Damage Assessment of Historic Earthen Buildings After the August 15, 2007 Pisco, Peru Earthquake

Research Report

Claudia Cancino

In collaboration with Stephen Farneth, Philippe Garnier, Julio Vargas Neumann, and Frederick Webster

Los Angeles 2009

The Getty Conservation Institute

Damage Assessment of Historic Earthen Buildings After the August 15, 2007 Pisco, Peru Earthquake

By Claudia Cancino
In collaboration with Stephen Farneth, Philippe Garnier, Julio Vargas Neumann, and Frederick Webster

THE GETTY CONSERVATION INSTITUTE
LOS ANGELES

The Getty Conservation Institute
1200 Getty Center Drive, Suite 700
Los Angeles, CA 90049-1684 United States
Telephone 310 440-7325
Fax 310 440-7702
E-mail gciweb@getty.edu
www.getty.edu/conservation

The Getty Conservation Institute (GCI) works internationally to advance conservation practice in the visual arts—broadly interpreted to include objects, collections, architecture, and sites. The GCI serves the conservation community through scientific research, education and training, model field projects, and the dissemination of the results of both its own work and the work of others in the field. In all its endeavors, the GCI focuses on the creation and delivery of knowledge that will benefit the professionals and organizations responsible for the conservation of the world's cultural heritage.

Contents

CHAPTER 1

Background Information

Introduction

The Pisco earthquake of August 17, 2007, resulted in 519 deaths and 1366 injured, with a total of 650,000 people affected and 80,000 dwellings damaged.[1] Some of those tragic losses resulted from the collapse of vernacular and monumental buildings, made of different materials and construction techniques, in the states of Ica, Lima, Huancavelica, Ayacucho, and Junín, among others.[2] Immediately after the earthquake, several national and international organizations, as well as academic institutions with expertise in developing rapid assessments of earthquake damage, traveled to the region to prepare preliminary reports on the conditions of the buildings and structures hit by the earthquake. Some of those reports described damage to structures built of earth.[3]

The existence of earthen architecture in Peru goes back to the *formativo temprano* or initial period (1800/1500–900 bce). This construction technique has been used throughout the country for almost four thousand years and has proven to be a sustainable resource for the evolution of Peruvian culture. Historic earthen buildings, structures, and settlements are a sign that the society which created them was advanced enough to design suitable construction techniques and properly maintain them through time.[4] In response to their understanding of the effects of seismic activity on earthen structures, early Peruvian cultures wisely chose to build their sites over stable soils and developed reinforced construction techniques to dissipate the energy generated by seismic events.[5]

Post-earthquake assessments offer an opportunity to understand why buildings fail and provide information that can serve as the basis for the improvement of seismic performance. For centuries, lessons learned from earthquakes and other natural disasters have been used to advance construction techniques and more recently, such lessons have fostered the development of the engineering and historic preservation disciplines, as well as the testing and review of current building codes and disaster management policies and procedures.

The history of Peruvian architecture exemplifies this process. Buildings made of earth were constructed by earlier civilizations, such as those at Caral, using mudbrick (adobe), mud mortar, and wattle and daub (*quincha*).[6] The knowledge acquired by those earlier earthen builders was probably later disseminated to other regions of the continent, and magnificent earthen structures and urban complexes such as Huaca del Sol y de la Luna (100–800 ce), Chan-Chan (850–1476 ce), and Tambo Colorado (1476–1534 ce) were constructed along the coast of Peru. During the Spanish period (1534–1821 ce), monumental churches and urban houses were originally constructed by importing construction techniques from Spain. However, after very significant earthquakes in 1586, 1687, 1746, and others, materials were changed and techniques were modified.[7] Using the original construction techniques developed by the Incas and earlier Peruvian cultures, the Spaniards started building with quincha, adobe, and rammed earth (known as *tapial*) around Peru and other areas within the Spanish viceroyalty. Major cathedrals, government palaces, estates (*haciendas)*, and urban residences (*casonas*) were built of earthen materials, many of which are still standing in Peru, Chile, Ecuador, Argentina, Colombia, and other Latin American countries. During the viceroyalty period, simple reinforcement techniques such as buttresses were used in order to better withstand earthquake forces and avoid out-of-plane movements and overturning of massive adobe walls. After Peruvian independence in 1821, earth continued to be the predominant build-ing material throughout the country. Unfortunately, earthquake damage and the introduction of reinforced concrete at the end of the nineteenth century encouraged developers, building officials, engineers, and architects to substitute new materials for earth and the tradition was lost, at least in major cities.[8] At that time, the Peruvian government nearly banned the use of mud-brick, rammed earth, or wattle and daub throughout the country.

After the May 31, 1970, Moment Magnitude (M_W) 8.1 earthquake, with an epicenter located near the coast of central Peru, research and investigation to improve seismic performance of earthen buildings commenced in Peru.[9] This initiative was largely driven by universities and academic institutions as a reaction to the elimination of earthen construction as part of the Peruvian Building Code. Since then, a series of recommendations to reduce the seismic vulnerability of mostly new adobe buildings have been published by the Ministerio de Transportes y Comunicaciones and included in the Peruvian Building Code. The *Norma Técnica de Edificación NTE E. 080 Adobe* (*Technical Standard 80 for Construction in Adobe*) became the model for other countries facing the same challenge of regulating seismically resistant new earthen construction.

However, contradictory opinions exist about the ability of Peruvian earthen buildings to withstand large earthquakes. Some believe that earthen buildings are weak and incapable of withstanding earthquakes under any circumstance, while others underestimate the destructive potential of earthquakes because many buildings have successfully stood for centuries. While earthen buildings in general are vulnerable to seismic events, a great number of them in Peru have survived major seismic events. Post-earthquake assessments of historic earthen buildings further an understanding of their seismic performance, including the potential effects of traditional retrofit measures and/or proper maintenance.

A prerequisite for the development of retrofitting guidelines is a good understanding of the structural behavior of the subject site; where it is necessary to intervene and where it is not. Seismic activity presents an opportunity to assess and investigate affected buildings, to document the level of destruction, and to gain preliminary understanding of how historical buildings perform during an earthquake. The Pisco earthquake of August 15, 2007, was the result of stress released by the Nazca plate against the South American continental plate.[10] It had a M_W of 7.9–8.0 (United States Geological Services–USGS, Harvard University-CMT Catalogue); a maximum local Modified Mercalli Intensity (MMI) of VII-VIII (Instituto Geográfico del Perú – IGP, Geophysical Institute of Peru); and its epicenter was located at S 13.35 and W 79.51 at a depth of 39 km (USGS). Preliminary reports indicated that significant earthen sites were damaged by the earthquake. A rapid assessment of some of the buildings was commissioned by the Getty Conservation Institute (GCI)'s Earthen Architecture Initiative (EAI) to better understand their failure. The main objective of the survey, the subject of this report, was to understand seismic damage including external factors affecting the seismic performance of historic earthen structures and to aid in the design of retrofitting techniques in order to preserve the outstanding earthen architecture in Latin America.

Institutional Background

For many years, the GCI has taken a leading role in setting the standards and establishing appropriate methodologies for the conservation of earthen sites. The GCI's strong commitment to preserving earthen architectural heritage has generated training programs, research, and field projects worldwide that have deepened the understanding of earthen architecture and its particular vulnerabilities. Research and laboratory testing was carried out in the 1990s under the Getty Seismic Adobe Project (GSAP, 1992–2002), a multidisciplinary research effort that designed, tested, and advocated less-invasive, stability-based retrofit programs for historic adobe buildings in California.

In recent years, destructive earthquakes in regions with significant earthen architectural heritage—particularly the earthquakes in Bam, Iran (2003), Al-Hoceima, Morocco (2004), Kashmir, Pakistan (2005), and Pisco, Peru (2007)—focused renewed attention on the inherent weakness and subsequent collapse of unreinforced earthen structures during seismic events. The GCI took particular interest in the impact of these events on earthen sites as it sought to understand why research work undertaken here and elsewhere was not being widely implemented in order to safeguard earthen sites located in seismic zones. To address the latter, the GCI organized the Getty Seismic Adobe Project Colloquium in April 2006 at the Getty Center in Los Angeles, California. The meeting brought together a group of professionals with expertise in earthen conservation, building standards, and earthquake engineering to discuss the current state of knowledge and the challenges of preserving our earthen cultural heritage in active seismic zones. The colloquium was primarily an opportunity to evaluate the impact that the GSAP research and guidelines have had on the field locally and internationally and to discuss the feasibility of implementing the GSAP guidelines in other contexts. It also allowed the exchange of information and prioritization of future work in the field of retrofitting of historic earthen sites.

The work developed by GSAP is documented in three GCI publications: *Survey of Damage to Historic Adobe Buildings after the January 1994 Northridge Earthquake* (1996), *Seismic Stabilization of Historic Adobe Structures: Final Report of the Getty Seismic Adobe Project* (2000), and *Planning and Engineering Guidelines for the Seismic Retrofitting of Historic Adobe Structures* (2002); the final volume is also available in a Spanish-language translation. *The Proceedings of the Getty Seismic Adobe Project 2006 Colloquium* was published in 2009. All of these publications, as well as a brief video of the GSAP seismic shake-table testing program are available on the GCI's Web site.[11]

Scope of Work: Goals and Target Audience

As noted in the Northridge earthquake survey, "the challenge of improving the seismic performance of historic earthen sites is to ensure adequate life safety while protecting historic fabric and cultural value."[12] Since this statement was made in

1996, many academic institutions have pursued research that demonstrates that both life safety and the preservation of the fabric may be accomplished in tandem.[13]

From October 28 to November 2, 2007, the GCI, in collaboration with Peruvian institutions, utilized the methodology employed in the Northridge survey to conduct an assessment of historic earthen sites damaged in the August 15, 2007, Pisco earthquake. The survey was organized in response to a request for assistance received by the GCI from the Instituto Nacional de Cultura del Perú (INC, Peruvian National Institute of Culture).

Analysis of conservation problems and their causes, and decisions on appropriate solutions to preserve an earthen site needs to be carried out by a multidisciplinary team. Each of the involved disciplines—architecture, conservation, history, engineering, and planning—provides a different and complementary point of view that enriches the intervention and benefits the preservation of the site. In the Pisco survey, a multidisciplinary team of national and international earthquake engineers, preservation architects, and conservators, all with extensive experience in earthen architecture, visited a total of fourteen buildings and rapidly documented the visible and apparent damage incurred by the earthquake.[14]

The faculty members of the School of Architecture at the Universidad Peruana de Ciencias Aplicadas (UPC, Peruvian University of Applied Sciences) preselected the sites according to various criteria, such as, type, historical significance and quality of the buildings, distance to epicenter, damage, access to facilities, and available time. The selected sites were mainly cultural sites (e.g., churches and haciendas), but experts could also see the vernacular architecture in the vicinity. The survey was limited to a one-week timeframe and does not claim to be comprehensive. Rather, it provides a snapshot of the issues found at typical heritage sites as representative of the earthquake's impact.[15] This work is able to provide some insight into the performance of these types of earthen structures more widely in Latin America.

This survey aims to provide information to cultural institutions, owners, and building officials responsible for the preservation of historic earthen sites to help them understand earthquake damage to such sites and to emphasize the need to enhance seismic performance through investment in minimally invasive, locally available, and easy-to-implement technical repair and retrofitting interventions, as well as regular maintenance.

Notes

1 Johansson, et al., "A Reconnaissance Report on the Pisco, Peru Earthquake of August 15, 2007," 1.

2 Ibid.

3 A complete list of the reports consulted for the elaboration of this document is found in the bibliography.

4 This point is well explained in Williams León, *Arquitectura y Urbanismo en el Antiguo Perú*, Historia del Perú, Procesos e Instituciones, Vol 9, 382.

5 Ibid., 467.

6 Caral is the largest recorded site in the Andean region, dating earlier than 2000 bce, and appears to be the model for the urban design adopted by Andean civilizations that rose and fell over the span of four millennia. It is believed that Caral may answer questions about the origins of Andean civilizations and the development of the first cities.

7 Bromley and Barbagelata, *Evolución Urbana de la Ciudad de Lima*, 53, 69, 71, 111.

8 Cement was first imported to Peru in 1860. The early use of cement is described more fully in Chapter 3.

9 A detailed description of M_W, M_L and MMI are provided in Chapter 2.

10 Earthquake Engineering Institute (EERI), “Learning from Earthquakes: The Pisco, Peru Earthquake of August 15, 2007,” EERI Special Earthquake Report, 1, and Fernando Lázares La Rosa et al., “Análisis de Acelerogramas Sismo de Ica del 15 de Agosto del 2007,” 10.

11 Publications are available at http://www.getty.edu/conservation/publications/.

12 Tolles et al., *Survey of Damage to Historic Adobe Buildings After the January 1994 Northridge Earthquake*, 3.

13 Some of this research is documented in Hardy, Cancino, and Ostergren, *Proceedings of the Getty Seismic Adobe Project 2006 Colloquium*.

14 See Appendix for a list of participants and institutions.

15 For a list of sites visited see sidebar, pp. 43–45.

CHAPTER 2

The Pisco Earthquake

Description of the Pisco Earthquake

On August 15, 2007 at 23 h. 40 min. 57 sec. UTC (18 h. 40 min. 57 sec. local time), a M_w 7.9–8.0 earthquake occurred off the coast of central Peru.[1] The areas most affected by the earthquake were within the states of Ica, Huancavelica, and Lima. The official death toll was 519 people, with 1,366 injured. A total of 58,581 houses were destroyed or demolished as a result of the severe damage induced and 13,585 houses were affected to some degree.[2] The Peruvian government estimated US $450 million in losses as a direct cause of the event and an estimated reduction in the economic growth of 0.3% for 2007[3].

The government of Peru led the response to the earthquake through the Instituto Nacional de Defensa Civil (INDECI, Institution of National Civil Defense). INDECI was supported by the military, the national private sector, and the international community including national governments, international NGOs, and United Nations agencies. The initial response entailed searching for survivors, evacuating the injured, removing rubble, ensuring security, and meeting the needs of the affected people. A consolidated appeals process (CAP) in the wake of the earthquake raised approximately US$37 million, US$9.5 million of which was provided by the Central Emergency Response Fund (CERF).[4]

The cities of Pisco (80% destroyed), Ica and Chincha in the Ica region, and San Vicente de Cañete in the Lima region, were the most heavily affected. However, the earthquake was also felt in Lima, as well as various other Peruvian cities, including Pucallpa, Iquitos, Contamaná, Trujillo, and Cajamarca.

The coast of Peru has a history of very large earthquakes. The epicenter of the August 15, 2007, earthquake was located near the epicenters of the 1908 (M_W 8.2) and 1974 (M_W 8.1) earthquakes and north of the 1942 (M_W 8.2) and the 2001 (M_W 8.4) earthquake epicenters. The largest earthquake along the coast of Peru was a M_W 9.0 earthquake that occurred in 1868, which was centered about 700 km southeast of the August 15, 2007, epicenter.[5]

Characteristics

An earthquake (also known as a tremor or temblor) is the result of a sudden release of energy in the earth's crust that creates seismic waves Earthquakes are recorded with a seismometer, also known as a seismograph. The size of the earthquake is measured by its Moment Magnitude (MMS or M_W) or its related and mostly obsolete Richter magnitude (M_L). Intensity of shaking is measured on the Modified Mercalli Intensity Scale (MMI).

At the earth's surface, earthquakes manifest themselves by shaking and sometimes displacing the ground. When a large earthquake epicenter is located offshore, the seabed sometimes suffers sufficient displacement to cause a tsunami. In its most generic sense, the word *earthquake* is used to describe any seismic event. Earthquakes are caused mostly by rupture of geological faults, but also by volcanic activity, landslides, mine blasts, and nuclear experiments. An earthquake's point of initial rupture is called its focus or hypocenter. The term *epicenter* refers to the point at ground level directly above the hypocenter.

A summary of the August 15, 2007, earthquake epicenter location and magnitudes reported by the Instituto Geofísico del Perú (IGP, Geophysical Institute of Peru) and by three other international agencies is shown in Table 2.1. The difference between M_W and M_L estimates reported by IGP may be due to saturation of the local scale, resulting in the M_L estimate being larger than 6.8.[6]

Table 2.1: Earthquake parameters

Agency	Epicenter location		Depth (Km)	Magnitude		
	Latitude S°	Longitude W°		M_W	M_S	M_L
IGP (Peru)	-13.670	-76.760	40	7.9		7.0
USGS (USA)	-13.354	-76.509	39	8.0		
HU-CMT (USA)	-13.73	-77.04	34	8.0	8.0	
ISC (www)	-13.358	-76.522	30		7.8	

Sources: Data from IGP: Instituto Geofísico del Perú (Geophysical Institute of Peru, www.igp.gob.pe/); USGS: United States Geological Survey (earthquake.usgs.gov); HU-CMT: Harvard University Centroid-Moment-Tensor Project (http://www.globalcmt.org/); ISC: International Seismological Centre (www.isc.ac.uk/).

According to the theory of plate tectonics, the surface of the earth is modeled as being made up of about a dozen large tectonic plates, which move very slowly. Because they do not all move in the same direction, plates often directly collide or move laterally along each other, a tectonic environment that makes earthquakes frequent. An *inter*plate earthquake is an earthquake that occurs at the boundary between two tectonic plates. If one plate is trying to move past the other, they will be locked until sufficient stress builds up to cause the plates to slip relative to each other. The slipping process creates an earthquake with land deformations and resulting seismic waves which travel through the earth and along the earth's surface. Some areas of the world that are particularly prone to such events include the west coasts of North and South America, the northeastern Mediterranean region (Greece, Italy, and Turkey, in particular), Iran, New Zealand, Indonesia, Japan, and parts of China.

Relatively few earthquakes occur in *intra*plate environments, most occur on faults near plate margins. By definition, intraplate earthquakes occur along faults in the normally stable interior of plates. Compared to earthquakes near plate boundaries, intraplate earthquakes are not well understood and the hazards associated with them may be difficult to quantify.

The August 15, 2007, earthquake was generated in the boundary between the Nazca and the South American plates, in which the Nazca plate slid underneath the South American plate (Figures 2.1–2.3). The plate movement or velocity of relative displacements between these plates has been estimated as 70–80 mm/yr.[7] The August 2007 interplate earthquake occurred in an identified seismic gap—based on recorded earthquakes from 1940 to 1996—along the coast of central Peru, as presented in Figure 2.4.[8]

Figure 2.5 presents the intensity map generated by the United States Geological Survey (USGS)'s ShakeMap tool after the earthquake.[9] The maximum intensities

FIGURE 2.1 (LEFT)
Satellite image showing the area of the earthquake in relationship to the world. The circle indicates the epicenter. © 2011 Google-Imagery; © 2011 TerraMetrics, NASA; Map data © 2011 Geocentre Consulting, MapLink, Tele Atlas, Whereis (R), Sensis Pty.

FIGURE 2.2 (RIGHT)
Satellite image showing the area of the earthquake within Peru. The circle indicates the epicenter. © 2011 Google-Imagery; © 2011 TerraMetrics, NASA; Map data © 2011 DMapas/El Mercurio, Europa Technologies, Google, Lead Dog Consulting, MapLink, Inav/Geosistemas SRL.

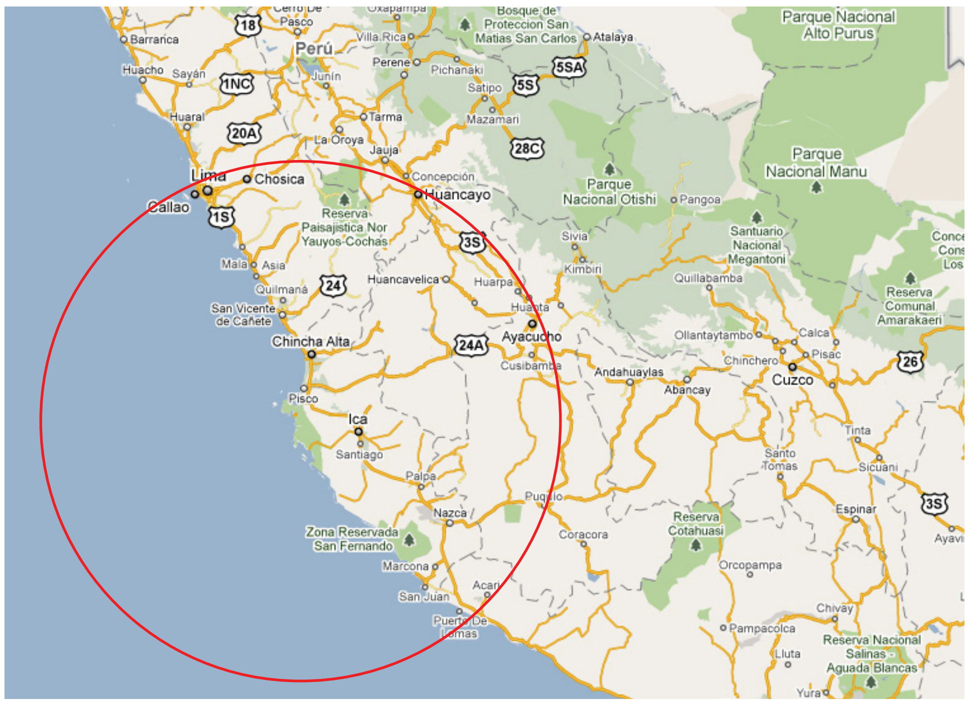


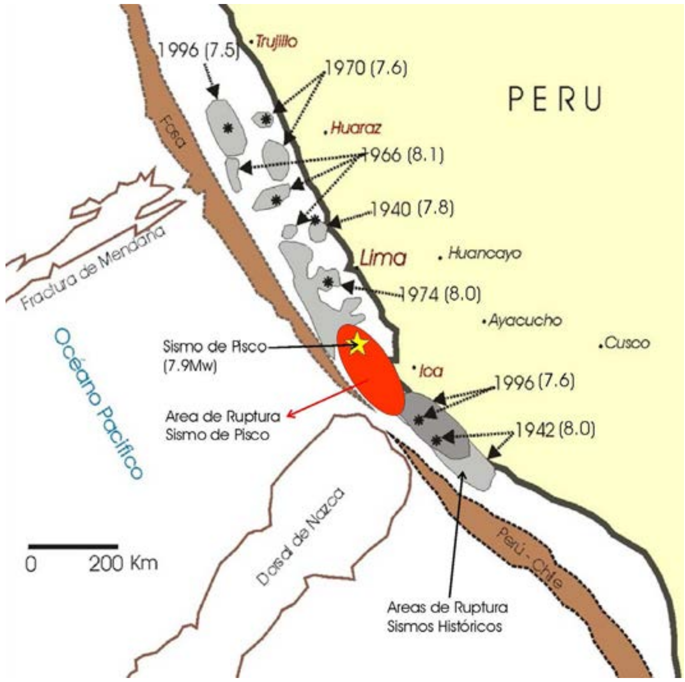
FIGURE 2.3
Map showing the region affected by the earthquake. The circle indicates the epicenter. © 2011 Google-Map data; © 2011 DMapas/El Mercurio, Google, MapLink.

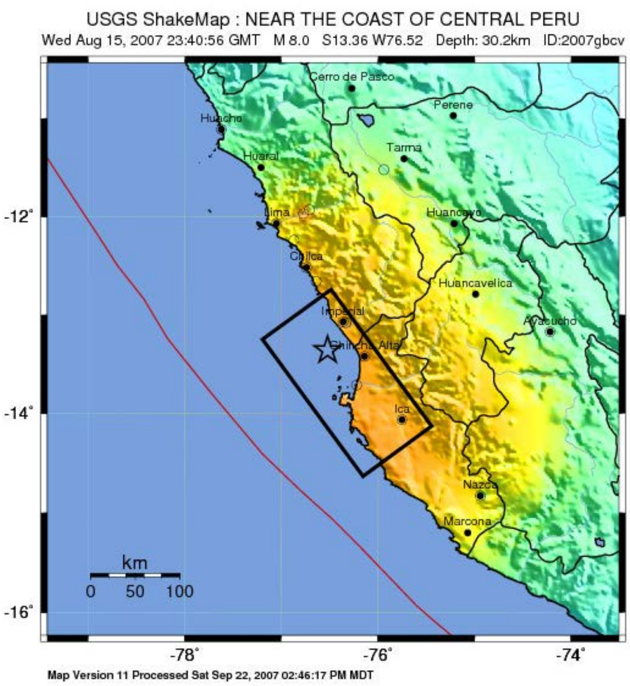
(MMI VII) were reported to have occurred between the cities of Imperial, to the north, and Ica, to the south. Even though the city of Lima was classified with intensity MMI VI, little damage was reported there. IGP reported the distribution of 355 aftershocks with local magnitudes equal to or larger than M_L 3.0, which occurred from August 15 to 20, 2007.

Seismic engineers can define length, area, depth, angle, and direction of the fault rupture or movement of plates, analyzing the data recorded by accelerometer stations through finite fault modeling. According to the location and distribution of aftershocks, IGP suggests a rupture occurring south-eastward in an area of approximately 150 × 100 km. Chen Ji and Yuehua Zeng also estimated the source of the August 15, 2007, rupture from teleseismic broadband inversion.[10] From the latter, two predominant slip areas are observed at the epicenter and at a region southeast of it (Figure 2.6).

A total of eighteen accelerometer stations recorded the main shock on August 15, 2007, with most of the instruments being located in the city of Lima and two installed in the city of Ica. Table 2.2 presents a summary of the peak ground

FIGURE 2.4
Gap and location of historical interpolate earthquakes in relation to epicenter. The yellow star is the location of the epicenter. The thick black line is the identified seismic gap.





PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
POTENTIAL DAMAGE Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
ESTIMATED INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

FIGURE 2.5
Intensity map generated using USGS ShakeMap tool. The map includes the location of the gap (red line), the rupture process area (rectangle), and the epicentral location (star) as estimated by USGS.

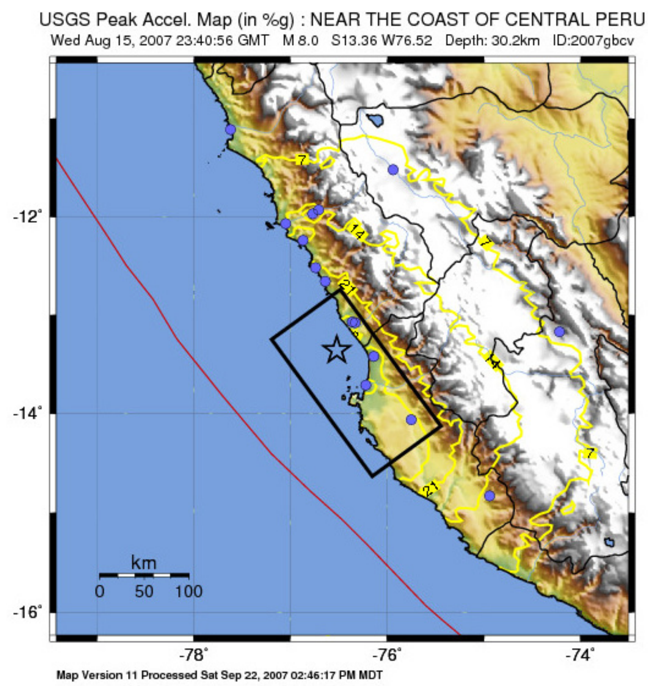


FIGURE 2.6
Peak Ground Acceleration. The red thick line indicates the plate's boundary and the star indicates the main shock's epicenter.

Table 2.2: Horizontal and vertical peak ground acceleration (PGA) values for the east-west, north-south and vertical recorded ground motions

Station	CISMID (Lima)	San Isidro (Lima)	Callao (Lima)	La Molina (Lima)	Universidad Ica (Ica)
E-W PGA (cm/s^2)	73.7	54.49	100.9	78.1	272.2
N-S PGA (cm/s^2)	59.98	57.88	58.41	18.46	334.1
Vertical PGA (cm/s^2)	32.58	32.21	31.7	56.21	192.2
Site conditions (NEHRP)	C	C	D	C	D
Site conditions $V_{s\text{-}30}$ (m/s)*	250	—	350	470	250
R_{epi} distance (km)†	159	152	159	145	117
R_{jb} distance (km)‡	103	96	105	86	0.0
R_{rup} distance (km)§	112.6	105	112	98	36.9

*$V_{s\text{-}30}$ values from Tavera et al. (2009). †R_{epi} is the epicentral distance. ‡R_{jb} is the Joyner-Boore distance definition. §R_{rup} is the closest distance to the fault rupture, from Abraham and Shedlock (1997): 14.
Source: Data from Taucer, Alarcon, and So (2008): 5.

acceleration values for each orthogonal component (east-west, north-south, and vertical) at these stations, including some relevant characteristics like site conditions and source-to-site distance computed using three different methods.

From the eighteen accelerometer stations, only four time-histories from the city of Lima and one from the city of Ica (located at approximately 150 km and 110 km from the epicenter, respectively) were available to the public by mid-November 2007, on the Web site of the Centro Peruano Japonés de Investigaciones Sísmicas y Mitigación de Desastres (CISMID, Peruvian-Japanese Center of Seismic Investigation and Hazard Reduction), part of the Universidad Nacional de Ingeniería (UNI, National University of Engineering) (Figure 2.7).

These time histories indicated the length and amplitude distribution in time of the ground motion. All recordings show total durations of approximately 300 seconds, including 160 seconds of strong amplitudes followed by relative uniform and smaller ones that last 20 to 30 seconds and a final sequence of larger motions. The principal explanation for the duration and distribution of these ground motions is the rupture model having two zones of large displacements, which generated the two packs of motions.[11]

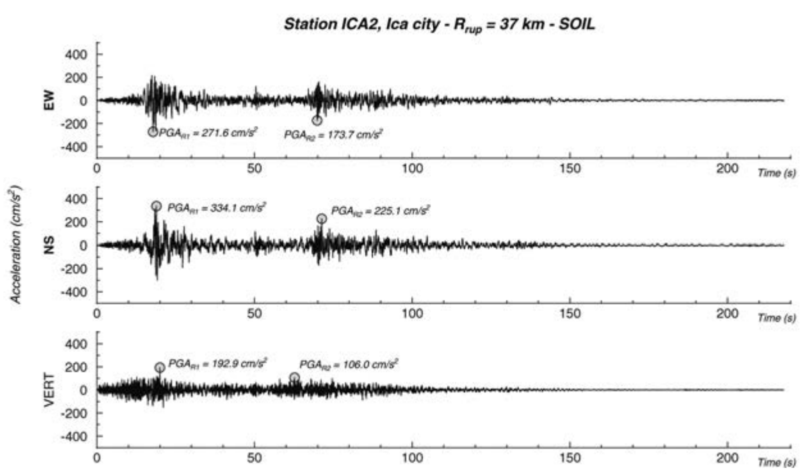


FIGURE 2.7
Strong ground motion recordings at CISMID's Ica 2 Station.

This confirmed that the M_W 7.9 August 15, 2007, Pisco earthquake had two strong ground accelerations and a south-east fault slip. These two extraordinary seismic characteristics had an impact on the performance of the built structures and may explain some of the damaged reported during the survey.

Geological Description of the Affected Region

There have been numerous studies carried out by several national and international institutions to define the geology of the affected area. In 1998, CISMID carried out detailed subsoil investigations for the cities of Pisco and Tambo de Mora.[12] In 2004, the INDECI, in collaboration with the United Nations Development Programme (UNDP), started a program called *sustainable cities*, developing risk assessments for most cities around the country. After the earthquake, INDECI, UNDP, and CISMID, in collaboration with the Fondo de Reconstrucción del Sur (FORSUR, Recovery Fund for the South) and the World Bank, expanded their original research and produced detailed hazard and risk maps of several cities in southern Peru.[13] All these studies provide valuable information to assist in understanding the geological performance of the affected area during the earthquake. The following geological maps (Figures 2.8–2.17) graphically describe the geological characteristics where the visited sites are located.[14]

It is important to mention that most of the sites presented in the maps (the churches of Chilca and Coayllo, Hacienda Arona y Montalván, Hacienda San José, the cathedrals of Ica and Pisco, as well as the churches of San Javier de Ingenio and San José) were located over alluvial deposits of the Quaternary era. Alluvial deposits are composed of the cementation of alluvium material (from the Latin, *alluvius*, from *alluere*, "to wash against")—loose, unconsolidated soil or sediments that have been eroded, reshaped, and deposited by flowing water in a non-marine setting. Alluvium is typically made up of a variety of materials, including fine particles of silt and clay and larger particles of sand and gravel. This soil is not particularly suitable for construction. Furthermore, INDECI has registered soil liquefaction in Pisco and Ica during the 1716 and 1813 earthquakes respectively.

Tambo de Mora was one of the most damaged cities in Chincha during the August 15, 2007, earthquake. As seen in Figures 2.9–2.11, it is located on an alluvial and marine deposit (south and north) beside the Pleistocene Cañete formation consisting of alternating layers of sand and silt stones. Ground water level is very shallow in the marine deposit and shows at the surface at some locations.[15] The geology of Tambo de Mora was probably the cause of the soil liquefaction, as described on page 21.

The geology of Pisco can be divided in two main formations.[16] The first one is the Pisco formation, described as a lithologic sequence of white color composed of diatomite with intercalation of tuff sandstones and shales; the second one is the alluvial deposit of the Quaternary era. In Pisco, the areas considered high risk (indicated in red on Figure 2.12) are a combination of both geological formations and should not be considered suitable for any kind of construction system unless with strong, reinforced, and expensive foundations. These areas present high amplifications of seismic waves (> 3 times acceleration at bedrock level Tp>1.40) with a bearing capacity between 0.50–0.75 kg/cm^2 and the phreatic level located between 1.0–1.8 m. According to INDECI, at the center of the city, 1.2 m of sandy clay over-

FIGURE 2.8
Geology map around the cities of Cañete and Mala. The Churches of Chilca and Coayllo are located over alluvial deposits of the Quaternary era (grey).

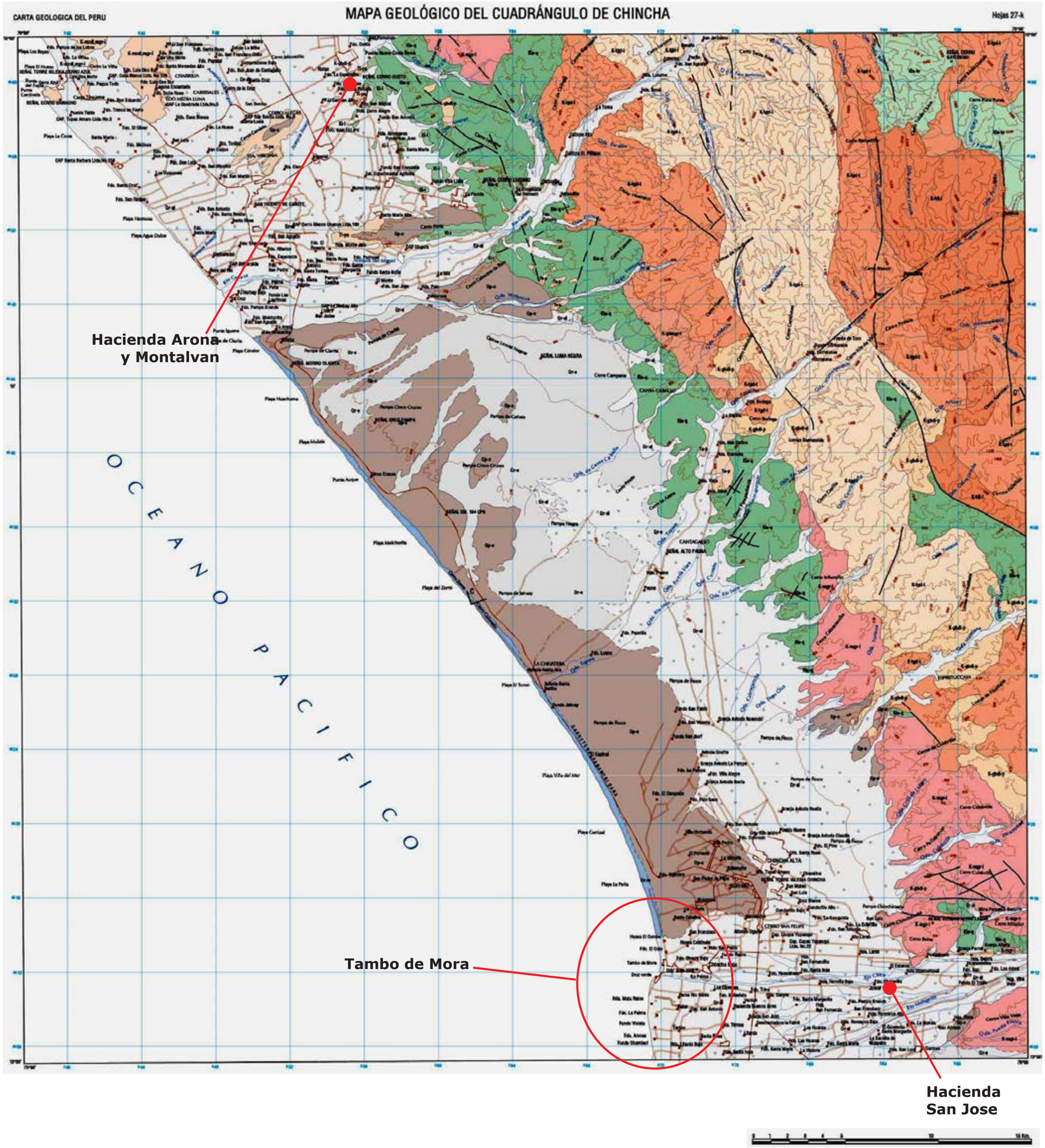


FIGURE 2.9
Geological map around the cities of Cañete and Chincha. The Hacienda Arona y Montalván and Hacienda San José are located over alluvial deposits of the Quaternary era (grey). The Cañete formation (in grey also) is where most of the landslides will take place. The city of Tambo de Mora is located over marine deposits.

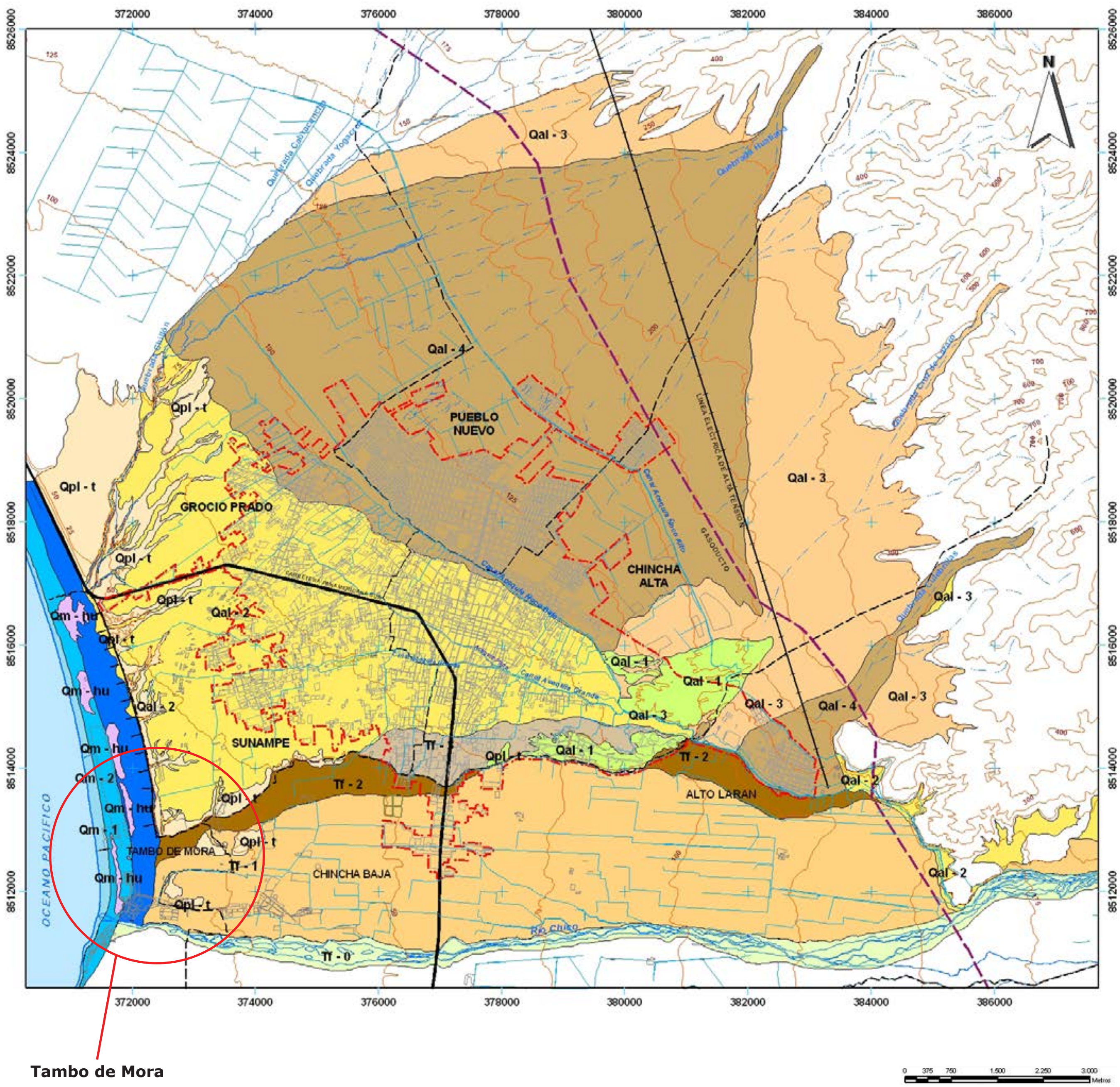


FIGURE 2.10

Detailed geological map of the city of Chincha. The light-pink-shaded areas near the ocean are continuously saturated by water; marine deposits are shown in blue. The area in brown, close to the valleys and around the river is agricultural land.

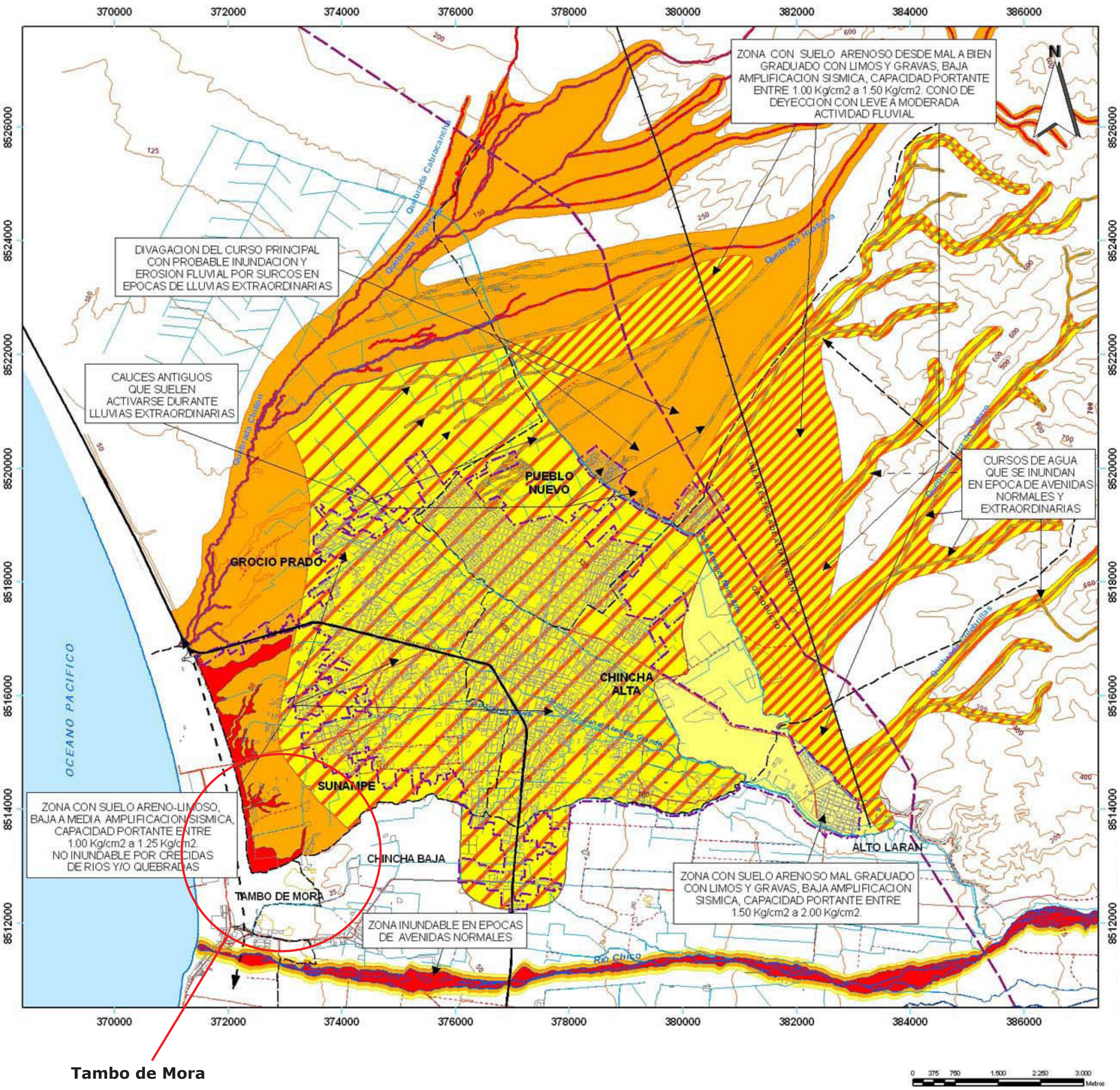


FIGURE 2.11

Risk map of the city of Chincha. The areas marked in red and orange are considered high risk for earthquake, floods, and landslides, conditions exacerbated by rain and constant fluvial erosion of the soil. The city of Tambo de Mora (circled in red), which was severely affected by the earthquake, is located almost directly above the earthquake's epicenter.

FIGURE 2.12
Risk map of the city of Pisco. The areas marked in red and orange are considered at high risk for earthquake because of the sandy nature of the soil. The epicenter of the larger aftershock was almost at the latitude of the city of Pisco.

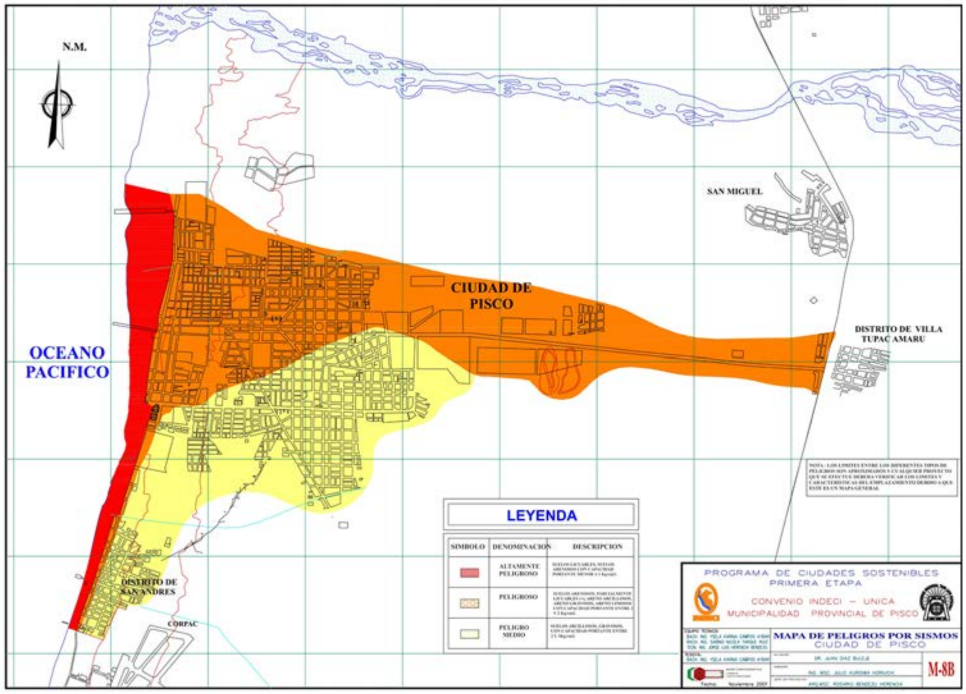


FIGURE 2.13
Terrain view of the city of Pisco. Pisco's main square is indicated by a red circle. © 2011 Google-Imagery; © 2011 DigitalGlobe, Cnes/Spot Image, GeoEye.

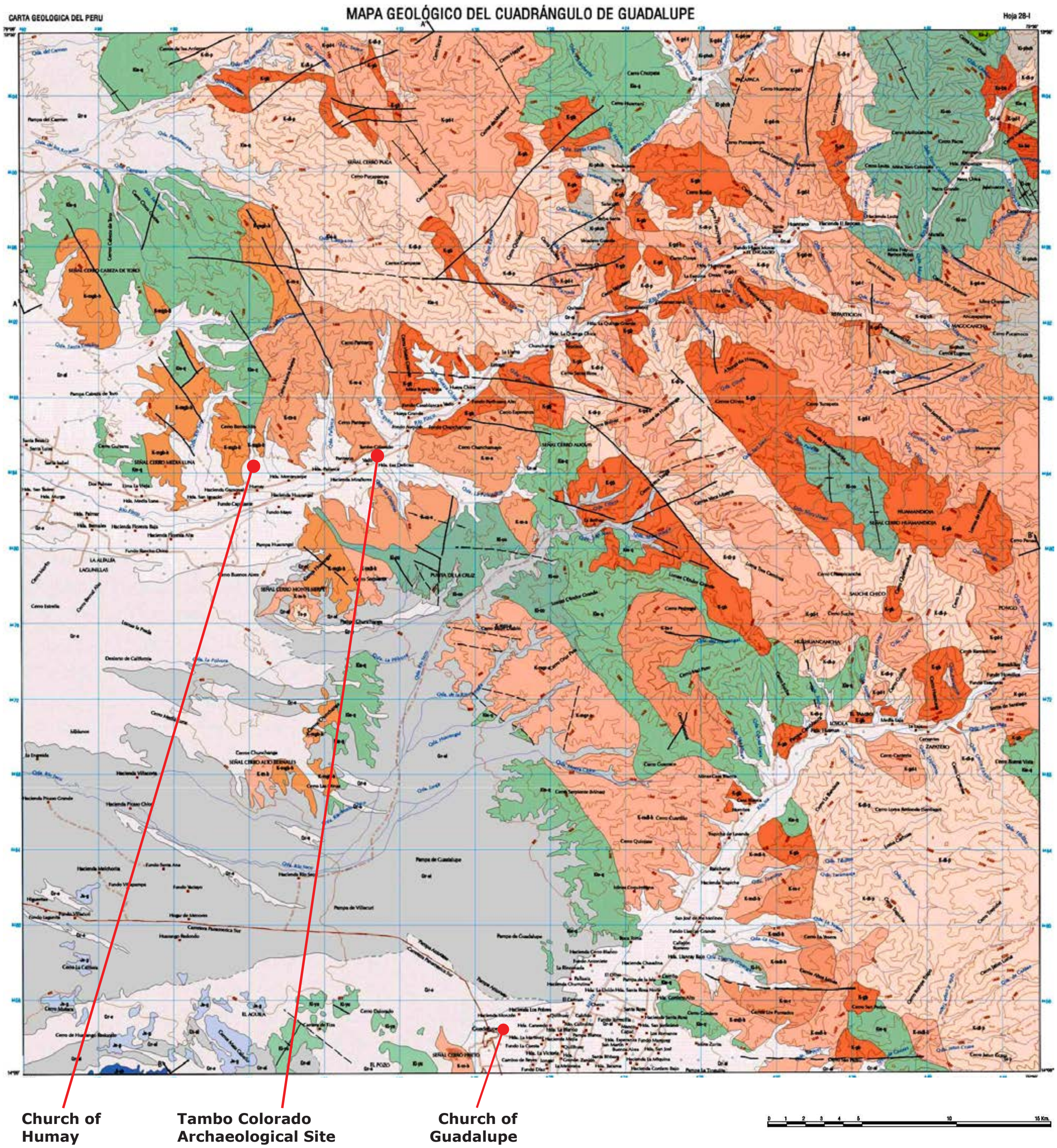


FIGURE 2.14

Geological map showing Humay, Guadalupe, and Tambo Colorado. The Church of Humay and the Church of Guadalupe are located over alluvial deposits of the Quaternary era (grey). The Archaeological site of Tambo Colorado however is at the base of a rocky formation (orange).

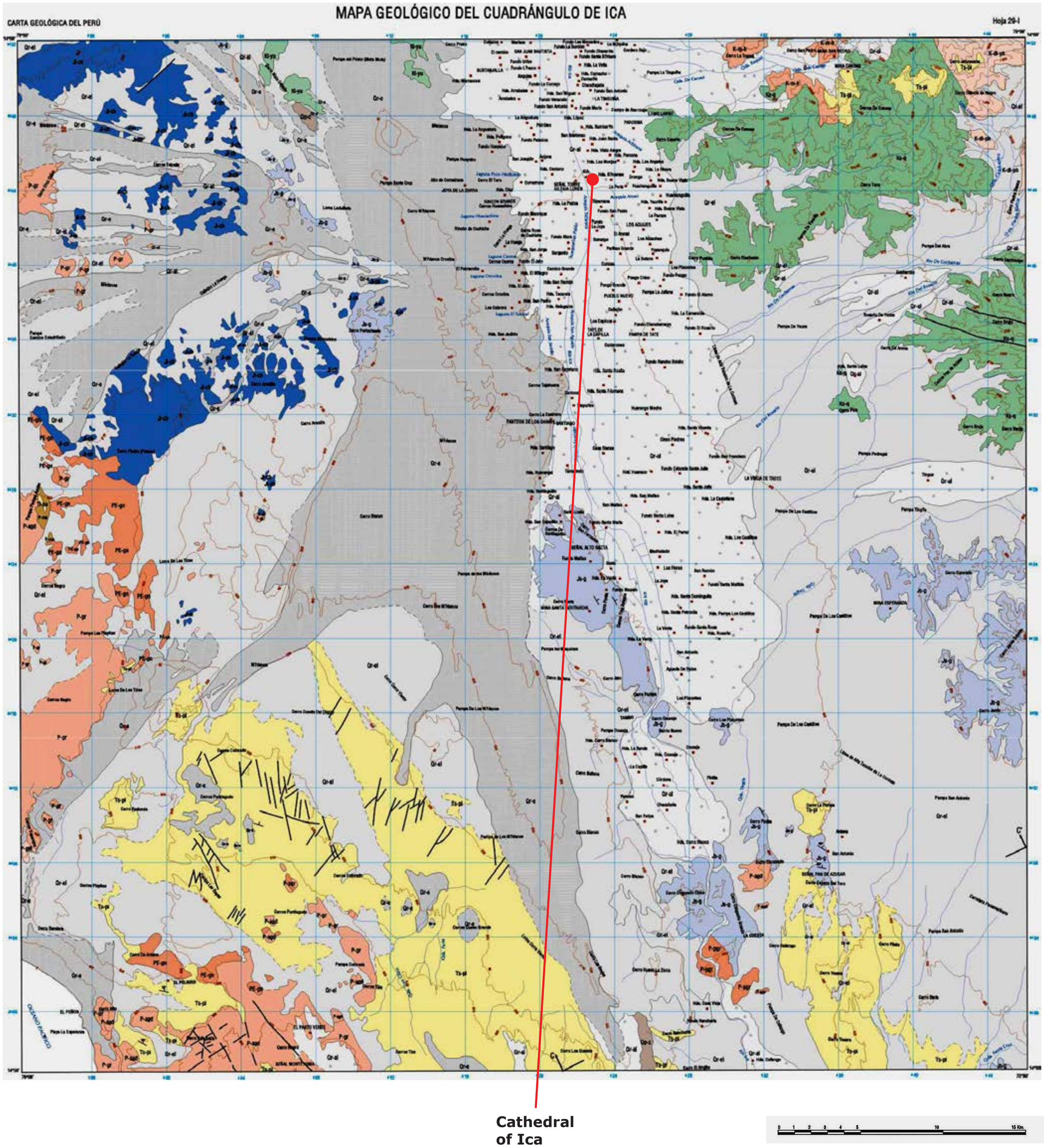


FIGURE 2.15
Geological map around the city of Ica. The Cathedral of Ica is located over alluvial deposits of the Quaternary era (grey).

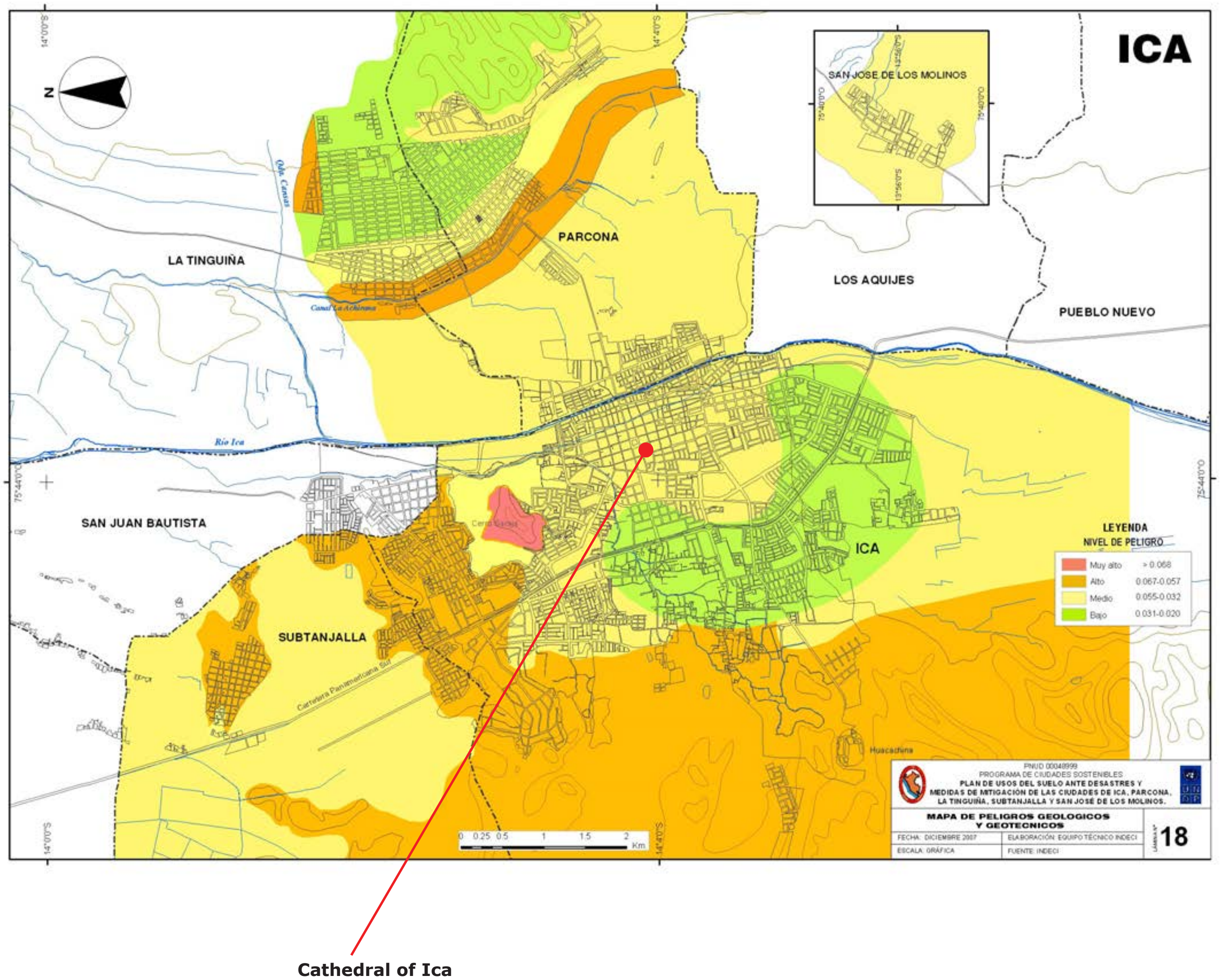


FIGURE 2.16
Risk map of the city of Ica. The Cathedral of Ica is located within the urban environment over an area considered to be at medium seismic risk.

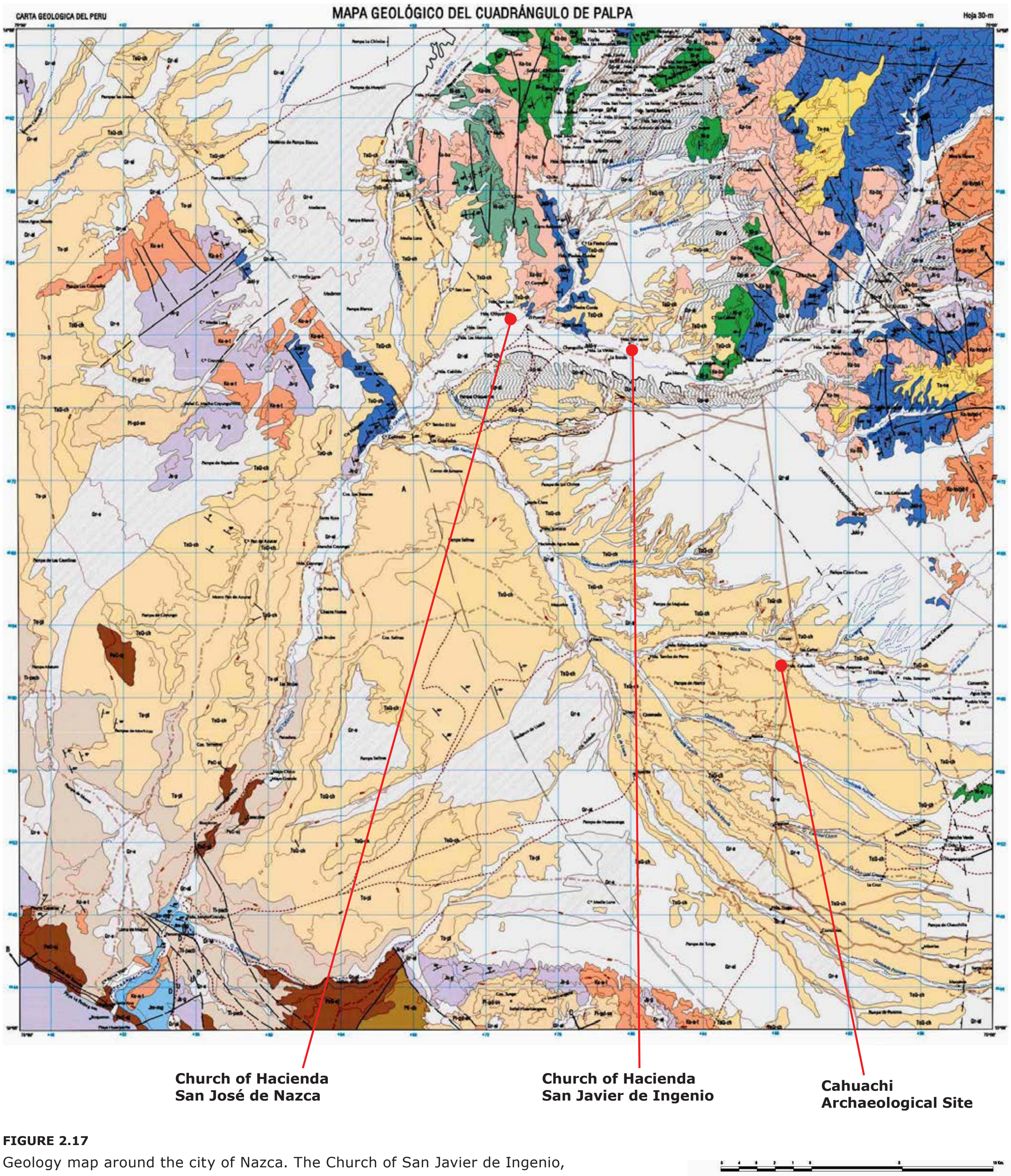


FIGURE 2.17
Geology map around the city of Nazca. The Church of San Javier de Ingenio, the Church of San José de Nazca, and the archaeological complex of Cahuachi are located over alluvial deposits of the Quaternary era (grey).

lies fine, silty sand to depths between 2.0 to 4.25 m, followed by poorly graded gravel.

Effects of the Earthquake in the Affected Region

A number of reports written by earthquake engineers are listed in this report's bibliography. They carefully describe some relevant geotechnical features that are explained by the geological structure of the region described above. The most important recorded effects that are worth explaining are liquefaction and landslides. They are included in this report to provide perspective on the magnitude of the earthquake's effects on historic or existing buildings.

Liquefaction

Liquefaction is the process by which saturated, unconsolidated soil or sand is converted into a suspension during an earthquake. The town of Tambo de Mora–due to its location above marine deposits and sand–was severely affected by liquefaction. This was recorded in several reports where liquefied sand was observed inside houses and on the sides of the streets.[17] Most of the buildings affected were one- or two-story confined concrete masonry structures that suffered settlement between 0.2 to 1.0 m relative to street level (Figure 2.18). According to the Tambo de Mora citizens, the area had experienced liquefaction during the 1970 and 1974 earthquakes but no preventive action was taken.

Landslides

Landslides were reported along the Pan–American Highway, which extends north to south from Alaska to Chile crossing Peru along its coast.[18] When the GCI team visited the area, the Pan-American Highway had already been repaired. However,

FIGURE 2.18
Liquefaction at a site in Tambo de Mora.
Image: Courtesy Jorge Alva Hurtado.

FIGURE 2.19
Landslide effects at the Pan-American Highway.

according to information recorded the area most affected by landslides was the section between Tambo de Mora and Pisco (Figure 2.19).

Notes

1 The moment magnitude scale (abbreviated as MMS; denoted as M_w, where $_w$ indicates work accomplished) is used by seismologists to measure the size of earthquakes in terms of the energy released. The magnitude is based on the moment (also called torque force) of the earthquake, which is equal to the rigidity of the earth multiplied by the average amount of slip on the fault and the size of the area that slipped. The MMS is now the scale used by most seismological and earthquake institutions to estimate magnitudes for all modern, large earthquakes. The MMS scale was developed in the 1970s to succeed the 1930s-era Richter magnitude scale, M_L. Even though the formulae are different, the new scale retains the familiar continuum of magnitude values defined by the older one.

2 Office of the Resident Coordinator, *Situation Report No. 21, Earthquake in Peru*, 1.

3 Taucer, Alarcon, and So *2007 August 15 Magnitude 7.9 Earthquake near the Central Coast of Central Perú,* 2.

4 CERF is a humanitarian funding mechanism established by the United Nations to enable more timely and reliable assistance to victims of natural disasters and armed conflicts. It was approved by the United Nations General Assembly on December 15, 2005, and launched in March 2006.

5 United States Geological Survey (USGS), *Magnitude 8.0—Near the Coast of Central Peru*, Earthquake Summary.

6 The Richter magnitude scale, also known as the local magnitude (M_L) scale, assigns a single number to quantify the amount of seismic energy released by an earthquake. Due to the fact that M_L is obtained from measurements taken from a single, band-limited seismograph, its values saturate when the earthquake is larger than 6.8. To overcome this shortcoming, Gutenberg and Richter later developed a magnitude scale based on surface waves (M_S) and another based on body waves (M_B). Unfortunately, M_S and M_B can saturate when the earthquake is big enough.

7 Taucer, Alarcon, and So, *2007 August 15 Earthquake,* 2.

8 Tavera et al., "Ground motions observed during the 15 August 2007 Pisco, Peru, earthquake."

9 D.J. Wald et al., "TriNet ShakeMaps: Rapid generation of peak ground motion and intensity maps for earthquakes in southern California."

10 Ji and Chen, "Preliminary results of the August 15, 2007 Mw 8.0 coast of central Peru earthquake." USGS used the broadband teleseismic waveforms downloaded from the National Earthquake Information Center data center. Waveforms are first converted to displacement by removing the instrument response and then used to constrain the slip history based on a finite fault inverse algorithm.

11 Ibid; Tavera et al., "Ground motions," 83.

12 Lermo et al., "El terremoto del 15 de Agosto de 2007 (MW+7.9), Pisco, Peru. Mapas de clasificación de terrenos con fines de diseño sísmico para las ciudades de Pisco, Ica y Lima-Callao," 233–68.

13 Kuroiwa and Peña, *Manual para el Desarrollo de Ciudades Sostenibles,* 78; and Centro Peruano Japonés de Investigaciones Sísmicas y Mitigación de Desastres (CISMID) et al. "Informe Final del Estudio de Microzonificación Sísmica y Zonificación de Peligro de Tsunami en las Ciudades de Chincha Baja y Tambo de Mora," 88–91.

14 Geological maps can be viewed on the Web site of the Instituto Geológico Minero y Metalúrico at www.ingemmet.gob.pe.

15 Kuroiwa and Peña, Manual para el Desarrollo de Ciudades Sostenibles, 78.

16 Lermo, et al., "El terremoto del 15 de Agosto de 2007 (MW+7.9), Pisco, Peru. Mapas de clasificación de terrenos con fines de diseño sísmico para las ciudades de Pisco, Ica y Lima-Callao."

17 Taucer, Alarcon, and So, *2007 August 15 Earthquake*, 15.

18 Ibid., 16–18.

CHAPTER 3

Earthen Architectural Heritage in Peru

No miremos el pasado por chauvinismo o vanidad nacional: busquemos su enseñanza. (Don't look at the past based in national pride: Look for what the past can teach you.)

—Fernando Belaúnde Terry, Architect and Former President of Peru (1965–1968 and 1980–1985)

Earthen construction is believed to have been used in Peru for more than four thousand years. There has been extensive research and publication on the history of Peruvian culture by well-respected writers, historians, and/or archaeologists such as Garcilaso de la Vega, Felipe Guamán Poma de Ayala, Julio C. Tello, Luis E. Valcarcel, María Rostworowski de Diez Canseco, Ducio Bonavia, Roger Ravines, and Luis Lumbreras, among others. Although most of the remarkable findings and analysis of the evolution of Peruvian culture has been extremely useful in understanding the development of the Peruvian built environment, there are few publications that specifically address the history of Peruvian construction and architecture.[1] This section does not attempt to be a comprehensive account, but rather highlights the historical events that influenced the evolution of earthen architecture in Peru, particularly regarding its ability to withstand earthquakes.

Ancient Peruvian Cultures (before 1535)

One of the best compilations of the history of Peruvian architecture and urban planning prior to the arrival of the Spanish was written by Carlos Williams in 1981.[2] Williams mentions the lack of published material about ancient architecture and urbanism not only in Peru but in the Americas.[3] His most important contribution is his analysis of the cultural value of ancient buildings. Williams describes each period and identifies the most important building categories according to their function, structural and material composition, and cultural significance.

As background to the earthquake assessment, highlights from the historical development of Peruvian earthen structures derived from Williams are presented in the following section.

There is a clear evolution of pyramid constructions between 2,000 bce and 500 ce in central Peru, most of which were built of earth.[4] Their pyramidal shapes, which according to Peruvian archaeologists resembled mountains, were able to withstand seismic events (Figures 3.1. and 3.2). Furthermore, in most cases, the materials used were adobe for the exterior, earth and stone for the interiors, and heavier rocky materials at the bottom of the structures.[5] The material selection may have been a way to dissipate the energy generated by a temblor.

FIGURE 3.1
View of Huaca Pucllana, one of the earliest pyramidal constructions in Lima, photographed in 2007.

FIGURE 3.2
Huaca Arco Iris, Trujillo, Peru, as seen in 1999.

Remarkable examples of the complex construction techniques used in ancient times are the Huacas del Sol y de la Luna, built during the Moche period (100 ce to 800 ce) outside of the city of Trujillo. Hastings, Mansfield, and Moseley estimated that 143 million adobe blocks were used to build only the first pyramid.[6] The complexity of Mochican earthen construction was not limited to ceremonial buildings, but applied also to residential housing, where the use of stone foundations in combination with adobe and *quincha* walls with limited openings and flexible roofing systems was common practice.[7]

However, it is the Wari culture (500 ce to 900 ce) that developed one of the most sophisticated earth and stone construction techniques in Peru before the arrival of the Incas and the Spanish. The Waris developed domes and vaulted roofing systems using locally available materials including traditional wooden seismic-resistant construction details to tie the walls in the corners, seen for the first time at the Wiracochapampa site in Huamachuco.[8] The knowledge acquired by the Waris and the Mochicas was picked up by the Chimus in the northern part of the country. The

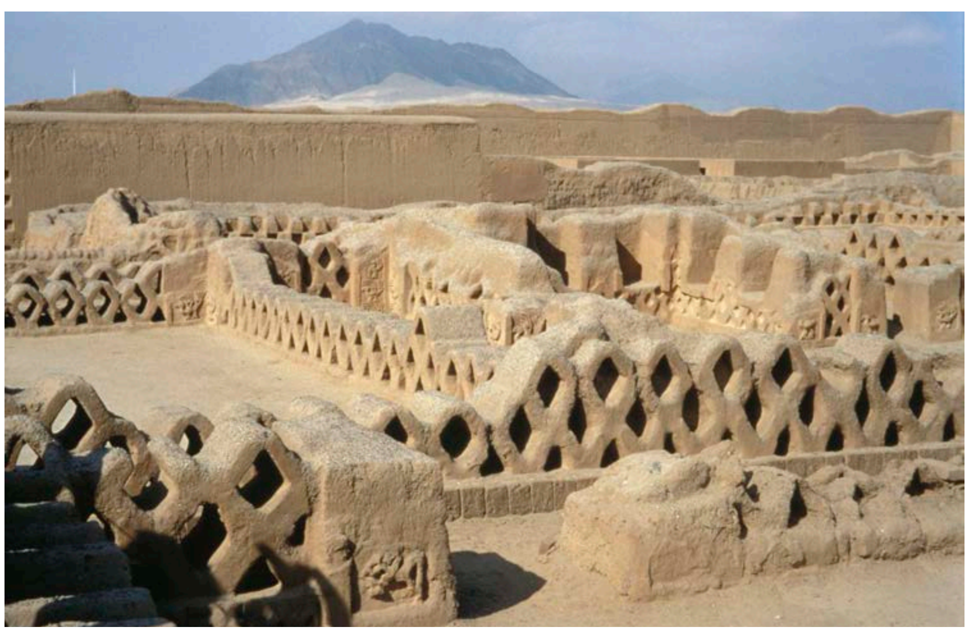


FIGURE 3.3
Tschudi Palace, Chan-Chan archaeological site, as it appeared in 1999.

FIGURE 3.4
Pyramidal wall, Tschudi Palace, Chan-Chan archaeological site, photographed in 1999.

vast adobe city of Chan Chan was built by the Chimús around 850 ce and lasted until its conquest by the Inca Empire in 1470 (Figure 3.3). The city is composed of nine walled citadels which housed ceremonial rooms, burial chambers, temples, reservoirs, and some residential housing. The walls themselves were constructed of adobe brick covered with a smooth surface into which intricate designs were carved. However, the pyramidal cross section of these high walls (Figure 3.4) is the most remarkable seismically resistant design; it allowed the earth walls to withstand earthquakes, letting them rock, but remain stable as a result of their own weight.

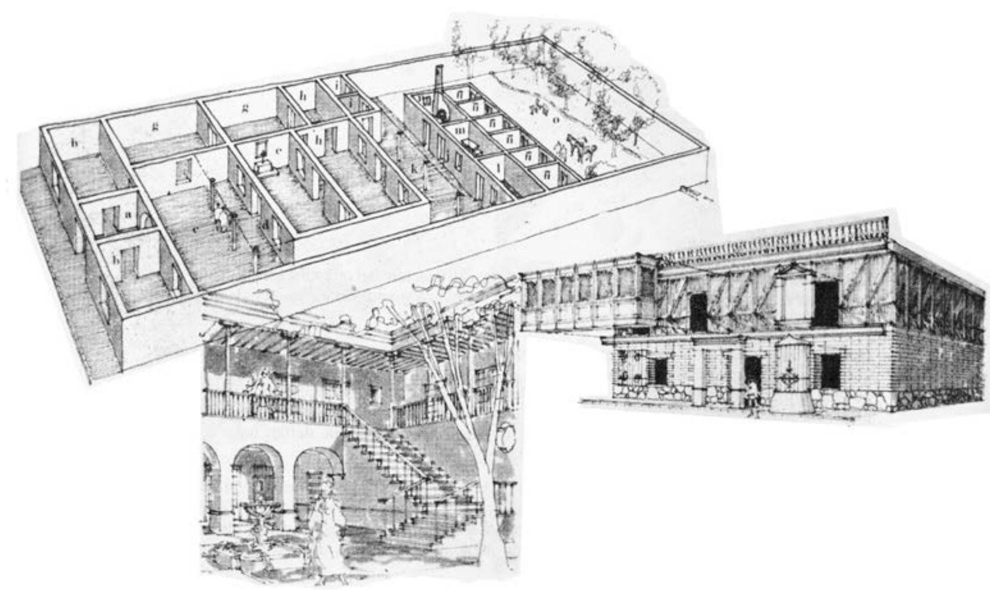
Williams doesn't mention further developments of adobe construction during the Inca period and concentrates most of his analysis on the carving of stone, but mentions the need to further study the earthen construction methods in an attempt to recover these extremely efficient and suitable construction techniques.[9] Santiago Agurto Calvo provides greater detail regarding the evolution of ancient earthen architecture, though limited to the Lima region.[10]

The Spanish Viceroyalty (1535–1821)

Probably the earliest publication mentioning adobe as the material of choice for the construction of colonial houses in Lima comes from Padre Bernabé Cobo's *Historia de la Fundación de Lima* in 1629.[11] In 1748, Juan and Ulloa mentioned for the first time the use of quincha for the construction in Lima of residential buildings, known as *casonas* (Figure 3.5).[12] The use of earthen materials was not limited to vernacular constructions. Viceroy D. Melchor de Navarra y Rocafull, Duque de la Palata, started the construction of the fortifications of Lima around 1684. These were built of 5–6 m high, 5 m wide adobe walls that protected the city for almost two hundred years (Figures 3.6–3.8).[13] They were demolished as part of an urban enhancement during the government of President José Balta in 1871 that left only one of the original towers still standing.

In Peru, quincha is a traditional construction system consisting of wooden panels with cane reeds that create an earthquake-resistant framework, which is covered in mud plaster. Quincha is a Spanish term widely known in Latin America, bor-

FIGURE 3.5
Drawing of a typical casona of Lima. The first floor is of adobe masonry and the second floor of quincha.



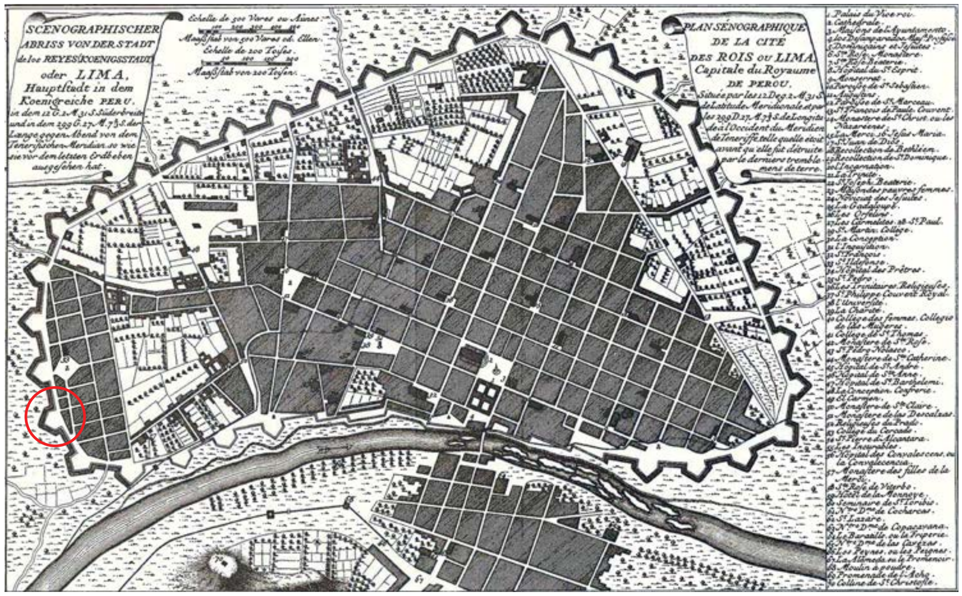


FIGURE 3.6
A 1752 map of Lima and its city walls by Jacobo Nicolás Bellín. The location of the remaining section of city walls seen in the satellite view is indicated by red circle.

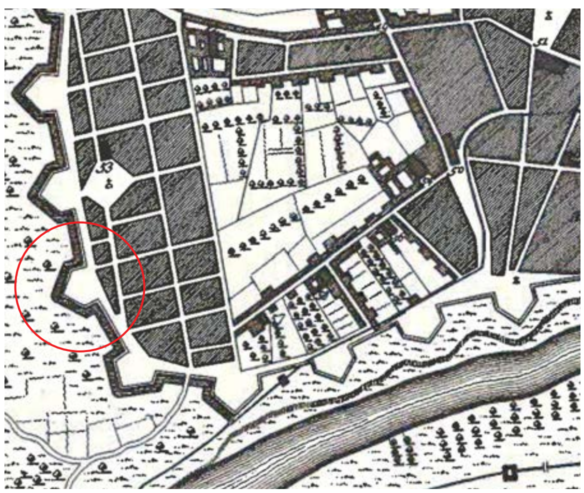


FIGURE 3.7 (LEFT)
Detail of the 1752 Lima city map showing the location of the remaining section of the city walls circled in red.

FIGURE 3.8 (RIGHT)
Aerial view of Lima with the remaining section of the original city walls indicated by red circle. © 2011 GeoEye, Google.

rowed from the Quechua word *qincha* (*kincha* in Kichwa), which means fence, wall, enclosure, corral, or animal pen.[14]

Historically, this type of construction was used in all Spanish and Portuguese colonies throughout Central and South America, but similar techniques called wattle and daub have been used elsewhere for more than six thousand years.[15] In the case of quincha, the reed is made by weaving thinly split canes between elements of the framework and is attached by leather straps nailed to the wooden elements, then covered by mud plaster; in some cases a finish layer of either lime wash or thin mud plaster was applied as a decorated surface. The final result is a standardized panel that can be repeated and used as partitions for different types of construction (Figures 3.9 and 3.10).

The lightweight quality of the quincha panels and its performance during earthquakes allowed Peruvians to use them in the construction not only of second stories of buildings, but also in complex roofing systems for domes, pillars, lanterns, and vaults. The wooden framework was transformed into trusses and collar beams and the cane reed connected them across the vault, dome, or flat roof (Figure 3.11). Ferruccio Marussi Castellán, an architect who has extensively studied quincha as a

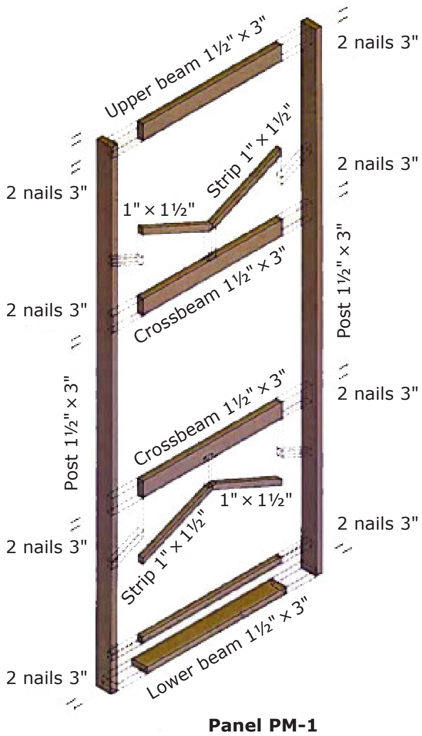


FIGURE 3.9
Axonometric drawing of different elements of quincha panels.

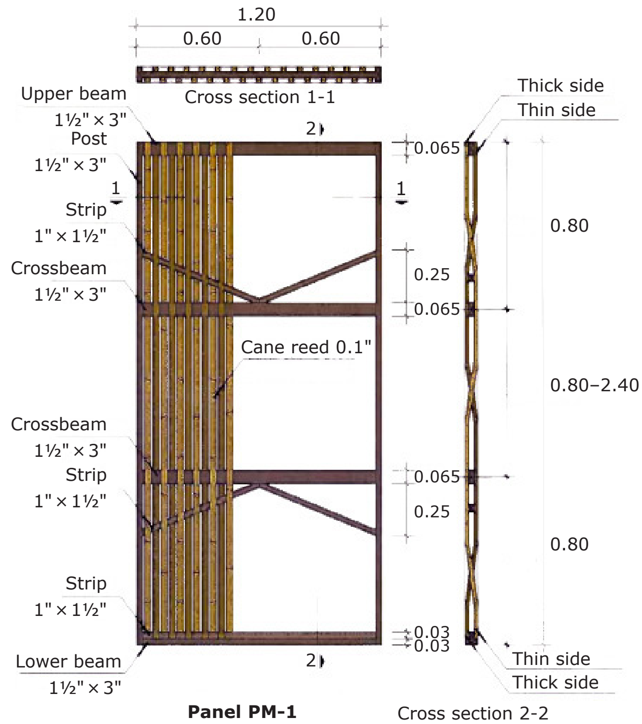
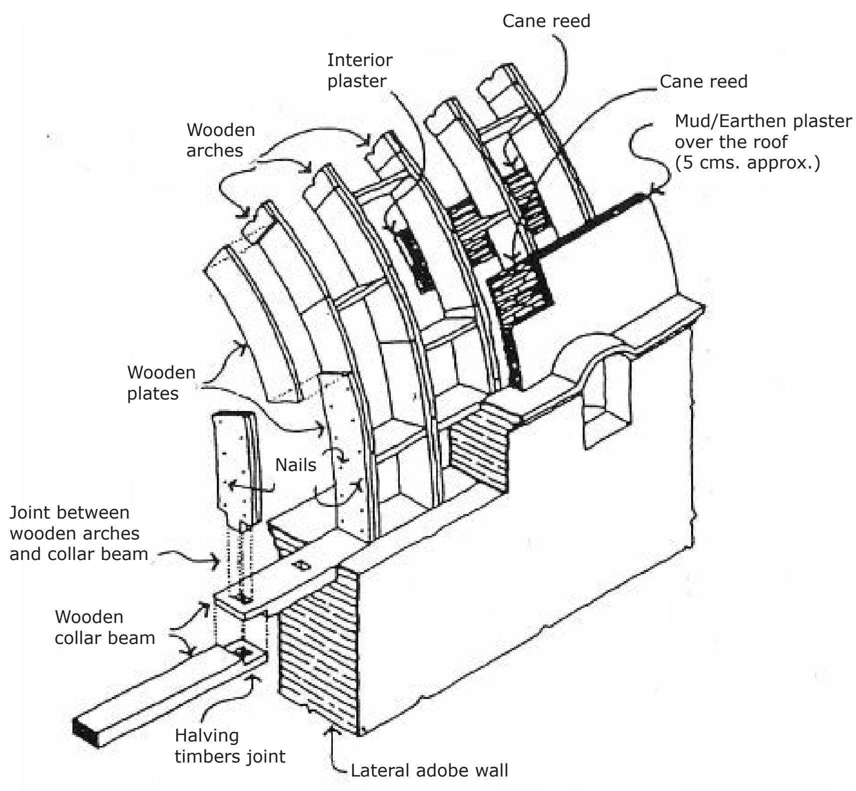
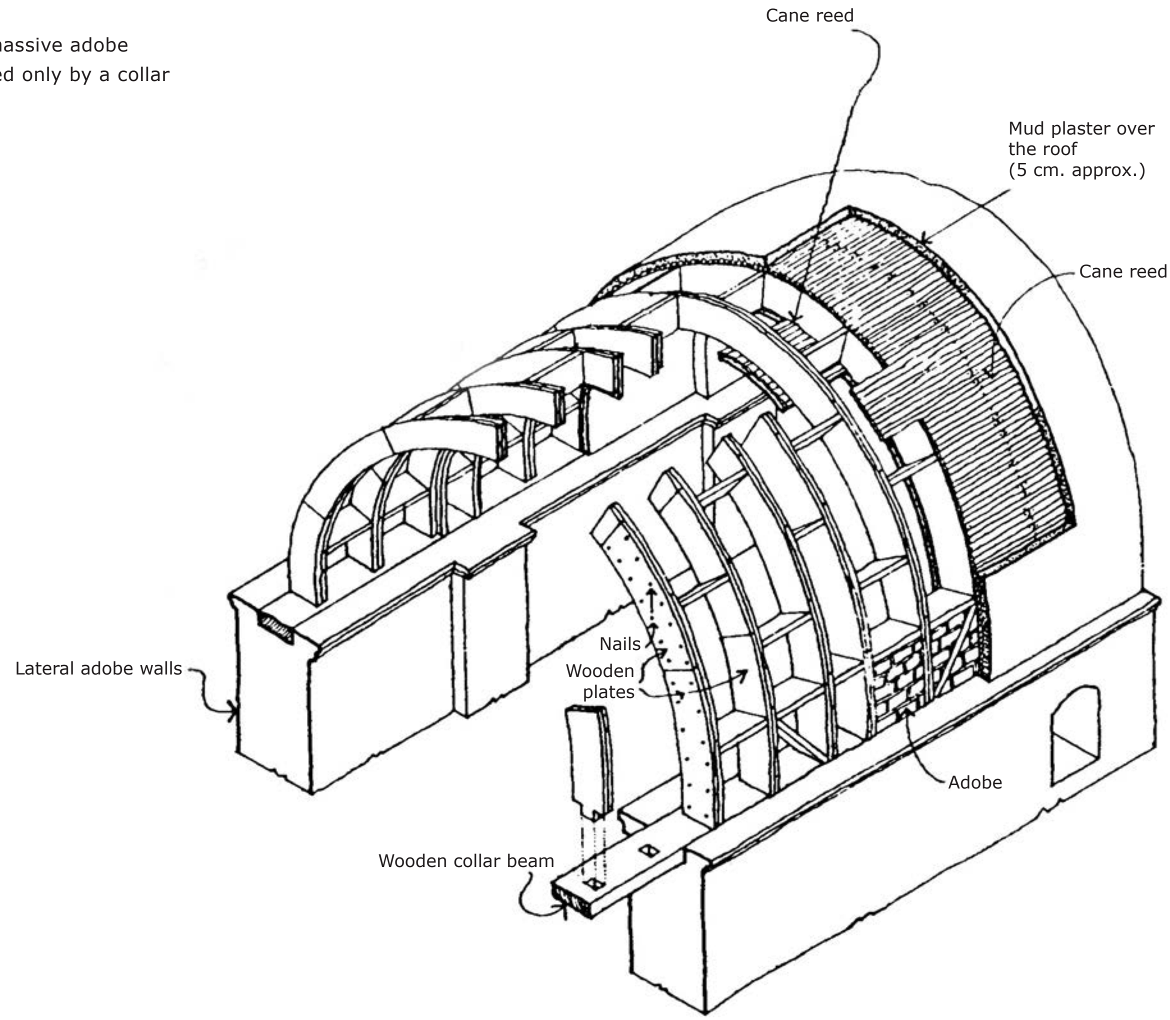


FIGURE 3.10
Scheme of a quincha panel showing the different structural and non-structural elements and their dimensions.

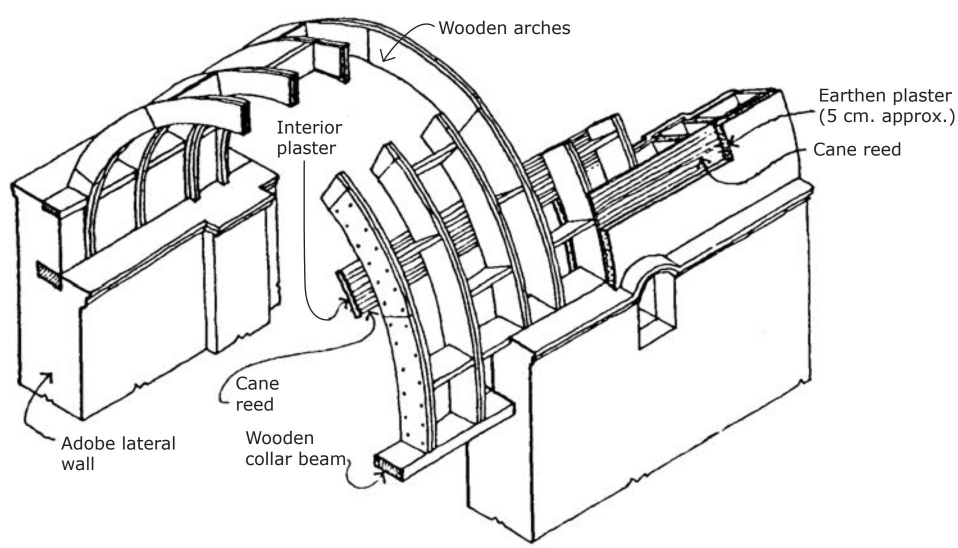
FIGURES 3.11
Detail of a collar beam over adobe walls.



FIGURES 3.12
The vault over massive adobe walls is connected only by a collar beam.



FIGURES 3.13
Vault embedded in the wall at the arches' bearing point.



traditional construction technique in colonial monumental buildings, analyzed a series of Spanish churches in order to understand their structure, (Figures 3.12 and 3.13) reproducing a series of drawings that clearly explains the way quincha vaults and domes were constructed.[16] Marussi also studied the materials used to connect those elements in detail.[17]

The *Crónicas* or early publications of the Spanish Viceroyalty period are extremely important as they are now considered original research sources. The Peruvian National Library, which held most of the Viceroyalty's historical documents—such as the 1613 *Padron de Indios* requested by Viceroy Marqués de Montes Claros, among others—was partially destroyed by fire on May 11, 1943.[18] Although the Peruvian National Library has started a program to restore documents damaged by the fire, most of them were lost.

In 1945, Juan Bromley and José Barbagelata's *Evolución Urbana de la Ciudad de Lima* was published. Written in 1942, it compiled historic data in existence before the fire.[19] The book includes reproductions of maps of the city of Lima from 1535 to 1945. Bromley and Barbagelata discuss the impact of earthquakes, including the destruction of the church and hospital of San Lázaro after the 1586 earthquake and the damage to the vaults of the second Cathedral of Lima after the October 19, 1609 earthquake.[20] The *Libros de Cabildos*—a compilation of almost three hundred years of *ayuntamiento* (municipal council) meetings in Lima—explains that after the 1609 earthquake, authorities decided to rebuild the cathedral, reducing the height of the stone walls supporting the vaults.[21] This is probably the first unofficial recommendation for seismic stabilization in Peru during the Viceroyalty.

It was not until the earthquake of October 28, 1746, that the ayuntamiento of Lima officially decided to modify existing construction techniques. The 1746 earthquake resulted in ten thousand deaths, and only twenty-five houses of a total of three thousand in Lima remained. Viceroy D. José A. Manso de Velasco asked the mathematician D. Luis Gaudin to study the buildings' damage and to develop technical recommendations to improve their resistance to seismic events.[22] These recommendations, the first to be developed in the Americas, probably had an influence on the recommendations developed for the reconstruction of the city of Lisbon after the 1755 earthquake.[23]

Gaudin, who had taken the chair of mathematics at San Marcos University in Lima in 1744, happened to be a technically sophisticated, forthright supporter of building codes.[24] He presented his report to the *cabildo* (municipal government) advocating: (1) the use of mud, cane, and adobe as construction materials instead of lime, brick, or stone (2) the use of quincha for wall partitions (3) an increase in the width of adobe masonry walls (4) the addition of buttresses to lateral, adobe, church walls (5) the lowering of the height of church towers (6) the limitation of construction of bow windows, and (7) assuring adequate plazas and public space to serve as refuge in case of disasters, among other recommendations. Although this is probably the most important *ordenanza* (ordinance) dictating the way buildings were constructed from that moment until the beginning of the twentieth century, it was not the first one, as this report describes later (Figure 3.14).

Other important authors, such as Héctor Velarde (1946) and Alfredo Benavides (1961), referenced Bernabé Cobo and Bromley and Barbagelata to compile their research. More detailed publications that addressed the construction materials and techniques used during the Spanish period were compiled by Emilio Harth-Terré.[25] In a 1962 publication referencing early construction documents (known as

FIGURE 3.14
Buttress at the Church of Carabayllo in Lima, probably added after Gaudin's recommendations, as seen in 2007.

FIGURE 3.15
Detail of the dome of the Church of Santo Domingo, Lima.

Conciertos de Obra), he described the use of adobe and quincha as well as other construction materials such as brick, stone, gypsum, and wood for the construction of important Viceroyalty buildings in Lima.[26] Harth-Terré describes adobe's original dimensions—up to 78 cm in length with additives of straw and dung—and even prices based on the 1577 *Ordenanza del Cabildo*. Harth-Terré also comprehensively describes the improvement in proper materials and techniques used for foundations, and structural and partition walls, as well as the different types of decorated surfaces, particularly for residential housing.

From Harth-Terré's 1975 publication, it is worth mentioning the chapter describing the system of highly qualified *maestros and aprendices* (masters and apprentices) responsible for the construction of buildings in major cities, including the strict training they underwent over several decades. Fray Diego Matamoros was one of the maestros who bravely and inventively decided to use—apparently for the first time—wood, cane, and lime for the construction of the dome of the Church of Santo Domingo in 1666 (Figure 3.15). This dome survived the October 20, 1687, earthquake without further damage while others were completely destroyed. Later, the 1702 *Ordenanza del Cabildo* commanded the use of wood, mud, and cane for ceiling construction, including vaults.[27] This is the earliest document found regulating earthen construction during the Spanish period. Two hundred and fifty years later this decision was revoked.

José García Bryce published a remarkable description of Peruvian architecture during the Viceroyalty and Republican (1821–present) periods.[28] He defines three main building typologies during the Viceroyalty: the casona, the church, and the convent or monastery, and a number of minor types including *cabildos* (city halls), hospitals and *asilos* (assisted living facilities), schools, military fortresses, commercial buildings, and infrastructure.[29] Although his article focused mostly on the stylistic evolution of these prototypes, some sections are dedicated to the inventive use of adobe and quincha for the construction of the Viceroyalty's major buildings (Figures 3.16–3.18). Similar publications devoted to the evolution of styles are the product of the remarkable research done by Antonio San Cristóbal Sebastián in a series of books dedicated to the history of Spanish architecture in Peru.[30]

FIGURE 3.16
Conservation work on quincha construction at Casona San Marcos, Lima, in 2003.

FIGURE 3.17
Detail of wooden frame and cane in quincha construction at Casona San Marcos in 2003.

Bryce mentions the reconstruction, between 1657 and 1674, of the vault of the Church of San Francisco with quincha as an attempt to upgrade the building techniques to withstand earthquakes under the supervision of the maestros Constantino de Vasconcellos and Manuel Escobar, probably following the Matamoros experience in the Church of Santo Domingo (Figures 3.18–3.20).[31] He also described the inventive use of wood, cane, and mud for the vaults and columns of the Cathedral of Lima after the 1746 earthquake. The final layout and construction system of the Cathedral of Lima was finished in 1755 under the supervision of the Jesuit priest, Juan Rerh, and the maestro, Francisco Becerra, who were responsible for the cathedral's actual design and structure (Figure 3.20).[32]

The Republican Period (1821–present)

Bryce mentions the addition of other types of residential buildings at the beginning of the Republican period, such as ranchos and large, Renaissance-revival houses, which used the same materials for their construction: adobe and quincha walls for masonry and sometimes stone and brick for portals and columns.[33]

Two important milestones in Peruvian construction history occurred during the second half of the nineteenth century. First is the creation of the Comisión Central de Ingenieros Civiles (Civil Engineers Professional Association) in 1852. Second is the introduction of cement to Peru in the 1860s. Its first recorded use was for the construction of a drainage system made of brick and cement mortar in Lima in 1869.[34] To properly make use of this new industrial product in the modern era, the Escuela Especial de Ingenieros de Construciones Civiles y Minas (School of Civil and Mining Engineers) was created in 1876. Teodoro Elmore was the first professor to teach a section on architecture. However, it was not until 1910 that a separate architecture school was proposed based on a teaching plan designed by Santiago

FIGURE 3.18 (LEFT)
Replacement of the cane, reed, and wooden elements in the quincha dome at the Church of San Francisco in Lima, ca. 1970.

FIGURE 3.19 (RIGHT)
View of the dome of the Church of San Francisco from the convent cloister, as seen in 2008.

FIGURE 3.20
Interior view of the Cathedral of Lima as it appeared in 2011.

Basurco. Basurco and Elmore were both trained in the United States and Europe and other fellow architects followed them to teach at this school. New building types and construction materials, such as brick masonry with cement mortar, cast iron, and reinforced concrete, were taught and subsequently used in modern construction in Peru.

On August 13, 1868, an earthquake of approximately M_W 9.0 hit just off the coastline at the Peru–Chile border. A tsunami followed, which devastated the city of Arica, Peru, (present-day Chile). Wave damage was reported in Hawaii, New Zealand, and Japan. The earthquake heavily damaged the cities of Arica, Tacna, Moquegua, Ilo, Torata, Iquique, and left the city of Arequipa in ruins. The tsunami razed a large part of the Peruvian coast, killing thirty people in Chala, about one hundred in Arica, and two hundred in Iquique. The headland at Arica was fractured, as were the hills of La Caldera, next to the baths of Yura (Arequipa). About four hundred movements or aftershocks were counted up to August 25, 1868.[35]

There are no reports on the impact of the 1868 earthquake on the construction industry in Peru until the second term of President Nicolás de Piérola (1895–1899), when the Ministerio de Fomento y Obras Públicas (Ministry of Development and Public Works) was created. As part of its core mission, the ministry was in charge of regulating the construction industry. President Piérola, advised by Santiago Basurco, state engineer and founder of the school of architecture, suggested the proscription of adobe for construction, probably as a result of the devastation from the 1868 earthquake. Subsequently, during the first term of President Augusto B. Leguía (1908–1912), and after the M_W 8.2 earthquake in 1908, the state banned the use of adobe and quincha for the construction of urban housing.[36] From that time on, adobe and quincha were replaced with cement, brick masonry, and reinforced concrete to build very significant structures.[37] However, many existing buildings were made of earth, and earthen construction was still very much in use in the rural areas.

The Peruvian Building Code and Seismic Earthen Construction Research

Table 3.1 lists the most significant earthquakes in Peru, their Moment Magnitude (M_W) and the approximate number of fatalities.

There were four major earthquakes between 1940 and 1980 that triggered the government's regulation of materials and techniques and support of further research in the construction industry. On May 24, 1940, a M_W 8.2 earthquake hit the coast of Lima, destroying most of the port of Callao. On October 16, 1966, a M_W 8.1 earthquake hit the city of Lima. This earthquake, centered just off the coast from Callao, claimed about 125 lives and injured some 3,000 people. A religious festival was being held in Callao and several people were killed when some of the churches collapsed. Forty-one years later, the same type of collapse at the Cathedral of Pisco resulted in 200 deaths. In Lima, 2,300 houses suffered severe structural damage. The town of Huacho north of Lima was the most severely damaged with over 20,000 inhabitants left homeless. Landslides and huge ground cracks were reported along the Pan American Highway north of Ancón. This shock generated a tsunami with heights of 4.0 meters at La Punta-Callao.

On May 31, 1970—four years after the 1966 quake, a time interval that many Peruvians believe exists between strong earthquakes—a M_W 7.9 earthquake hit the

Table 3.1: Significant historic earthquakes in Peru

Year	Date	Location	M_W	Fatalities
1619	February, 14	Trujillo	7.7	350
1664	May, 12	Ica	7.3	400
1687	October, 20	Lima	8.5	600
1746	October, 28	Lima		5,000
1821	July, 10	Camana	8.2	162
1868	August, 13	Arica	9.0	25,000
1908	December, 12	Off the coast of central Peru	8.2	unknown
1913	November, 4	Abancay		150
1940	May, 24	Callao	8.2	249
1942	August, 8	Off the coast of central Peru	8.2	30
1943	January 30	Yanaoca		200
1946	November, 10	Ancash	7.3	1,400
1947	November, 1	Satipo	7.3	233
1948	May, 11	Moquegua	7.4	70
1950	May, 21	Cusco	6.0	83
1953	December, 12	Tumbes	7.4	7
1958	January, 15	Arequipa	7.3	28
1960	January, 13	Arequipa	7.5	57
1966	October, 17	Near the coast of central Peru	8.1	125
1968	June, 19	Moyobamba	6.9	46
1969	October, 1	Comas region, Chile	6.4	136
1970	May, 31	Chimbote	7.9	50,000
1974	October, 3	Near the coast of central Peru	8.1	78,000
2001	June, 23	Near the coast of Peru	8.4	138
2001	July, 7	Near the coast of Peru	7.6	1
2005	September, 26	Northern Peru	7.5	5
2006	October, 20	Near the coast of central Peru	6.7	unknown
2007	August, 15	Near the coast of central Peru	8.0	514

Source: Data from United States Geological Survey. (earthquake.usgs.gov/regional/world/historical_country.php#peru)
Note: Location and M_w are approximate values based on data available at the time of the event. The same is applicable for casualties.

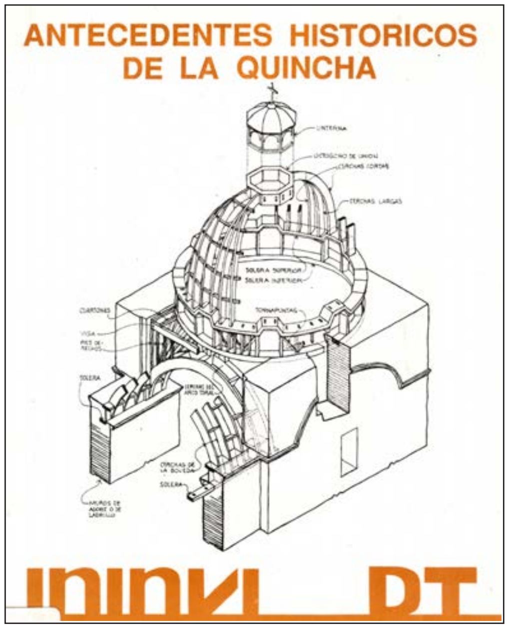
city of Chimbote, a major fishing port in northern Peru. Damage was reported from as far north as Chiclayo, to as far south as Lima. However, coastal towns near the epicenter and towns in the Callejón de Huaylas, the eastern valley along the Santa River between two main central Andes *cordilleras* (ranges), suffered the most. Among them, the coastal city of Casma sustained severe damage to 90 percent of its structures and Chimbote reported almost 3,000 deaths and damage to 70–80 percent of its structures. Although the earthquake itself caused much death and damage, severe losses were also caused by a landslide or *huayco*, which swept down the steep slopes of the Cordillera Blanca from Nevados Huascarán into the Callejón de Huaylas. The city of Yungay, along with thousands of its residents, was buried under meters of mud, earth, water, boulders, and debris. The 1970 earthquake resulted in approximately 50,000 deaths, but was not the worst in Peruvian history.

Four years later, on October 3, 1974, a M_W 8.1 earthquake resulted in seventy-eight thousand deaths. Many buildings around the city of Lima were severely damaged. Liquefaction caused by ground shaking occurred in several parts of the Lima area, principally in the port of Callao. Part of this district is built on landfill and water-saturated sediment, factors that structurally jeopardize not only earthen buildings but also those constructed using modern materials. This geological factor combined with lack of seismic design and construction methods contributed to the collapse of many modern buildings, such as a new, four-story, reinforced-concrete building at the Universidad Agraria (University for Agricultural Studies) in the La Molina district of Lima.[38]

After the 1970 earthquake the seismic engineering community decided to develop a seismic building code. In 1974, the Peruvian government published the first National Building Code, which did not include and therefore essentially banned new earthen construction. In 1976, the Peruvian government created the Servicio Nacional de Capacitación para la Industria de la Construcción (SENCICO, National Training Service for the Construction Industry) that was in charge of training construction workers around the country. Training in traditional construction techniques such as adobe or quincha was not included in the curricula.

Despite more than sixty years of continuous efforts to interdict earthen construction throughout the country—from Piérola's first attempt in 1911, until the exclusion of earthen construction techniques in the 1974 building code—rural communities continued to use this material. Incidentally, most likely also around 1970, a group of structural engineers decided to further investigate reinforcement techniques to improve traditional earthen construction systems rather than abolish them. Academic efforts lead by Peruvian universities such as the Pontificia Universidad Católica del Perú (PUCP) and the Universidad Nacional de Ingenieria (UNI) resulted in the creation of a state organization in charge of research and development of standards for construction materials and techniques. In 1981, President Fernando Belúnde Terry, an architect and planner by training, created the Instituto Nacional de Investigación y Normalización de la Vivienda (ININVI, National Institution for Housing Research and Standardization). This institution was the first entirely dedicated to scientific research for housing and construction in Peru, including the study of traditional and modern materials to provide adequate living conditions to the Peruvian population. Many publications dedicated to proper adobe and quincha construction techniques were published by ININVI (Figure 3.21). In our opinion, the most important achievement of this institution and its associated structural engineers was the inclusion of the *Norma Técnica de Edificación NTE E. 080 Adobe* (Technical Standard 80 for Construction in Adobe) as part of *the National Building Code* in 1985 (Figure 3.22). Despite the fact that ININVI publications were mostly dedicated to new construction, the materials produced were consulted by many architects and engineers pursuing further study on these techniques in the following decades.

In 1992, President Alberto Fujimori dissolved the Ministerio de Vivienda (Ministry of Housing), which held responsibility for regulation of the housing and construction sectors, and moved these functions to the Ministerio de Transportes y Comunicaciones (Ministry of Transportation and Communications, formerly Ministry of Development and Public Works). In 1995, also under President Alberto Fujimori, ININVI became part of SENCICO and ultimately disappeared.



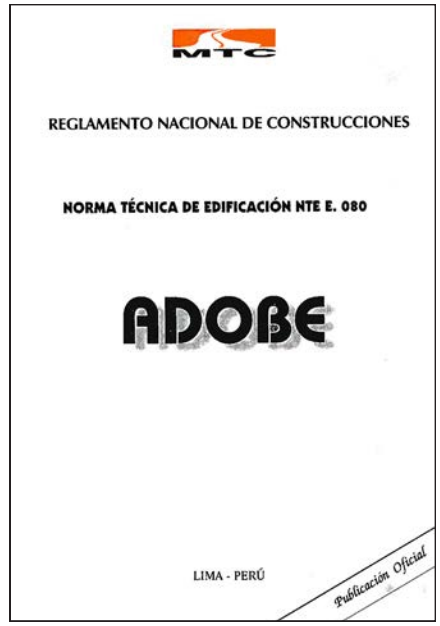


FIGURE 3.21 (LEFT)
Cover of the ININVI publication on historical aspects of quincha construction published in 1989.

FIGURE 3.22 (RIGHT)
Cover of the *Norma Técnica de Edificación NTE E. 80 Adobe* (*Technical Standard 80 for Construction in Adobe*).

During the term of President Alejandro Toledo, the Ministerio de Vivienda, Construcción y Saneamiento del Perú (Peruvian Ministry of Housing, Construction, and Sanitation) was reinstated and is today the institution that regulates building construction nationwide. Specifically, the renovated SENCICO, as a distinct entity within the ministry, is the institution responsible for research, design, and development of the Peruvian National Building Code.[39] The Gerencia de Investigación y Normalización (Research and Standardization Board) of SENCICO has assumed the core objectives of former ININVI and continues to research traditional construction techniques.

The current version of the *Norma Técnica de Edificación NTE E. 080 Adobe* was reviewed for the first time in 2000 and is currently undergoing a second technical review under the aegis of SENCICO. It presents a declaration of scope, general requirements, and definitions of structural elements and components. It also describes the seismic behavior of adobe buildings, provides calculations for seismic design and specifications for the design of adobe walls, and recommends placing reinforcement in slender walls to improve their behavior during an earthquake.

Surveys performed after past earthquakes have shown that adobe buildings suffer much more damage when located on soft soils rather than on firm soils. The current review intends to increase the soil coefficient for adobe buildings on intermediate soils to allow new earthen construction only on rock or very dense soils. The norm also intends to recommend that adobe buildings be constructed with sufficient wall density in both principal directions, with floor plans as symmetrical as possible. Small wall openings centered within walls are recommended, and reinforcement should be provided to tie the walls together. Construction of foundations and plinths with stone masonry is recommended. The 1985 code required the use of bond beams on the tops of all adobe walls and it appears that the new version retains this requirement. It will strongly recommend continuous reinforcement as mandatory for all adobe walls, independent of their slenderness, at least for zones of high seismicity and where collapse of adobe houses has been reported. The reinforcement of adobe walls using cane, welded wire mesh, or the recently-added geotextile mesh is recommended.

However, the new version of the *NTE E. 080* intends to also include norms for *tapial* and quincha for the first time, and will consider guidelines and recommendations for the retrofitting of existing and historic buildings made of adobe*,* quincha, and tapial for the first time as well.

Notes

1 Williams León, *Arquitectura y Urbanismo en el Antiguo Perú*, Historia del Perú, Procesos e instituciones, Vol 9, 371–72.

2 Ibid., 367–585.

3 Ibid., 371.

4 Ibid., 403.

5 Ibid., 433.

6 Hastings, et al.,"The adobes of Huaca del Sol y de la Luna," 36.

7 Cristobal Campana developed comprehensive research studying the ceramics of the Mochica period. Scale models of residential housing were extremely detailed during this period. Williams León, *Arquitectura y Urbanismo*, 491–97.

8 Williams León, *Arquitectura y Urbanismo*, 513–14.

9 Ibid., 569.

10 Agurto Calvo, *Lima Prehispánica*, 177.

11 Cobo, *Historia de la fundación de Lima*.

12 Ulloa, Juan, and Saumell, *Viaje a la América Meridional,* 42–43.

13 Paz Soldán, *Geografía del Perú,* 66.

14 Real Academia Española Web site: http://www.rae.es/.

15 For instance at the sites of Çatalhöyük (Turkey) and Shillourokambos (Cyprus).

16 Marussi Castellan, "Bóveda a base de quincha en las edificaciones monumentales del virreinato del Perú," 147–56.

17 Ibid., 59–66.

18 National Peruvian Library Web site: http://www.bnp.gob.pe/.

19 Bromley and Barbagelata, *Evolución Urbana de la Ciudad de Lima*, 129.

20 Ibid., 35.

21 The *Libros de Cabildos* of Lima are forty five volumes of proceedings of meetings of the municipality of Lima, from 1535 and 1824.

22 Bromley and Barbagelata, *Evolución Urbana*, 71.

23 Duarte Fonseca, *1755 O Terramoto de Lisboa*, 86.

24 Walker, *Shaky Colonialism,* 91.

25 See: Harth-Terré and Márquez Abanto, "Historia de la casa urbana virreinal en Lima" and Harth-Terré, "*Perú, Monumentos Históricos y Arqueológico."*

26 The *Conciertos de Obra* were detailed descriptions of construction processes written by master masons and stored at the ayuntamiento, probably for tax purposes. Most of them still exist at the National Historic Archives; Harth-Terré and Márquez Abanto, "Historia de la Casa Urbana Virreinal," 58–100.

27 Harth-Terré, "*Perú, Monumentos Históricos y Arqueológico,"* 45.

28 García Bryce, *La Arquitectura en el virreinato y la República*, 11–166.

29 Ibid., 20.

30 San Cristóbal Sebastián's research includes the following titles: *Arquitectura Virreynal Religiosa en Lima* (1988); *Lima: Estudios de la Arquitectura Virreinal* (1992); *La Catedral de Lima: Estudios y Documentos* (1996); *Fray Diego Maroto: Alarife de Lima, 1617-1696* (1996); *Arquitectura Planiforme y Textilográfica Virreinal de Arequipa* (1997); *Esplendor del Barroco en Ayacucho: Retablos y Arquitectura Religiosa en Huamanga* (1998).

31 García Bryce, *La Arquitectura*, 64.

32 Ibid., 29.

33 Ibid., 98.

34 Bromley and Barbagelata, *Evolución Urbana,* 94.

35 Silgado Ferro, "Historia de los sismos más notables ocurridos en el Perú (1513–1970)," 36.

36 García Bryce, *La Arquitectura*, 125.

37 Peru's first cement company, Compañía Nacional de Cemento Portland, opened in 1916, followed by its affiliate, Compañía Nacional de Cemento Portland Pacasmayo, in 1946.

38 United States Geological Survey, Historic Worldwide Earthquakes.

39 The Web site for the Ministerio de Vivienda, Construcción y Saneamiento is at http://www.vivienda.gob.pe/ and SENCICO at http://www.sencico.gob.pe/.

CHAPTER 4

Earthen Architectural Heritage in the Affected Area

Un alumno de la Escuela de Ingenieros preguntó a Don Teodoro Elmore, profesor de construcciones civiles, en qué forma debía proceder para fabricar buenos adobe; dando a su pregunta toda la gravedad de una consulta técnica y Elmore respondió sencillamente: Amigo mío, búsquese un adobero. (A student from the School of Engineering asked Mr. Teodoro Elmore, professor of construction, how to technically prepare adobes. Elmore replied, "Look for a good adobe mason, my friend.")

—José Gálvez in Nuestra Pequeña Historia, 1930

This section characterizes the structural damage observed at the visited sites during the assessment performed by the GCI team. A summary of preliminary observations of each of the surveyed buildings is given, with detailed descriptions and graphic examples of damage prototypes. The description of the observed damage includes the likely cause or causes and the expected hazard posed by each. The influence of preexisting conditions, such as previous earthquake damage, including incompatible or inadequate previous interventions, and lack of maintenance is also discussed. Finally, conclusions are given and preliminary recommendations presented in an attempt to enhance seismic performance of earthen buildings in Peru.

Limitations

The survey was conducted under a limited timeframe (two days), but with sufficient time to obtain a snapshot and gather general observations on damage typologies. More definitive conclusions regarding modes of failure would have required further studies, more background information, and additional time to analyze the structures visited. Furthermore, location of the debris from fallen structures helps to explain why the buildings failed, but unfortunately most of the debris was removed from the sites before the visits occurred. Significant sites had not been adequately documented prior to the earthquake, nor was damage systematically documented after the quake, which hampered the ability to analyze failure mechanisms and the effect of pre-existing conditions.

During the trip, the team concentrated on assessing twelve historic buildings and two significant archaeological sites.[1] However, the team was aware that the types of buildings visited—although significant for the region and the country—do not represent the vast majority of non-monumental dwellings in rural areas and small towns. This same limitation applies for the type of damage and modes of failure characterized in this report. Generally speaking, historical monumental buildings perform better than vernacular housing, probably as the result of better workmanship during their construction and from maintenance over time.

The reconnaissance visit offered an outstanding opportunity to understand building failures and to propose directions for future research (Figure 4.1). Considering the specific limitations noted above, the recommendations concentrate on identifying

FIGURE 4.1
GCI team member Luis Villacorta recording the assessment of earthen historic sites damaged by the 2007 earthquake in Pisco, Peru. 2007.

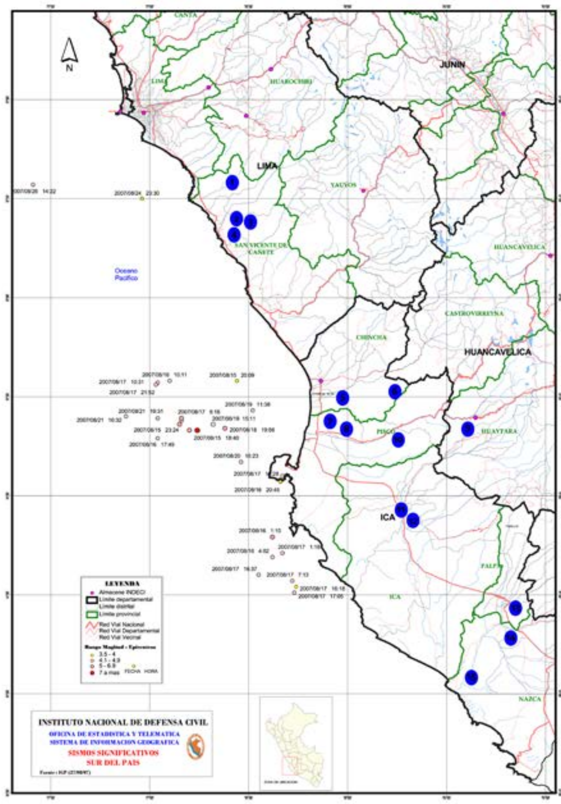
potential areas of study rather than providing specific technical solutions for seismic retrofitting.

Summary of Observations

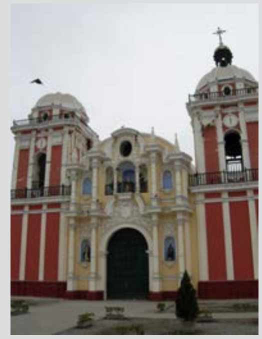
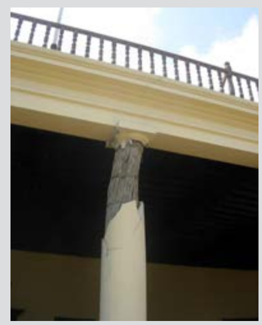
The locations of sites visited in conjunction with the damage assessment can be found in Figure 4.2. The sidebar (pp. 47–49) summarizes the preliminary comments provided by GCI consultants about the sites visited October 30 and 31, 2007.[2]

FIGURE 4.2
Map shows location of sites in relation to significant earthquakes in 2007. Images below show sites as they appeared during the October 28 to November 2, 2007 post-earthquake assessment. From left to right: (1) Church of Chilca (2) Church of Coayllo (3) and (4) Hacienda Arona y Montalván: Main state house and worker residences (5) Hacienda San José (6) Church of El Carmen (7) Cathedral of Pisco (8) Church of San José (9) Church of San Javier de Ingenio, Nazca (10) Cahuachi archaeological site (11) Cathedral of Ica (12) Church of Guadalupe (13) Church of Huaytará (14) Tambo Colorado archaeological site (15) Church of Humay.

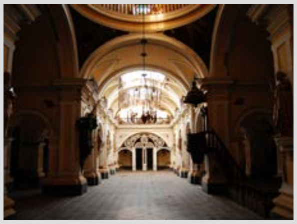
Site Locations



Buildings visited by the GCI team, October 30 and 31, 2007

Name	State before the EQT	Comments	MMI	Photo after EQT
Iglesia de Chilca (Church of Chilca), Cañete	Evidence of past interventions using concrete elements after previous earthquakes.	Collapse of the quincha lantern in the dome of one of the towers. Extensive cracking between the towers and the frontispiece of the facade. Interior cracking in the central vault as well as at the junction between arches, columns, and the vault.	VI–VII	
Iglesia de Coayllo (Church of Coayllo), Cañete	Lack of repairs following previous earthquakes left the building in poor condition. Serious termite damage to the wooden elements of the vaulted roof system, as well as weak connections between lateral walls, vaults, and buttresses.	Total collapse of the central section of the quincha vault, likely due to the combination of materials, conditions, and variations in wall thickness.	VI–VII	
Hacienda Arona y Montalván (Montalván and Arona estate chapel, main house and worker residence area), Cañete	*Chapel:* Visible termite damage on wooden structural elements. *Main house:* Visible termite and beetle damage to wooden beams and adobe walls. *Worker residences:* The residences were probably not maintained over time.	*Chapel:* Visible separation of adobe walls and displacement of tower indicates lack of connections between the walls, the roof, and the tower in the chapel. *Main house:* The heavy dirt layer over the roof and long spans between roof beams could have provoked rotation of colonnades. *Worker residences:* Thinner walls collapsed, walls overturned out-of-plane, separation at corners, and diagonal shear cracks.	VI–VII	 
Hacienda San José (San José estate main house), Chincha	The estate has been properly maintained over time. However, it seems several interventions such as replastering and the use of new materials have been undertaken prior to the earthquake.	No collapse where walls were of thick adobe (mostly the main house). Quincha walls collapsed where severe termite damage was present. Heavy damage to the dome of one of the chapel towers. Evidence of separation cracks at the roof, wall juncture, and corners. Severe detachment and loss of plaster around the chapel and main house.	VII	

Name	State before the EQT	Comments	MMI	Photo after EQT
Iglesia del Carmen (Church of El Carmen), Chincha	The church was maintained and additions had been made. Use of modern materials was recorded.	The upper portion of the facade is substantially damaged and the left tower partially collapsed. Horizontal and vertical cracks were visible on the main facade at the connections with the towers. The team was not able to enter the site to assess the interior. However, no visible damage to the interior of the church was observed.	VII	
Catedral de Pisco (Cathedral of Pisco), Pisco	The dome at the intersection of the vaults was at some point reconstructed in reinforced concrete. The nave vault appears to have been framed with lightweight truss arches, probably fabricated by welding rebar pieces to form arches.	Total collapse of vaulted roof. Side walls of the nave appear to have been tall and thin with slender concrete pilasters. The combination of reinforced concrete elements with earthen materials appears to be the cause of roof and wall collapses. The concrete dome and columns that survived the earthquake probably pounded the remaining earthen walls until collapse.	VII	
Iglesia de San José (San José Church), Nazca	The site was abandoned in 1970 and the vault totally collapsed after an earthquake in 1996. There is strong evidence of the use of diverse original materials.	It appears that the 2007 earthquake exacerbated existing cracks; quincha towers in the facade are extremely unstable. Walls show little damage, but significant wooden decay of the arches and framework of the quincha decorations was observed.	VII	
Iglesia de San Javier de Ingenio (San Javier de Ingenio Church), Nazca	Vaulted roof and ceiling made of fired brick with brick arches partially collapsed (1940 or 1942 earthquakes).	Main facade seems to be structurally disconnected from the body of the church. Walls 1.5 m thick constructed of fired brick with pockets of adobe showing severe beetle damage. Sacristy dome with similar construction technique has wall paintings with structural cracking.	VII	
Sitio Arqueológico Cahuachi (Cahuachi Archaeological site), Nazca		There is no evidence of damage. This may be a result of the structural composition of the structure (pyramid), quality of original material, ongoing reconstruction, and the type of soil where the structure is located, or the distance from epicenter.	V	

Name	State before the EQT	Comments	MMI	Photo after EQT
Catedral de Ica (Cathedral of Ica), Ica	There is evidence of previous interventions using modern materials.	The facade is not connected to the adobe side walls. The towers seem to be out-of-plane generating stress on the vault. The gable appears to have rocked outward. There is evidence that the exterior nave walls rocked and the interior pillars rotated outward. The quincha vaulted roof system failed between the wooden arches. The canes –probably in bad condition–collapsed at midspan, but the vaults themselves did not fail. The central dome did not collapse but strong cracking and detachment of mud plaster was observed.	VII	
Iglesia de Guadalupe (Church of Guadalupe), Ica	The towers were rebuilt of concrete frame elements and fired brick infill. One end of the vault has a concrete arch with a brick infill above the adobe wall.	Total collapse of middle section of the facade as well as the quincha vault. The towers probably hit the middle part of the facade and precipitated the collapse of the vault.	VII	
Iglesia de Huaytará (Church of Huaytará), Huancavelica	Structure over Inca stone walls, with adobe and fired brick belfries. Evidence of original buttresses and traditional wooden reinforcement techniques.	No evidence of structural cracking but severe dome collapse in the upper sections one of the towers. Moisture damage due to the presence of water from leaking roof.	V	
Sitio Arqueológico Tambo Colorado (Tambo Colorado archaeological site), Ica		No noticeable damage except traces of diagonal cracking between adobe block and mortar. Vertical cracking at the junction of perpendicular walls, among others, was observed.	VII	
Iglesia de Humay (Church of Humay), Ica	The church apparently is far from its original floor plan with sections made of new materials. The remaining tower is of fired brick.	Collapse of huge middle section of the vault, with severe termite damaged wooden arches and beams, old joints made of leather strapping, and new joints of steel plates. Weak connections between the walls and the vaulted roof system were observed.	VII	

Estimates are provided for the intensity of the earthquake around the location of each site. Detailed descriptions are provided in the Damage Assessment Typologies section (pp. 46–55).

Damage Assessment Typologies

Adobe, typically used to build thick and massive walls, is a low-strength building material that is able to resist compression but is weak in response to tensile forces. The stresses absorbed by an adobe wall during an earthquake normally exceed the wall's tensile strength. The building dissipates the energy released by the earthquake through crack formations that divide the wall into isolated blocks that pound against each other until the structure suddenly collapses. *Quincha,* on the other hand, is a relatively high-strength building construction technique with thin and very flexible membranes. The wooden frame and the cane structure can absorb the tensile stress, producing only superficial cracks on its surface. Collapse normally occurs when wooden elements are decayed or disconnected from one another and the cane elements are exposed to extreme compression and are unable to function structurally.

Tolles et al., in 1996, stated that the extent of earthquake damage to an adobe structure "is a function of (a) the severity of the ground motion, (b) the geometry of the structure, i.e., the configuration of the adobe walls, roof, floors, openings, and foundation systems, (c) the existence and effectiveness of seismic retrofit measures, and (d) the condition of the building at the time of the earthquake." [3] In the Peruvian case, this applies to quincha as well.

The severity of the ground motion is impossible to control or prevent and is conditional to the soil type on which the structure is built. Soft soils will amplify the energy frequency or the ground motion acceleration generated by the earthquake while firm or rocky soils will absorb them, producing less damage to still-standing structures and allowing more time for occupants to leave the building before sudden collapse occurs. Buildings over soft soils suddenly collapse in less time than

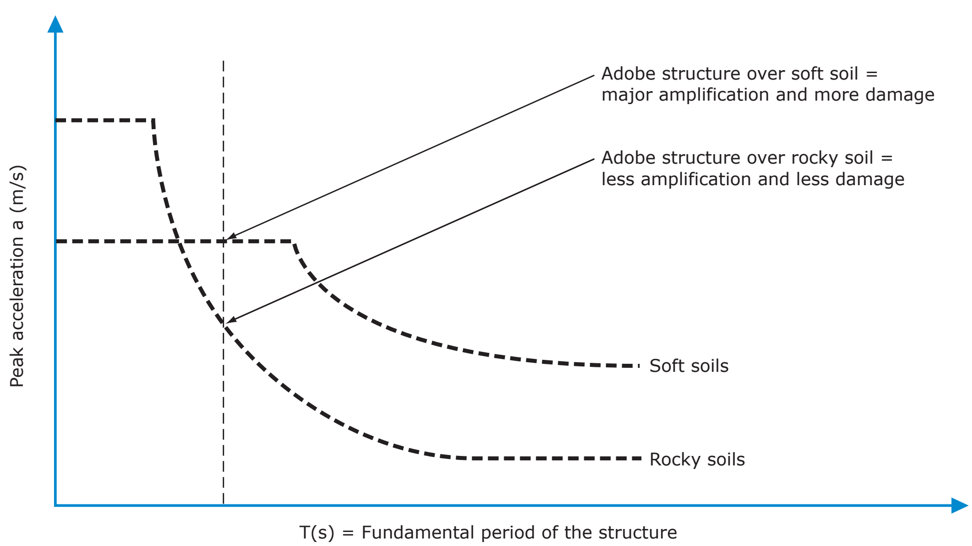


FIGURE 4.3
Diagram showing the theoretical response spectrum of an adobe building over rocky vs. soft soil.
Drawing: Claudia Cancino.

the ones built over rocky soils and, in most of the cases, fall with occupants still inside (Figure 4.3).

The cities of Pisco and to some extent Chincha and Ica are built over soft soils whose geological characteristics are described in Chapter 2.

The geometry of a building is a critical function of its ability to withstand a seismic event. It is now accepted that thick adobe walls perform more adequately than thinner ones during a seismic event, because the thicker the wall the easier it is for it to rock and remain stable. Furthermore, adobe walls connected to other walls perpendicularly or those reinforced with buttresses also perform more adequately than those with no reinforced elements. Limited openings along the walls reduce patterns of weakness and increase seismic resistance.

Tolles et al. provide excellent descriptions of the damage typologies for adobe walls after the 1996 Northridge earthquake in California, United States. The survey performed in 2007 in Peru found similar damage typologies in the adobe walls of the visited sites. As a complement to the work performed in 1996, the following section provides descriptions, figures, and photographs of damage failures observed in quincha walls, vaults, and domes after the August 15, 2007, earthquake in southern Peru.

Quincha Deterioration Mechanism

Most of the earthquake damaged sites visited were constructed with domes, vaults, and walls made of quincha. Although Chapter 2 provided information about quincha construction details and when it came into use in Lima and other cities, no explanation was given about how the technique deteriorates through time.

Regular maintenance of these structures was expected in the ancient and colonial eras in Peru, including the occasional replacement of the wooden structural elements, cane reed, and leather straps. With time and lack of maintenance, wooden elements were damaged by the presence of termites and the connections started to fail. The leather straps became brittle and the reed cane detached from the structure, resulting in loss of flexibility and tensile strength (Figures 4.4 and 4.5). The state of deterioration of this construction system influenced the way buildings performed during the August 15, 2007, earthquake.

Dome / Vault Failure

A number of the sites visited exhibit failure of the quincha domes or vaults. This primarily took the form of partial or total collapses in vaults and shifts or total collapses of domes over church towers.

FIGURE 4.4 (LEFT)
Quincha detail showing leather strap conditions, Cathedral of Ica, in October 2007.

FIGURE 4.5 (RIGHT)
Quincha detail showing deteriorated wooden arches at the Church of San José de Nazca, in October 2007.

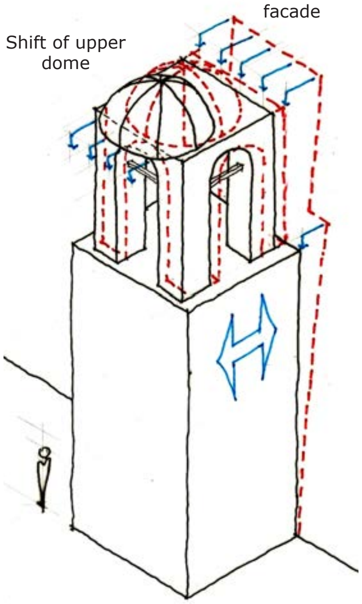


FIGURE 4.6
Scheme of mode of failure of typical church tower. In red, original position of tower. In blue, rocking of tower.

FIGURE 4.7
Detail showing total collapse of church tower dome at the Church of El Carmen in Chincha, as it appeared in October 2007.

FIGURE 4.8
Detail showing shift of church tower dome at the Estate Church of San José, Cañete, as it appeared in October 2007.

Shift or Total Collapse of Church Tower Domes

The churches of Chilca, El Carmen and Huaytara, and San José Estate Chapel.

In these four structures, the structural difference between the quincha pillars and the adobe towers during pounding precipitated the dome's failure, shift, and in some cases eventual collapse (Figure 4.6). In most of the sites visited, severe termite damage was observed under detached plaster in all the wooden structures of the quincha pillars, vaults, and domes. The damage was not limited to the wooden elements, but was also present in the cane mesh that ties all elements of the wooden frame and the entire panel together. The damaged pillars of the towers did not resist the stresses of the earthquake. They failed and transmitted stress to the vaults, which, weakened by the poor condition of their wooden elements, moved horizontally and in some cases collapsed (Figures 4.7 and 4.8).

Partial or Total Vault Collapse

Church of Coayllo, Cathedral of Pisco, Churches of San José and San Javier, Cathedral of Ica, Church of Guadalupe, and Church of Humay.

Vault collapse is probably the most dramatic consequence of the earthquake and caused the greatest number of fatalities, particularly at the Cathedral of Pisco. The causes of the vaults' collapse are multiple and a result of cumulative issues over time.

As mentioned before, wooden structural elements and the cane mesh of the quincha were heavily damaged by termites in most of the visited sites. In the case of the vaults, the damage was observed at the wooden arches and at their connections to the top of the adobe walls or pilasters. There is also evidence of total dis-

FIGURE 4.9
Earthquake damage to the Church of Guadalupe in Ica, as seen in October 2007.

connection between the adobe walls and the facade, particularly at the Church of Guadalupe (Figure 4.9), which occurred either before the earthquake or at the moment of the earthquake. Another pre-earthquake condition contributing to collapse is the presence of a heavy layer of dirt or cement mortar over the vault, probably due to lack of or inappropriate maintenance.

The rocking of the walls, compounded by a possible lack of proper connection to the roofing system, and a lack of connection between the roofing system and the facade, created stress in the flexible quincha roof. At the moment of the earthquake, the vault tried to restrain the rocking of the walls, adding stress to the deteriorated trusses and their connections until failure. The final result was the total collapse of the entire vault (Figure 4.10). At the churches of Coayllo, Guadalupe, Humay, and the Cathedral of Pisco, the presence of reinforced concrete arches at the end of

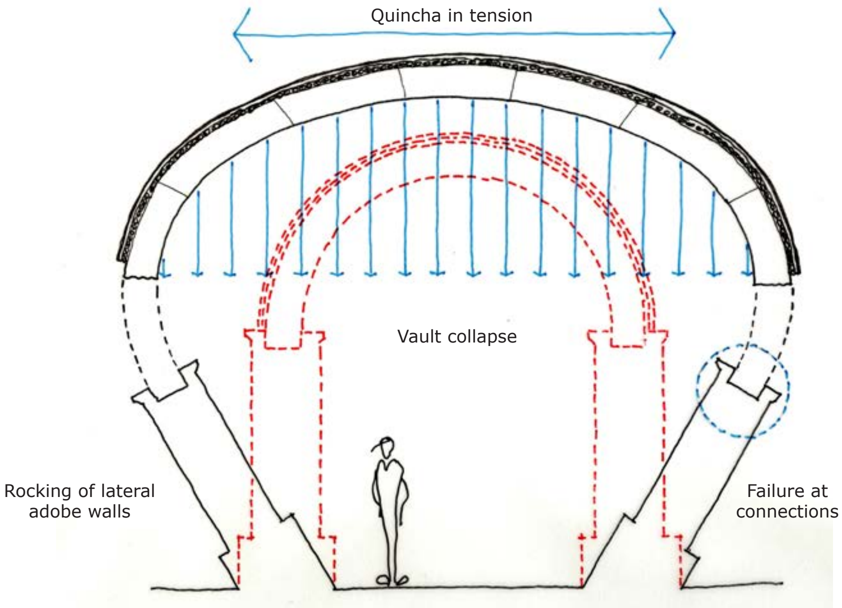


FIGURE 4.10
Scheme of vault under tension, In red: original position of the vault. In black: exaggerated displacement during earthquake.

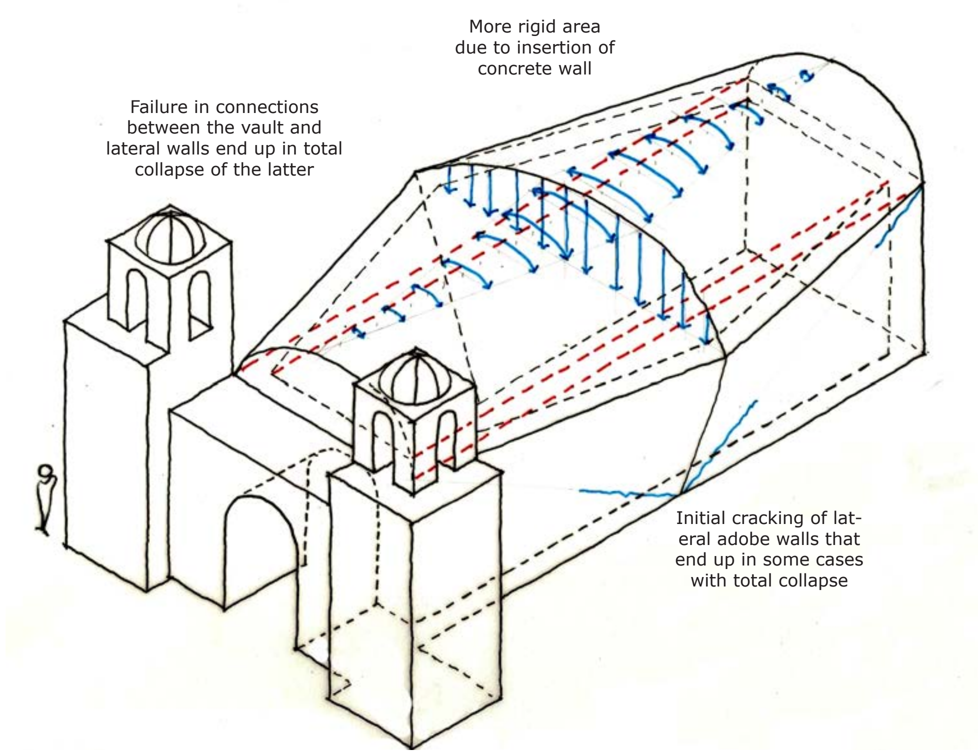


FIGURE 4.11
Scheme of vault total collapse and out-of-plane behavior of adobe lateral walls, as seen at the Church of Coayllo, Cañete.

Figure 4.12
View of the total collapse of the vault at the Church of Coayllo, Cañete, as seen in October 2007.

the vaults stiffened the structure at both ends, which, in conjunction with the deteriorated arches, created transversal tension and induced the quincha vault to fail (Figures 4.11 and 4.12).

At the Cathedral of Ica, the architectural configuration of the building helped it to partially withstand the earthquake. The presence of lunettes between the arches, as well as side chapels, prevented the total collapse of the vault which also seemed to have a heavy layer of dirt on top of the roof (Figures 4.13–4.16).

It is important to mention that the cathedral's architectural configuration, as well as its materials and construction technique, were used for the construction of

FIGURE 4.13
Detail of vault failure in the main nave of Cathedral of Ica following the Pisco earthquake, as seen in October 2007.

FIGURE 4.14
View of crack where partial collapse of the vault occurred at the Cathedral of Ica, as seen in October 2007.

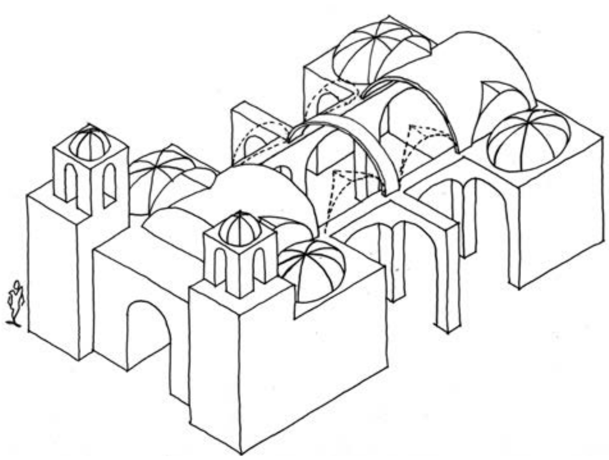


FIGURE 4.15
Scheme of the Cathedral of Ica detailing the position of quincha arches, lunettes, and pilasters.

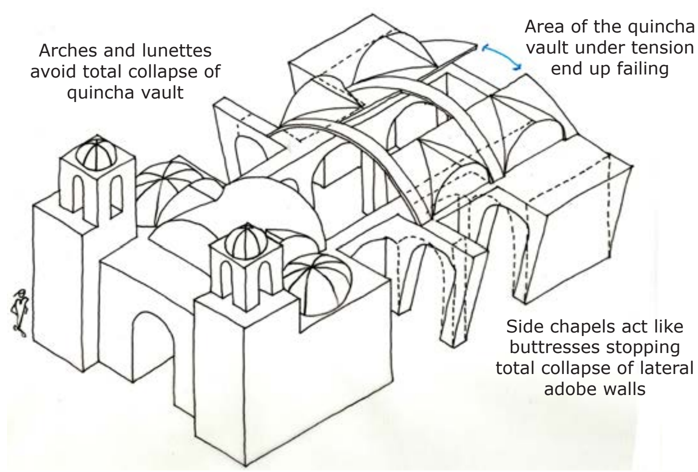


FIGURE 4.16
Scheme of vault partial collapse at the Cathedral of Ica.

most of the Spanish earthen churches still standing along the coast of Peru and in other Latin American countries. Particularly in the case of the cathedral, the short distance between the pillars along the central nave, as well as their height, contributed to the building's ability to withstand the earthquake despite its proximity to the epicenter.

Out-of-Plane Collapse

When entire vaults or domes collapsed, it was clear that walls (front facades or lateral walls) rocked until connections failed, resulting in partial vault collapse (Figures 4.9 and 4.17–19). In the case of the Church of Guadalupe, the concrete tower pounded the earthen façade until collapse of its upper section induced partial collapse of the vault (Figures 4.9 and 4.17). In the case of the Church of Coayllo, partial out-of-plane collapse of more recently constructed adobe walls caused the total failure of its vault (Figure 4.18).

FIGURE 4.17
Scheme of facade failure as seen at the Church of Guadalupe, Ica.

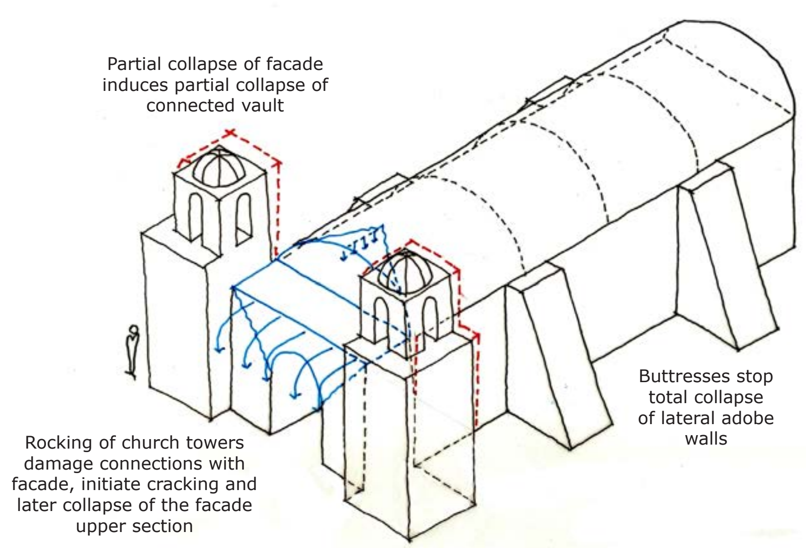


FIGURE 4.18
Partial out-of-plane failure of adobe lateral wall at the Church of Coayllo, Cañete, as seen in October 2007.

FIGURE 4.19
A stand-alone adobe wall at the Church of Chilca showing out-of-plane failure in October 2007.

FIGURE 4.20
Arona y Montalván estate workers residences showing out-of-plane collapse, October 2007.

A much more obvious example of this type of failure, however, was observed at stand alone walls at the Church of Chilca (Figure 4.19) and at the main house and worker residences of the San José and Arona y Montalván Estate respectively (Figure 4.20), where wall sections collapsed. In both cases, the slenderness ratio of the walls didn't withstand the rocking during the earthquake. The process for this type of failure is very well explained by Tolles et al. who write, "Flexural cracks begin as vertical cracks at transverse walls, extend downward vertically or diagonally to the base of the wall, and extend horizontally to the next perpendicular wall . . . after cracks have developed, the out-of-plane stability of a wall is dependent on the slenderness ratio, connection to the structure, vertical loads, and the condition of the wall at its base."[4]

Damage to Columns and Pillars

Damage to columns and pillars was observed at the Cathedral of Ica and the Arona and Montalván Estate. It was interesting to observe how flexible the quincha structural elements were, improving the ability of the whole building to withstand seismic events without collapsing.

In the case of the Cathedral of Ica, the hollow pillars constructed with wooden frames and cane mesh plastered with mud and gypsum suffered from plaster detachment at their bases. It seems that the quincha pillars were able to absorb most of the energy and only plaster detachment at the bases was recorded (Figures 4.21 and 4.22).

In the case of the Arona y Montalván Estate main house, it seems that the roof of the veranda moved in two directions: parallel and perpendicular to the long facade of the building. A resulting gap was observed at the roof of the building between the veranda and the main house, as well as a crack between the veranda and the main tower (Figure 4.23). The plaster detachment at the upper section of the columns could be the result of the rotation of the columns. The balustrade and the bases seem to have prevented the whole structure from collapsing. (Figures 4.24–4.27)

FIGURE 4.21 (LEFT)
View of plaster detachments on the bases of pillars in the central nave, Cathedral of Ica, as seen in October 2007.

FIGURE 4.22 (RIGHT)
Detail of plaster detachments at quincha pillars of the Cathedral of Ica, October 2007.

Plaster Detachment

Although plaster detachment is not structural damage, it is important to mention it as a condition worth study and repair. Well-maintained plaster layers contribute in a major way to the overall coherence of the structure.

Many plaster detachments were observed on vaults, domes, walls, columns, and pillars of the visited sites (Figures 4.28 and 4.29). Furthermore, and most importantly, previous unrepaired plaster detachments left the wooden elements of the quincha roofing systems, as well as columns and pillars, exposed to the environment which generated termite damage, as observed at the Churches of San José and San Javier de Ingenio in Nazca.

FIGURE 4.23
Displacement gap in the roof of the Arona y Montalván Estate main house, Cañete, as seen in October 2007.

FIGURE 4.24
Plaster detachment on the colonnade of the Arona y Montalván Estate main house, Cañete, as seen in October 2007.

FIGURE 4.25
Detail of plaster detachment and rotation of column at the Arona y Montalván Estate main house, Cañete, October 2007.

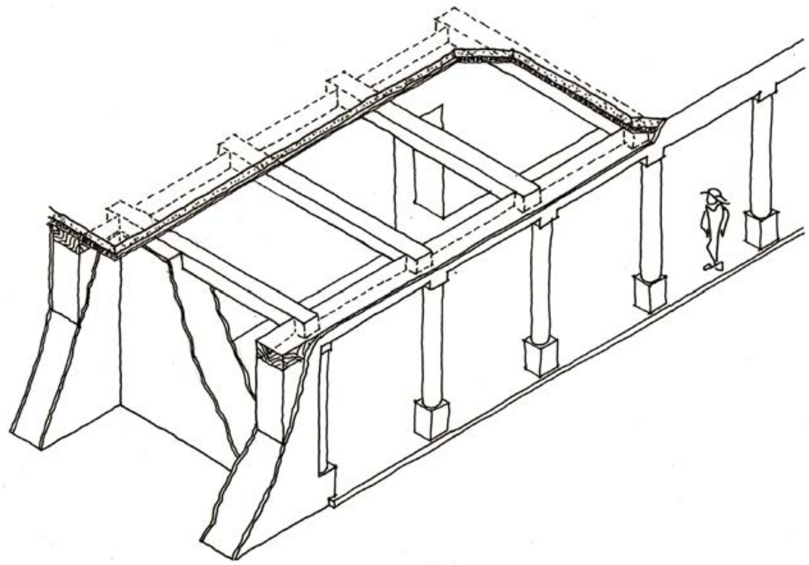


FIGURE 4.26
Scheme of the roofing system of the Arona y Montalván Estate main house.

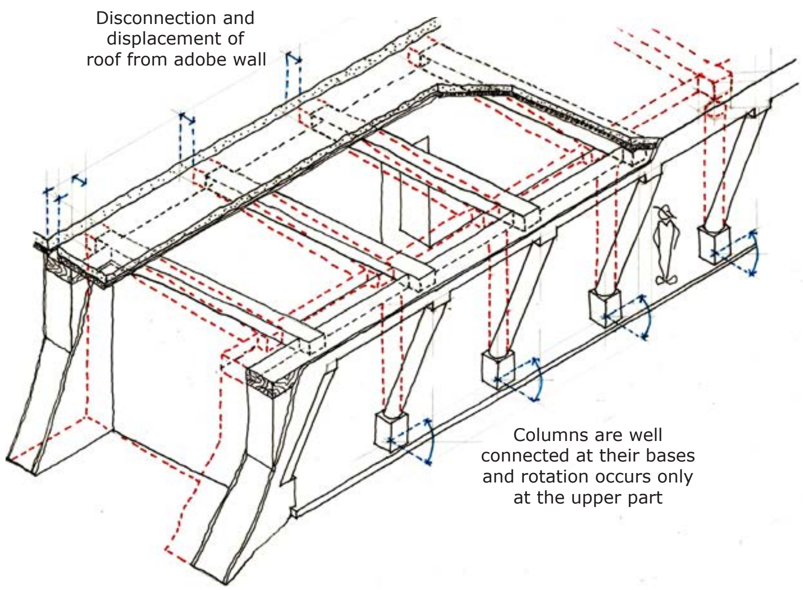


FIGURE 4.27
Scheme of roofing failure at the Arona y Montalván Estate main house. In red: the original position of the roofing system. In black: exaggerated displacement under seismic activity. In blue: direction of rotation of columns and crack displacement.

During the earthquake, the damaged wooden structural elements failed, structurally disconnecting the walls and inducing collapse. When previous plaster detachments were repaired with incompatible materials such as layers of cement over the quincha vaults or domes, heavier loads were applied to the earthen walls inducing out-of-plane collapse. That was probably the case at the Church of Coayllo and the Cathedral of Pisco.

Conclusions

Upon completion of the site assessment and after further reflection on the modes of failure of the visited structures, the team concluded the following:

- Earth construction in Peru represents a great part of its cultural and vernacular heritage. It is one of the main materials for the construction of today's

FIGURE 4.28
Plaster detachment on the dome of the Cathedral of Ica, as seen in October 2007.

FIGURE 4.29
Detail of plaster detachment on dome at the Church of Chilca, in Cañete, as seen in October 2007.

Peruvian settlements.[5] The historical, social, cultural, and economic values of earthen architecture have to be considered while proposing guidelines for retrofitting.

- Over the centuries, earth has been used alone and as a part of sophisticated building systems (e.g. quincha), demonstrating the abilities of Peruvians to develop appropriate solutions to seismic activity. These local materials and traditional techniques have required the expertise of master masons who exploited the material's strength while making accommodations for its weakness. Evidence suggests that the evolution of Peruvian building technologies attempted to address seismic reinforcement. Indigenous knowledge developed over time to improve the use of earth as a building material in earthquake-prone areas.
- Social changes and modernization at the end of the nineteenth century introduced new industrialized building technologies and materials. However, concrete use was limited to the main cities, leaving earth as the predominant construction material in rural areas. Local knowledge on how to properly maintain and build earthen dwellings declined over time, leaving earthen buildings prone to decay and more susceptible to subsequent damage induced by earthquakes. Concerns about the life/safety and seismic performance of earthen buildings have been the impetus for banning earth as a suitable contemporary construction material.
- Earth remains the predominant building material in the existing building stock. Therefore, effort is needed to improve seismic performance of new earthen construction and to develop solutions to reduce the vulnerability of significant existing earthen sites.
- The field survey focused on earthen buildings of cultural significance that had experienced numerous previous earthquakes. In the case of some of the churches, previous damage had not been repaired. During the August 2007

earthquake, seismic damage was a result of the cumulative effects of seismic activity, and lack of maintenance and repair.

Influence of Building Typology

The two basic types of structures visited exhibited fundamental differences in their construction and consequently in their seismic performance. The solutions for improving structural performance during earthquakes must also be completely different for these two types of structures.

- The *hacienda* or estate-type structures were characterized by square to rectangular spaces of modest plan area and relatively short wall spans. The solid adobe walls were not tremendously thick and a few cross walls of quincha were of little help in bracing the adobe walls. The roofs were flat with joists or *vigas* bearing on the walls. Damage to these structures was the result of walls not being tied together at their intersections and the roof joists not anchored to the tops of the walls.
- Church structures were characterized by the massive, long, tall walls of the nave, unsupported, except at the ends, by the facade wall and transepts or sanctuary walls, and lightweight brittle roof/ceiling framing of wooden arches and quincha, which provided no restraint to the rocking movement of the long walls.

Impact of the Lack of Maintenance on the Structure

The structural integrity and seismic performance of earthen historic sites are a result of: (1) the bonding between adobe blocks (2) the wall to foundation, wall to wall and wall to roof connections and (3) the condition and structural integrity of the quincha wooden frames. The seismic behavior of the visited sites was affected by maintenance issues that significantly reduced the structural integrity of the building, including:

FIGURE 4.30
Out-of-plane of adobe wall failure due to lack of proper wall-roof connections. Main estate house, Hacienda San José, Cañete, as seen in October 2007.

FIGURE 4.31
Separation of main façade from vault at the Church of Hacienda San José de Nazca, as seen in October 2007.

FIGURE 4.32
Displacement of upper dome due to failure of connections with tower pillars, Church, Hacienda San José, Cañete, as seen in October 2007.

FIGURE 4.33
Detail showing week mortar adhesion strength at the Church of Coayllo, Cañete, as seen in October 2007.

FIGURE 4.34
Detail showing beetle damage to the adobe walls at the worker residences of the Hacienda Arona y Montalván, Cañete, in October 2007.

FIGURE 4.35
Detail showing termite damage to wooden framework at the Church of Hacienda San José de Nazca, in October 2007.

FIGURE 4.36
Detail showing termite damage to wooden framework at the Church of Hacienda San José de Nazca, October 2007.

- Loss of structural integrity and lack of connections between damaged wooden elements of quincha vaults, pillars, and walls, which isolated parapets, partitions, and facades affecting their stability (Figures 4.30–4.32)
- Pre-existing and unrepaired structural cracking and weak mortar to block adhesion strength, which induced further cracking (Figure 4.33)
- Moisture damage to the quincha and adobe walls, to such an extent that the walls suddenly collapsed
- Beetle damage in the adobe blocks that reduced the strength of the wall (Figure 4.34)

FIGURE 4.37
Detail showing the mixture of building materials used at the Church of Coayllo, as photographed in October 2007.

FIGURE 4.38
Detail showing the mixture of building materials used at the Church of Chilca, as photographed in October 2007.

FIGURE 4.39
Detail showing the mixture of building materials used at the Hacienda Arona and Montalván in Cañete, as photographed in October 2007.

- Termite damage to the wooden framework of the quincha walls, which contributed to partial or total collapse of entire structures (Figures 4.35 and 4.36).
- Addition of different building materials and systems into the structure. Areas of fired brick or stone, and in a number of cases reinforced concrete frames with infill of adobe or fired brick, had an effect in the building performance of the visited sites (Figures 4.37–4.39).

Modes of Failure

While it is difficult to assess the structural interactions of the systems exhibited in the building assessment, a number of general observations can be made:

- The performance of load-bearing adobe walls was consistent with behavioral expectations for thick and slender adobe walls as observed in previous earthquakes and shake table testing research:
  - — Massive adobe walls generally moved and rocked independently of each other, forming (or reopening) cracks, but generally remained standing.
  - — Slender adobe walls of the estate-worker residences were unable to resist the rocking movement and collapsed entirely once the vertical cracks isolated them from the building's structural system.
  - — Both of these seismic behaviors are an affirmation of the basic premise of GSAP that suggests that adobe walls with adequate height-to-thickness ratios will achieve stability without a great deal of strengthening.[6]
- In churches with vaulted wood and quincha roofs, the massive adobe walls moved independently of the vaults when the connections failed, causing them to lose bearing and then collapse. These original construction systems had notched, wooden base plates to tie arched roof beams into the walls and also heavy adobe wall extensions above the arches' bear-

ing points to try to lock the vaults into the top of the adobe walls. When the wooden base plates were in good condition or constrained by other elements, such as the lunettes, the arches stood still, while the vaults collapsed between them.

- There appear to be three possible modes of wall/roof movements to explain the damaging effects to the very flexible quincha ceiling/roof systems:
  - The long nave walls move more or less together. The arched/vaulted roof framing must deform the ends, being embedded in a mass of adobe on top of the walls. The deformations are too great for the deteriorated arches to withstand and they collapse. (not very likely)
  - The long nave walls do not move out-of-plane very much, but the arched/vaulted roof, being very flexible, responds to the earthquake vibrations in the vertical direction, bouncing up and down at mid-span. The quincha roof/ceiling, made of wooden elements, cane, and mud plaster, is flexible but brittle after lack of maintenance resulting in failure of the roof system (somewhat likely).
  - The longitudinal nave walls move out-of-plane independently of one another Again, the flexible roof/ceiling system cannot hold the walls together and cannot accommodate the relative displacement of the nave walls. (most likely).

Recommendations

1. There are already a number of technical options based upon scientific research and worth disseminating for building safely with earth and retrofitting historic earthen sites located in earthquake zones. The work developed by PUCP, UNI, and GSAP is crucial to understanding how buildings behave during earthquakes, as well as for the conservation of earthen sites located in seismic regions.
2. There is potential to develop less-invasive alternative retrofitting techniques by adapting traditional and historical methods and materials in order to increase safety in existing earthen buildings. Scientific data needs to be acquired to apply engineering concepts and values to traditional retrofitting systems.
3. In Peru, there are important institutions, organizations, and a community of experts with a comprehensive understanding of the problem who exhibit a strong will to support the preservation of earthen architecture. These conditions could well support and initiate research, implementation, and dissemination of enhanced retrofit methods and the proper conservation methodologies for site maintenance and retrofitting.
4. There does not appear to be a readily obvious solution to the church-roof collapse problem. Ideally, there should be a mechanism to ensure that the walls move in concert and that the roof/ceiling framing system is flexible *and* strong enough to withstand the deformations caused by the out-of-plane wall movement. This could potentially be achieved by such things as tie rods made with a compatible and locally available material anchored to the longitudinal walls across the nave width. This does not guarantee the relative inward movement, but it does resist relative outward movement and couples the walls so that they would move back and forth together. In addition, tying the tops of the walls together all around will also help to limit the relative movement of the walls. In

addition, the roof structure, including the quincha portion, needs to be strong enough to absorb the vertical vibrations without collapse.

5. There is a strong need to develop guidelines for seismic retrofitting using local materials and low-tech solutions for its implementation. Simple interventions to connect walls to roofs (as recommended by the GSAP guidelines) in the building prototypes visited during the assessment would have limited their failure and reduced damage. A program of intervention for minimal strengthening methods, easy repair techniques, and site maintenance would reduce loss of life and damage in future earthquakes.

Notes

1 The historic buildings visited can be placed in two categories: 1) Ecclesiastical adobe buildings with q*uincha* vaults and domes and; 2) *Haciendas* or estates, composed of adobe buildings with a courtyard and side chapel also with quincha vaults.

2 Consultants Stephen Farneth, Philippe Garnier, Julio Vargas Neumann and Frederick Webster each provided a summary report. Most of the comments presented in the table are extractions from those reports.

3 Tolles et al., *Survey of Damage to Historic Adobe Buildings after the January 1994 Northridge Earthquake,* 17.

4 Ibid. 19.

5 A great part of the population cannot afford other building material, especially in rural areas and small towns.

6 Tolles, Kimbro, and Ginell, *Planning and Engineering Guidelines for the Seismic Retrofitting of Historic Adobe Structures*, 41–43.

Appendix:
List of Participants and Institutions

Name	Institution	Discipline	Contact information
Claudia Cancino	Getty Conservation Institute (GCI), Earthen Architecture Initiative	Architect; Architectural Conservator	ccancino@getty.edu
Philippe Garnier	CRATerre	GCI consultant Architect; Director of Urban Settlements	philippe.garnier@grenoble.archi.fr
Stephen Farneth	Architectural Resources Group	GCI consultant Architect with expertise on earthen retrofitting projects	steve@argsf.com
Patricia Navarro Grau	Patrimonio Perú	GCI consultant Architect	pnavarrograu@yahoo.es
Urbano Tejada	CIDAP – Centro de Investigación, Documentación y Asesoría Poblacional	GCI consultant Engineer	utejada@gmail.com
Julio Vargas Neumann	Pontificia Universidad Católica del Perú	GCI consultant Seismic engineer	jhvargas@pucp.edu.pe
Fred Webster	Independent consultant	GCI consultant Structural engineer; GSAP team member	FAWebster@aol.com
Norma Barbacci	World Monuments Fund	Architect	nbarbacci@wmf.org
Juan Pablo de la Puente	World Monuments Fund	Lawyer	jpdelapuent@gmail.com
Ana María Hoyle	Instituto Nacional de Cultura	Archaeologist	amhoyle@inc.gob.pe
Jorge Lambarri	Instituto Nacional de Cultura	Architect	jlambarri@inc.gob.pe
Hugo Wilfredo Torres Reyna	Instituto Nacional de Cultura	Architect	wilfredo.torres@polimi.it
Miguel Cruchaga Belaunde	Universidad Peruana de Ciencias Aplicadas	Architect; Dean of the School of Architecture	mcruchaga@upc.edu.pe
José García Calderón	Universidad Peruana de Ciencias Aplicadas	Architect; Professor	jgarcia@upc.edu.pe
Mario Segami	Universidad Peruana de Ciencias Aplicadas	Architect; Director of the School of Architecture	msegami@upc.edu.pe
Mirna Soto	Universidad Peruana de Ciencias Aplicadas	Architect; Professor of Conservation	pcarmsot@upc.edu.pe
Luis Villacorta Santamato	Universidad Peruana de Ciencias Aplicadas	Architect; Professor	lvillaco@upc.edu.pe lvillacorta@ucss.edu.pe

Bibliography

Abrahamson, N.A., and K.M. Shedlock. "Overview." *Seismological Research Letters* 68, no. 1 (1997): 9–23.

Agurto Calvo, Santiago. *Lima Prehispánica.* Lima: FINANPRO, Empresa Financiera: Municipalidad de Lima, 1984.

Arriola Vigo, Viviana, and Urbano Tejada Schmidt. *Manual de Quincha Pre-fabricada para Maestros de Obra. Elaboración de Paneles y Procesos Constructivo.* Lima: Centro de Investigación, Documentación y Asesoría Poblacional CIDAP, 2008. http://www.cidap.org.pe/site.shtml?apc=I---ix-x-x1-&s=L&e=i&m=Manuales.

Atkinson, Gail M., and David M. Boore. "Empirical ground motion relations for subduction-zone earthquakes and their application to Cascadia and other regions." In *Bulletin of the Seismological Society of America* 93, no. 4 (2003): 1703–29.

Benavides Rodríquez, Alfredo. *La Arquitectura En El Virreinato Del Perú Y En La Capitanía General De Chile.* Santiago de Chile: Editorial Andres Bello, 1961.

Bromley, Juan, and José Barbagelata. *Evolución Urbana de la Ciudad de Lima.* Lima: Concejo Provincial de Lima, 1945.

Burneo, Reinhard Augustin. *Orígenes y Evolución del Conjunto Arquitectónico de la Casona de San Marcos. Programa para la Conservación del Patrimonio Cultural.* Lima: Tarea Asociación Gráfica Educativa, 2002.

Carbajal Fabio, Gaby Ruiz, and Cliff J. Schexnayder. "Quincha construction in Peru." In *Practice Periodical on Structural Design and Construction* 10, no. 1 (2005): 49–55.

Centro Peruano Japonés de Investigaciones Sísmicas y Mitigación de Desastres (CISMID), Fondo del Reconstrucción del Sur (FORSUR), Universidad Nacional de Ingeniería (UNI), and World Bank. "Informe Final del Estudio de Microzonificación Sísmica y Zonificación de Peligro de Tsunami en las Ciudades de Chincha Baja y Tambo de Mora." Lima: CISMID, 2008. http://www.cismid-uni.org/redacis/articulos.php.

Cobo, Bernabé. *Historia de la Fundación de Lima.* Lima: Imprenta Libera, 1629.

Duarte Fonseca, João. *1755 O Terramoto de Lisboa.* [The Lisbon Earthquake]. Lisboa: Argumentum, 2005.

Earthquake Engineering Institute (EERI). "Learning from Earthquakes: The Pisco, Peru Earthquake of August 15, 2007." EERI Special Earthquake Report. Oakland: EERI, 2007. Http://www.eeri.org/lfe/pdf/peru_pisco_eeri_preliminary_reconnaissance.pdf.

Ferrigni, F., B. Helly, A. Mauro, L. Mendes Victor, P. Pierotti, A. Rideaud, and P. Teves Costa. *Ancient Buildings and Earthquakes: Reducing the Vulnerability of Historical Built-up Environment by Recovering the Local Seismic Culture: Principles, Methods, Potentialities.* Bari: Edipuglia, 2005.

Gálvez, José. *Nuestra Pequeña Historia.* Lima: Universidad Nacional Mayor de San Marcos, 1966.

García Bryce, J. *La Arquitectura en el virreinato y la República*. Historia del Perú, Procesos e instituciones, 9. Lima: Editorial Juan Mejía Baca, 1980: 11–161.

Hardy, Mary, Claudia Cancino, and Gail Ostergren, eds. *Proceedings of the Getty Seismic Adobe Project 2006 Colloquium: Getty Center, Los Angeles, April 11–13, 2006*. Los Angeles: Getty Conservation Institute, 2009.

Harth-Terré, E. *Perú, Monumentos Históricos y Arqueológicos.* México: Instituto Panamericano de Geografía e Historia, 1975.

Harth-Terré, E., and A. Márquez Abanto. "Historia de la casa urbana virreinal en Lima." In *Revista del Archivo Nacional del Perú* 27, no. 1 (1962): 1–100.

Harvard University Centroid-Moment-Tensor Project (HU-CMT). http://www.globalcmt.org/.

Hastings, C. Mansfield, and M. Edward Moseley. "The Adobe*s* of Huaca del Sol y Huaca de la Luna." In *American Antiquity* 40, no. 2 (1975): 196–203.

Instituto Geofísico del Perú. (IGP). www.igp.gob.pe/.

Instituto Geológico Minero y Metalúrgico (INGEMMET), Ministerio de Energía y Minas del Perú. www.ingemmet.gob.pe/.

Instituto Nacional de Defensa Civil (INDECI). www.indeci.gob.pe

International Seismological Centre (ISC). http://www.isc.ac.uk/.

Ji, Chen, and Yuehua Zeng. "Preliminary Results of the August 15, 2007 Mw 8.0 Coast of Central Peru Earthquake." United States Geological Survey Report, 2007. http://earthquake.usgs.gov/eqcenter/eqinthenews/2007/us2007gbcv/finite_fault.php.

Johansson, Jörgen, Paola Mayorca, Tatiana Torres, and Edwin Leon. "A Reconnaissance Report on the Pisco, Peru Earthquake of August 15, 2007." Report by Japan Society of Civil Engineers (JSCE), Japan Association for Earthquake Engineering (JAEE) and University of Tokyo, with the collaboration of Centro Peruano Japonés de Investigaciones Sísmicas y Mitigación de Desastres (CISMID), 2007. http://www.jsce.or.jp/report/45/content.pdf.

Kanno, T., A. Narita, N. Morikawa, H. Fujiwara, and Y. Fukushima. "A New Attenuation Relation for Strong Ground Motion in Japan Based on Recorded Data." *Bulletin of the Seismological Society of America* 96, no. 3 (2006): 879–97.

Kuroiwa, Julio, and Joel Salas Peña. *Manual Para el Desarrollo de Ciudades Sostentibles*. Lima: Programa de las Naciones Unidas para el Desarrollo (PNUD), 2008. http://www.pnud.org.pe/data/publicacion/CiudadesSostenibles8_Cap6.pdf.

Lázares La Rosa, Fernando, Juan Pablo Almora, Jorge López Vásquez, Jorge Jonathan Cabrejos Hurtado, and Ramiro Piedra Rubio. "Análisis de Acelerogramas Sismo de Ica del 15 de Agosto del 2007." [Analysis of Accelerograms, Ica Earthquake of August 15, 2007]. Lima: Centro Peruano Japonés de Investigaciones Sísmicas y Mitigación de Desastres (CISMID), 2007. http://www.cismid.uni.edu.pe/descargas/redacis/redacis57_p.pdf.

Lermo, Javier, Marlene Limaymanta, Yanet Antayhua, and Fernando Lázares. "El terremoto del 15 de Agosto de 2007 (MW+7.9), Pisco, Peru. Mapas de classificación de terrenos con fines de diseño sísmico para las ciudades de Pisco, Ica y Lima-Callao" [Maps of soil classification for seismic design for the cities of Pisco, Ica and Lima-Calla]. In *El Terremoto de Pisco (Peru) del 15 de Agosto de 2007 (7.9* M_W*)*, edited by Hernando Tavera, 233–68. Lima: Instituto Geofísico del Perú, 2008. http://khatati.igp.gob.pe/Webs/cns06/libro/trabajo_17.pdf.

Ludeña Urquizo, Wiley, and José Ignacio López Soria. "La racionalidad ingeniero arquitectural" [The architectural engineer rationality]. In *Construyendo el Perú: Aportes de Ingenieros y Arquitectos; Actas del I Congreso de Historia de la Ingeniería y la Arquitectura " Ernesto Malinowski": 1 y 2 de Julio de 1999, Colegio de Ingenieros del Perú,* 223–31. Lima: Universidad Nacional de Ingeniería, Proyecto Historia-UNI, 2000.

Marussi Castellan, F. *Antecedentes Históricos de la Quincha.* Lima: Instituto Nacional de Investigación y Normalización de la Vivienda INIVI, 1989.

______. "Bóveda a base de quincha en las edificaciones monumentales del virreinato del Perú." In *Informes de la Construcción* 37, no. 377 (1986): 59–66.

______. "El adobe y la quincha." In *Navapalos 1987: Año Internacional de las Personas sin Hogar, III Encuentro de Trabajo Sobre la Tierra como Material de Construcción,* 147–56. Madrid Servicio de Extensión Agraria: Ministerio de Agricultura y Pesca y Alimentación, 1990.

Ministerio de Transportes y Comunicaciones. *Norma Técnica de Edificación NTE E. 080 Adobe*. Lima: Ministerio de Transportes y Comunicaciones, 1985

Ministerio de Vivienda, Construcción y Saneamiento. http://www.vivienda.gob.pe/.

National Peruvian Library. http://www.bnp.gob.pe/.

Office of the Resident Coordinator. *Situation Report No. 21, Earthquake in Peru*. Lima: Sistema de Naciones Unidas en el Perú, 2007. http://www.onu.org.pe/Upload/Documentos/sismo/SituationReportNo21.pdf.

Patronato de Lima. *Jornadas de Lima. Programa de Toma de Conciencia del Centro Histórico de Lima. Patrimonio Cultural de la Humanidad.* Lima: Duplotécnica S.A., 1992.

Paz Soldán, Mateo. *Geografía del Perú, Obra Póstuma del D.D. Mateo Paz Soldán.* Paris: F. Didot, 1862.

Proyecto Regional de Patrimonio Cultural y Desarrollo PNUD UNESCO. *Adobe en América y Alrededor del Mundo, Historia, Conservación y Uso Contemporáneo. Exposición Itinerante.* In *Adobe in the Americas and Around the World, History, Conservation and Contemporary Use. Travelling Exhibition.* Lima: Industrial Gráfica S.A., 1984.

Real Academia Española. http://www.rae.es/.

Reuter, Jas, Corporación Financiera de Desarrollo (COFIDE) and Proyecto Regional del Patrimonio Cultural PNUD/UNESCO. *¡Salvemos Lima!* Lima: Oficina de Asuntos Culturales de Cofide, 1982.

San Cristóbal Sebastián, Antonio. *Arquitectura Planiforme y Textilográfica Virreinal de Arequipa*. Lima: Universidad Nacional de San Agustin de Arequipa, 1997.

______. *Arquitectura Virreynal Religiosa en Lima*. Lima: Librería Studium, 1988.

______. *Esplendor del Barroco en Ayacucho: Retablos y Arquitectura Religiosa en Huamanga.* Lima: Banco Latino: Ediciones Peisa, 1998.

______. *Fray Diego Maroto: Alarife de Lima, 1617-1696*. Lima: Epigrafe S.A. Editores, 1996.

______. *La Catedral de Lima: Estudios y Documentos*. Lima: Museo de Arte Religioso de la Catedral de Lima, 1996.

______. *Lima: Estudios de la Arquitectura Virreinal*. Lima: Epígrafe Editores, 1992.

Seminario Stulpa, Patricia. "Teodoro Elmore y su aporte a la ingeniería y a rquitectura Peruana." In *Construyendo el Perú: Aportes de Ingenieros y Arquitectos; Actas del I Congreso de Historia de la Ingeniería y la Arquitectura "Ernesto Malinowski": 1 y 2 de Julio de 1999, Colegio de Ingenieros del Perú,* 80–94. Lima: Universidad Nacional de Ingeniería, Proyecto Historia-UNI, 2000.

Servicio Nacional de Capacitación para la Industria de la Construcción (SENCICO). http://www.sencico.gob.pe.

Silgado Ferro, Enrique. “Historia de los sismos más notables ocurridos en el Perú (1513–1970).” In *Geofísica Panamericana* 2, no. 1 (1973): 179–243.

Taucer, Fabio, John Alarcon, and Emily So. *2007 August 15 Magnitude 7.9 earthquake near the Central Coast of Central Peru.* Edited by Fabio Taucer. Joint Research Centre Scientific and Technical Reports. EUR 23359 EN. Luxembourg: Office for Official Publications of the European Communities, 2008. http://elsa.jrc.ec.europa.eu/publications/JRC45107.pdf.

Tavera, Hernando. *El Terremoto de Pisco (Peru) del 15 de Agosto de 2007 (7.9 M_W).* Lima: Instituto Geofísico del Perú, 2008. http://khatati.igp.gob.pe/Webs/cns06/libro/indice.htm.

Tavera, Hernando, Isabel Bernal, and Henry Salas. “El Sismo de Pisco del 15 de Agosto, 2007 (7.9Mw) Departamento de Ica – Peru (Informe Preliminar).” Lima: Peru, 2007. http://khatati.igp.gob.pe/Webs/cns06/reportes/2007/sism_150807.pdf.

Tavera, Hernando, Isabel Bernal, Fleur O. Strasser, Maria C. Arango-Gaviria, John E. Alarcón, and Julian J. Bommer. “Ground motions observed during the 15 August 2007 Pisco, Peru, earthquake.” In *Bulletin of Earthquake Engineering* 7, no. 1 (2009): 71–111.

Tolles, E. Leroy, Edna E Kimbro, and William S Ginell. *Planning and Engineering Guidelines for the Seismic Retrofitting of Historic Adobe Structures.* Los Angeles: J. Paul Getty Museum, 2003.

Tolles, E. Leroy, Edna E. Kimbro, Frederick A. Webster, and William S. Ginelli. *Seismic Stabilization of Historic Adobe Structures: Final Report of the Getty Seismic Adobe Project*. Los Angeles: Getty Conservation Institute, 2000.

Tolles, E. Leroy, Frederick A. Webster, Anthony Crsoby, and Edna E, Kimbro. *Survey of Damage to Historic Adobe Buildings after the January 1994 Northridge Earthquake.* GCI Scientific Reports. Los Angeles: The Getty Conservation Institute, 1996.

Ulloa, Antonio, Jorge Juan, and Andrés Saumell. *Viaje a La América Meridional*. Crónicas de América, 59A-B. Madrid: Historia 16, 1990.

United States Geological Survey (USGS). Historic Worldwide Earthquakes. Peru. http://earthquake.usgs.gov/regional/world/historical_country.php#peru.

———. *Magnitude 8.0 – Near the Coast of Central Peru*. Earthquake Summary. http://earthquake.usgs.gov/eqcenter/eqinthenews/2007/us2007gbcv/#summary.

Universidad Nacional de Ingeniería, Proyecto Historia-UNI. *Construyendo el Perú: Aportes de Ingenieros y Arquitectos; Actas del I Congreso de Historia de la Ingeniería y la Arquitectura “Ernesto Malinowski”: 1 y 2 de Julio de 1999, Colegio de Ingenieros del Perú.* Lima: Universidad Nacional de Ingeniería, Proyecto Historia-UNI, 2000.

Universidad Nacional de Ingeniería. *Construyendo el Perú II. Aportes de Ingenieros y Arquitectos, Actas del II Congreso de Historia de la Ingeniería y La Arquitectura en el Perú” Fernando Belaúnde Terry,” 28 y 29 de Noviembre de 2000.* Lima: Universidad Nacional de Ingeniería, Proyecto Historia-UNI, 2001.

Velarde, Héctor. *Aquitectura Peruana*. México: Fonda de Cultura Económica, 1946.

Wald, D.J., V. Quitoriano, T.H. Heaton, H. Kanamori, C.W. Scrivner, and C.B. Worden. “TriNet ShakeMaps: Rapid generation of peak ground motion and intensity maps for earthquakes in Southern California.” In *Earthquake Spectra* 15, no. 3 (1999): 537–55.

Walker, Charles F. *Shaky Colonialism. The 1746 Earthquake-Tsunami in Lima, Peru and its Long Aftermath.* Durham and London: Duke University Press, 2008.

Williams León, Carlos. *Arquitectura y Urbanismo en el Antiguo Perú*. Historia del Perú, Procesos e Instituciones, 9. Lima: Editorial Juan Mejía Baca, 1980: 369–575.

Image Credits

Centro de Investigación, Documentación y Asesoría Poblacional (CIDAP)
Figures 3.9, 3.10

Centro Peruano Japonés de Investicaciones Sísmicas y Mitigación de Desastres (CISMID)
Figures 2.7, 2.18, 2.19

Ferruccio Marussi Castellán
Figures 3.11–3.13

Juan Günther Doering
Figures 3.5–3.7

Google
Figure 2.1
© 2011 Google-Imagery; © 2011 TerraMetrics, NASA; Map data © 2011 Geocentre Consulting, MapLink, Tele Atlas, Whereis (R), Sensis Pty.

Figure 2.2
© 2011 Google-Imagery; © 2011 TerraMetrics, NASA; Map data © 2011 DMapas/El Mercurio, Europa Technologies, Google, Lead Dog Consulting, MapLink, Inav/Geosistemas SRL.

Figure 2.3
© 2011 Google-Map data; © 2011 DMapas/El Mercurio, Google, MapLink.

Figure 2.13
© 2011 Google-Imagery; © 2011 DigitalGlobe, Cnes/Spot Image, GeoEye.

Figure 3.8
© 2011 GeoEye, Google.

Instituto Geofísico del Perú
Figure 2.4

Instituto Geológico Minero y Metalúrgico, Ministerio de Energía y Minas del Perú (INGEMMET)
Figures 2.8, 2.9, 2.14, 2.15, 2.17

Instituto Nacional de Defensa Civil (INDECI)
Figures 2.10–2.12, 2.16, 4.2 (map)

J. Paul Getty Trust
Figures 3.15–3.17, 3.19, 3.20, 4.1, 4.2 (images), 4.3, 4.6, 4.9–4.11, 4.13, 4.15–4.17, 4.19, 4.21, 4.26, 4.27, 4.36 (Claudia Cancino, GCI)

Figures 4.2 (images), 4.7, 4.8, 4.20, 4.22, 4.25, 4.30, 4.33 (Philippe Garnier)

Figure 4.12 (Patricia Navarro Grau)

Figures 3.1, 3.14 (Gail Ostergren, GCI)

Figures 3.2–3.4 (GCI staff)

Ministerio de Cultura [successor to Instituto Nacional de Cultura del Perú (INC)]
Figures 4.2 (images), 4.4, 4.5, 4.14, 4.18, 4.23, 4.24, 4.28, 4.29, 4.31, 4.32, 4.34, 4.35, 4.37–4.39

Programa de las Naciones Unidas para el Desarrollo (PNUD), United Nations Educational, Scientific and Cultural Organization (UNESCO)
Figure 3.18

Servicio Nacional de Capacitación para la Industria de la Construcción (SENCICO) [Successor to Instituto Nacional de Investigación y Normalización de la Vivienda (ININVI)]
Figures 3.21, 3.22

United States Geological Survey
Figures 2.5, 2.6

The Getty Conservation Institute