled and edited by Ayhan Irfanoglu and Cynthia Perry, also of WJE, based on photos and text from Peru by Fierro. Fierro acknowledges the assistance of local officials and members of the engineering community in Peru in providing access, accommodations, and information. In particular, he thanks Jorge Ojeda, Executive Director of Autodemas; José Tong, Dean of the Colegio de Ingenieros de Lima; Daniel Torrealva and Alejandro Muñoz, Universidad Catolica del Peru; Javier Pique, Universidad Nacional de Ingenieria; Adolpho Gonzalez, Colegio de Ingenieros de Tacna; Antonio Blanco, Dean of the Colegio de Ingenieros del Peru; and Julio Eguia, driver from Autodemas.

Initial surveys indicated that most damage occurred in areas to the east and southeast of the epicenter of the main event and that historic structures and old houses sustained the most severe damage. Adobe houses were most vulnerable. School buildings also performed poorly, except for the few new ones designed to the 1999 code. Most of the damage could be attributed to configuration problems such as soft stories or short-column effects. Both new and older schools with short column problems performed poorly. Schools designed according to the 1999 Peruvian code had isolation details between infill masonry walls and the concrete framing, and thus avoided the short column failures.

Moquegua: Moquegua was the city hardest-hit by this earthquake. The records (see Figure 2) indicate that the peak ground acceleration was 0.30g and the response spectra had a plateau at approximately 0.65g-0.70g in the range from about 0.15 seconds to 1 second (see Figure 3). The damage in Moquegua is mainly to old and new adobe houses. Numerous adobe buildings collapsed in the downtown area, and many others sustained heavy damage to the point of being almost unstable. In the area of San Francisco, the hillside was nearly totaled due to collapse of new adobe houses. One school had a partial collapse due to short columns (Figures 9 and 10). The cathedral lost one of its vaults, and the Church of Belen sustained damage to its tower and walls.

Arequipa: The ground accelerations were apparently not very high in Arequipa, a city of 700,000 located about 120 miles inland from the epicenter of the main event. There are no ground motion records from Arequipa, apparently due to instru-

Figure 9 *School building in Moquegua. Partial collapse due to failure of short columns. (Photo: E. Fierro)*

Figure 10 *View of the collapse of one of the short columns in the school building shown in Figure 9. (Photo: E. Fierro)*

ment malfunction. However, local people reported that the duration of motion was approximately one minute. Primarily historical buildings and older stone masonry structures sustained damage. An estimate of 0.10g appears reasonable for the peak ground acceleration in Arequipa, based on observed damage patterns.

The city's historic cathedral, built in 1612, sustained heavy damage, mainly due to the collapse of one of its towers. The cathedral is situated on the Plaza de Armas in Arequipa's historic center, a UNESCO World Heritage site. It was damaged by previous earthquakes and fire, and was substantially rebuilt in the 19th century. Both towers were apparently rebuilt most recently in about 1940. A photo extracted from a video taken during the earthquake shows part of the collapse sequence of the tower (Figure 11). The tower on the left collapsed and fell through the vaulted dome above the main altar of the cathedral.

Many cathedrals and religious monuments sustained damage, such as the Convent of Santa Catalina, founded in 1579. Many traditional domed and vaulted structures were extensively damaged. Most of the historical monuments are made with blocks of sillar (consolidated volcanic ash) laid with lime or cement mortar. Sillar is also used for housing. A damaged vaulted ceiling in an older home is shown in Figure 12. Many of the older roofs were made with heavy blocks of low strength sillar supported by steel rails.

Tacna: The University Jorge Basadre in Tacna has two campuses, and some damage was observed in both. In the old campus building, some parapet walls at the fourth floor had to be demolished, since they were unstable in the out-of-plane direction. On the new campus, a three-story building had moderate damage to the infill masonry in the form of diagonal cracking. However, the infill was strong enough to form diagonal compression struts between the beam-column joints, which cracked the corner-column

Figure 11 *Cathedral of Arequipa, still photo from sequence taken during main event. (photo purchased by E. Fierro)*

joints in shear on the first and second floors. The poorly detailed columns of the elevated tank located on the roof (fifth floor) had significant damage but did not collapse. The Colegio Nacional Mariscal Caceres sustained extensive damage to approximately 60 short columns in the typical campus buildings. The school principal was building temporary wooden classrooms following the earthquake.

A municipality building outside Tacna suffered severe damage to the short columns and to the few masonry walls that existed. The building had typical poor short-column configuration without any transverse reinforcement, which caused these columns to crush and lose several inches of height. The building is not readily repairable and will be demolished.

The Peruvian National Institute for Civil Defense reports that distribution of relief material is ongoing. Peru may need long-term international financial and technical support for repair and rehabilitation of the damaged historic structures, which are an important part of its international cultural heritage.

Lifelines

Curtis Edwards, Pountney Consulting Group, Inc., San Diego, California. The Post-Earthquake Investigation Committee of the Technical Council on Lifeline Earthquake Engineering (TCLEE), a technical council of the American Society of Civil Engineers (ASCE), organized a team of five TCLEE members with support from ASCE to perform a reconnaissance of the lifelines in the earthquake area. The team consisted of Curtis Edwards (team leader); John Eidinger, G&E Engineering Systems, Oakland, California; Mark Yashinsky, Caltrans, Sacramento, California; Anshel Schiff, Precision Instruments, Los Altos Hills, California; Bill Byers, Burlington Northern-Santa Fe Railroad, Kansas City, Kansas.

Figure 12 *Damge to typical historic dwelling with vaulted roof constructed of "sillar" blocks. (Photo: E. Fierro)*

In general, lifeline damage was less than expected compared to that of other similar magnitude events. This was apparently due to the large distances between major population centers and the general absence of lifelines in other areas.

There was greater damage in cities 300 to 500 km southeast of the original epicenter (Atico) than in cities that were closer. The larger cities in this area of southern Peru are located in the upper elevations away from the coastal area. All of these areas had some lifeline damage, with the majority of damage in the area in and around Moquegua. Landslides (rockfalls and poorly compacted fills) caused most of the damage to roads, railroads, and water systems. There were no reports of major lifeline damage in areas north of Atico.

Water Systems: The majority of land east of the Andes is very dry and requires use of imported water or ground water. A number of major rivers flow to the Pacific Ocean, most of which are dammed or otherwise diverted at a number of locations to meet potable and agricultural uses. The government is in the process of completing major dams, canals, and potable water supply systems in each province (state) in southern Peru. Most of the damage in the upper reaches of this system was due to landslides blocking exposed canals. There was no reported damage to dams, and tunnel systems had not been inspected at the time of our investigation.

There are major water treatment plants in Arequipa, Moquegua, and Tacna. The Arequipa plant overall had minor damage, but sloshing damaged the tube settlers and the circular clarifier effluent troughs. In addition, there was a minor chlorine leak due to unrestrained chlorine cylinder storage. The Arequipa plant is at 100% capacity, and operators indicated that to maintain service to the city, they could not take a clarifier out-of-service for repairs. There was additional damage to the laboratory. The Moquegua plant had significant damage to fiberglass baffles in the flocculation basin, which were not repaired at the time of our inspection. As a result, the clarifiers were out-of-service, leaving only the sand filters and chlorination as the only remaining treatment processes. Tacna has two treatment plants that suffered minor damage. The major damage was to an older partially buried reinforced-concrete clearwell. The columns and roof were heavily corroded and near collapse.

There was minimal damage to water distribution systems in these cities. Breaks of the PVC, asbestos-cement, and cast-iron pipes appeared to be due to shaking and were repaired within two weeks after the event. There were no reports of damage to water storage tanks. Most of these are constructed of reinforced concrete, and those in the flatter regions are elevated. One steel water tank at the Ilo power plant had stretched anchor bolts, but no other damage or leakage.

Railroads: The railroads of Peru do not constitute a network, but include separate entities not physically connected. Two of these sustained extensive damage: PeruRail, a common carrier providing freight and passenger service; and the industrial railroad of the Southern Peru Copper Corporation, which transports copper concentrate from inland mines to a smelter and refinery on the coast, and supplies and equipment to the mines. Major line segments, with a combined length on the order of 700 km, were out of service for three to seven days. The most severe damage involved material sliding or falling onto the track, or embankment failures. In some cuts, track was buried under as much as 5 meters of material (Figure 13).


Figure 13 *Rock Fall Blocking PeruRail Line. (photo: PeruRail)*

There was no railroad bridge damage, but few bridges are located in the affected areas. Tunnel damage was minor. Within distances of about 300 km from the epicenter and 150 km from the rupture surface, damage did not correlate with distance, indicating that other factors were more important in determining the extent of damage. Obvious factors include depth of cuts, height of fills, side slopes, and differences in the material affected.

Highway Systems: There was widespread damage to the highway system as a result of the earthquake. Much of this damage was due to the poor performance of loosely compacted fills, and rock falls and landslides from steep-cut slopes. The area affected by the earthquake is extremely arid and mountainous. The primary highway system consists of the north-south Pan-American Highway, a well-maintained two lane blacktop road. In addition, there are also many packed-earth and unimproved local roads. The roads are cut out of the sides of mountains with fill material used to support the outside shoulder and roadway. The uphill slopes were not closely inspected to remove loose material or sufficiently graded to prevent slides. The material used for the fills was often fine silts and sands that were poorly compacted. During the earthquake, material on the uphill side fell onto the roadway, and material on the downhill side lurched or spread away from the roadway. On the Pan-American Highway, a concerted effort was made to keep the road open, even when half the roadway was obstructed due to rockfalls or subsidence. This damage continued to impede travel for months after the earthquake.

Highway structures such as bridges and culverts were also damaged due to the use of poorly compacted material around abutments and wingwalls. This resulted in subsidence of the bridge approaches. In addition, liquefaction caused failure of some wingwalls and approaches. Most bridges were in use 30 days later, but one older steel truss bridge was closed due to failure of bearing supports (Figure 14). Box culverts also performed poorly due to loosely compacted material. An 18’-by-40’-tall single-box culvert remained undamaged on the Pan-American Highway, but the roadway over the culvert settled several feet, and the wingwalls were shattered due to active pressure from the surrounding soil.

The severity of damage to the highway system can be reduced in the future by replacing weak fills along roads and highway structures with 90% compacted material. Slopes

Figure 14 *Damaged bridge abutment. (photo: Yashinsky)*

above roads should be carefully inspected for loose material, which should be removed or draped to prevent future movement. Catchment walls should be constructed between slopes and roads to prevent falling rocks from impeding traffic.

Power Systems: Overall performance of power systems was relatively good. In Moquegua, power was disrupted for about 12 hours; disruption in most other areas was limited to a few hours unless a local feeder was damaged.

The most significant observation was at a new coal-fired power-generating station built to high seismic standards. It experienced types of damage not observed in gas- and oil-fired plants in the United States. The anchorages of three of the main boiler structure support columns were damaged or failed, and at least two boiler tubes failed. Systems used for the lateral restraint of the boiler were also damaged, but this has been observed before. The bases of two large coal-unloading clamshell-scoops cranes mounted on a pier failed, and the cranes fell into the ocean.

A new 220/138 kV transmission substation was damaged. Transmission voltages in California, where most earthquake damage to power systems has occurred, are primarily 115 kV, 230 kV and 500 kV. The performance of 115 kV equipment has been very good, but damage to some types of 230 kV switchyard equipment has been common. Because there is so little 138 kV and 161 kV equipment, its earthquake performance is not well-known. The 1999 Chi-Chi, Taiwan, earthquake demonstrated the vulnerability of 161 kV equipment, and this earthquake has now demonstrated the vulnerability of some 138 kV equipment. It also appears that some of the damaged 220 kV equipment was of the same type that has been qualified to IEEE (Institute of Electrical and Electronics Engineers, Inc.) Standard 693 (1). The ground motions that caused the damage were most likely less than 0.5 g, so the equipment did not survive a moderate earthquake as defined in the IEEE Standard.

Other Lifelines: The only airport known to have been affected by the earthquake was in Arequipa. The only damage reported was the loss of two control-tower windows. This type of damage has been common in U.S. earthquakes. The airport did not close as a result of the damage, and the effects on operations were probably minimal, as there are relatively few operations (takeoffs and landings) relative to airport capacity.

Communications between Lima and Arequipa were disrupted due to damage to microwave transmission towers and break(s) in the land-based optical-fiber cable that links the two cities. The reported failure of this cable most likely was associated with a damaged bridge used to carry the cable over a river and dry wash, or with slumping of the shoulder of the road that contained the buried cable. The reported failure of the submarine cable disrupting communications with Chile would be consistent with the design and location of the cable of the Pan-American Cable System. The damage to communication systems could not be confirmed.

There is no natural gas system in southern Peru. Gasoline and liquid fuels are transported by truck. Deliveries suffered minor delays due to highway damage. The port facilities in southern Peru are relatively small in comparison to the main port near Lima. There was no report or major damage to the ports, tank farms, or support facilities.

Health Impacts of the Earthquake

Kimberley Shoaf, UCLA Center Public Health and Disaster Relief. A team of five social scientists from a variety of disciplines traveled to southern Peru in September with support from EERI's Learning from Earthquakes Program.

The earthquake had profound effects on the population in four departments: Arequipa, Ayacucho, Moquegua, and Tacna. The impacts include a small number of fatalities, with a larger number of injuries and persons whose homes were damaged or destroyed. In addition, the health care infrastructure in southern Peru was severely damaged.

Injuries and Deaths: Seventy-seven people died as a result of the earthquake, with an additional 68 people missing and presumed dead. The majority of both the fatalities and missing persons are from the Province of Camana in the Department of Arequipa, where the tsunami hit. The low overall death total is attributed by both officials and the population to the fact that the earthquake occurred on a Saturday afternoon when most people were awake and either at home or out in the streets and parks. Given the large amount of damage to schools, most felt that they were lucky the earthquake did not occur when children were in school.

The deaths from the tsunami are tragic reminders of the need for education and tsunami warning systems. In spite of the fact that a large tsunami hit the same region in 1868, local officials claimed that there were no plans or education in place for tsunamis, because none was ever expected in southern Peru. In contrast, Lima and Callao have both educational plans and a tsunami warning system in place. While officials state that they did not believe that the area was vulnerable to tsunamis, the local population had heard of previous tsunamis; it is a part of local legend that the elderly talk about.

Health Care System: Hospitals and health centers were damaged in the earthquake. While some of the damage was structural, a great deal of nonstructural and functional damage created problems in providing health care to the affected population. Five hospitals in the region were damaged to some extent. The adobe hospital in the community of Aplao in the Province of Castilla was significantly damaged and completely out of operation. Unfortunately, it is the only hospital providing service to the provinces of Castilla, Condesuyos, and Caylloma. Travel from these provinces to Arequipa for health care takes as long as 15 hours. Plans are currently being studied to replace the hospital in Aplao with a seismically resistant one, and to establish one or two other hospitals in these isolated provinces. In all, 169 health care centers (hospitals and health centers) were damaged or destroyed in the four departments.

Not only were health care buildings damaged and closed by the earthquake, but health care personnel were affected as well. It was estimated that approximately half of the health care personnel in Moquegua were victims of the earthquake. Similar numbers of affected personnel are expected in the other four departments.

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