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HOW PERUVIAN SEISMIC CODE GREATLY IMPROVED BUILDING RESPONSE TO REAL EARTHQUAKES

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SUMMARY

Actual response of school buildings, with almost identical architecture and configuration, subjected to a moderate to severe shaking was analyzed. A group of these was designed with 1977 Peruvian Standard while another was designed with 1997 updated Standard. Those designed with the former 1977 Code suffered damage while the ones designed with modern 1997 Standard did not experience damage whatsoever. This evidences Peruvian practice has achieved real protection of essential and other building structures due to an strategy based on drastically limiting displacements. Although allowable displacements are similar to worldwide practice, computed displacements are large based on large R values.

INTRODUCTION

After 20 years, in 1997 the Peruvian Technical Committee for Seismic Resistant Design issued a new standard which profited from experiences from earthquakes worldwide between 1985 and 1996. One of its key features was the increase on computed lateral displacements (over 3 fold). Building structures so designed became much more rigid than those obtained using specifications from the former 1977 code. This paper presents a comparison of the seismic response of actual state school buildings to the June 21st, 2001 Atico (Arequipa) earthquake (Mw=8,4) in southern Peru. This structures are located at the same region thus assuming were subjected to the same shaking, with identical architectural distribution (2 story) in which the only variable is the seismic design code and more precisely the procedure for calculating lateral displacements. Field information was collected after the earthquake, dynamic analysis were performed. It could be observed that buildings designed using the higher displacement requirements from the 1997 code evidence no damage al all whereas those designed using the former code, with requirements similar to world standards had short column failures almost widespread in spite of being separated from partition walls. This strongly suggest the current Peruvian Standards produces buildings

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that fully respond to the requirements for essential buildings, that is to maintain operation after a strong earthquake, limiting damage and precluding collapse.

EARTHQUAKE MOTION

Earthquake in Southern Peru (Arequipa Region) on June 23rd 2001

"The earthquake occurred in Arequipa on June 23rd 2001 at 15 hours 33 minutes local time caused important damages in Departments of Arequipa, Moquegua and Tacna and to the cities of Arica and Iquique in Chile. National Institute for Civil Defense (INDECI) indicates the earthquake produced 74 dead people, in addition to 64 dissapeared, 2,689 injured and 217,495 homeless in the whole affected region. People disappeared due to the effects of a tsunami caused by the earthquake and was responsible for the destruction of around 2000 housing units at beaches of Camana city". Zamudio [1]

Geophysical Institute of Peru (IGP) located the epicenter of this earthquake at coordinates ituto Geofísico del Perú (IGP) 16.20° S, 73.75° W; that is at 82 km NW of the town of Ocoña, closer to Atico, as shown in Figure 1.

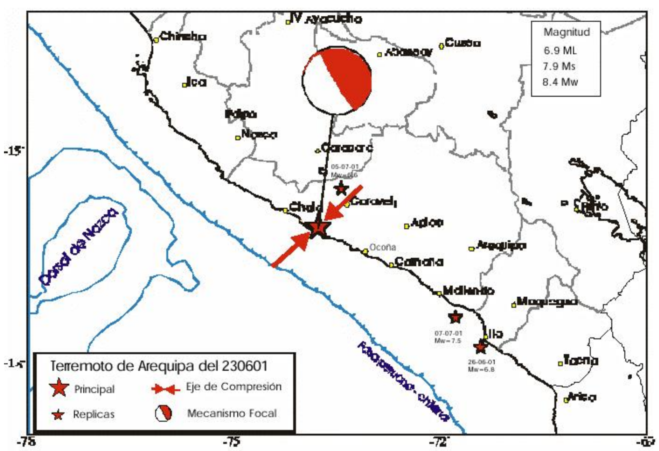

Figure 1. Focal Mechanism and stress orientation. Earthquake of June 23rd, 2001. Arequipa, Peru.

National Seismic Network registered a total of 134 aftershocks in the first 24 hours, many of them producing intensities between III and Y in Modified mercallu Scale (MM) in the city of Arequioa, which is the largest city in southern Peru. (1 000 000 inhabitants).

Intensities and seismicity of the region

Peru Japan Center for Earthquake Engineering Research and Disaster Mitigation (CISMID) of the Faculty of Civil Engineering of the National University of Engineering (UNI) maintains a network of accelerographs having registered the main event in the Moquegua Station, (a city south of Arequipa, around 400km away from the epicenter). Peak acceleration value obtained for the E-W direction was 295.3 gals, in the N-S direction 220 gals and 160.6 gals in the vertical component. In Figures 2 and 3 the registered accelerographs are plotted.

"Damage produced by this seismic event showed once again that structures built which do not follow technical standards and are built without technical supervision, with poor workmanship and low quality materials will have a high level of seismic vulnerability", CISMID [2].

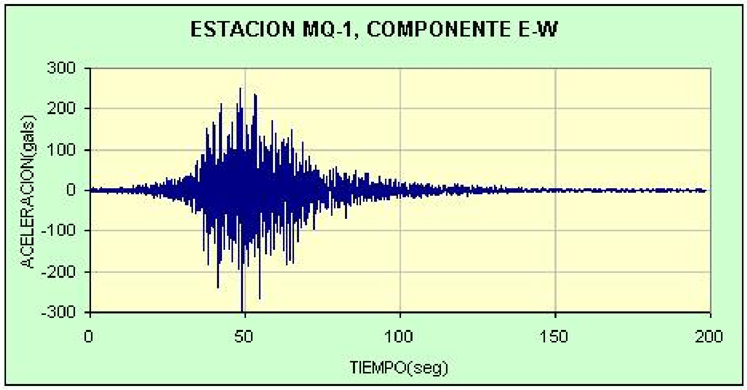

Figure 2. Acceleration Record in Moquegua, Peru. E-W Component. Earthquake of June 23rd, 2001 Arequipa. (Mw=8.4) PGA= 295.3 gals.

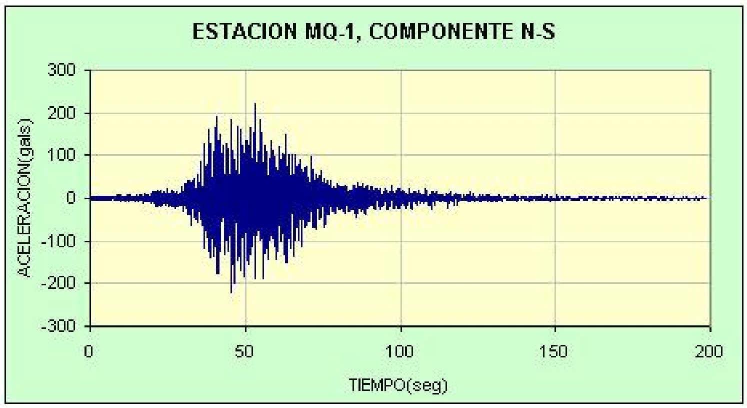

Figure 3. Acceleration Record in Moquegua, Peru. N-S Component. Earthquake of June 23rd, 2001 Arequipa. (Mw=8.4) PGA= 220.0 gals.

COMPARISON OF PERUVIAN 1977 AND 1997 SEISMIC STANDARDS

Allowable Displacements

One of the important changes between 1977 and 1997 was displacement control. This was done in two ways. Through a substantial increment of computed displacements and through a reduction of the allowable drift. In 1997 separate limitations were introduced for different structural materials.

En la 1977 standard the maximum interstory displacement was 0.01 (1/100) of story height, in the case where nonstructural elements could be damaged. It that was not the case and additional 50% was allowed, rising up to 0.015 (1/66).

En Table 1 a comparison of drift control in both standards is presented. It can be observed the 1977 Standard allowed a greater flexibility. Although limits allowed in 1997 Standard are not far from current practice worldwide, it meant a significant improvement in terms of separate limits as a function of material. For most buildings which in Peru are made of reinforced concrete the increased was 43%. Limits for masonry structures was more stringent based on local experience since brick walls crack al very low distortions (1/1000).

Table 1 Drift limitations in 1977 and 1997 Peruvian Seismic Standards

	1997 Standard	1977 Standard	Increased limitation
PREDOMINANT MATERIAL	$\left(\Delta_I / he_i \right)$	$\left(\Delta_I / he_i \right)$	$\left(\frac{\Delta_{77}}{\Delta_{97}} - 1 \right) \cdot 100$
Reinforced concrete	0.007	0.010	43%
Steel (*)	0.010	0.015	50%
Masonry	0.005	0.010	100%
Timber	0.010	0.015	50%

Base Shear

In 1977 Standard base shear was computed through the classical expression:

$$H = \frac{Z \cdot U \cdot S \cdot C}{R_d} \cdot P$$

where R_d intended to represent ductility factor, and where $C = \frac{0.80}{\left(1 + \frac{T}{T_s}\right)}, \quad 0.16 \leq C \leq 0.4$

In 1997 Standard a similar expression was used, but this time R was considered to be only a Response reduction factor.

$$V = \frac{Z \cdot U \cdot S \cdot C}{R} \cdot P$$

where the spectral amplification function $C = 2.5 \left(\frac{T_p}{T} \right)^{1.25} \leq 2.5$

Since changes were introduced in the Z and C coefficients to reflect international tendencies. Z was to reflect effective peak ground acceleration of the zone and C was to reflect response amplification

In Table 2 a comparison of seismic parameter for standard buildings and firm soil is presented.

Table 2 Comparisons between base shear factors in 1977 and 1997 Standards

Seismic Standard	1977	1997
Z factor	1	0.4
U factor	1	1
S factor	1	1
C factor (for short periods)	0.4	2.5
ZUCS	0.4	1

It can be observed that if R values did not change it would result in a force larger for a factor 1/0.4=2,5. However an important consideration decided by the Standards Committee in 1997 was to maintain the force level at the same values of the 1977 Standard. As can be seen from Table 2, change in these coefficients meant a 2,5 fold increased in the forces. Because of that the Committee decided to multiply the R factor by 2.5 in order to maintain base shear at the same level. R_d was renamed, R, Response Reduction Factor, and including the ductility and overstrength factors. A comparison of these values is shown in Table 3.

As it can be seen R factors appear to be rather large, but it must be kept in mind that they include as adjusting factor and do not represent expected ductility only.

Table 3. Response Reduction Factor in and 1997 Peruvian Seismic Standards

EARTHQUAKE RESISTANT STRUCTURAL SYSTEM	1997 Standard Response Reduction Coefficient R	1977 Standard Ductility Factor Rd
Steel frames	10	6
Reinforced Concrete frames	10	5
Dual systems	10	4
Reinforced Concrete Shear Walls	7.5	3
Reinforced masonry	6	2.5
Timber construction	7	4

Displacement Spectra

For displacement computation this change in R factor meant an important increase in calculated values. 1977 Standard specified that actual displacements was to be estimated multiplying computed values times ¾ R_d. On the other hand the 1997 Standard specified that actual displacements were to be computed multiplying analysis values time R values. By considering a factor of 1R instead of 3/4R an additional increment was included. Actual displacement corresponds to an inelastic behavior

$$\Delta_{actual} = \Delta_{computed\ from\ analysis} xR$$

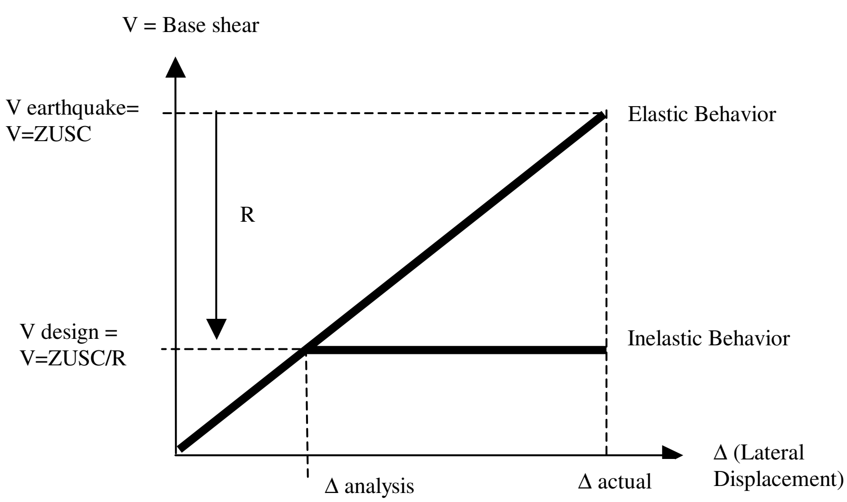

Figure 4. Actual displacement computation.

In the 1997 Standard, design displacement spectrum is as follows:

$$S_d = \frac{1}{\omega^2} S_a = \frac{1}{\omega^2} \frac{ZUSC}{R} g$$

$$S_d = \frac{T^2}{4\pi^2} \frac{ZUS}{R} \left[2.5 \left(\frac{T_p}{T} \right)^{1.25} \right] g = \frac{ZUST_P^{1.25} T^{0.75}}{1.6\pi^2 R} g$$

In the 1977 Standard, design displacement spectrum was as follows:

$$S_d = \frac{1}{\omega^2} S_a = \frac{1}{\omega^2} \frac{ZUSC}{R_d} g$$

$$S_d == \frac{T^2}{4\pi^2} \frac{ZUS}{R_d} \left[\frac{0.80}{\left(1 + \frac{T}{T_s}\right)} \right] g = \frac{0.20 ZUST_S T^2}{\pi^2 R_d (T_s + T)} g$$

In Figure 5 a comparisons of Displacement Spectra corresponding to both Standards 1977 and 1997 is presented for the case of school buildings where importance factor U, has also been increased, from 1,3 to 1,5. Both graphs are for Soil Profile I, S=1.

Table 4. Seismic Parameters for displacement spectrum comparison, 1977 and 1997 Standards

Seismic Parameter	CHARACTERISTIC	**1977 Standard**	**1997 Standard**
ZONE	Peruvian Coast	1	3
Zone Factor (Z)		1.0	0.4
Importance Factor or Use (U)	Category B	1.3	1.3
Parameter de soil (S)	Rocks or very rigid soils	1.0	1.0
Parameter de soil (Tp)	Rocks or very rigid soils	0.3	0.4

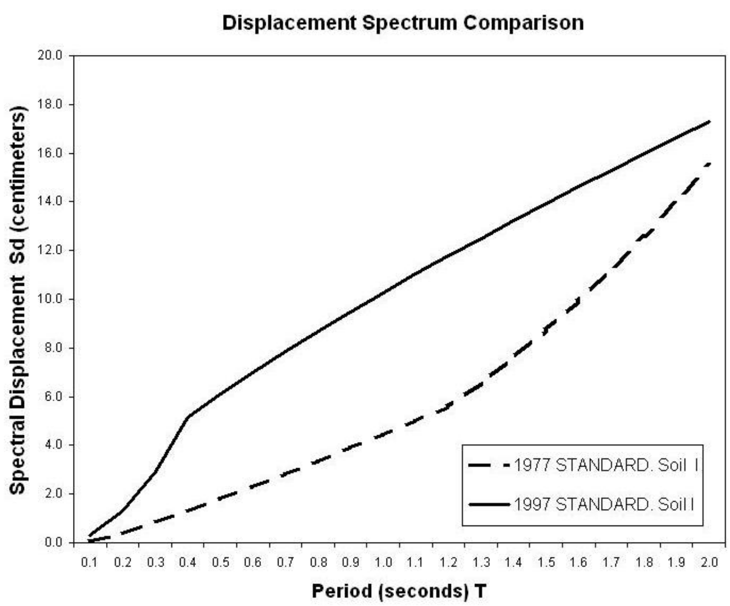

Figure 5. Comparison of Displacement Spectra, 1977 Standard (N-77) and 1997 Standard (E030-97). Buildings Category "B"

In Figure 6 a similar comparisons of Displacement Spectra is presented but including the soil factor for the three soil profiles considered in both standards. corresponding to both Standards 1977 and 1997 is presented for the case of school buildings where importance factor U, has also been increased, from 1,3 to 1,5. Both graphs are for Soil Profile I, S=1.

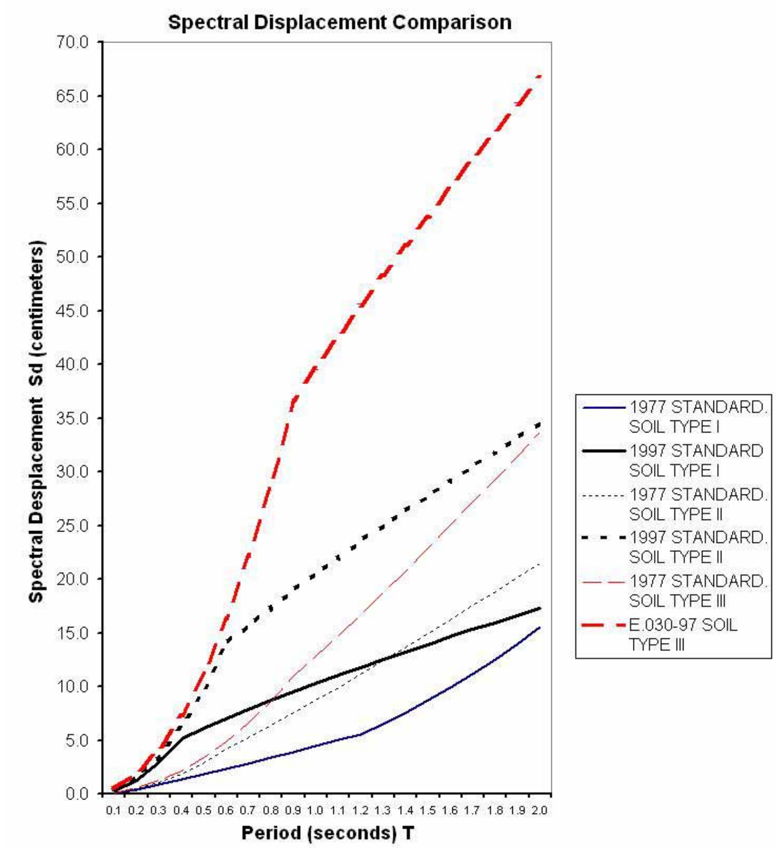

Figure 6. Influence of Soil Profile in Displacement Spectra, 1977 Standard and 1997 Standard. Buildings Category "B".

In Figure 7 the ratio between spectral displacement in 1997 standard and 1977 Standard is given for all three soil profiles. It can be appreciated that displacement demand has increased more than 3 fold for short period structures. This comes from two sources. Increment in the R factor, which as explained before was multiply time 2.5. And from the specification that actual displacements are obtained multiplying displacements from structural analysis times full R instead of ¾. By comparison 1997 Standard will produce displacements larger in 2.5 x 4/3= 3.33 times. Additionally this is to be compared with displacement limitations which , as shown in Table 1, have also increased by a minimum of 43/%.

As a result structural designs based on the 1997 Peruvian Standard will produce much more rigid structures than with former 1977 Standard. Actual school buildings so designed have performed extremely well in June 21 2001 earthquake with no damage while similar structures designed according to the former Code have suffered widespread damage. Should this be the way to follow to give real protection to essential structures?. This experience seems to indicate this is the correct approach.

BUILDING RESPONSE

Structures in study

In the last decade of the XX century a large program of school building was carried out by the Peruvian Government. Thousand of standardized pavilions were built all over Peru. Most two and three story buildings. In 1997 a new version of Peruvian Seismic Standards was released, after 20 years, this meant new more rigid designs were necessary due to increased requirements.

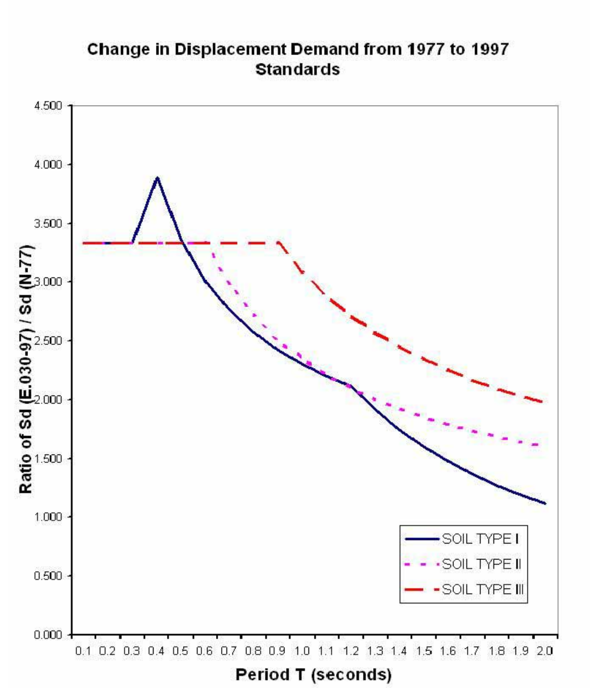

Figure 7 Comparison in Displacement Spectra, 1977 Standard and 1997 Standard. Buildings Category "B".

In order to compare the response to the same earthquake of these structures which are similar in architecture but with different in structure three schools designed with 1977 Standards and two designed with 1997 Standard were chosen. All located in the same region. This way, the main variable in the response was the design standard. Martel [6]

Table 5. Building schools designed with 1977 seismic standard

School	**Location**	**Year of construction**
Chucarapi	Islay, Arequipa	1993
José M. Morante	Ocoña, Arequipa	1994
San Agustín de Hunter	Hunter, Arequipa	1994

Two school buildings built after the 1997 Seismic Standard were chosen with similar architecture to the older ones.

Table 6. Building schools designed with 1997 seismic standard

School	**Location**	**Year of construction**
C. E. N° 40199	Socabaya, Arequipa	1999
C. E. N° 40052 – Buenos Aires de Cayma	Cayma, Arequipa	1999

In Figure 7 location of these buildings in the Arequipa Region is shown.

Figure 7 Arequipa Region in southern Peru with location of school buildings in this study.

Structures shown in Figure 8 (1977 Standard) are built with reinforced concrete frames in the longitudinal direction, although, as can be seen in the plan view, columns are oriented with the strong axes in the transverse direction, because of gravity load framing. This is a flexible direction.

In the transverse direction seismic resistance is provided by solid confined masonry, being this a very stiff system.

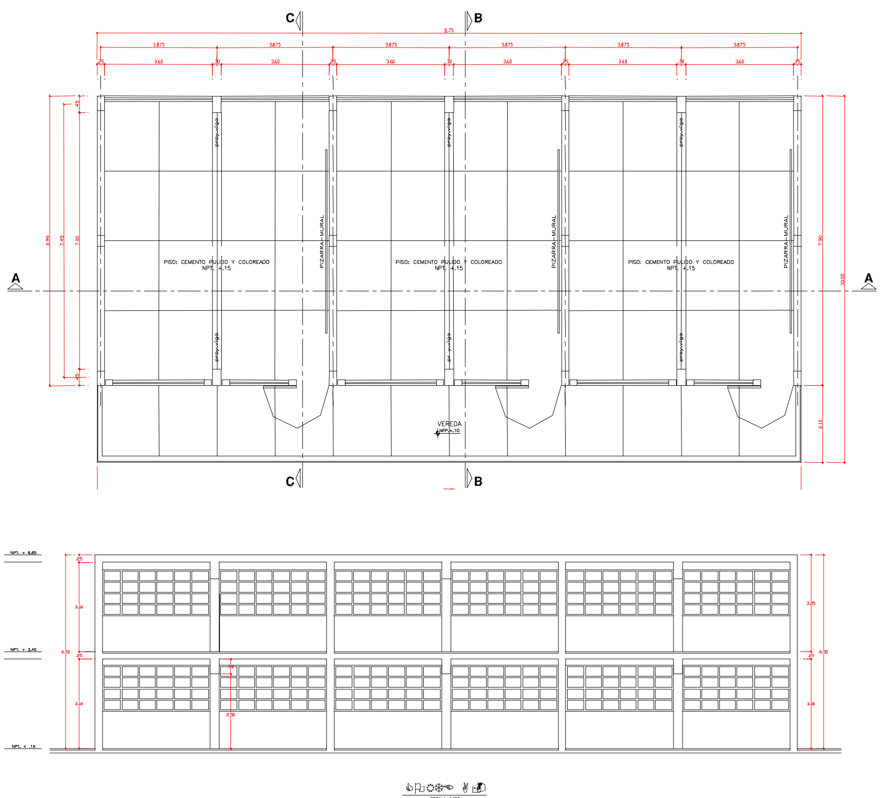

Figure 8 Elevation and first floor plan of school buildings

Schools shown in Figure 9 were designed with 1997 Standard and columns have now small flanges in the longitudinal direction giving the structure a higher stiffness. In the transverse direction the seismic resistance system is the same based on masonry walls.

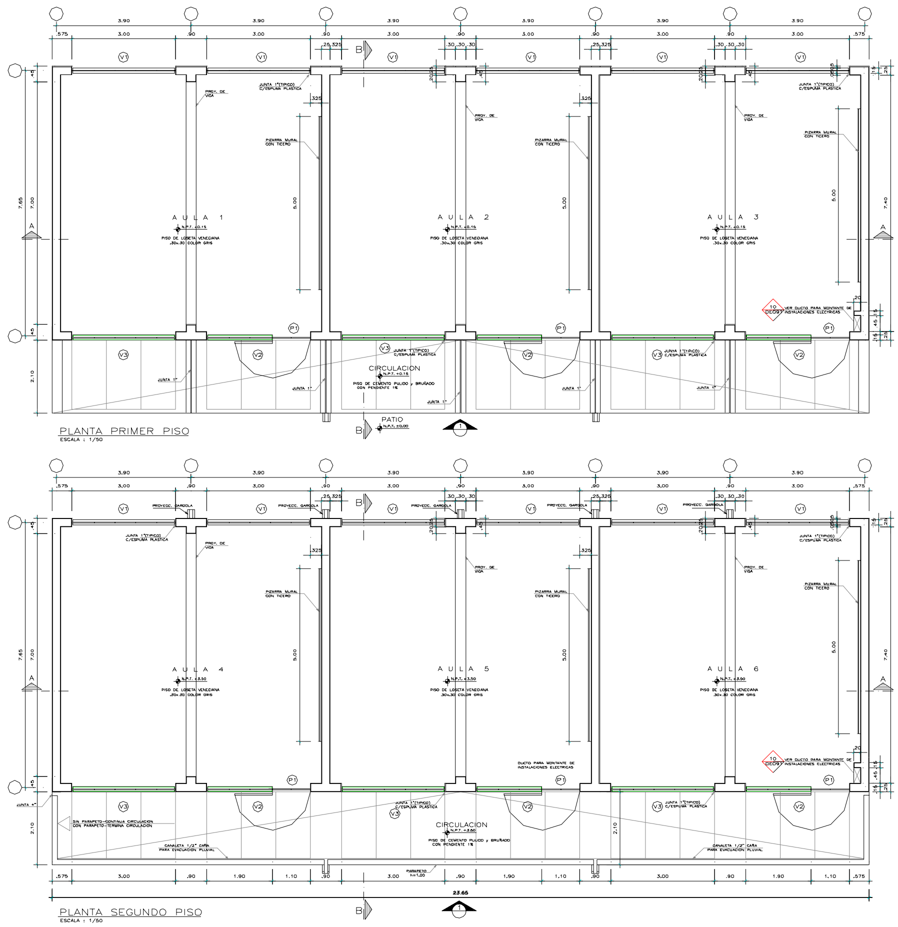

Figure 9 First and second floor plan of school buildings designed with 1997 Standard. Note T shape columns which provide larger stiffness in longitudinal direction

Actual Seismic Response to 2001 Earthquake

Schools built under 1977 Seismic Standard

All these schools experienced the 21 June 2001 earthquake. **All** those designed with the 1977 standards suffered damage. In most cases related to short column behavior, in spite of a seismic separation specified in blue prints and actually built. Evidence of excessive lateral displacement could be observed in most cases, although designs comply with the current Standard at the time. As seen all in other seismic .areas damage is related to excessive deformation. Photographs shown in Figure 10 shown the type of damage observed in these schools.

Schools built under 1997 Seismic Standard

None of the schools in the region designed and built under the 1997 Standard suffered damage at all. Stiffness was larger enough as to make seismic separation unnecessary. Figure 11 shows post earthquake condition of these schools.

Figure 10. Damage to building designed using 1977 Standard.

Even when peak ground acceleration must have been higher than design acceleration (record showed above with almost o.3g was registered 100km south from Arequipa region where schools were located, even further from epicenter) , there was no damage and the schools continue to operate unharmed.

Figure 11. Post earthquake condition of school building designed using 1997 Standard.

Displacements Analyses

School buildings are considered essential structures in the 1997 Standard, the importance factor was increased in relation to 1977 Standard. Besides this fact no other changes were introduced in the computation for base shear. Martel [6].

A comparison of computed relative story displacements from a spectral dynamic analysis in the longitudinal direction is shown in Table 8. It can be seen than displacements of school under 1997 Standard have been reduced to almost one third of the older 1977 structure.

Table 7. Comparison of parameters for school buildings. Note a 15% change in base shear.

	1977 Standard	1997 Standard
Z	1	0.4
U	1.3	1.5
S	1.4	1.4

C (máx for short periods)	0.4	2.5
Reduction Factor	Rd = 4	R = 10
Base Shear	H =18.2% P, or	V = 21% P

Table 8. Ratio (1997/1977) of computed interstory displacements in longitudinal (X) direction

Story	Diaphragm	Load	ΔX 1977	ΔX 1997	ΔX 1997/ΔX 1977
2	D2	SX	0.02898	0.01328	0.458075
1	D1	SX	0.04184	0.01536	0.367113

CONCLUSIONS

Seismic Standards

Change in Peruvian Seismic Standards resulted in higher computed lateral displacements. Around three times that specified in the older 1977 Standard. Structures designed using 1997 new Standard have to be much more rigid than before.

Analysis

Spectral dynamic analysis performed on all school building structures showed a reduction to one third in computed displacements.

Response

All buildings designed with 1977 Standard experienced structural and nonstructural damage. None of the schools in the region designed and built under the 1997 Standard suffered damage. Stiffness was larger enough as to make seismic separation unnecessary. Even when peak ground acceleration must have been higher than design acceleration (record showed above with almost o.3g was registered 100km south from Arequipa region where schools were located, even further from epicenter) , there was no damage and the schools continue to operate unharmed. Therefore seismic response improved greatly with 1997 Standard.

Costs

Changes in structural element dimensions to achieve additional stiffness increase costs by 15%. No cost was involved after the earthquake because of absence of damage. However structures designed with 1977 Standards had to be repaired, they could not be used for several months and cost of retrofitting an stiffening reach up to 40% of initial cost.

Clearly designing and building stiffer structures has resulted in a much better performance, no damage and continuity of service. Peruvians have achieved what was always expected of seismic standards.

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