Report on the Damage Investigation of the 2001 Atico Earthquake in Peru

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Chapter 1. Outline of the Investigation

1-1. Background and purpose of the investigation

At 3:33 pm local time in Peru on June 23, 2001, (June 24, 5:33 am Japan time), a earthquake of magnitude 7.9 occurred near the coast of southern Peru, the epicentral region. This earthquake caused serious damage, with 102 killed, 1,368 injured, and 11,043 houses destroyed in the vicinity of the provinces of Arequipa, Moquegua and Tacna (Figures as of June 26, 2001).

Epicenter (http / / www.disasterrelief.org / Disasters / 010626peruquake2 /)

On June 28, Japan delivered relief goods comprising 40 tents and 2000 blankets (specifically for cold districts) to the severely damaged area to meet the immediate needs of the victims, followed on July 3 by emergency grants-in-aid totaling US$500,000. The Japanese government also offered other countries' aid agencies bailout funds and relief goods. Many Japan-based and overseas NGOs were directly involved in providing on-site assistance.

1-2. Hypocenter determined by the U S Geological Survey

Date & Time:	JUN 23, 2001, 20:33:14.1
Region:	Near Coast of Peru
Epicenter:	16.265 S, 73.641 W
Depth:	33 km (fixed)
Magnitude:	Ms 8.2, Mw 8.3, Mw 8.4 (Harvard)

Chapter 2 A Site Investigation of the Earthquake-Damaged Region

2-1 Damage in the province of Arequipa

2-1-1 Outline

The province of Arequipa, located in the southern part of Peru, has a population of slightly over 1,000,000, of which 800,000 are concentrated in the capital, Arequipa City. Arequipa City is located at an elevation of 2,300 m at the foot of Mt. Misti, which produces a great deal of volcanic ash. In Arequipa City, the stricken population reached 790,000. Of the 160,000 dwellings in the city, 1,600 dwellings were seriously damaged or collapsed, and 5,300 dwellings sustained minor damage. Sillar (white volcanic rock) dwellings were extensively damaged, and brick dwellings suffered minor damage. The suburbs of the city also sustained more serious damage than the central part. Socabaya District, a new residential area, sustained damage caused by liquefaction.

2-1-2 Jorge Basadre Elementary School

This school, located in the southern part of Arequipa City, suffered damage to its building, which was constructed in 1975 and consists of a one-storied reinforced concrete building 3 m in height. It is 7 spans in the longitudinal direction; the brick spandrel walls are about 2 m high and columns (25 cm x 35 cm, 30 cm x 45 cm) have limited effective height. In the span direction there are 1-span brick walls acting as separators, located at every other vertical plane in the structure. Major damage was observed in between the beam-column joints and the column capitals in the longitudinal direction as well as in the span direction. This building escaped total collapse due to its being light and only one-storied. Insufficient shear reinforcement and structural management of brick walls are considered problematic. There appears to be no problem with the materials or construction.

Picture 2.1.2-1. Appearance of schoolhouse. One-storied, brick spandrel wall.

Picture 2.1.2-2. Separation wall in span direction. Damaged capital and beam-column joints. Shear in upper part of brick separation wall.

Picture 2.1.2-3. Shear failure of column. Shortened column due to high spandrel wall. Shear reinforcement intervals of 30 cm.

Picture 2.1.2-4. Damaged beam-column joint. Supported with wood.

2-1-3 Liquefaction area in the ** District

Digging to a depth of 1 m creates a stream, since the water table is only 80-100 cm below the soil surface. This district has the lowest elevation in Arequipa, and is close to a river. Several active volcanoes, including Mt. Misti, are near this area, where granite is quarried. Dwellings leaned towards the river due to outflow of soil following liquefaction.

Picture 2-1-3-1. Elevated manhole due to liquefaction.

Picture 2-1-3-2. Full view of a building affected by liquefaction.

Picture 2-1-3-3. Separated boundary due to the inclination of the building caused by liquefaction.

Figure 2-1-3-4. Large cracks in the walls and floors caused by inclination of the building.

2-1-4 Goyenecye Hospital

This hospital is located in the central area of Arequipa City. This is a one-storied sillar building. Story height is 5-6 m. Wall thickness is about 80 cm. Major damage includes collapse of walls at the corners of the building, damage to joints of upper openings in the longitudinal direction, and damage to parts where buildings are adjacent to each other. A beam in the span direction was added to the roof after the hospital was damaged by an earthquake in 1960.
Another newly constructed sillar building within the same lot was intact.

Picture 2-1-4-1. Appearance of the building. Masonry, unique window shape. Beam added to the roof.

Picture 2-1-4-2. Walls with damaged corners.

Picture 2-1-4-3. Damaged upper opening. Damaged part where buildings are adjacent and at right angles to each other.

Picture 2-1-4-4. New masonry building.

2-1-5 San Augustin Hunter District Elementary School

Two schoolhouses were constructed in 1993 and 1995, respectively. The one constructed in 1993 is three-storied and RC-framed. The other is one-storied and RC-framed. The latter was intact but the former suffered slight damage. Although hollow bricks were used for nonstructural walls and spandrel walls in the former schoolhouse, they had collapsed out-of-plane because no reinforcement was provided within the walls. In both buildings, there were 3 cm wide slits around nonstructural walls revealing the insulating foam inside. The columns were intact.

Picture 2-1-5-1. Full view of the building constructed in 1995. It was intact.

Picture 2-1-5-2. Full view of the schoolhouse constructed in 1993.

Picture 2-1-5-3. On the near right, the hollow brick walls of the second and third floors can be seen to have collapsed.

Picture 2-1-5-4. Slit (black part) between the wall and the structural column.

Picture 2-1-5-5. Partial damage to nonstructural walls.

Picture 2-1-5-6. Classes are now being held in a temporary school building constructed on the playground.

2-1-6 Bridge to Centro

This masonry bridge crosses the river, which runs past the Centro (the central part of the old town) in Arequipa City. Displaced stone blocks used for the balustrade, ripples in the road surface, and cracks on the surface indicating extension in the crosswise direction can be seen. A loosened joint in the upper arch can also be observed. The lowermost foundation part of the bridge was intact.

Picture 2-1-6-1. A bridge near Centro. Masonry arched bridge.

Picture2-1-6-2. Damaged balustrade. Outwardly-displaced balustrade. Road surface showing ripples.

Picture 2-1-6-1. Loosened arch. Loosening between the surface of the arch and other stone masonry was observed.

Picture 2-1-6-2. Crack in arch. Crack on the surface of the arch. Some masonry blocks were cracked and displaced.

2-1-7 Cathedral

This cathedral, built of sillar blocks, is located at the front of Plaza de Armas. After the earthquake, one of the two towers collapsed and another closely escaped collapse. Loosening of the decorative arch due to the earthquake was also observed. This cathedral had been repeatedly hit by previous earthquakes and was repaired every time. The tower which escaped collapse was internally reinforced with steel beams after collapsing in past earthquakes. Repairs have been initiated with the aid of the Spanish Government. There was a "Danger" sign placed by INDECI (National Institute for Civil Defense).

Picture 2-1-7-1. Full view of the Cathedral. The left tower has collapsed. The right-hand tower, which just escaped collapse, under repair at the time, was reinforced with scaffolding.

Picture 2-1-7-2. Tower under repair.

Picture 2-1-7-3. Partially collapsed tower.

Picture 2-1-7-4. Decorative arches on both sides at the front and loosened due to the earthquake, under repair.

Picture 2-1-7-5. 'Danger' sign placed by INDECI.

2-1-8 Old store with sleeping quarters near the Centro

This three-storied building is located on the edge of the Centro (central old town) in Arequipa City. The third floor of this building, which faces the road leading to the high bridge, is a store. The second floor faces the road that passed under the bridge. The building was constructed of a more or less random mix of sillar blocks and bricks. This building, called a "Tambo", was an inn for merchants. The building was old and

there is a plan to redevelop it.
The roof of the top floor and the roof arch between buildings fell to the ground. There were many cracks, probably due to the earthquake, and loosening of joints.

Picture 2-1-8-1. Damage to the top floor. The third floor, facing the road Falling roof eaves.

Picture 2-1-8-2. Appearance of the first and second floors. Masonry and brick. Limited damage due to the earthquake but the building is structurally impaired.

Picture 2-1-8-3. Structure of the top floor roof. Steel rail and sillar roof.

Picture 2-1-8-4. Falling roof arch. Out-of-plane deformation of masonry wall with falling arch.

2-1-9 Fundo el Fierro Arequipa

This used to be a luxurious residence, but was rebuilt as a shopping center after being damaged in the 1960 earthquake. Before reconstruction, it had two stories (basement level plus one floor). After the 1960 earthquake, the basement was filled in and the first floor rebuilt into a shopping center. Reconstruction was conducted with the technical cooperation of SENCICO (National Service for Trading to the Construction Industry). Only sillar blocks were used for reconstruction and the original structure was not changed. This building was intact after the earthquake.

Picture 2-1-9-1. Full view of the one-storied shopping center.

Picture2-1-9-2. Sillar blocks were used as structural elements.

2-2 Damage in the province of Moquegua

2-2-1 Outlines

The province of Moquegua, which is located in the southeast part of the province of Arequipa, has a population of nearly 150,000. About 67,000 live in Moquegua City. The province is located at an elevation of 1,400 m and has a mild climate. In Moquegua City, the stricken population reached nearly 30,000. Of the approximately 17,000 dwellings, 4,300 dwellings suffered serious damage, including collapse, and 3,000 sustained slight damage. Adobe and sillar dwellings were extensively damaged; brick dwellings suffered minor damage. The seriously affected San Francisco District is located on the top of a hill. Adobe dwellings, occupied by low-income people, collapsed and some were killed by this earthquake. There is a plan to move the residents in this District to the Pampa de Chanchan District in the suburbs. Liquefaction was observed in Socabaya District.

2-2-2 Side wall of the river

The revetments of the river running through Moquegua City moved toward the river. It was difficult to ascertain from a distance; however, it can be assumed from the state of deformation that the revetment was constructed using gabions.

Picture 2-2-2-1. Deformation of the revetments.

Picture 2-2-2-2. Deformation of the revetments.

2-2-3 Simon Bolivar Elementary School

This school was established in 1711, and the schoolhouse was constructed in 1968. A collection of books from the National Library was transferred to this school library.

I) A two-storied building

A two-storied building with a 6 x 1 span, with a structure in which brick walls are inserted into RC frames. The span in the longitudinal direction is 6 m, the span direction has a length of 3 m, and the story height is about 3.5 m. Columns on the first floor were shortened because they were limited in height by the nonstructural wall (brick; 2 m in height). Shear failure and bond splitting were observed in these short columns. The space between hoops was a very wide 25 cm.

Picture 2-2-3-1. Full view of the schoolhouse.

Picture 2-2-3-2. Damaged short column.

Picture 2-2-3-3. Short column. Wide space between lateral reinforcing bars.

II) A two-storied building

This two-storied building with 4 x 3 span has a structure of brick walls inserted into RC frames on the first floor and concrete blocks on the second floor. The story height is about 3.5 m. An engineer designed the first floor, and the second floor was homemade. Only the second floor suffered damage from the earthquake: there were shear cracks on the wall in the span direction, and the roof supports collapsed.

Picture 2-2-3-4. Full view of the building.

Picture 2-2-3-5. Some of the roof supports collapsed.

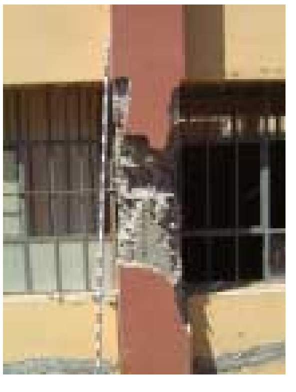
Picture 2-2-3-6. Damaged wall in the span direction.

2-2-4 Moquegua Private College

I) A three-storied building

Constructed in 1995 with a 7 x 2 span. Its stretcher has an anomalous span length. Most columns in the northern part of the first floor show shear failure. The ground had been dug up to inspect the foundations.

Picture 2-2-4-1. Appearance of the building.



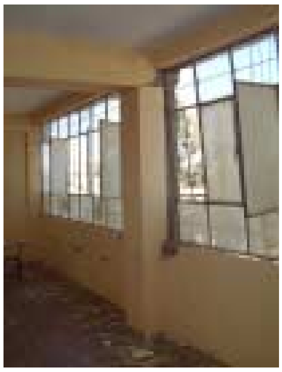
Picture 2-2-4-2. Damaged column.

Picture 2-2-4-3. Soil investigation.

II) A four-storied building

Hollow brick walls are infilled into RC frames. The building was constructed in 1991 with a 9 x 1 span. Two spans to the north side had separated with expansion joint. It was thought that this separation resulted due to the rigidity of the staircase. There was also a plan for the building to be extended upward. All partition walls consisted of bricks. Shear failures were observed over doors on partition walls and in decorative beams in corridor walls. There was a window in the upper part.

Picture 2-2-4-4. Brick wall of the staircase.



Picture 2-2-4-5. Damaged long column.

Picture 2-2-4-6. Damaged short column.

Picture 2-2-4-7. Bar arrangement of the extended part.

2-2-5 Adobe houses in the Centro District

In the Centro District, the damage rate of adobe buildings was no higher than that in the San Francisco District. The damaged adobe houses were studded. There is no standard for adobe blocks; most were about 40-80 cm in size. Adobe walls are occasionally built two layers thick. INC (Peru's National Institute of Culture) has been conducting measurements of crack width in affected buildings for potential widening. The walls of affected adobe walls collapsed mostly out-of-plane. Safety measures, such as the hooping of entire buildings, are required.

Picture 2-2-5-1. Street scene in Centro.

Picture 2-2-5-2. An adobe house saved from damage.

The collapsed house nearby was removed. The shape of the roof is called moginete-style. Bamboo-like lumber is used.

Picture 2-2-5-3. A wall likely to fall out-of-plane. The space widened to this extent in the week after the earthquake.

Picture 2-2-5-4. Unit length of an adobe block.

Picture 2-2-5-5. Equipment for measuring increases in crack width, installed by INC.

2-2-6 Anterior wall of Plaza de Armas

This is the façade of a building constructed in 1792. It also suffered damage from the earthquake of 1868, in which the back surface of the wall was removed. Damage from this earthquake was not too serious: some of the sillar blocks in upper wall toppled. However, a bench is still in place beneath the part where some sillar blocks fell, and people still sit on the bench. This is extremely dangerous because of the risk of more falling objects. We informed INC of this.

Picture 2-2-6-1. Full view of the wall.

Picture 2-2-6-2. Damage from the earthquake in 1868. The back surface of the wall detached.

Picture 2-2-6-3. Falling upper wall.

Picture 2-2-6-4. Displaced upper wall.

2-2-7 San Francisco District

Approximately 80% of the buildings in this area are made of adobe, and most suffered some degree of damage. This district contains a ravine. Houses on the sloping areas suffered more damage than on the bottom, probably due to soil amplification. The construction of dwellings had started from the upper slopes and was extending to the bottom. No major damage was observed in non-adobe buildings. The inhabitants of buildings on this sloping area will be relocated to the Pampa de Chanchan District, which, although known to be comprised of soft bentonite, is the only available district to which people can be moved since the other potential site for relocation, the San Antonio District, is already overcrowded. The Peru-Japan Center for Seismic Research and Disaster Mitigation (CISMID) conducted a geological survey of the Pampa de Chanchan and advised that adobe buildings should be limited to one story.

Picture 2-2-7-1. San Francisco District. It appears to be ravine.

Picture 2-2-7-2. The size of adobe blocks used. The adobe walls are thinner than those used in the Centro District.

Picture 2-2-7-3. Damaged adobe building. Walls collapsed.

Picture 2-2-7-4. Greater damage seen in sloping areas. Less damaged non-adobe buildings (two or more storied). The blue buildings are temporary dwellings.

2-2-8 The Pampa de Chanchan District

It is planned to move the population from the seriously damaged San Francisco District to the Pampa de Chanchan district. However, its expandable clay soil is now under survey and measures are being discussed. Problematic illegal occupancy has already occurred. Some people have already obtained homes in other districts and rent illegally occupied dwellings to others. Roads to the center of the city are under construction in the area.

Picture 2-2-8-1. Watercourse and illegal occupancy.

Picture 2-2-8-2. Illegal occupancy.

2-2-9 A column holding a sunshade at the poolside of the El Mirador Hotel

Flexural failure of a column holding a sunshade at the poolside of the hotel occurred at its base. Two columns had supported a roof slab. One column carried only a roof frame and the other carried a roof slab; the latter column base suffered flexural shear failure. The reinforcement bars, which were jointed at the terminal hinge region, had buckled.

Picture 2-2-9-1. Full view.

Picture 2-2-9-2. A column supporting a roof slab. Flexural shear failure at column base.

Picture 2-2-9-3. The other column is intact. Flexural cracks are observed in the beam.

Picture 2-2-9-4. Column base. Reinforcements are jointed at the terminal (right terminal).

Picture 2-2-9-5. Column base. Buckled main reinforcement.

2-3 Damage in the province of Tacna

2-3-1 Outline

The province of Tacna is located in the southernmost part of Peru, adjacent to Chile and Bolivia, and has a population of nearly 280,000. Of these, nearly 250,000 people are concentrated in Tacna City. In Tacna City, the stricken population reached 190,000. Of the 55,000 dwellings, 3,700 dwellings sustained serious damage, including collapse, and 14,000 dwellings suffered slight damage. In the city, some adobe buildings collapsed. In the Ciudar Nueva District, a new residential area, the town hall, which is a reinforced concrete building, suffered serious damage including shear failure of columns.

2-3-2 SENCICO Tacna Branch Office

The steel and R/C frames supporting the roof of the SENCICO workshop suffered damage. These frames became deformed out-of-plane together with the frame in the span direction, which exerts a tensile force on the steel frame, resulting probably in removal of the steel frame at the joint with the concrete member.

Picture 2-3-2-1. Gable of workshop. Damage at the connection of the steel frame spanning the right non-level part.

Picture 2-3-2-1. Damaged connection of steel frame with concrete member.

2-3-3 Ward office (Ciudar Nueva)

This building, which used to be a ward office and was scheduled to be used as a disaster refuge, suffered damage from the earthquake. It consists of a first floor with concrete block walls infilled into RC frames and a second floor with hollow brick walls infilled into RC frames. Construction engineers were not involved in planning or design. The longitudinal direction comprises 4 spans, and the span direction has 3 spans. The column size is 55 cm x 35cm, 6-D18, and Ø8@200 at the core. Some columns had no lateral reinforcing bars. There are no beams in the span direction. Damage was limited to the first floor. In particular, the posterior columns of the building, which were short due to the high spandrel wall that occupied and limited the space available for columns, showed occurrence of shear failure.

Picture 2-2-3-1. Appearance of the building. The parapet on the rooftop toppled.

Picture 2-2-3-2. Damaged CB wall and column.

Picture 2-2-3-3. Shear crack in the wall. First floor: concrete block wall. Second floor: brick wall.

Picture 2-2-3-4. Shear failure of the short column. No lateral reinforcing bar.

2-3-4 Colegio Nacional Mariscal Caceres

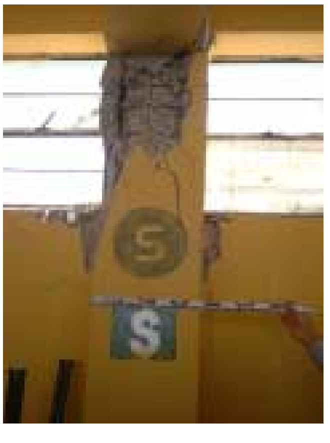
This is a two-storied schoolhouse with an 8 x 1 span, constructed in 1994. In the longitudinal direction, which extends to the northeast, it has a span of 4 m, a length of 5 m in the span direction, and a story height of about 3 m. Deformed bars were also used as lateral reinforcing bars; the size of columns was 45 cm x 36 cm, width at the core measured about 20 cm, and the thickness of covering concrete was about 7.5 cm. There is a wall in the span direction every other span. Structural calculations may have been performed for the walls; however, different diameters of reinforcement bars of columns and different types of reinforcing

hoops were used (round steel for parts where nonstructural walls were attached, and deformed bars for parts without nonstructural walls). Concrete blocks were used for the walls.
A two-storied schoolhouse at the same site and facing in the same direction, which was constructed with assistance from Japan in 1990, suffered slight damage, including a shear crack in one column.

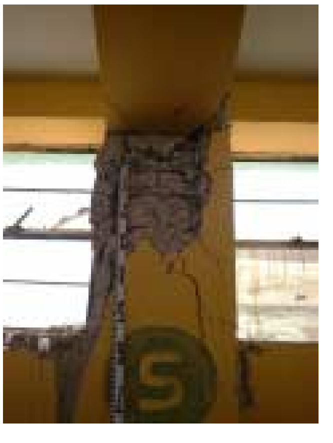
Picture 2-3-4-1. Full view of schoolhouse.

Picture 2-3-4-2. Shear failure of the column on the corridor side resulting from shortened columns due to limited vertical space, occupied by the spandrel wall.

Picture 2-3-4-3. The length of the compressed column was about 145 cm.



Picture 2-3-4-4. Shear failure of the column on the window side about 35 cm in width.



Picture 2-3-4-5. The space between the lateral reinforcing bars of the shortened column measured about 12 cm.

Picture 2-3-4-6. Most columns on the window side of the first floor show shear failure due to their shortness.

Picture 2-3-4-7. The outside of column on the window side. This column has few lateral reinforcing bars.

Picture 2-3-4-8. A two-storied schoolhouse (1990) Constructed with assistance from Japan.

Picture 2-3-4-9. Damaged column. A shear crack was observed in one column.

Picture 2-3-4-10. Classes are now being conducted in a temporary structure.

2-3-5 Residential area

This residential area is located in the bottom of a landfilled valley. A three-storied building suffered serious damage. Building workmanship was questionable because not all columns were vertical and there are some honeycombs. Reinforcements were not attached to the walls of the staircase, and these walls collapsed.

Some brick buildings were under repair work.

Picture 2-3-5-1. Damaged three-storied building.

Picture 2-3-5-2. Damaged wall of stairhall
The wall of the stairhall on the third floor collapsed.

Picture 2-3-5-3. Concrete blocks.

Picture 2-3-5-4. Repair work nearby.

2-3-6 Hipolito Unanue Hospital

This is a national hospital with 5 floors and 1 basement level, constructed around 1950. Its structure features an R/C frame with CB wall and several brick walls. It sustained minor damage, including slight cracks in nonstructural walls. After the earthquake, both public water supply and sewerage broke down, and the gas supply facility was seriously damaged. The steam machine (used by the hospital for disinfection) was also damaged and needed to be replaced, but the entire set of equipment, including buried piping, should in fact be replaced. Normally, groundwater is pumped into an elevated water tank, but the pump did not work after the earthquake. Even now, only outpatients and emergency patients are accepted, and the number of hospital beds is very limited. The structure of the building itself is intact, but hard putty was used in the window frames, which increases the risk of shattering glass during the next earthquake.

Picture 2-3-6-1. Full view of the building.

Picture 2-3-6-2. Cracks between nonstructural walls and structural member Crack (stairhall).

Picture 2-3-6-3. Broken window. Hard putty was used.

2-3-7 Jorge Basadre Grohmann National University

Jorge Basadre Grohmann National University is home to 8,000 students in 14 faculties including 30 departments. The damaged FACF building was constructed in 1996. There are flexural shear cracks at the column bases in the southwest corner and shear cracks at the joints between the upper and lower terminals on the first floor. The inner pillars on the first floor have flexural cracks at the upper and lower ends.
A seismometer was supplied by JICA and installed by CISMID.

Picture 2-3-7-1. Damaged wall and beam-column joints.

Picture 2-3-7-2. Damaged capital.

Picture 2-3-7-3. Damaged wall. Emergency support.

Picture 2-3-7-4. The seismometer.