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SYNOPSIS Results from many efforts to better understand the nature of ground motions and the seismic behavior of structures in Cusco, Peru, give now the possibility to combine several sources of information to produce estimates of seismic hazard and risk. A model is presented which estimates expected damage, based on geotechnical characteristics and intensity-damage relations derived for several types of buildings representative of Cusco's constructions. The study area was divided into smaller sections covering the whole city. This information, along with the geographic distribution of soil types and construction density, allows computation of expected losses during a given event for sites distributed throughout the city.

INTRODUCTION

Cusco, the oldest city in South America, has suffered several earthquake events during it's almost 1,000-year life time. Records for the last 100 years show severe earthquake-related injuries, death and property loss.

The spatial distribution of damage has demonstrate some correlation between the local geotechnical conditions and the dominant parameters of earthquakes. In order to better assess the seismic risk at different scales, the relationships between ground motion, local geology, and soil behavior should be clarified. Valuable database on geology, hydrology, seismicity, soil behavior, and the output of a regional seismic hazard analysis are placed together along with their correspondent geographic location in order to model the geotechnical characteristics of the study area.

The characterization of the building stock based on construction age, use, structural type, location, plant configuration, structural design, state of conservation, and material, has been defined. Vulnerability curves were assigned to each category taking into consideration the type, age, natural frequency of vibration, and the known statistics. The correlation of the geotechnical modeling with the vulnerability of buildings in the study area should provide a valuable tool for seismic damage assessment on buildings and, in turn, a solid database is expected to be established in order to make possible practical implementation of better structural design and city planning.

GEOGRAPHICAL ENVIRONMENT

The Cusco Valley, is located between 71.9 and 72.3 west longitude, and between 13.4 and 13.6 south latitude. Elevations range from 3,070 meters at the Huatanay River mouth to 4,852 meters that correspond to the Pachatusan Peak.

The floor of the Cusco Valley, 30 km. in length and an average width of 12 km., with an average elevation of about 3,115 meters, is divided by the Angostura and Oropesa narrows into three oval areas of flat-lying land, which are called the Cusco, Oropesa and Lucre Basins. The Cusco Basin is the largest basin where the city of Cusco, including the districts of San Sebastian and San Jeronimo, is located. The next portion of the valley to the south, the Oropesa Basin, has less width and a flatter floor than the Cusco Basin. The Lucre Basin shows the least relief of all three basins. The area of study covers approximately 80 km^2.

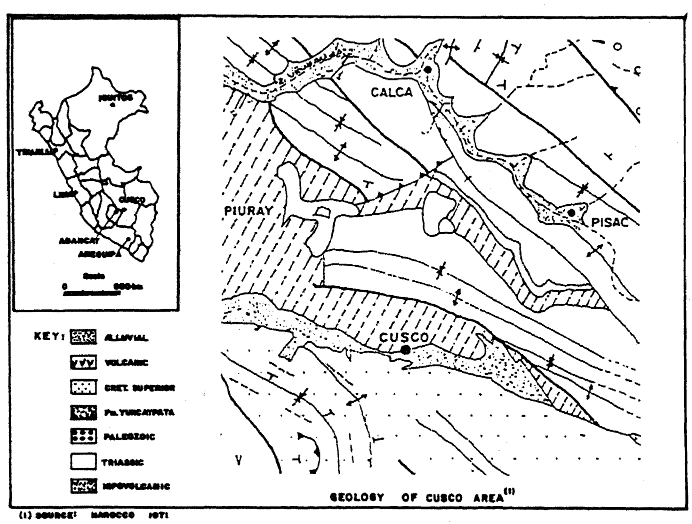


Figure 1. Geology of the Cusco Valley

GEOLOGY AND TECTONICS

The Cusco Basin used to be occupied by an ancient lake. The geology of this area corresponds to the lacustrine strata of the San Sebastian formation. Igneous rock masses are located within the Valley. The Rumicolca mass is the largest exposure of igneous rock within the Cusco region. Stone from Rumicolca and the Rodadero mass was extensively used by Inca and Spanish builders, and are the principal source of rock used in modern construction.

Seismic activity in the Cusco area may be related to the active Quaternary "Cusco Faulting System," that divides the Eastern branch of the Andes mountain chain from the Altiplano structural unit (Benavente, R., 1992, Marocco, 1977). This more than 100- km. faulting system crosses the Cusco area, starting from Abancay city, in the northwest, through Urcos city, in the south. About 40 km. south east of Cusco, there is another system, the Vilcanota Faulting System. These faulting systems and Geology of the Cusco Valley is illustrated in Figure 1.

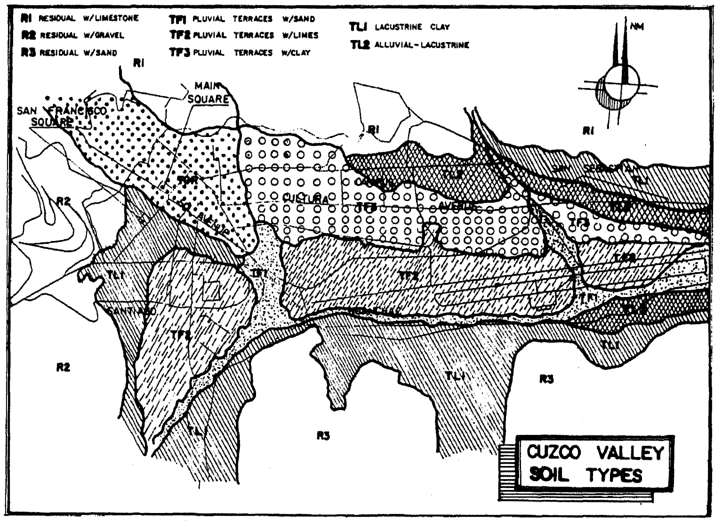


Figure 2. Soil types in Cusco area.

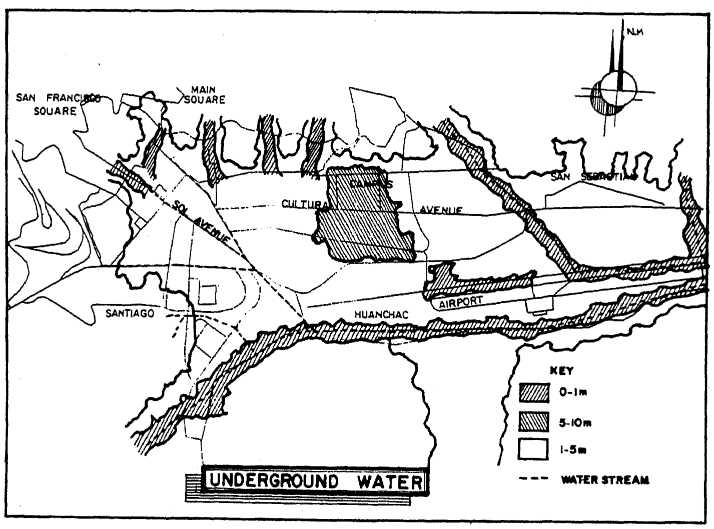


Figure 3. Underground Water in Cusco Valley.

SOILS AND HYDROLOGY IN CUSCO VALLEY

The evaluation of about 500 soil site studies is summarized in the soils map shown in Figure 2. These studies were compiled from several sources such as government institutions, private companies, and work performed by the authors. The Cusco Valley is drained by the Huatanay river, with a total fall of 50 m. Tributaries to this river vary greatly in amount and permanency of flow. Underground water level, as illustrated in Figure 3, is shallow due to the lacustrine nature of the valley varying from between 0 and 1.0 meter in the lower basin to between 1.0 and 5.0 meters in the upper basin. In upper areas, the water table is more than 5 meters deep. The number of rainy days in a year averages about 175.

SEISMIC HISTORY OF THE CUSCO VALLEY

During the present century important data on earthquakes have been recorded by the Instituto Geofísico del Perú, universities and other Peruvian government sponsored institutions. Major earthquakes have occurred in the Cusco Valley in 1823, 1870, 1875, 1943. Other earthquakes occurred damaging seriously some vicinity towns such as Quiquijana in 1717; Paruro, Oropesa, Lucre, in 1746; Chumbivilcas, Abancay and Cotabambas in 1875; Yanaoca and Pampamarca in 1943, Livitaca 1991 (Polo, 1904, Ericksen, et al., 1954). However, the most significant seismic events for the Cusco area are the March 31, 1650, September 18, 1941, May 21, 1950; and April 5, 1986 earthquakes.

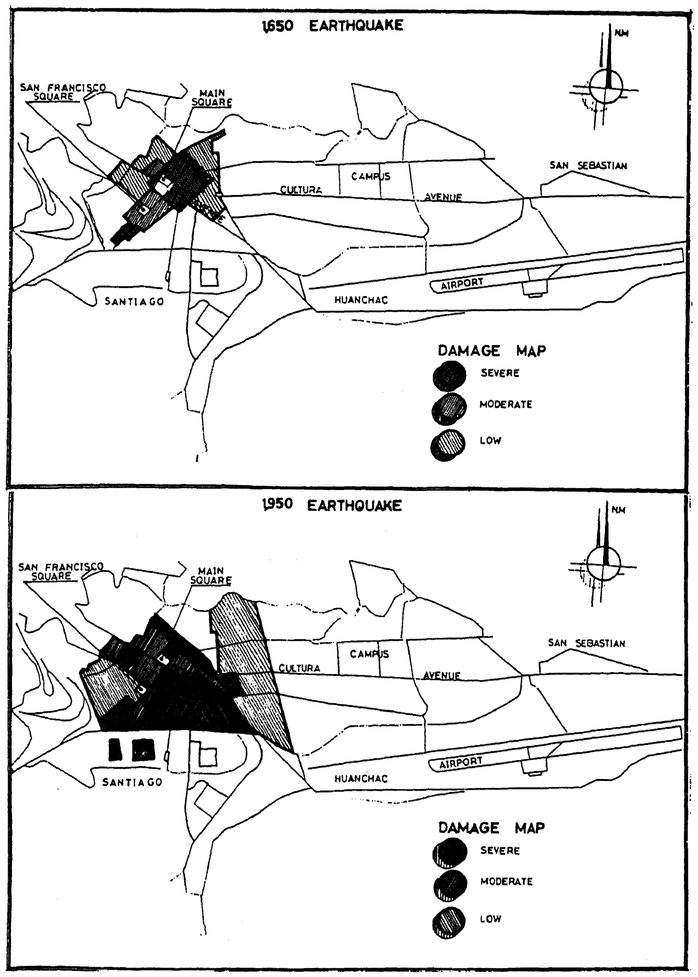


Figure 4. Damage from the March 31, 1650 and the May 21, 1950 earthquakes.

On March 31, 1650. A strong earthquake, followed by many strong aftershocks for several days, destroyed nearly all of Cusco. People in Lima, 350 km. northwest of Cusco, felt the strongest shock (Polo, 1904).

On May 21, 1950, more than half the buildings of Cusco were seriously damaged by another shock (Ericksen, et al., 1954). The damage was extensive within an epicentral area of about 12 km^2, with minor damage within a surrounding area of about 500 km^2. The earthquake was considered local in effect since it was felt over a total area only of 16,000 km^2. The depth of focus was considered to be located within 8 to 9 km. The distribution of damage caused by both the March 31, 1650, and the May 21, 1950 (Ericksen, et al., 1954) earthquakes is shown in Figure 4.

The major factors for the extensive seismic damage were poor construction and age of buildings. The maximum intensity in this area was estimated to be VII on the MMI scale, with an acceleration less than 300 gals. (Ericksen, et al., 1954). Colonial churches, some more than 350 years old, and old adobe and combined adobe and rock or brick structures were the most seriously damaged. The most extensive damage was to buildings resting on a thick water-saturated alluvial gravel, the TGR soil deposits, (see Figure 2).

The Cusco earthquake of May 21, 1950 was probably of tectonic origin. An extensive fissure was considered as evidence of a bedrock fault beneath unconsolidated sediments at the south side of the Cusco Basin. Liquefaction and slope stability failure were reported in the same area (Ericksen, et al., 1954).

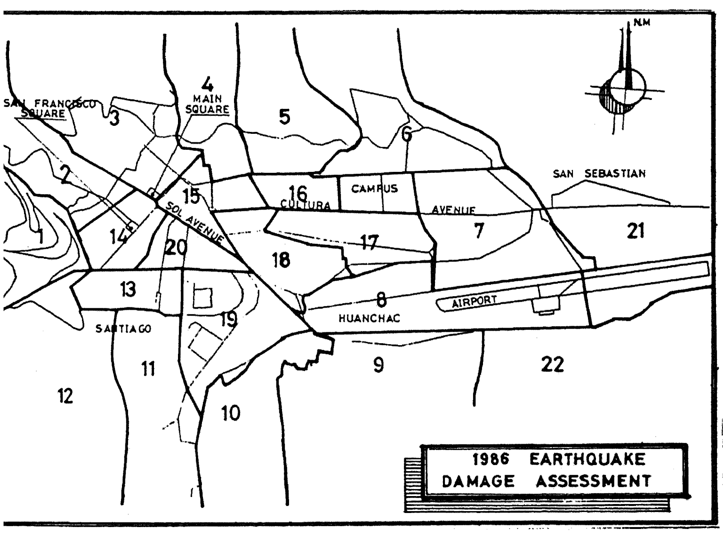


Figure 5. Damage assessment map for the April 5, 1986 erthqke.(University Cusco, 1986).

On April 5, 1986, more than 50,000 people were affected by a earthquake. The epicenter was 20 km. northwest of Cusco, and the magnitude was 5.8 on the Richter scale, the duration was 3 to 5 secs. The shock was felt over a total area of about 12,000 km^2. Isoseismal maps for this event (Huaco, et al., 1986) and for the May 21, 1950 (Ericksen, et al., 1954) phenomenon show MMI values of III about 100 km around Cusco.

The most extensively damaged buildings were the old adobe houses. More than 21,000 adobe houses were affected within the urban area. Inventory of building stock and damage estimation was performed by the University of Cusco and the Instituto Nacional de Cultura (Aparicio and Marmanillo, 1989). For a more accurate damage assessment, the city area was divided into 22 smaller sections as shown in Figure 5. Geologic risk assessment maps developed by the Instituto Geofísico del Perú, and by the University of Cusco, Catholic University of Lima, and the CERESIS are shown in Figure 6.

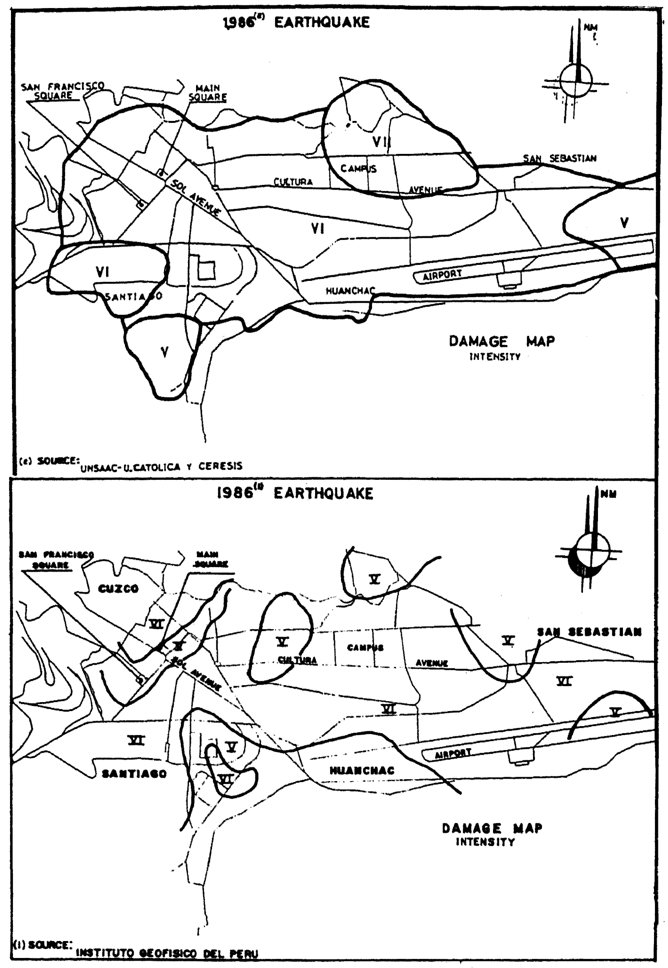


Figure 6. Geologic Risk Maps (Instituto Geofísico del Perú, 1986, and UNSAAC-CERESIS-U Catolica, 1986)

LOCAL EFFECTS

The duration and frequency content of the ground motion depend on local geological and soil conditions (Mendes, 1991). Landslides in Cusco are very frequent. The rock and gravel displaced by slides vary in amount from a few cubic meters to the enormous mass of material represented by the prominent scar on the Picol Peak, which is visible for a distance of 20 km. Liquefaction, lateral spreading, densification and strength reduction are other local effects reported on past earthquakes for the Cusco area. The correlation of seismic intensity and local effects is presented in Figure 7.

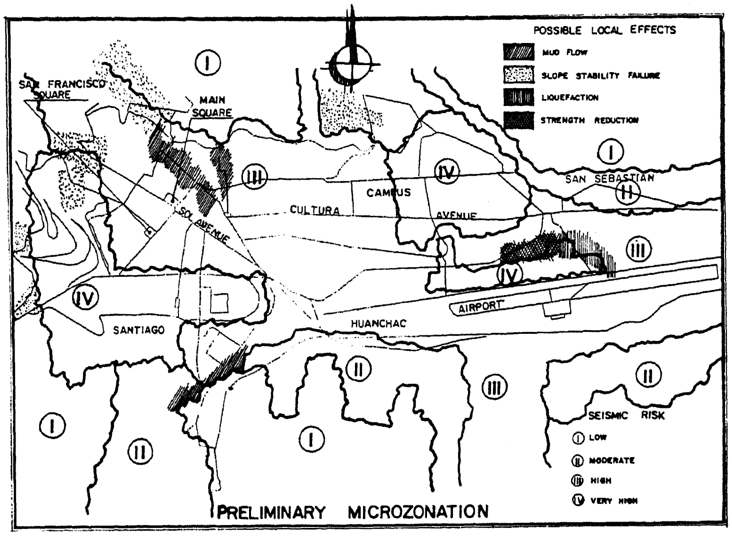
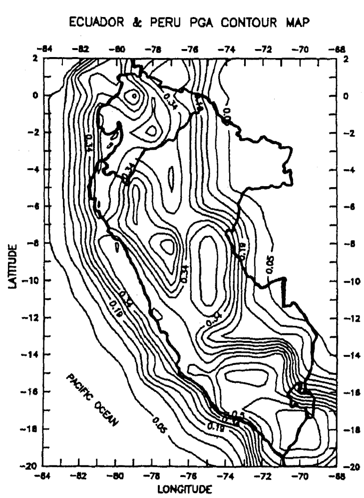


Figure 7. Local Effects and seismic risk.

HAZARD ANALYSIS

A methodology, suggested by Thiel and Zsutty (1987), applies peak ground accelerations and soil related factors as independent variables in their seismic damage functions. For this study, PGA having a 10 percent chance of being exceeded over a 50-year period is estimated to be 3.5 g for the Cusco area, as shown in the PGA map of Figure 8, (Candia, 1990, and Candia & Sprenke, 1992). This probabilistic value was calculated using statistical data for the last 100 years with selected attenuation relationships. In a related deterministic study, currently undergoing, using the Tambomachay Fault as a local seismic source for the city of Cusco, Candia and Perez estimated the maximum ground acceleration to be 0.38 g.



re 8. PGA Map: 10% probability exceedance, for a time period of 50 years. (Candia & Sprenke, 1992).

BUILDING INVENTORIES

Man-made structures in Cusco consist primarily of buildings of low rise importance and middle rise office buildings and monuments. In general, buildings can be classified according to their age and structure, configuration in plan and height, as follows:

A. Masonry stone buildings prior to 1900, in ba and regular shape. Freq > 3 Hz.
B. Adobe buildings prior to 1950. Freq. > 3 Hz.
C. Adobe buildings constructed or retroffited after 1950. Freq > 2.5 Hz.
D. Modern RC buildings designed for some latera load. Freq < 2 Hz.

The characterization of the building stock has been defined based on: use, structural type, location, plant configuration, structural design, state of conservation, and material. Vulnerability curves were assigned to each category taking into consideration the type, age, natural frequency of vibration, and on the statistics. Vulnerability is shown in Table I.

TABLE I. Vulnerability of buildings in Cusco

BUILDING TYPE	INTENSITY (M.M.)			
	VII	VIII	IX	X
A	1%	5%	10%	50%
B	2%	10%	30%	70%
C	0.5%	1%	5%	10%
D	0.1%	0.5%	1%	2%

GENERAL CHARACTERISTICS OF STRUCTURES

The majority of buildings in Cusco were constructed principally of adobe and combined adobe and rock or brick structures. Three major factors make adobe buildings the most important single source of structural damage and associated casualty risk due to earthquake ground motion in Cusco: a) adobe buildings represent the most seismically vulnerable type of buildings in Cusco Valley, b) zones of higher expected ground shaking intensity are occupied mostly by adobe buildings, and c) compared to other classes of buildings, adobe buildings tend to be occupied at relatively higher densities. Most of the houses in Cusco are one or two stories high. Adobe walls are not reinforced, and ceilings and upper floors are supported by wooden logs. Roofs are made with wood and covered with reeds to support the roof tiles. Wooden structures practically are limited to the roof supports; thus, fire hazard is minimum.

MODEL TO ESTIMATE EXPECTED DAMAGE

A model developed by Mendes (1991) was adapted with the following assumptions:

1. The study area was divided into 22 smaller sections i (i=1,u); covering the whole city.
2. Buildings were classified according to their age, structure, and configuration, in 4 types

j, (j = 1,c). Buildings type A, B, and C are predominantly 2 stories.

. Seismic sources, k (k=1,cs), with associate probability of occurrence Fk(.)
. MMI intensity levels, l (l=1,int), from V to X. Ground behavior is incorporated.
. Four periods were considered for time occurrence of earthquake, m (m=1,P): 6-9, 9-18, 18-21, 21-6 hours.

The modeled functions are given by:

LF = Individual loss function

$ILF_{i,j,k} = C_{i,j} a_i n_i N_{i,j} \Sigma V_{i,j,k,l}(a_{l,j})/A_j$

LF = Global loss function:

$GLF_{j,k} = \Sigma ILF_{i,j,k}$

ffected population:

$AP_{j,k,m} = \Sigma \Sigma V^{P}_{i,j,k,l}(a_{l,j})/A_j \; N_{i,j} \; P_{j,m}$

ensity of losses index:

$DL_{j,k} = GLF_{j,k} / \Sigma C_{i,j} a_i n_i N_{i,j}$

ensity of population affected index:

$DPA_{j,k} = AP_{j,k,m} / P_{j,m}$

Global loss function for all the sources:

$$GLF_j = \int GLF_{j,k} \, dF_k$$

here:

$S_{j,k,l}(w)$ = power spectrum response
$V_{i,j,k,l}$ = mean vulnerability for $S_{j,k,l}(w)$
$V^{P}_{i,j,k,l}$ = mean value of affected population
A_j = area of the unit j
$N_{i,j}$ = amount of buildings i in unit j
$a_{l,j}$ = area of MMI intensity l in unit j
$P_{j,m}$ = population in unit j, in time m
$C_{i,j}$ = mean household value/m^2 of building class i in unit j

ONCLUSIONS AND RECOMMENDATIONS

n important geotechnical database has been ollected and extrapolated for the city of usco, Peru.

ontrol technologies as required for civil tructural applications such as building design nd construction in the Cusco area clearly need urther development and enhanced efforts tilizing better quality materials, updated onstruction regulations and urban planning nvolving geotechnical and structural aspects.

t is important to document the repair and etrofitting of damaged structures as well as he design and construction of new ones so that heir effectiveness can be valued in the future

etails of the tectonic environment and geologic rocesses, must be evaluated in order to stimate reliable boundaries of seismic source ones that can be used for a local seismic azard analysis of the Cusco area. An improved uilding inventory is needed as well for further nhance risk assessment in the study area.

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