Structural Lessons from Wenchuan 5-12 for Disaster Risk Reduction

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Summary

The immediate response to a disaster is emergency rescue and relief, followed by rebuilding communities and physical infrastructure to a standard sufficiently robust to survive a similar event in the future with little loss. The building of resilience into neighbouring communities which did not suffer the disaster in order to achieve a similar robustness is equally important but it is often delayed, perhaps indefinitely, during the recovery process. Retrofitting deficient structures is a more sophisticated task than rebuilding to modern standards. There is insufficient research and training of structural engineers in structural risk assessment and methods of retrofitting. Wenchuan 5-12 provided a valuable field laboratory (at horrendous cost) for identifying good and bad features of common structures. These features will be discussed for the dominant forms of reinforced concrete and load bearing masonry construction. The implementation of a comprehensive risk reduction program will require cooperative engagement of local communities, government, professionals and contractors which presents yet more challenges to the structural engineer.

Keywords: Disaster reduction, risk assessment, earthquakes, seismic resistant design, retrofitting

1. Introduction

When a major natural disaster strikes there are four phases of response.

The first phase is emergency response – evacuation, food, shelter, medical and health services.

The second phase is recovery – rebuilding social cohesion, dignity, self respect, habitat and infrastructure, and rehabilitating ecosystems.

The third phase is the development of a disaster management plan. This addresses mitigation of the disaster through early warning systems and community education, identifying exposure to hazards and fragility of social and physical infrastructure. The assessment of exposure and vulnerability is followed by the development of feasible methods of retrofitting or rebuilding with adequate resilience. The disaster management plan is essentially dynamic, continuing to evolve during the fourth phase of response to a disaster. The plan needs to be incorporated in the recovery phase – building back better – so that risk of disaster is reduced.

The fourth phase is disaster risk reduction (DRR) – the implementation of the disaster management plan.

Disaster risk reduction is a critical factor in the global effort to reduce poverty. Affluence is no protection from disaster. However, a disaster is a temporary setback to economic growth in rich countries, but a permanent setback in poor countries. It is clear that it is immensely cost effective and beneficial to global sustainability to invest in DRR *before* disaster strikes, so that only the third and fourth phases outlined above are activated without the pain and suffering of the first two.

A major challenge in the development of a disaster management plan in the absence of an actual

disaster is the identification of the true nature of the hazards, and of the exposure and vulnerability of the social and physical infrastructure to these hazards. In this paper, focussing on the structural engineering aspects of DRR, the robustness or fragility of buildings revealed by Wenchuan 5-12 is used to develop ideas for assessment and retrofit of buildings for the rest of China not affected by this earthquake. (About 4% of the area of China was affected by Wenchuan 5-12 and about 0.4% was severely damaged.)

2. Risk

A qualitative definition of risk is frequently given as

$$\text{(Risk)} = \text{(Hazard)} \times \text{(Vulnerability)} - \text{(Capacity)}$$

This is not a numerical definition as in risk engineering where reliability is seen as the probability of survival and risk as the probability of failure in the service life of a structure or facility. In structural engineering (hazard) x (vulnerability) approximates to load effect and (capacity) to resistance in Limit State Design.

Acceptable risk as an annual probability of "failure" is a function of the number of lives lost, or "cost", of the event. We experience an actual risk of loss from natural hazards which is far higher than acceptable risk from manmade facilities [1]. For example, for dams the acceptable risks for new design or for review of existing design versus the probable loss of life [2] are compared in Figure 1 with actual losses in recent major disasters, including Indian Ocean tsunami 2004, Pakistan earthquake 2005, Yogyakarta Earthquake 2006, Tropical Cyclone Nargis 2008 and Wenchuan 5-12 Earthquake 2008.

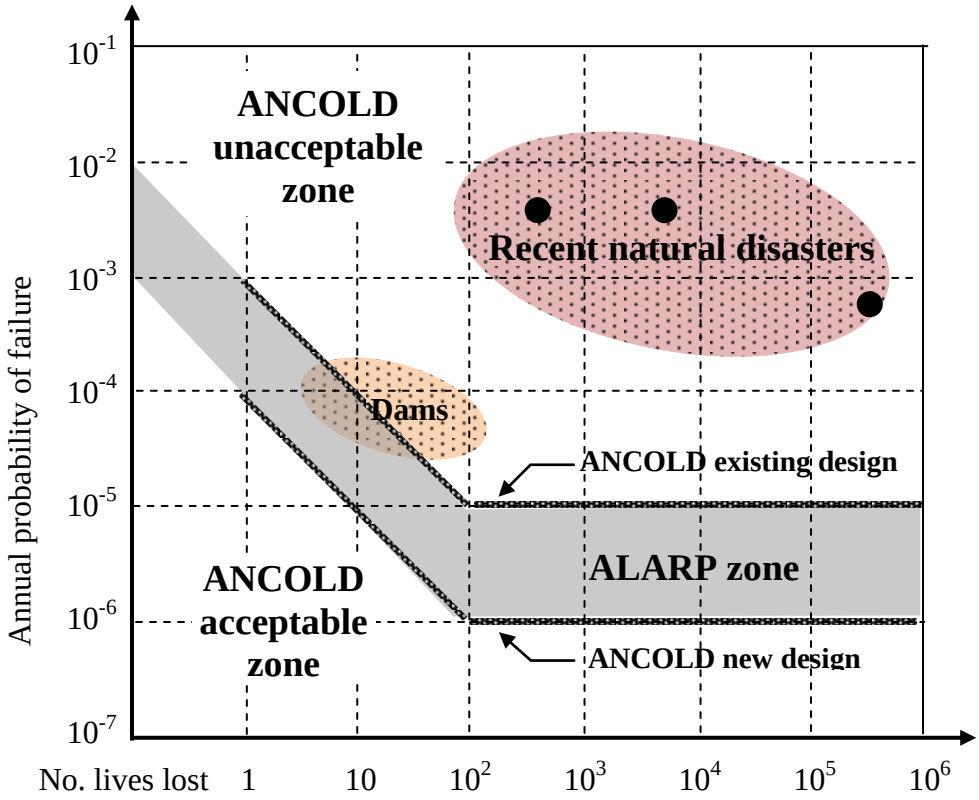


Figure 1 – Comparison of acceptable risk for design of large dams with risk from natural disasters

It is clear that reducing the risk from natural disasters to an acceptable level cannot be achieved by structural engineering intervention alone. This requires the integration of structural risk reduction into a holistic disaster risk reduction plan, for which the concept of a *Disaster Limit State* was developed for events more rare than those considered in the *Ultimate Limit State* [3].

In the contest of retrofitting buildings, using the lessons from Wenchuan 5-12, we have to recognise that there is no exclusive structural solution to rendering all buildings in China earthquake proof. The best practice for retrofitting has to be combined with disaster management planning including emergency response.

3. Seismic zone and design load

Identification of seismicity and interpretation of its significance is a key element of the decision process of relocation, reconstruction or retrofitting. A key source of design ground accelerations is GSHAP, the global seismic hazard map of the world (http://www.seismo.ethz.ch/GSHAP/global/). This maps the peak ground acceleration (m/s2) with a 10% probability of exceedance in 50 years, or a 475-year return period. A segment of the map which includes China is shown in Figure 2.

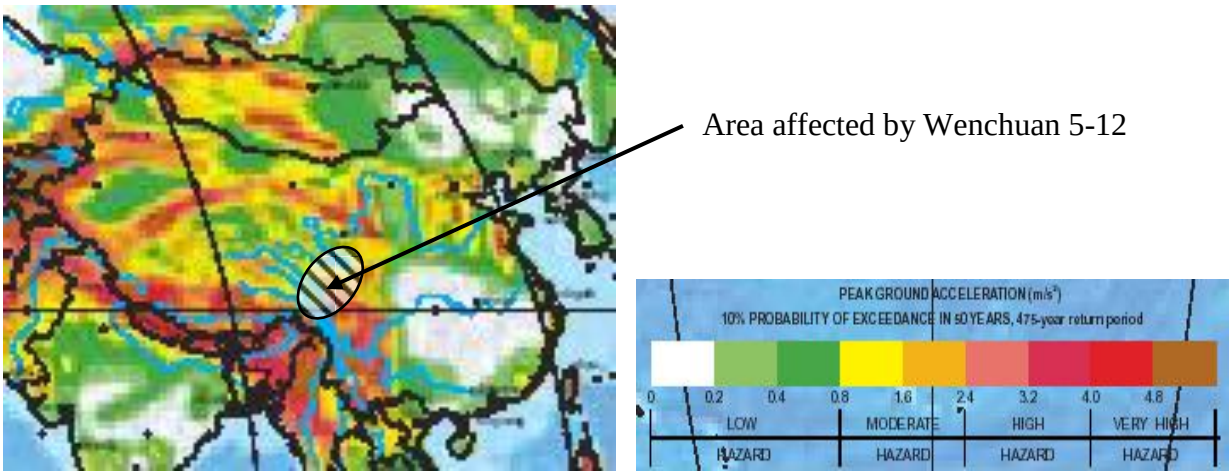


Figure 2 – Part of GSHAP including China

The Chinese Code for Seismic Design of Buildings (CSDB) has design ground accelerations which are consistent with GSHAP. It will be observed that Chengdu and all of Sichuan is in a moderate or high hazard zone. However, very populous areas of east central China have very low seismic hazard. Strategies for disaster risk reduction are significantly different between low hazard and high hazard regions of seismicity.

This map also reveals that although the area affected by Wenchuan 5-12 is huge, the area is a small part of China, and the whole country remains at risk of a major earthquake regardless of the occurrence of Wenchuan 5-12. The issue of retrofitting and disaster risk reduction for all of China remains, even while efforts for recovery from Wenchuan 5-12 are in progress.

Seismic zones in China are classified in the range VI to XI (6 to 11). These zones correspond approximately to the Modified Mercalli Intensity (MMI) scale VI to XI for which a peak ground acceleration is deduced to produce the observed level of damage. These are compared with the seismic zones and corresponding ground accelerations in the Uniform Building Code (UBC) of the USA in Table 1 [4]. There is good correspondence between the codes.

Table 1 – Comparison of seismic zones and design peak ground accelerations of PR China and USA

CSDB Seismic Zone	6	7a	7b	8a	8b	9
UBC (USA) Seismic Zone	1		2A	2B	3	4
CSDB ground acceleration (x g)	0.05	0.1	0.15	0.2	0.3	0.4
UBC ground acceleration (x g)	0.075		0,15	0.2	0.3	0.4

The China Earthquake Association has produced an estimate of the spatial distribution of earthquake intensity of Wenchuan 5-12 corresponding to observed ground accelerations (Figure 3).

Superimposed on this map is the approximate boundary between design Intensities VI and VII, drawn from CSBD.

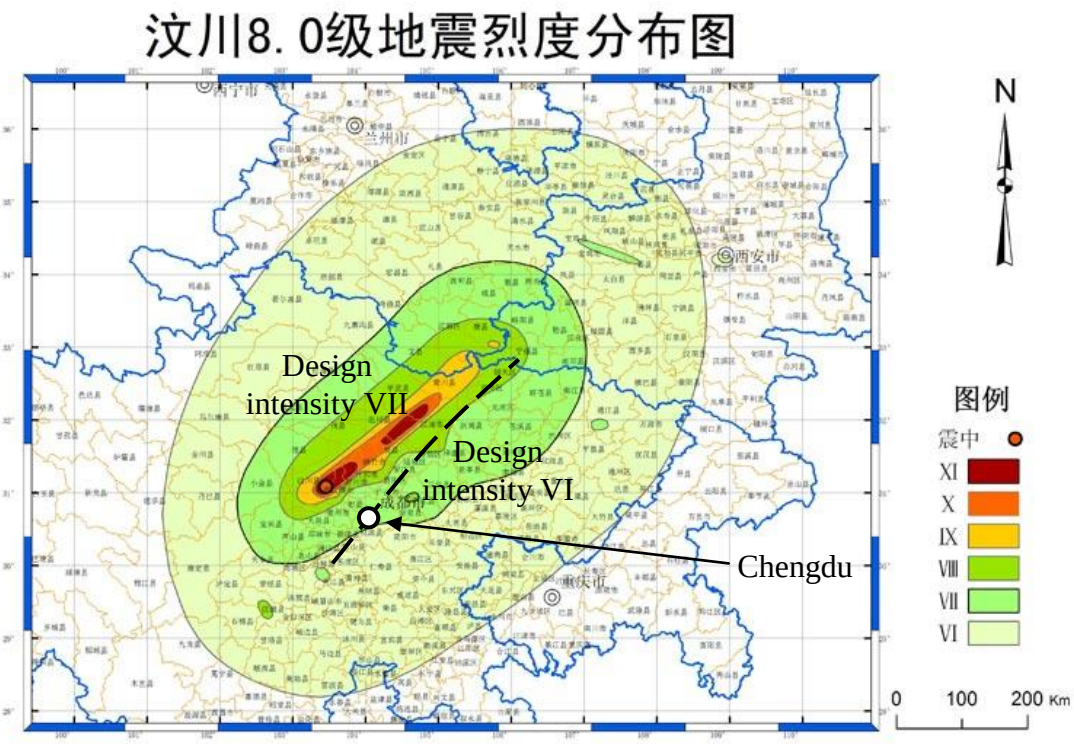


Figure 3 – Estimated intensities of Wenchuan Earthquake (www.cea.gov.cn)
The design Intensities VI and VII taken from the CSBD are superimposed.

From Figure 2 it can be seen that along the fault which moved the intensities were much greater than the design intensity (VII). This is not to suggest that the CSBD is wrong, as it can be argued that the return period for an earthquake of this magnitude is much greater than the nominal 475 years. However, it does indicate the need to reconsider the target return period for key infrastructure such as schools, hospitals, emergency services, communications, etc. There would also be value in reviewing CSBD design intensities in the vicinity of known major faults.

The standard return period (475 years) for the design earthquake loading has been found satisfactory for individual buildings, the loss rates being acceptable and sustainable by insurance, if necessary. For buildings with high social impact on failure (e.g., schools, hospitals) such loss rates are not acceptable and a significantly higher return period, e.g., 5000 years, needs to be considered. The use of a higher return period is an essential component of the *Disaster Limit State* [3] mentioned above.

Unfortunately design ground accelerations other than the standard design value for 10% probability of exceedance in 50 years are not readily available. The ratio of the design value for 10% probability of exceedance in 500 years to the standard design value varies with seismicity of the region and the proximity to active faults and carries much uncertainty in the estimate. It appears that this ratio is much higher for low seismic hazard regions than for high seismic hazard regions. Thus the difference between design peak ground accelerations for low and high hazard regions is not as marked for rare events considered for structures which have a critical post disaster function. This question needs more research and development.

4. Performance of structures in Wenchuan 5-12

In spite of the high intensity of the earthquake along the fault a significant number of structures survived, sometimes with only minor damage. Structures with load bearing masonry supporting RC floors sometimes performed better the RC framed structures.

Figure 4 depicts two load bearing masonry school buildings at Bailu School, about 30m apart, one on each side of the fault, with a final vertical displacement of about 2 metres between them. Remarkably, the building on the upthrust side is intact, in spite of the cantilever balconies. The intact building is more modern than the damaged one, and perhaps designed to the modern seismic standard. This would be CSBD intensity 7 – rather less than the intensity it experienced.

Figure 4 – Bailu school buildings (photo courtesy Prof Bixiong Li, Sichuan University)

Figure 5 depicts an apartment building with shops on the ground floor in the town centre of Hanwang, close to the major fault and the epicentre of a major aftershock. The town centre is beyond rebuilding. The building is of load bearing masonry construction. The detail shows the failure of the wall with a doorway under racking forces, repeated in every bay of the building. Solid masonry infill walls might have saved this building, but some doorways are functionally necessary.

Figure 5 – Apartment building in Hanwang irreparably damaged by racking forces

A number of common structural deficiencies have been identified, Most of which apply to RC framed buildings and most of which are well known to structural engineers conversant with seismic design. These are considered with the retrofitting options in the following sections.

4.1 'Strong beam – weak column' instead of 'weak beam – strong column'

It is desirable to have damaged localised at the ends of beams by having the beams weaker than the columns in resisting bending moments at connections. In practice this is difficult in initial design and even more difficult to retrofit. One possibility is to increase the confinement of the column near the connection with added hoop steel and encasement. Alternatively, a radical change from portal frame action is possible by the use of shear walls in masonry or concrete.

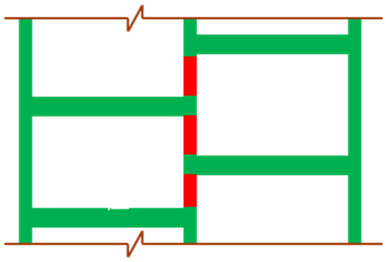
Figure 6 – Weak columns at Dujiangyan (photo courtesy Prof Bixiong Li, Sichuan University)

4.2 Soft storey

There have been many instances of buildings with open ground floor which collapsed, with the upper floors more or less intact. A possible retrofit is to insert shear walls into the soft storey, to make the soft storey sway stiffness similar to the storeys above. However, this could lead to stronger racking forces in the upper storeys, for which the capacity must be checked

Figure 7 – Weak Soft storey failure (photo courtesy Prof Bixiong Li, Sichuan University)

4.3 Short columns attracting shear



The sway stiffness of a column is proportional to the cube of its height. Steps in floor level and partial height infill masonry which shorten the sway length of the column should be avoided. Retrofitting is difficult, but perhaps possible by inserting shear walls regularly spaced.

Figure 8 – Short columns unable with withstand the shear forces which they attract (photo courtesy Prof Bixiong Li, Sichuan University)

4.4 L- and T-shaped floor plans instead of rectangular

Lateral displacements are greatly amplified in buildings where the centre of mass is offset from the centre of sway stiffness in all directions. This phenomenon can occur in schools, hospitals, hotels and major office and accommodation blocks. Balance can be restored in some cases by inserting shear walls in selected locations. Buildings with complex floor plans can be separated into separate buildings with rectangular floor plans. However, articulation to allow separate sway motions between the buildings can be difficult.

4.5 Pounding of adjacent buildings

This phenomenon occurs in adjacent multistorey buildings with inadequate separation. Retrofitting will require a case-by-case solution.

4.6 Staircases not integrated into seismic resistance

Unfortunately the CSBD allows the design of staircases for gravity loads alone, while the rest of the

building is designed to resist seismic forces. Many staircases collapsed during Wenchuan 5-12 while the rest of the building sometimes remained standing, due to the participation of the staircases in the racking of the building [5]. Tragically, many students died in stairwells while evacuating the buildings.

4.7 Substandard construction

Substandard construction can be quite obvious from the workmanship of the finished product. The problem lies within hidden defects such as missing or insufficient reinforcement, bars not properly located in beams, columns and slabs, lack of stirrups and ties, etc. Further, the structure might be well built but simply lacking the strength and ductility to resist a major earthquake. Wenchuan 5-12 has made it possible to build a database of structural performance in relation to intensity of seismic load such that, with experience, visual inspection of buildings in areas not affected by this earthquake, will in most cases lead to a decision on the need for and feasibility of retrofitting.

5. Assessment of seismic fragility

Reference has already been made to seismic fragility. The challenge is to translate the structural condition assessment into a format for making rational decisions to relocate, replace or retrofit. In Japan the Institute for Earthquake Research carried out a detailed seismic retrofit of schools damaged in the Niigata Earthquake (1998). A Structural seismic performance index, I_s, was developed (Ministry of Education, Culture, Sports, Science and Technology Japan, 2008).

The Structural Seismic Performance Index, I_s, is defined as follows:

$I_s = E_0 \, x \, S_D \, x \, T$

E_0 = Basic Capacity Index (≤ 1.0) = C (strength index) x F (ductility index)

S_D = Structural balance index (≤ 1.0)

S_D = 1.0 if plan is rectangular, storeys have equal sway strength and stiffness

T = Aging index (≤ 1.0)

Criteria for I_s

$I_s < 0.3$	high risk of collapse in earthquake
$0.3 \leq I_s < 0.6$	potential risk of collapse
$0.6 \leq I_s$	low risk of collapse

Target for schools: $I_s > 0.7$

The structural balance index refers to the soft storey and short column deficiencies and irregular floor plans mentioned above.

To have confidence in using the seismic performance index as a decision tool will require experience and practice, and in the author's view, professional training of structural engineers in this specialist work, innovative thinking, and research to fill some of the knowledge gaps.

6. Guidance Notes on Safer School Construction

A cooperative effort of the Inter-Agency Network for Education in Emergencies (INEE) and the Global Facility for Disaster Reduction and Recovery (GFDRR) at the World Bank, in partnership with the Coalition for Global School Safety and Disaster Prevention Education, the IASC Education Cluster and the International Strategy for Disaster Risk Reduction (ISDR) has resulted in the issue of Guidance Notes on Safer School Construction [8]. The guide is intended for use by local government authorities and education departments, who, in partnership with all stakeholders will achieve the objective of structurally sound new building and retrofitting of existing schools.

The challenge for the structural engineer, and for national professional societies of structural engineers, is to be effectively engaged in their essential contribution to achieving safer school construction,

7. Conclusions

This paper has addressed the structural lessons from Wenchuan 5-12 from the perspective of disaster risk reduction. The emphasis has been on devising ways to retrofit those regions yet to experience a major earthquake so that when it happens they will not be a similar disaster to May 12, 2008.

It would appear that there are shortcomings in professional capability to assess seismic fragility of buildings and to design appropriate retrofitting measures. Further professional training and research are needed.

The structural engineering profession is challenged to provide the leadership and to engage with the community in achieving effective disaster risk reduction against all natural hazards, including earthquakes.

8. References

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