



REPAIR AND SEISMIC RETROFITTING OF HOSPITAL AND SCHOOL BUILDINGS IN PERU

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SUMMARY

The earthquake that hit southern Peru on June 23, 2001 ($M_w=8.4$) caused important damage to the hospital and school infrastructure of southern Peru and northern Chile. The affected zone was declared in emergency, the repair and retrofitting of the buildings had to be done quickly and with limited economic resources. While developing the reinforcement or retrofitting projects, the construction documents of the buildings under reparation were often unavailable, and it was impossible to follow the published international recommendations defining the seismic protection levels and methodology. The performance objectives adopted were below those indicated as basic by FEMA. The general strategy was to increase the resistance and rigidity levels by the inclusion of concrete or masonry walls. Nowadays, most of the repaired or retrofitted buildings are in use, and although it was not possible to provide them with an optimal seismic performance, an important reduction on their vulnerability has been attained. This experience suggests the need to develop procedures for seismic retrofitting of buildings in developing countries, with reduced objectives, but feasible in technical and economic terms.

THE SOUTHERN PERU EARTHQUAKE OF JUNE 23, 2001

At 3:33 p.m. local time of June 23, 2001, a strong earthquake hit southern Peru, with epicenter on the coast near the town of Atico, in the Arequipa region. The cities of Arequipa (second largest Peruvian city), Moquegua, and Tacna in Peru were mostly affected, as well as Arica in northern Chile; even in La Paz, Bolivia, the vibration was felt in tall buildings. At least 75 persons were killed, most of them due to

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the tsunami in the town of Camaná, close to the epicenter. The magnitude reported by the National Earthquake Information Center was $M_w=8.4$, while the Peruvian Geophysical Institute, IGP [1], reported a value of $M_s=7.9$. However, in comparison to the earthquakes of Lima 1746 and Arica 1868, the 2001 Atico earthquake was not as severe, both as a geological event and as the destruction observed. Therefore, on the engineering point of view, based on the observation of the damage and reported intensities, the June 23, 2001 Atico earthquake may be classified as a moderate one.

AFFECTED SCHOOL AND OTHER EDUCATIVE BUILDINGS

Most of the school buildings in Peru are constructed by the national government. For example, the National Institute for Educative and Health Infrastructure (“Instituto Nacional de Infraestructura Educativa y de Salud”-INFES), created in 1992, was responsible for 3166 school constructions in the 1992-2001 period, Coll and Vargas [2]. Also, other institutions like local governments and parents school associations, have constructed other school buildings with their own economic resources, resulting in a variety of architectural models, quality of construction and materials.

It is common to find typical classroom buildings having 1 story to 3 stories, with 2, 3 or 4 classrooms per story. In the longitudinal direction, the usual structure is a concrete frame; the transversal direction structure features a combination of masonry bearing walls and concrete frames. The walls are typically made of clay masonry and have confinement concrete elements. In most cases, the roof is a one-way joist slab, supported on the transversal elements (frames or walls). Stairways are usually an independent structure, leading to a distribution corridor in the upper stories where the classrooms are located.

During the November 12, 1996 Nazca earthquake in Peru ($M_w = 7.5$), several school buildings had a poor performance. The common damage was short column failures in the longitudinal direction due to tall non-structural masonry walls with windows. This moderate earthquake showed clearly that the longitudinal direction of traditional school buildings had excessive lateral displacements.

The Peruvian seismic code of 1997, SENCICO [3], replaced an older code from 1977, emphasizing the increase in rigidity requirements. Among the most important changes, we may mention: 1) calculated lateral displacements were increased; 2) allowable lateral drifts were reduced; and 3) educational buildings were declared as essential buildings, with a importance factor of 1.5 (the highest of the code), similar to hospital or emergency facilities. This decision was established on the idea that school buildings are used as temporary shelters in case of a disaster. Therefore, in the longitudinal direction, the school buildings designed and built after 1997 have stronger concrete columns than the ones built before the 1997 code, in order to comply the drift limitations and avoiding the short column effect.

The “Casimiro Cuadros” school in Arequipa features building blocks constructed in different years, using different codes and design criteria, as well as a visible difference in quality of construction. At this site, the seismic base movement in the 2001 earthquake must have been similar for all the blocks; however, each block had a distinct behavior (fig. 1). The old blocks had flexible systems and showed the short column failure, with so much damage that the blocks had to be demolished. On the other hand, the rigid block, designed and built according to the 1997 seismic code criteria, was undamaged. What happened in the “Casimiro Cuadros” school is a good example on what could be observed in other schools buildings in the affected zone: flexible traditional blocks with shear failure in columns due to the short column problem, and rigid new blocks without any damage.



Fig. 1. “Casimiro Cuadros” school in Arequipa: old and new blocks (left) and short column failure in old block (right).

In the city of Moquegua, the “Angela Barrios” school (an older type) was one of the most affected. At the corner block, the interior columns failed due to the short column effect (fig. 2, left), losing more than 0.3m height; then, the roof fell inclined producing the failure of the exterior columns (fig. 2, right). This school is located in a sloping area, and the affected block was elevated between 2 to 4 meters above natural terrain. It is probable that a foundation problem and a bad quality of the construction may have increased the natural vulnerability of this structural system.



Fig. 2. “Angela Barrios” school in Moquegua: interior column general failure (left), and exterior column failure (right).

The “San Agustín” National University in Arequipa had also several buildings damaged due to their flexibility, with short column effect present in several blocks. In the Electronics Engineering block it was intended to avoid the short column effect by using a window between the column and the walls; however, the poor rigidity of the building and the window rigid frame were enough to produce the shear failure (fig. 3, left). Another collapsed structure was the first floor staircase of the main library (fig. 3, right).



Fig. 3. “San Agustín” National University in Arequipa: short column typical failure (left), and library staircase collapse (right).

Some older school blocks in the affected area had little damage, due to the great rigidity provided by the infill walls in the frames. A traditional school building without damage (fig. 4, left) has its rear facade coinciding with the property limit, which was closed up with an infill wall all long. Also, the new school buildings in the affected region, designed and constructed according to the 1997 seismic code, had no damage, neither structural, nor in windows, doors, or infill masonry walls (fig. 4, right). The structural seismic resistant system of these blocks consists of masonry bearing walls in the transverse direction and strong concrete columns in the longitudinal direction.



Fig. 4. Traditional school without damage due to infill wall at rear facade (left), and new school buildings featuring strong columns in the longitudinal direction without any damage (right).

AFFECTED HOSPITALS

The June 23, 2001 earthquake caused slight damages to the structural systems of hospitals in the affected area. However, several buildings in three important hospitals had to be evacuated due to extended non-structural damage, in the cities of Arequipa, Tacna (southern Peru), and Arica (northern Chile).

In the National Hospital “Carlos Alberto Seguín Escobedo” of Arequipa, the taller seven-story block had extended damage to non-structural walls; all floors except the first one were evacuated. In February 16, 1979, an earthquake ($M_s=6.7$) had produced damage to non-structural walls, which were repaired, but no structural retrofitting was performed. In the “Hipólito Unanue” Hospital in Tacna, all the upper stories of

the 3 six-story buildings were evacuated and emergency constructions had to be installed (fig. 5, left); besides the non-structural walls, the sanitary installations were also damaged (fig. 5, right).



Fig. 5. “Hipólito Unanue” hospital in Tacna had damage to non-structural walls and sanitary installations.

The “Dr. Juan Noé Crevani” Hospital in Arica (northern Chile) was also evacuated due to several non-structural wall cracks; medical equipment was attached to these walls and they were unable to be secured. Previous studies had shown corrosion problems in the columns, and also vulnerability in non-structural elements due to excessive drift; these problems were determinant in the decision for evacuation.

All important hospitals in the affected area were built several decades ago, without the safety criteria and engineering knowledge of today. The structural system of these buildings consists of reinforced concrete frames, mainly thought on vertical loads; therefore, they lack of adequate resistance, ductility and rigidity for seismic forces. However, in these buildings in both directions, there are a large amount of non-structural walls attached to the main structure. During the earthquake, these walls reduced the lateral displacements and dissipated energy (fig. 6); by that way, they protected the vertical load carrying system.



Fig. 6. Non-structural walls controlled lateral displacements and dissipated energy during the earthquake in hospitals: Arequipa (left) and Arica (right).

OBJECTIVES, METHODOLOGY AND RETROFITTING STRATEGY

Objectives

The repair and retrofitting projects developed in the 2001-2002 period after the earthquake, had to follow the 1997 seismic code, SENCICO [3], which established that every retrofitted structure had to reach the same performance as a new building. By that time, a revised version of the 1997 seismic code was ready, but was not officially published until 2003, SENCICO [4]. The new code articles accept the possibility to use “other criteria” in this type of work. Somehow, the unpublished code document was used to support many of the decisions that had to be taken during the repair and retrofitting projects.

The seismic zone (coast) where the affected buildings are located is of high seismicity, according to the Peruvian code. In Table 1, the expected peak rock acceleration is shown for two hazard levels, Muñoz [5].

Table 1. Peak Rock Acceleration for Peruvian coast

Earthquake	Tr (years)	Peak Rock Acceleration (g)
Frequent	75	0.2
Rare	500	0.4

The limited economic resources, the unavailability of the building construction information, and the celerity needed to execute the reconstruction works, obliged to select performance objectives below the basic ones considered either by FEMA [6] or ATC [7]. Several works performed by the authors [8], [9], and other important local engineering firms, were used to set the main objective of retrofitting in the protection of lives for a 500-year return period. Only in a few cases it was possible to attain a functional performance for frequent earthquakes (Table 2).

Table 2. Performance Objectives

Earthquake	Performance	
	Functional	Life Safety
Frequent	☹ ?	
Rare		☺

Methodology

Once the main general objectives were decided, the methodology of work for the retrofitting project of a particular building could be reduced to the following steps:

- Compilation of the few construction information available and local site conditions.
- Get building information on the site. Damage plan drawings and structural systems. Identification of the structural configuration, and shape defects.
- Soil mechanics study.
- Sometimes, small concrete specimens were extracted for experimental tests.
- Definition of the reinforcing system for structural retrofitting.
- Structural analysis of the reinforced system considering elastic behavior.
- General check of the structure for rare earthquake by controlling lateral drift and the demand-capacity rate for internal forces.
- Structural design and detailing of the reinforcement system.

- Estimated cost.

General Strategy for Retrofitting

The retrofitted buildings were all constructed several decades ago, without seismic resistance criteria, reason for their limited resistance and ductility.

The general strategy consisted in increasing the lateral load resistance, and reducing drift to control the ductility demands on the existing elements. Structural walls of reinforced concrete and masonry were employed, mostly coupled, as well as strong frames of reinforced concrete beams and columns. Only a few times the generality of elements had to be reinforced.

The retrofitted buildings resistance was increased to the level reached using the 1997 Peruvian seismic code for new essential buildings. Fig. 7 features the seismic coefficient (resistant force as fraction of the building weight) for essential buildings, of either concrete or masonry walls, on hard soil. The drift for rare earthquake was limited to the values indicated in Table 3, which are slightly less than those established by the Peruvian seismic codes of 1997 and 2003 for new buildings.

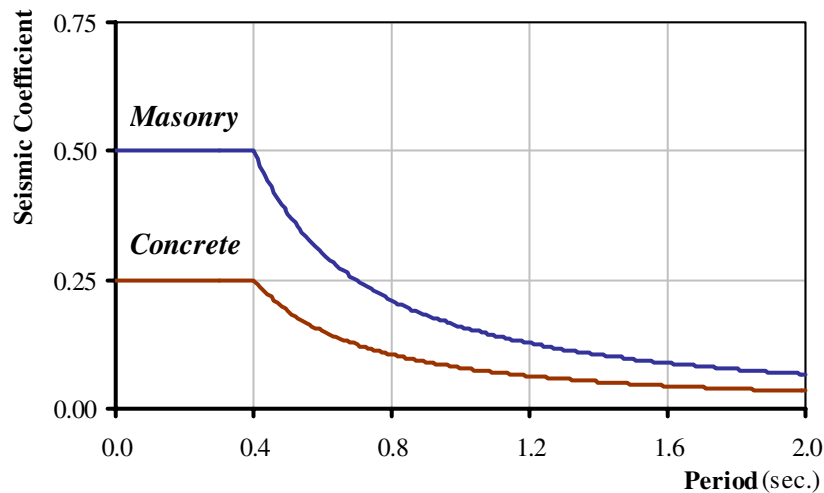


Fig. 7. Seismic Coefficient for hard soil according to Peruvian seismic code.

Table 3. Maximum drifts for rare earthquake in retrofitted buildings

Structural Material	Maximum calculated drift	Maximum allowable drift by Peruvian seismic code
Masonry	0.004	0.005
Reinforced Concrete	0.006	0.007

RETROFITTING TECHNIQUES FOR SCHOOL BUILDINGS

The 2001 earthquake produced extended damage to old school buildings. Recent figures indicate that nearly 150 different schools in southern Peru have been evaluated, and many of them have been repaired or are being retrofitted. The retrofitting was oriented to reinforce the longitudinal direction of these

buildings, which originally only featured flexible concrete frames. The transversal direction, with confined masonry walls, usually had enough wall density, and only confinement columns had to be added.

The confined masonry walls used in Peru are built using clay units; they may reach global displacement ductility values (ultimate displacement / elastic displacement) near to 4. These walls are able to reach ultimate shear stresses of 0.3 MPa or even more. In buildings featuring such masonry walls, the rate of the elastic demand for severe earthquake and final resistance is around 3, value that keeps the rare earthquake ductility demands below 4, and has a resistance comparable to the frequent earthquake demand.

For one-story buildings, usually masonry walls were included, along with concrete confinement columns of the existing frames and new beams on the roof. In figure 8 an affected one-story building and the retrofitted structural system are presented.



Fig. 8. One story school building damaged after the 2001 earthquake (left) and projected retrofitting in the longitudinal direction (right).

In case of two through four-story buildings, the retrofitting included small concrete walls and coupling beams. The concrete walls generally were constructed including the existing frame columns; the coupling beams have large inertia and were located inverted over the floor slab, as architectural parapets. In figure 9 an affected two-story building and the retrofitted structural system are presented.



Fig. 9. Two-story school building damaged after the 2001 earthquake (left) and projected retrofitting in the longitudinal direction (right).

In some cases, due to economic reasons, the shear walls had to be reduced in height or were replaced by masonry walls in the upper stories, reducing the overall performance. However, thanks to this kind of

decisions, many affected buildings could be repaired and retrofitted. Otherwise, the repair work would have been reduced to simple painting or mortar coverings, or installation repairs.

The repair and retrofitting costs on these school buildings ranked between 75 to 150 U.S. American dollars per square meter of constructed area. However, it should be mentioned that the higher value corresponds to cases where the electrical and sanitary installations, and general painting had to be redone.

RETROFITTING OF THE MOST IMPORTANT AFFECTED HOSPITAL

The National Hospital “Carlos Alberto Seguí Escobedo” of the city of Arequipa, is located on a terrain of 47 000 m², with 12 blocks, of 1 to 7-story buildings, making a gross total of 32 000 m² of constructed area. Almost all the buildings are several years old and did not fulfill the seismic code requirements. During the planning process, only some of the building plans were available, and these were only a crude reference, because afterwards, while proceeding with the job, several changes in the architecture and installations, plus structural repairs and modifications were found without any documentation. The soil mechanics study found a firm soil for the foundation and soil factors.

As the hospital buildings were constructed at different years and had different number of stories, different techniques had to be applied for the retrofitting. One-story buildings were found undamaged thanks to the high density of clay masonry walls; in these cases, the retrofit only consisted in adding confinement columns and beams around the more important walls for seismic resistance. In other one-story buildings with lower wall density, either concrete or masonry walls were added. The 3-story high administrative building needed new concrete walls and column jacketing.

The tallest hospital building is dedicated to hospitalization rooms and consulting areas, with 7 stories and a gross constructed area of 14 000 m². It was originally divided into two blocks by a 0.05 m central joint. The structure of this building was mainly conceived to support vertical loads, with reinforced concrete frames perpendicular to the facades, to support the floor slabs; also, there are some concrete walls in the elevator and staircase boxes (fig. 10).



Fig. 10. Main building of the Arequipa hospital before the retrofitting.

The architecture and equipment limitations practically restricted the retrofitting action to the lateral facades and some interior lines. The retrofitting system consisted in creating longitudinal rigid and ductile frames by jacketing columns and beams of both facades. In the transversal direction, some concrete walls were included. A plan view of the left block of this main hospital building is shown in fig. 11, with the

reinforcement elements shaded in red. In figure 12, one of the facades with the jacketed columns during the construction process is displayed.

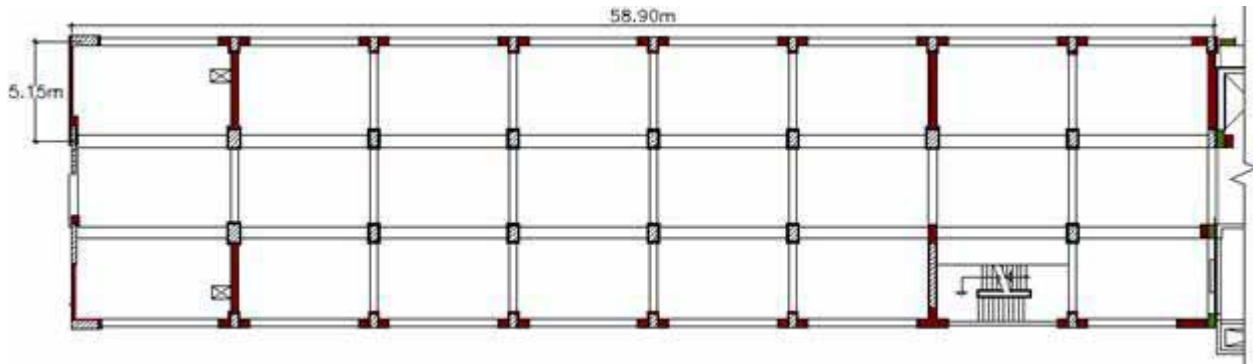


Fig. 11. Plan view of left block of the Arequipa main hospital building, displaying the retrofitting elements. Concrete walls in the transverse direction and ductile frames in the longitudinal direction (facades) were added.



Fig. 12. Main building of the Arequipa hospital, during the construction retrofitting process.

The evaluation results of the retrofitting for this main hospital 7-story building are indicated in Table 4. The fundamental periods in each direction were practically reduced to the third part and lateral displacements to the half. The lateral resistance was practically increased three times.

Table 4. Retrofitting system evaluation – drift control

	Longitudinal Direction		Transversal Direction	
	Unreinforced	Retrofitted	Unreinforced	Retrofitted
Period (sec)	1.2	0.4	1.5	0.8
Roof Displacement (cm)	18	8	22	13
Maximum story drift (%)	1.0	0.5	1.2	0.65

Even after the proposed retrofitting in this main building, the separation block joint of 0.05m was not enough, and had to be enlarged. At the joint area between the two blocks, new columns had to be built, in order to demolish the existing ones for the joint enlargement.

The amount of the proposed retrofitting for all the buildings was near to U.S. \$3 million (approximately U.S. \$95 per m²).

At the time of writing this paper (January 2004) the retrofitting works still are undergoing, and the authorities are thinking on reducing the retrofitting action at some buildings of lesser importance, which had no practical damage in previous earthquakes.

SITUATION OF OTHER AFFECTED HOSPITALS

In the affected buildings of “Hipólito Unanue” Hospital in the city of Tacna in southern Peru, the retrofitting works have begun; however, as the hospital is nearly 50 years old, the electrical and sanitary installations were found to be deteriorated and the assigned budget had to be increased. The buildings are now partially on service.

In the case of “Juan Noé Crevani” Hospital in the city of Arica in northern Chile, although several retrofitting studies have been performed, the construction works have not been initiated and the main building cannot be occupied. Apparently, the cost of the required structural retrofitting is too high.

CONCLUSIONS

- The school buildings that were affected in the 2001 Atico earthquake had flexible reinforced concrete frames. The common damage in these buildings was the short column failure.
- The hospital buildings had practically no structural damage, but most had non-structural wall cracking and some buildings presented installation damages.
- The repair and retrofitting of the affected buildings had to be done quickly and with limited resources. Only a few of the original plan drawings were available, as well as site studies.
- It was impossible to follow the recommendations of FEMA or ATC dealing with the procedures and general objectives, due to the limited starting information, the shortage of time to perform the retrofitting project, and mostly, due to strong economic conditionings.
- The selected retrofitting objectives were less than those considered as basic by FEMA or ATC. The retrofitting action dealt basically to guarantee a seismic performance to save lives for a 500-year return period. Only in a few cases it was possible to guarantee a functional level for earthquakes with 75-year return period.
- The general strategy for the retrofitting action was to increase the overall resistance of the buildings, and reducing the lateral drifts, in order to control the ductility demands on the structural elements that were not retrofitted.
- In most retrofitted buildings, confined masonry walls or concrete walls, coupled with strong beams, were added. At the main hospital building of the affected area, concrete walls were unable to be considered in the two principal directions, so walls were used in the transversal direction and ductile frames were used in the longitudinal direction.
- Due to strong economic limitations, in some cases it was decided to reduce the objectives even more and the extension of the retrofitting action. Thanks to this kind of decisions, it was possible

to provide some retrofitting to more buildings, which otherwise would only have been repaired in the coverings or installations.

- Many old school buildings with clay masonry-infill concrete frames were undamaged.
- The 2001 Atico earthquake did not damage buildings designed according to the 1997 Peruvian seismic code. This is an important achievement compared to the effects of the 1996 Nazca earthquake.
- School and hospital buildings in neighbor countries have also been damaged in recent moderate earthquakes. It is necessary to share related information, in order to develop common criteria to prevent damage and economic losses in such events in countries under development.
- The recommendations of FEMA, ATC or SEAOC, for building retrofitting are a simple reference with limited application in countries with economic difficulties. It becomes necessary to develop a methodology for building retrofitting with protection objectives feasible in economic terms and working conditions in countries under development.

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