INVESTIGATIONS ON THE PERUVIAN EARTHQUAKE OF MAY 31, 1970

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SYNOPSIS

In July 1970, studies in geology, seismology, earthquake engineering, lagoon control and glaciology were iniciated in order to know the seismic microzoning of the most important cities and to verify the physical security of the towns located in the macroseismic area and to repair the damaged structures. At present (December, 1972), the new city plans of the more important cities are ready and thousands of reinforced concrete and brick buildings have been repaired. However the small towns are still being studied, along with the lagoon control.

INTRODUCTION

On May 31,1970, at 3:23:28 p.m. local time an earthquake of magnitude 7.7 occured about 40 Km. west of the Peruvian coast,causing severe damage to over 83,000 Km.^{2} of the coast and mountain regions of this country. The death toll was estimated at about 70,000,including 20,000 that disappeared under an avalanche. More than 150,000 persons were injured. The material losses due to vibrations consisted in the total destruction of more than 70,000 houses; tens of thousands more remained with important damages. Hundreds of school buildings, along with dozens of hospitals and public buildings, were destroyed, and the water supply of most of the towns located in the macroseismic area were put out of service. Avalanches and landslides disrupted more than 70% of the road system in the affected area; its electric energy capacity was reduced in 90%; the irrigation system of more than a billion square meters was damaged.

The Peruvian government put a special commission in charge of the immense job of reconstructing the affected area. The name of this commission is CRYRZA (Commission for the Reconstruction and Rehabilitation of the Area Affected by the Earthquake of May 31,1970) and its president has the rank of a minister of state. In order to study the physical security and the soil conditions of the cities to be reconstructed, and to determine the locations of the future populated areas,a Technical Subcommittee was appointed; the members being the authors of this paper. At the same time as the vital services (water, electricity, comunications, etc.) were being restored, studies in geology, seismology, earthquake engineering, lagoon control, and glaciology were iniciated. The first three fields were studied directly by the CRYRZA Technical Subcommittee with the cooperation of dozens of local engineers, seismologists, and college graduates; the last two fields, by a UNESCO Mission.

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PART I - GEOLOGICAL STUDIES

I-1.-Physiographic features.- The principal physiographic feature of the affected area is the western chain of the Andes mountains. In Ancash this chain is divided into two branches, named the Cordillera Negra and the Cordillera Blanca. The two branches run parallel to the coast for 180 Km. forming the largest valley in Peru, the Callejon de Huaylas or Santa River valley. The peaks of the Cordillera Blanca are covered by glaciers.

I-2.-Regional geology.-There are outcroppings of sedimentary and volcanic rocks from the Upper Jurassic to Quaternary ages, and intrusive rocks from the Upper Cretaceous and Tertiary ages. The folded Mesozoic sediments beneath the slightly folded Tertiary volcanic rocks are exposed in the Cordillera Negra. The Quaternary sedimentary rocks are represented by alluvial deposits, eolic and fluvio-glacial material. The coastal batholith has intruded on the sedimentary and volcanic rocks found on the western flank of the mountain chain; while the batholith of the Cordillera Blanca is located in the central part of the chain (1) (Fig.1).

I-3.-Structural features.-Regionally, the following can be observed: 1.- There is a regional longitudinal fault along the coast from the Paracas peninsula (14°Lat.S.) to Paita (6°Lat.S.): this fault is in the ocean parallel to the coast, and its presence is inferred by the lack of Middle Tertiary rocks and the absence of the Cordillera de la Costa, which is present only in southern Peru. 2.-There is a regional fault in the Callejon de Huaylas, parallel to the Andes, that controls the Cretacous-Tertiary intrusive rocks on the western side.

I-4.-Geodynamics.- The earthquake reactivated the local fluvio-glacial deposits found along the regional fault in the Callejon de Huaylas. Many landslides took place during and after the earthquake. The most important dammed the Santa River, slightly flooding the town of Recuay; on the eastern side the ground level went down from 8 to 12 meters, and on the river (western, town side) reached a height of from 5 to 6 meters. Another interesting phenomena, causing nearly 20,000 deaths, was the Yungay-Ranrahirca avalanche caused by ice breaking off the peak of Mount Huascaran. It is estimated that the avalanche reached a speed of 400 Km./hr. The volume of this landslide, which changed the morphology of Yungay and Ranrahirca, was estimated at 80 million m^3 of material with a mean depth of 5 meters (2).

I-5.-Geological investigations.- The geological investigations consisted in geotechnical, geomorphological and geodynamic studies. The geotechnical studies included investigation of the kinds of soils present according to their origin, compaction, and stratification; variations in the ground-water levels: and some physical properties such as density, granulometry, strength, etc. From the geomorphological point of view, investigations were made of the terraces, the flood boundaries, and the Quaternary deposits of the avalanches. The potential risk due to avalanches, floods, settlements, and landslides were studied geodynamically. From the information derived in the geomorphological and geodynamics studies, it was possible to select the safest places within the Callejon de Huaylas for the relocation of the affected cities.

PART II - SEISMOLOGICAL AND GRAVIMETRIC STUDIES

The earthquake of May 31, 1970 had an intensity of VIII on the Modified Mercalli scale, as seen in Fig. 2. The map shown was drawn as a result of the field investigations made by the Instituto Geofisico del Peru soon after the earthquake (3). Instrument investigations in the area of the earthquake were planned as follows:

II-1.-Predominant period observations.- The predominant period investigation of the soils in the area to be microzoned was carried out using the technique developed in Japan, mainly by Kanai (4). They have shown both theoretically and experimentally that soils, according to their physical properties,behave selectively when vibrations are traveling through them. After the evaluation of the potential danger due to external geodynamics was made, the areas to be microzoned were chosen and locations selected for the microtremor observations.If it is assumed that the physical properties (density, rigidity, viscosity, etc.) and the thickness does not suddenly change over short distances laterally,it is possible to establish the predominant period zonification and use it as a criteria for microzoning. The number of points observed in each area varied from 12 to 30, according to the size of the area. The distances between points varied from 100 to 400 meters, and the measurements were made at night in order to avoid as much as possible disturbances by traffic and people. The predominant period of the soil corresponding to the site was obtained directly from the frequency-period curves.

By comparing the curves obtained in the area to be microzoned, it was observed that their shapes changed gradually from one predominant period to another. This relationship agreed in most cases with the geological and geotechnical observations made in the same area. The predominant period zoning of the city of Huaraz is shown jointly with the seismic microzoning in Fig. 5. The results of the microtremor studies in Huaraz show 5 kinds of soils; I.- 0.14 sec. of predominant period; II.- predominant periods of 0.20 and 0.25 sec.;III.- 0.25 sec. of predominant period; IV.- predominant periods of 0.20, 0.23, and 0.25 sec.; and V.-predominant periods of 0.25 and 0.33 sec. with complimentary periods of 0.50 sec. The limits between the zones in the predominant period zoning of Huaraz is not precise due to the poor density of the microtremor points. In spite of this, the predominant period zoning agrees more-or-less with the geological and structural damage investigations, as can be seen in Fig.4.

II-2.-Gravimetric studies.- Gravimetric observations were made in order to know the morphology and the depth of the rock foundation. Fig. 4 shows the contour lines drawn from the depths of the rock foundation in Huaraz. Two hundred and thirty observations were made throughout all Huaraz. After the data were collected and the residual calculated, Corbato's method (5) was used to determine the depth of the rock foundation. The relation between the morphology of the rock foundation and damage distribution, and microtremors, is not clear. The dynamic response of the soils seems to be uniformly high in the areas where the depth of the rock foundation varies gradually from 40 to 80 meters; in these areas the damage distribution was high and the predominant periods of 0.33 sec. were observed (fig. 4).

II-3.-Preliminar soil amplification studies.- The soil amplification studies consisted of the determination of the amplitude ratio between the aftershock recorded in the seismograph placed directly on the soil (mobile station) and another seismograph placed directly on the rock foundation (fixed station). This amplitude ratio was referred to as the "amplification spectrum" of the site. After taking simultaneous readings of four or five aftershocks, the mobile stations were moved to new locations. Once the records were analyzed and the data normalized, the amplification spectrum (amplification ratio versus frequency) was found. In Huaraz it was noted that the amplification of the soils ranges from 15 to 3 times.

These observed curves were adjusted with the theoretical ones, using the formulas developed by Kanai's group (4). In these formulas two parameters must be known; the seismic impedance and the relation between viscosity and rigidity. It was assumed that both parameters remain constant during the soil's response to any earthquake. In order to adjust the observable curves with the theoretical ones, a computer program was developed in which the parameters were calculated by the "trial and error" method jointly with the "least square" method. Using these procedures, it was possible to calculate the parameter values that best fit the observed curves. From these parameters the maximum spectrum acceleration of the site can be computed using the semi-empirical formulas given by Kanai (4).

In general, the idea was to find the parameters for all of the aftershocks recorded in each site. Having many calculated parameters for each site makes it possible, statistically, to find the most representative parameters of the soils. Also, if the parameters and the depth of the rock foundation for each site is known, it is possible to develop different models for calculating the dynamic behavior of the soil. Unfortunately this part of the study could not be completed due to lack of time and funds.

PART III - STUDY OF THE DISTRUBUTION OF DAMAGE IN BUILDINGS

This study was made in three stages; each with different objectives. First, a few days after the earthquake, an inspection was made of the affected area in order to estimate the percentage of damage (6). At the same time, the Peruvian Air Force took airphotos of the area for the same reason. Six weeks after the earthquake, more detailed studies of the distribution of damage were started in order to determine the influence of the soil on the seismic behavior of the buildings. In this way the cities could be zoned and the buildings classified as those to be demolished and those to be repaired. The buildings (damaged and undamaged) were inspected and information taken as to use, foundation characteristics, walls, roofs, materials used, damage in structural and non-structural elements, estimated cost of repair, etc. This information was taken on special forms for electronic computation. Later the percentage of damage on each type of building was plotted on maps of the affected area.

It was noted that only the cities of Chimbote and Huaraz were large enough that the influence of the soil could be clearly noted. The results of the studies in Chimbote are included in Ref. 8. The studies of Huaraz (Fig.4) show that while in the downtown area damages reached 90%, in Centenario, 2 kilometers north, the damages were 20%. The most notable characteristics of the soils in downtown Huaraz and Centenario are in that order, as follows: ground-water level, 0-2.7 m. and 5.00+ m.: soil settlement, yes and no; carrying capacity of the soil, 0.5-1.0 and 1.5-2.5 kilos/cm^2; predominant period of the soil, 0.25-0.33 and 0.25 sec. It should be noted that in downtown Huaraz, due to the height of the adobe buildings and the narrowness of the streets, more than 10,000 persons perished. In some of the smaller towns it was noted that there was no direct relation between the damage and the distance from the epicenter. In Coishco, 40 kilometers from the epicenter and on rocky soil, the damage was minimum and many of the adobe buildings survived and are inhabited. In Andahuasi, 150 kilometers from the epicenter in an area of transition between alluvial and rocky soil, buildings similar to those in Coishco suffered 100% damage. At this stage it was also decided that it was economically feasible to repair the concrete and brick buildings, and not those of adobe. The greater part of the repairable buildings were located in Chimbote.

The third stage of the evaluation of damage was carried out in order to prepare plans for restoration and was very thorough. The damage suffered by the different types of buildings may be summed up as follows:

Adobe buildings.- More than 90% of the buildings that were damaged were adobe and their collapse caused more than 40,000 deaths. As the degree of damage of this type of material is very sensitive to the intensities observed in the macroseismic zone (VI-VIII M.M.), their study was very useful in order to plot the isoseismics and to determine the influence of the soil.

Brick buildings.- The damage done to hundreds of brick buildings was studied, especially in the Chimbote area. The results are shown in Fig.6. Each point corresponds to the average damage of groups of buildings of the same type. Failures were noted in walls having unit shearing stress as low as 0.2 kilos/cm^2. This could be attributed to the low quality of the materials used and/or to a progresive failure of the walls, starting with the most rigid.

Concrete buildings.-More than 80% of the damage suffered by concrete buildings was due to the fact that they were not created taking seismic forces into consideration. This allowed a concentration of stresses on elements which resulted critical. Errors of 200-500% in the unit stresses were found in short columns when their true rigidity was not taken into account in the initial hypothesis of calculations. An example is found in a typical school building (Fig.7,8, and 9) where it can be observed that the central column has a clear height noticeably shorter than the other two columns, in direction X. As a result the short column received almost all of the shearing stress in that direction.

REPAIRING OF STRUCTURES DAMAGED IN THE EARTHQUAKE

The method followed for the preparation of the projects of repairing and reinforcing can be summed up as follows: 1^{o}) Detailed inspection in the field of all of the structural and non-structural damage and their layout on specially prepared plans made for this purpose (Fig.8 and 9b).

2°)Computer analysis of the structure to calculate the vertical and horizontal load, in the pre-earthquake stage. 3°) A comparative analysis of the results of steps 1 and 2, to determine the cause of the failures. 4°) Preparation of a new resistance system with the addition of new structural elements such as shearing walls. Preferably these should be in the outside corners of the buildings and should be "L" shaped so that their great rigidity attracts a large percentage of the shearing stress and offers the possibility of working outside the building and to reinforce the foundations without tearing up the floors inside. The dimensions of these walls were estimated by electronic computation so that the shearing stresses, as specified by the Peruvian Antiseismic Standards, in the existing columns would not exceed 4 kilos/cm^2. (This value is limited by the quality of the concrete used and the abutment of the undamaged columns).

5°)Design of the new structural system and preparation of the details for the repairing of the damaged elements, and 6°) Preparation of the plans, technical specifications, quantities, and budget. Repairing and reinforcement projects for about 100 concrete and 2,000 brick buildings were made using this method. In cases of serious damage in short columns and walls, the cost of repairing averaged between 30 and 40% of the value of the building. Where the foundations had settled this percentage sometimes reached 50 to 60%, but even in these cases it was decided to repair the structure in order to recover part of the investment and to gain experience in repairing techniques.

SUMMARY AND CONCLUSIONS

In general, the results of the geological, seismological and damage distribution studies were in good agreement with each other. Using the data from these investigations and the data from the reports of a number of missions that visited the affected area shortly after the earthquake, the microzoning maps of the following cities were prepared:

On the coast: Chimbote, Casma, and Huarmey, The studies in Chimbote were made under the direction and with the cooperation of a Japanese Mission headed by Dr. Ryohei Morimoto, Director of the Earthquake Research Institute of the University of Tokyo, Japan (8). In the Callejon de Huaylas (located in the Andes): Huaraz, Carhuaz, Recuay, and Caraz. Many other towns were studied,and although no seismic microzone maps were prepared for these locations, some recommendations were made in order to improve their physical security.

Both the soils quality and the danger of flooding by the rivers during the summer were taken into account in deciding the seismic zoning of the coastal cities. In all cases it was recommended that the cities studied remain at their present locations. In the Callejon de Huaylas, the most important consideration was the danger of future avalanches, as well as the soil characteristics. It was recommended that Caraz, Carhuaz and Huaraz remain in their present locations, but with some restrictions as to areas of future expansion. It was recommended that Mancos, and what remains of Yungay and Ranrahirca be relocated at Tingua, some kilometers south of their present locations. No restrictions were imposed on Recuay.

The seismic microzoning maps were used in the urban planning of the cities to be reconstructed. Because of its importance as the world's largest fishing harbor, the urban planning studies of Chimbote are being carried out in cooperation with a number of experts from the United Nations, under a program called "Plan Chimbote". The lagoons located in the mountains are under permanent control by the Corporation Peruana del Santa and discharge canals and tunnels are under construction.

ACKNOWLEDGMENT AND THANKS

Thanks are expressed to the authorities of CRYRZA, the National University of Engineering, the Geophysical Institute of Peru, the Geology and Mining Service of the Ministry of Energy and Mines, and to the local engineers who made this paper possible. We also wish to take this oportunity to express Peru's gratitude for the spontaneous and generous response from people all over the world at the time of this national disaster. Thank you.

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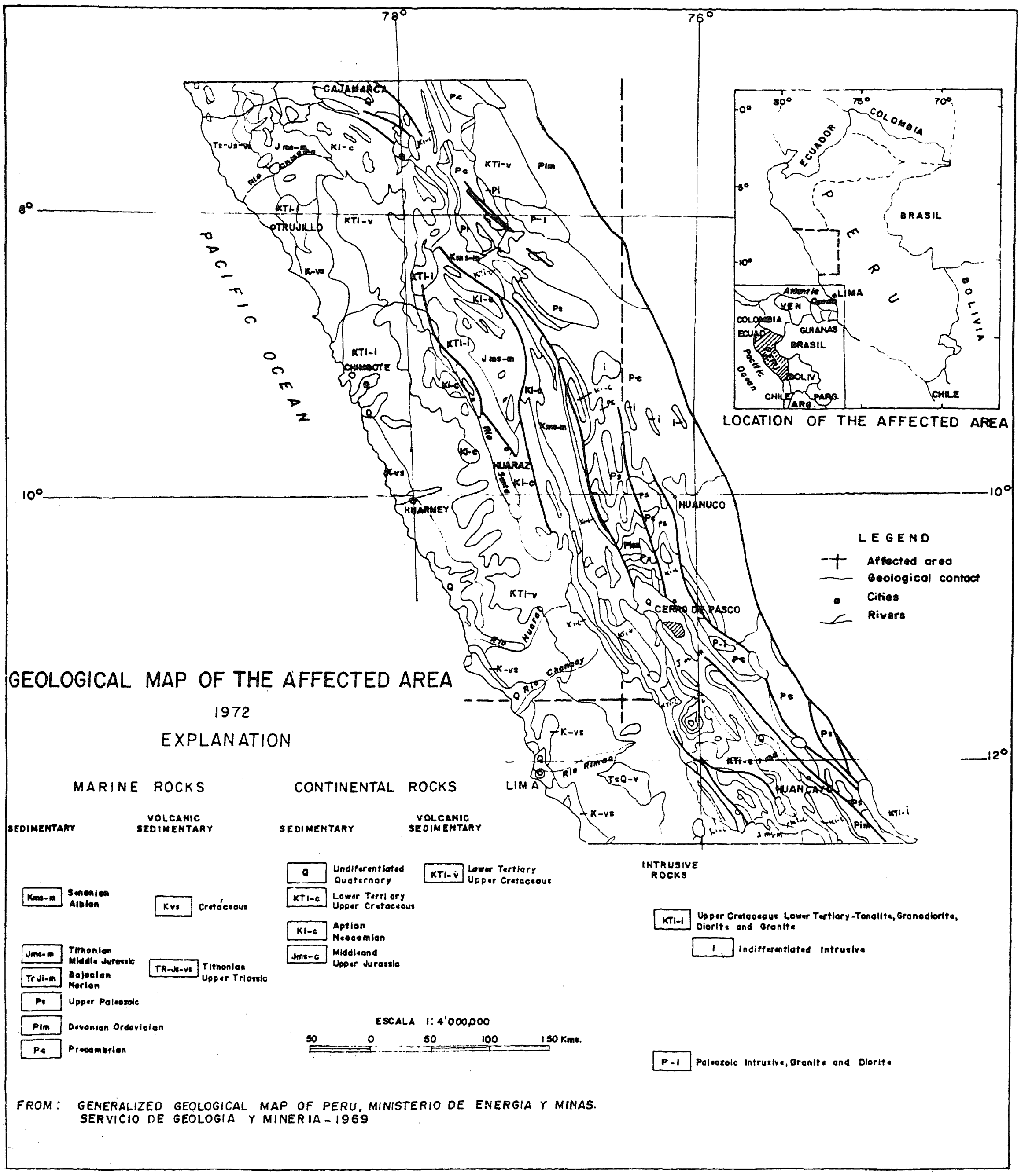

Fig. 1 - Geological Map

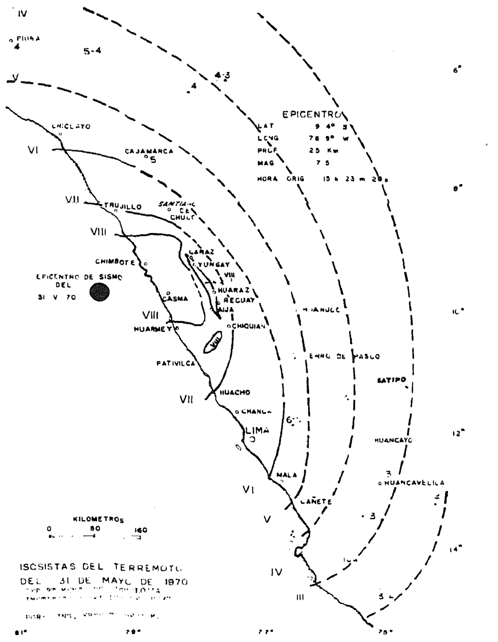

Fig. 2 - Isoseismical map of the May 31st, 1970 earthquake.

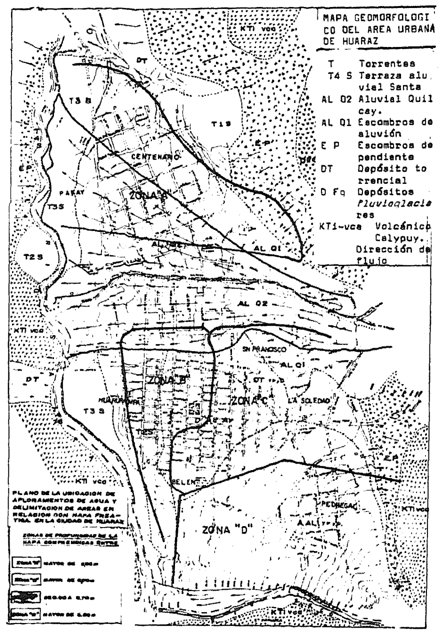

Fig. 3 - Geomorphological map and ground-water level in Huaraz.

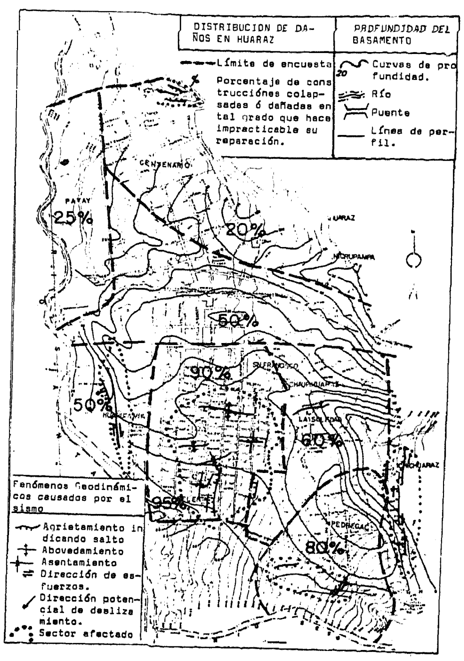

Fig. 4 - Map of the earthquake damage distribution, contour line of the depth of the rock foundation and geodynamic effect in Huaraz.

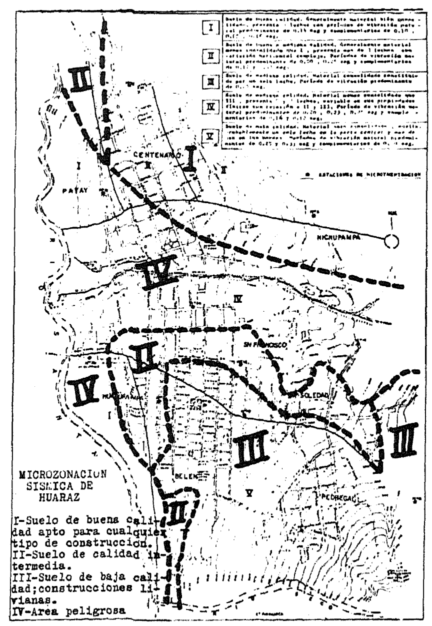

Fig. 5 - Map of predominant periods zoning and seismic microzoning in Huaraz.

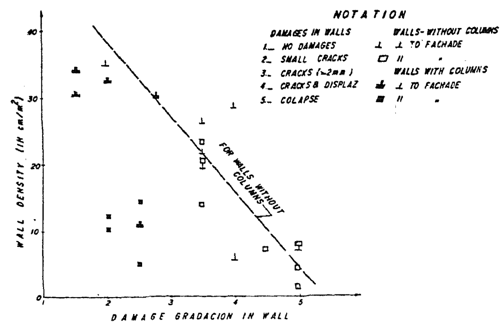

Fig. 6 - Damage vs wall density in houses with brick bearing walls

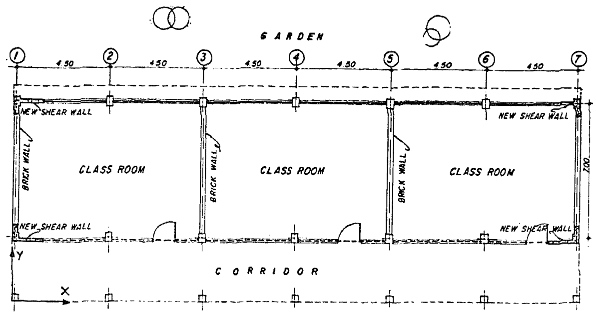

Fig. 7 - Plan of a typical school building

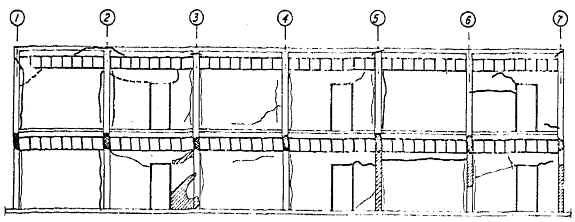

Fig. 8 - Damages (elevation)

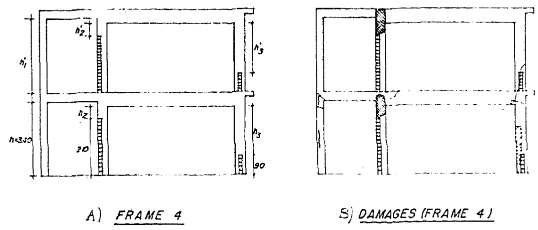

Fig. 9 -

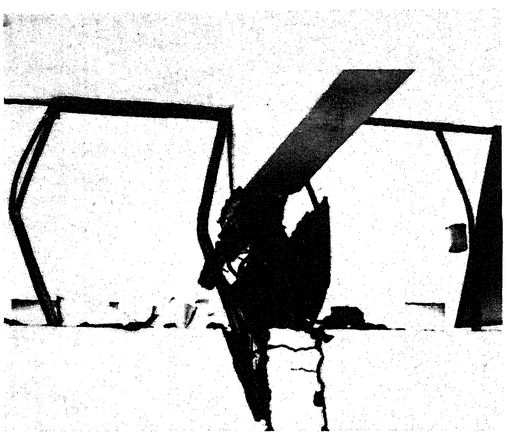

Fig. 10 - Damage to "short column"

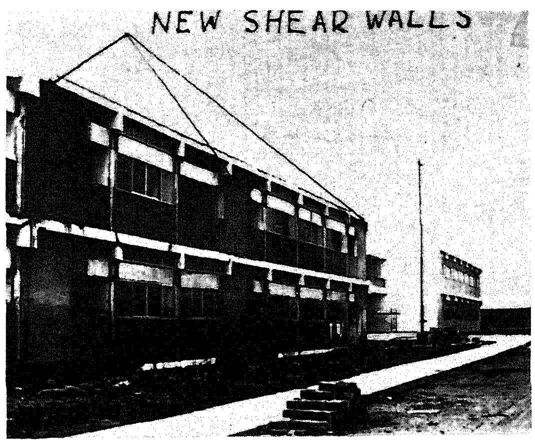

Fig. 11 - Repaired building