PERUVIAN SEISMIC DESIGN PRACTICE PRODUCED UNDAMAGED BUILDINGS IN PERU´S LATEST EARTHQUAKES

J.R. Pique[1] and R. Salinas[2]

[1] *Professor, Faculty of Civil Engineering, National University of Engineering, Lima .Peru*
[2] *Assistant Professor, Faculty. of Civil Engineering, National University of Engineering, Lima. Peru*
Email: jpique@uni.edu.pe; rsalinas@uni.edu.pe

ABSTRACT :

On August 15, 2007 an 8.0 Mw magnitude earthquake struck the Pacific coast of central Peru. Widespread destruction over a 300km diameter area was recorded, thousands of displaced people, collapsed houses and buildings, including school buildings, hospitals and other facilities. Records 100km from epicenter showed 0,35g and 0,50g peak ground acceleration. However some school and hospital buildings survived undamaged. These had in common a design with the latest Peruvian standards, from 1997, modified 2003. In 2001 an 8,4 Mw earthquake was recorded in southern Peru. A very large area was damaged, but at the time many school buildings post 1997 seismic standard were undamaged, while similar buildings design with older standards were all damaged. Many reinforced and masonry buildings were damaged, many collapsed, but those which follow the latest code were successful. Which factors in Peruvian practice produced safe buildings and which of these were code requirements?. The answer is a combination of stringent displacement requirements -those for essential buildings such as schools and hospitals are even more demanding- and extensive use of rigid shear walls. Even though drift limits are similar to other world codes, factors for computing lateral displacements result in rather high displacement demands. In addition irregularities are forbidden for essential buildings structures and so is the use of sole frame structural systems, to avoid unexpected unstable collapse mechanisms. A recount of experiences and an explanation for what has worked is what follows.

KEYWORDS: Seismic Codes, Seismic Response, Design Practice, Pisco earthquake.

1. INTRODUCTION

In 2003 Peru updated its latest seismic design code. This contained some changes with respect to the 1997 version, whose specifications represented a substantial change in seismic analysis and design criteria in the country. Significant changes with respect to previous design practice related to excellent response of school buildings design with the 1997 standard under s strong earthquakes were reported by Pique and Martel (2004). Current 2003 standard establishes a seismic design philosophy and criteria which sets two limit states, and new values for response reduction factor, R. It has also reduced computed displacements to 75% of that of 1997 code which were apparently too stringent. Has it worked again?. The answer is definitely yes and it is not a coincidence. We hope it can be of lessons fro other standards in seismic prone areas of the world.

Strong earthquakes in Peru, until the mid eighties, demonstrated high vulnerability of essential buildings such as hospitals and schools, which together represented 57% of damaged buildings. Structural damage was directly related to irregular configurations, shear failure in walls, local defects such as short columns (Kuroiwa, 2004). Having this in mind, 1997 and 2003 Peruvian seismic standards banned irregular configurations for essential buildings and require design for drastically limited lateral displacements. This practice has produce building structures that show a better performance than those designed with former more permissive standards. This has been observed during Atico (Arequipa), Peru earthquake of 2001 and last year Pisco earthquake of 2007. This last experience has again demonstrate that Peruvian practice of seismic design has achieved a real level of protection of essential buildings and other building types under a strategy based on limited displacements.

2. RECENT SIGNIFICANT EARTHQUAKES IN PERU

After the publication of the last Peruvian standards (1997, lightly modified in 2003), two significant earthquakes struck the central and southern coast of Peru. The first one was the Atico (Arequipa) earthquake in southern Peru, occurred on June 23rd 2001, affected Arequipa, Moquegua and Tacna regions in Peru, as well as Arica and Iquique in Chile. The second was Pisco earthquake, which occurred on August 15th 2007 and affected Pisco, Ica, southern Lima and some locations in the highlands.

2.1 Atico Earthquake. Southern Peru, 2001

Southern Peru coast was shaken by an earthquake rated as the largest in the region since the one in 1868 in Arica. Epicenter was located 82 km. NW of Ocoña, near Atico, in the Arequipa region (Tavera et al, 2001). After NEIC, magnitude was 8.4 (Mw) focal depth was 33 km. In Figure 1 earthquake epicenter is shown. Regions of Perú more affected were Arequipa, Moquegua, Tacna and Ayacucho; in Chile, the earthquake was felt in Arica and Iquique, whereas in Bolivia, it was felt as far as La Paz. Geophysical Institute of Peru (Tavera et al, 2001) reported extensive damage due to maximum intensities of VII, MMI in Ocona and Camana and Mollendo (Arequipa region near epicenter), and VII in Arequipa, Moquegua and Tacna cities. A tsunami occurred in Camana and caused the lost of 2000 houses. Although there was no record in the epicentral area, in the city of Moquegua, 300km from the epicenter an accelerograph was registered with 295 gals PGA in EW component and 220 gals in the NS, according to CISMID National Accelerographic Network, (Figure 2). Elastic response spectra (Figure 3) show buildings with the largest seismic demands in Moqugua belong to a wide range of periods, up over 1s, unusual for subduction zones earthquakes.

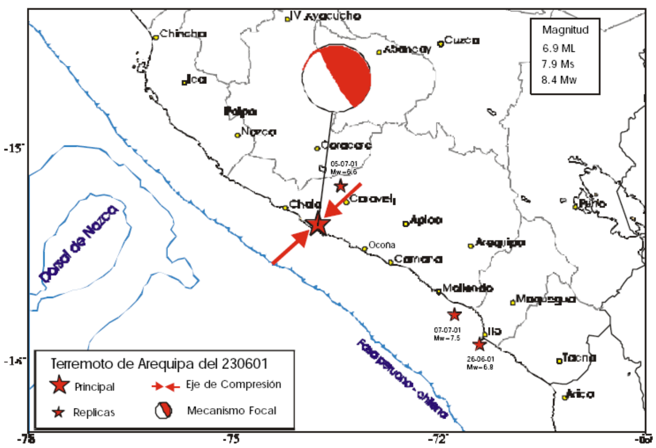

Figure 1. Epicenter location and stress orientation. Mw 8.4 Southern Peru earthquake. (IGP, 2001)

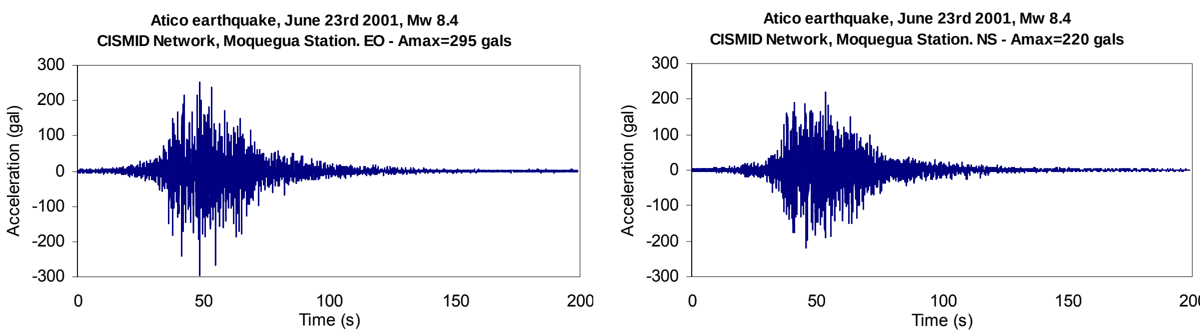

Figure 2. Ground motion records in Moquegua, 400 km to epicenter. Southern Peru earthquake, 2001.
Component EW: PGA = 295 gals. Component NS: PGA = 220 gals.

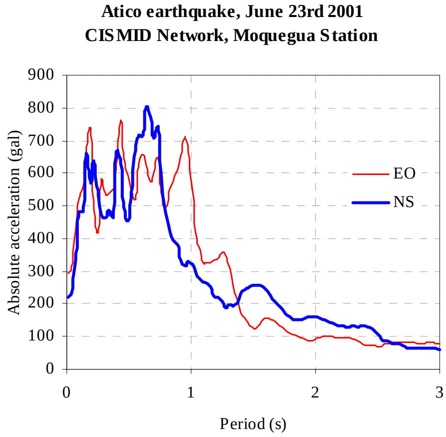

Figure 3. Acceleration response spectra. Moquegua ground motion record. Southern Peru earthquake.

2.2. Pisco Earthquake, 2007

This earthquake is considered the largest in the central region of Peru (Tavera et al, 2007) in recent times. Epicenter was located 74km west of the city of Pisco in Ica region. Magnitud was estimated at 8.0 Mw (NEIC) and focal depth 26km (Tavera, 2007). Figure 4 shows location of epicenter. Regions affected the most were: Ica, Huancavelica and south of Lima. According to Tavera (2007) intensities were VIII MMI in Pisco and Paracas; VII in Chincha and Ica city; VI in Callao and south of Lima. A tsunami of regional influence attacked Paracas, flooding private property and resort installations.

At almost 140km south east from the epicenter ground shaking was registered in Parcona and Ica. In Parcona (from Geophysical Institute of Peru) a PGA of 488 gals was registered in the EW component and 455 gals in the NS. In the city of Ica (from CISMID network) a PGA of 272 gals in the EW direction was recorded and 334 gals in the NS as can be seen in Figure 5. Elastic response spectra are shown in Figure 6. They show largest seismic demands was for buildings with periods up to 0.8s.

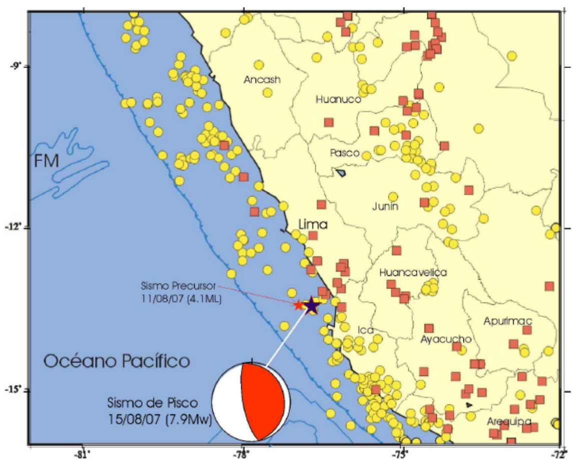

Figure 4. Epicenter location and seismic activity. Mw 8.0 Pisco earthquake. (IGP, 2007)

3. PERUVIAN STANDARD FOR EARTHQUAKE RESISTANT DESIGN

Base shear or modal spectral acceleration is computed as indicated in Eqn. 3.1, where factors are explained in Table 1.

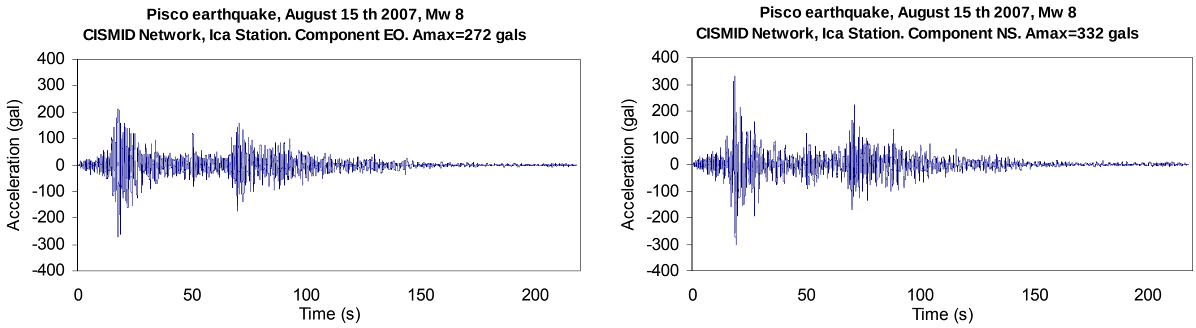

Figure 5. Ground motion records in Ica, 140 km epicentral distance. Pisco earthquake, 2007. Component EO: PGA = 272 gals. Component NS: PGA = 332 gals.

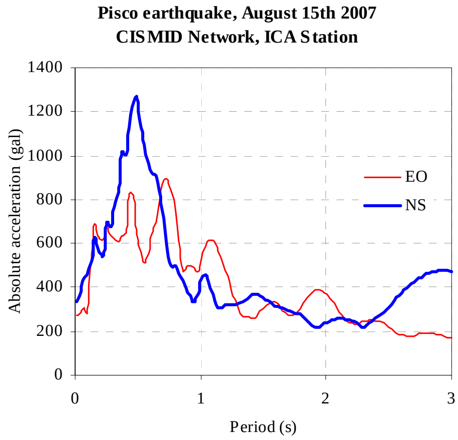

Figure 6. Acceleration response spectra. Ica`s ground motion record. Pisco earthquake.

As compared to older standards from 1977 these values result in an increment for earthquake shear (considering ZUCS to represent actual shear force from a severe earthquake) before being reduced by R to become design shear. To maintain similar strength requirement R values were increase 2.5 times, but since computed displacements are almost independent of R, to use larger values resulted in increases computed displacements.

$$V = \frac{Z \cdot U \cdot S \cdot C}{R} \cdot P \quad \text{or} \quad S_a = \frac{Z \cdot U \cdot S \cdot C}{R} \cdot g \qquad C = 2.5\left(\frac{T_p}{T}\right) \leq 2.5 \qquad (3.1)$$

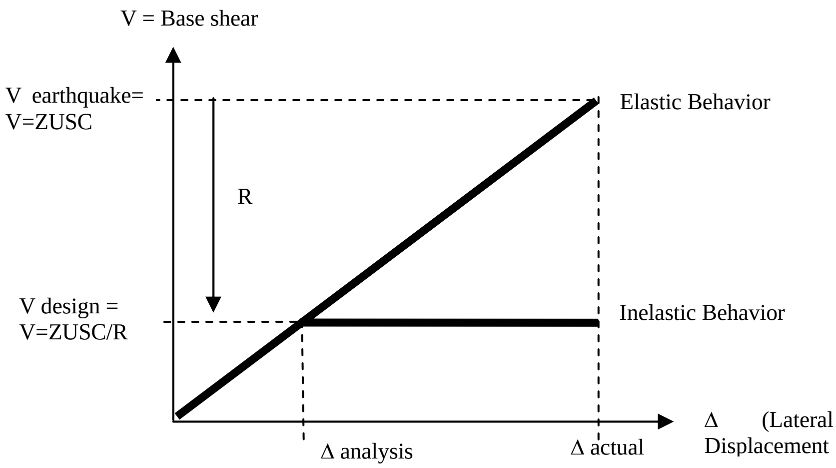

Figure 7. Design earthquake, computed from analysis and actual inelastic displacement

Table 1 Base Shear Factors in 2003 Standards

Factors	Meaning	2003 Seismic Standard
Z	Zone factor	0.4, 0.3, 0.15
U	Importance factor	1, 1,3, 1,5
S	Soil amplification factor	1, 1,2, 1,4
C (for short periods)	Seismic amplification factor	≤ 2.5
ZUCS (before dividing by R)	Earthquake shear	1 to 2.1

3.1 Displacement computation:

Actual lateral displacements are computed multiplying elastic displacements by ¾ R. (Eqn. 3.2, Figure 7). This means they are practically independent from R, and depend on ZUCS factors. This translates in displacements approximately 2.5 times than those from older standards,. On the other hand the 1997 Standard specified that actual displacements were to be computed multiplying analysis values time R values. Actual displacement corresponds to an inelastic behavior

$$\Delta_{actual} = \Delta_{computed\ from analysis}\ x\, 0.75R \qquad (3.2)$$

4. OBSERVED RESPONSE OF ESSENTIAL BUILDINGS

4.1 Actual Seismic Response to Southern Peru to 2001 Earthquake.

4.1.1. 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 8 shown the type of damage observed in these schools.

4.1.2. 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 9 shows post earthquake condition of these schools.

Figure 8. Damage to building designed using 1977 Standard.

Even when peak ground acceleration must have been higher than design acceleration (record showed above with almost 0.3g 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 9. Post earthquake condition of school building designed using 1997 Standard.

4.2.Pisco Earthquake 2007

Again we have observed (Salinas et al, CISMID 2007) buildings design and built with older standards have suffered extended damage and collapse. Figure 10 and 11 show two hospital facilities that had to be demolished after Pisco earthquake. In Figure 10 (right) a pavilion at the same hospital, but designed and built with latest seismic standards has no damage at all, even for the intensities reported. Structure has a higher wall density, in order to comply with stiffness requirements.

Figure 11 shows another hospital building, this from the social security and a school building, both designed with older standards and heavily damaged. On the other hand, in the same city of Pisco, new school buildings designed and built with 1997 and 2003 standards with no damage whatsoever.. Figure 13 shows a typical structural plan of these school buildings (Miranda et al, 2005). The structure is confined clay masonry in one direction and a frame with wide columns in the other. Older designs used slender columns which resulted in a flexible structure with large displacements. Because stringent limited displacements new designs had a need of more rigid columns which resulted in reduced displacements. These show excellent response.

Figure 10. “San Juan de Dios” Hospital, Pisco. Left: Old Pavilions, Right: New pavilion, designed with latest seismic standards

Figure 11. Antonio Skrabonja Social Security Hospital. School building, non structural and structural damage. 1977 design standard. Pisco

Figure 12. New school pavilions in Pisco. 2003 design standard. No damage.

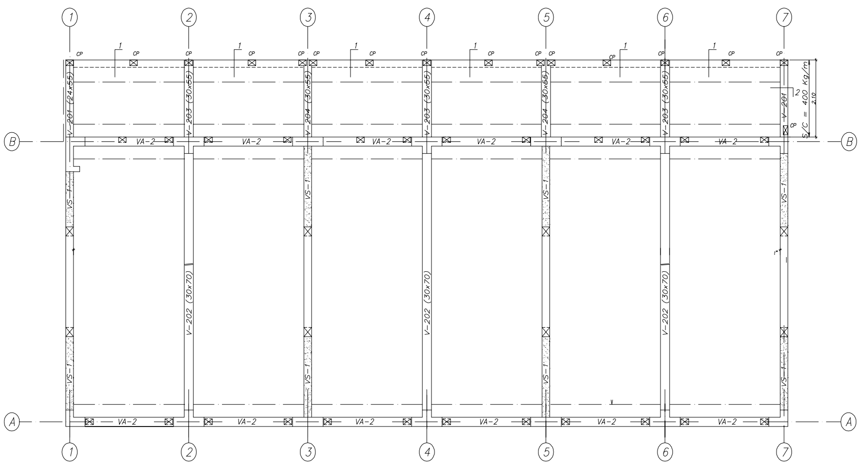

Figure 13- Typical school structure plan: Two or Three stories. Reinforced masonry in one direction. Wide concrete columns (small shear walls) in the other.

5. CONCLUSIONS

Largest amplifications are in the range of short structures, because og ground shaking frequency content is high for subduction earthquakes, in spite of that response is adequate.

Present Peruvian design practice seem to be very successful for building seismic response under moderate and severe earthquakes as observed after earthquakes in 2001 and 2007. Standard is simple to use and produces rigid structures with experiment little or no damage.

Usually computed displacements are estimated using gross moment of inertias. These are then compared with allowable displacements. A study carried out by Burgos, (2007) has demonstrated that if reduced stiffness is used in computing lateral displacements a significant increment will be obtained and allowable displacements may be exceeded. Since actual practice seems to give adequate behaviour, this reduced rigidity, which is required by some codes, may became excessively conservative and therefore using them may require more study.

Response of taller buildings (10-20stories) is still unknown, since most of them are located in Lima city where a strong earthquake is yet to occur in the following years.

REFERENCES

Burgos, M. (2007) Study of Capacity Design for Reinforced Concrete Frames as Design Alternative in Peruvian Standards. Master's thesis supervised by Dr. Javier Pique. Faculty of Civil Engineering. National University of Engineering. Lima. Peru

Kuroiwa, J. (2004). Disaster Reduction. Living in harmony with nature. Ed NSG S.A.C. Lima, Peru.

Miranda, O., Zegarra, A. Mejía, K. (2005) "Present "780" Module", as a proposed solution to School Deficit. (in Spanish). Congress of School Facilities. Zacatecas, Mexico.

Ministry of Housing Peru (2003). National Technical Standard E-030 "Earthquake Resistant Design". Lima, Peru. 1997 (in Spanish)

Pique, J. Martel, P. (2004) "How Peruvian Seismic Code greatly improved building response to real earthquakes". 13 WCEE. Vancouver. Canada. Paper 1825.

Salinas, R. et al. "Personal information. Visit to earthquake damaged Pisco area". CISMID Mission. Faculty of Civil Engineering. National University of Engineering. August 2007.

Tavera, H. et al. (2001) "Southern Peru Region Earthquake of June 23rd 2001: Seismological Aspects. National Center for Geophysical Data. Geophysical Institute of Peru. Lima. Peru. (in Spanish)

Tavera, H. (editor). (2007) "Pisco Earthquake (PERU) of August 15th, 2007. (7.9Mw). Seismology Division. Geophysical Institute of Peru. Lima. Peru. (in Spanish)