Preliminary seismic vulnerability matrix related with fortification intensity for Sichuan region

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Abstract. The significance to develop fortification intensity related vulnerability matrix for earthquake prevention and mitigation is emphasized in this paper. The way to acquire the fortification intensity data of buildings damaged in the great Wenchuan earthquake, from their construction years with the seismic zoning maps in three time periods, is reported. Preliminary statistical results of vulnerability matrices related with fortification intensity VI, VII and VIII, are presented for brick-concrete structure and frame structure buildings in Sichuan region. The results show clearly the decrease of vulnerability with increase of the fortification level.

1. Introduction

Vulnerability matrix is adopted widely in intensity based seismic risk analysis. It is mainly developed from earthquake damage data. In general, it shows the percentages of buildings in each of five damage categories, almost intact, slightly damaged, moderately damaged, severely damaged and collapsed, for each of four intensities VI, VII, VIII and IX. It is obvious that the the higher fortification level is adopted in design and construction of a building, the lower vulnerability of the building must be. The risk must be over or under evaluated for a city where the fortification intensity of buildings is different from that in the data base for development of the matrix. However, the matrices world wide are all not related with fortification intensity up to now. The reason of this shortcoming is the fact that the data on the fortification intensity of damage buildings are not available in most reports of damage surveys. The authors presented an idea to build fortification intensity related seismic vulnerability matrix[1], discussed why this kind of matrix is significant and how to acquire fortification intensity information from the damage data in Wenchuan earthquake[2]. A preliminary result is reported in this paper, as well the way we get the data.

2. What is the fortification intensity related seismic vulnerability matrix

For a given region, the expected direct loss in the next strong earthquake, in general, could be calculated by equation (1)[3].

$$E_L = \sum_{s=1}^{N} \sum_{I=1}^{9} \sum_{k=1}^{5} S_s \cdot P_s \cdot L_{ks} \cdot R_{ks}(I) \cdot P(I)$$

where, the three summations are for building type, intensity and damage category respectively; $S_s$ and $P_s$ are the total gross area and the mean unit replacement cost of the $s$ type buildings; $L_{ks}$ is loss ratio...
of the $s$ type building in $k^{th}$ damage category; $R_{ks}(I)$ is ratio of the $s$ type building suffered intensity $I$ in $k^{th}$ damage category, damage ratio in brief; $P(I)$ is occurrence probability of intensity $I$ in the region in a given time period, for seismic hazard.

The overall work of seismic engineering fortification has been carried for more than forty year in China[4], as well in Sichuan region. Now most buildings there are fortified. For buildings constructed in these years, the $R_{ks}(I)$ must be lower than that constructed before without fortification. Therefore, equation (2) is suggested instead of equation (1).

$$E_t = \sum_{s=1}^{N} \sum_{j=6}^{9} \sum_{I=6}^{9} \sum_{k=1}^{5} S_{js} \cdot P_{js} \cdot L_{jks} \cdot R_{jks}(I) \cdot P(I)$$

(2)

where summation with $j$ is added for fortification intensity, in subscript of the first four items on the right side an additional $j$ is also added correspond to fortification intensity. Values of the first two items should be estimated from statistics of regional data, while the value of $L_{jks}$ must be similar with that of $L_{iks}$. The key point is on estimation of, so called fortification intensity related damage ratio. All of $R_{iks}(I)$ for intensities VI, VII, VIII and IX consist of seismic vulnerability matrix, and must be built from damage data.

The matrix $R_{iks}(I)$ could be adopted also to estimate the number of death in a city or region in the next strong earthquake by equation (3).

$$E_D = \sum_{s=1}^{N} \sum_{j=6}^{9} \sum_{I=6}^{9} \sum_{k=1}^{5} S_{js} \cdot H_{js} \cdot D_{jks} \cdot R_{jks}(I) \cdot P(I)$$

(3)

where $H_{js}$ is mean number of people on unit gross area of building, $D_{jks}$ is death ratio of the $s$ type building in $k^{th}$ damage category.

The advantage of $R_{iks}(I)$ is obvious that it shows the benefit of fortification from the difference between losses of the building with and without fortification, and is conducive to fee rate determination of financial instruments closer to the reality, and improvement of their competitiveness in the market. Meanwhile, it is much more difficult to build the matrix, as much more damage data must be available. One can find from equation (2) that statistic data must be four times of those without fortification, since a matrix must be built for each of the four fortification intensities, and the higher fortification the less building data.

3. The way to acquire the fortification intensity information of damaged buildings

The great Wenchuan earthquake occurred 11 years ago, caused very bad damage. In the damage region, the measures of seismic engineering fortification has been carried out for more than thirty year, and fortification intensity of buildings constructed in most city/towns is VII, and in some city/towns is VI or VIII, is IX in few towns during some time period. It seems that the great earthquake provided an unprecedented opportunity to deal with the relation between fortification level and vulnerability of buildings.

The reason of there is not enough fortification information of buildings in post earthquake survey reports is probably that it is very difficult to access that information in the environment of rescue and resettlement, much more than to take picture of damage buildings, to get information of gross area, floor number and purpose of the building, and to evaluate its damage category. However, it is easy to know the year of a building construction.

Before the earthquake, seismic design codes of building were issued three versions in 1978, 1989 and 2001[6], respectively, and were in the main corresponding the years of three versions of national seismic zoning map in 1977[7], 1990[8] and 2001[9]. The fortification intensity of a building may be basically inferred from the construction year and the location on the corresponding map with certainty.

The fortification intensities adopted in 14 city/towns in northern Sichuan for the three time periods are inferred and listed in table 1. In the table, “Intensity in EQ” is in brief for intensity suffered during
Wenchuan earthquake, “In 80s”, “In 90s” and “In 01s” are for the fortification intensities in time periods of 1980s, 1990s and 2001-2008, respectively.

Table 1 The fortification intensities of 14 cities (towns) with their intensities suffered in the earthquake

| No. | City (Town) | Intensity in EQ | In 80s | In 90s | In 01s |
|-----|-------------|----------------|--------|--------|--------|
| 1   | Beichuan    | IX-X           | VIII   | VII    | VII    |
| 2   | Maoxian     | IX             | VIII   | VII    | VII    |
| 3   | Songpan     | VI             | IX     | ≥IX    | VIII   |
| 4   | Jiuzhaigou  | VI             | VIII   | IX     | IX     |
| 5   | Wenxian     | VIII           | VIII   | VIII   | VIII   |
| 6   | Pingwu      | VIII           | VI     | VII    | VII    |
| 7   | Jiangyou    | VIII           | <VI    | VI     | VII    |
| 8   | Mianyang    | VII            | <VI    | VI     | VII    |
| 9   | Anxian      | VIII           | VIII   | VII    | VII    |
| 10  | Luojiang    | VII            | <VI    | VI     | VI     |
| 11  | Mianzhu     | IX             | VI     | VII    | VII    |
| 12  | Qingchuan   | IX             | VI     | VII    | VII    |
| 13  | Jiange      | VII            | <VI    | VI     | VI     |
| 14  | Guangyuan   | VII            | <VI    | VI     | VI     |

4. Preliminary results

The authors went to the 14 city/towns for a supplementary survey last summer, acquired rich data on the construction years of damaged buildings mainly of brick-concrete structure and frame structure, and then inferred as fortification intensity of them with the seismic zoning maps. From data sort on reliability and statistic analysis on construction areas, a preliminary results of vulnerability matrices related with fortification intensity are worked out for the two types of buildings, and listed in table 2 and table 3, respectively.

Table 2. Fortification intensity related vulnerability matrices for brick-concrete structure buildings (%)

| Fortification intensity | Intensity | Almost intact | Slightly damaged | Moderately damaged | Severely damaged | Collapsed |
|-------------------------|-----------|---------------|------------------|--------------------|------------------|-----------|
| VI                      | VI        | 16.42         | 46.31            | 25.64              | 9.14             | 2.49      |
|                         | VII       | 26.05         | 13.38            | 42.63              | 17.93            | 0.00      |
|                         | VIII      | 8.55          | 22.28            | 39.12              | 16.63            | 13.42     |
|                         | IX        | 0.13          | 18.84            | 36.2               | 41.28            | 3.55      |
|                         | VI        | 79.63         | 13.17            | 4.95               | 2.25             | 0.00      |
| VII                     | VII       | 52.73         | 30.73            | 12.89              | 3.5              | 0.16      |
|                         | VIII      | 22.06         | 27.54            | 24.05              | 21.02            | 5.34      |
|                         | IX        | 2.13          | 11.54            | 34.95              | 23.31            | 27.42     |
|                         | VI        | 84.64         | 11.37            | 3.99               | 0.00             | 0.00      |
|                         | VII       | 65.40         | 29.05            | 3.24               | 2.31             | 0.00      |
|                         | VIII      | 31.58         | 39.20            | 11.55              | 10.04            | 7.63      |
|                         | IX        | 4.70          | 46.35            | 20.37              | 12.60            | 15.98     |

Table 3. Fortification intensity related vulnerability matrices for frame structure buildings (%)

| Fortification intensity | Intensity | Almost intact | Slightly damaged | Moderately damaged | Severely damaged | Collapsed |
|-------------------------|-----------|---------------|------------------|--------------------|------------------|-----------|
| VI                      | VI        | -             | -                | -                  | -                | -         |
|                         | VII       | 36.26         | 52.97            | 10.68              | 0.09             | 0.00      |
One can see from the tables that the percentages in almost intact, or in almost intact and slightly damaged categories for both types of buildings increase obviously as the increasing of fortification intensity from VI to VII and to VIII, while those in collapsed and severely damaged categories decrease too, in general, especially for brick-concrete structure buildings. The percentages in a few grids do not decrease with fortification intensity increasing one degree, especially for frame structure buildings, as unexpected. The authors believe that it may come from the limited number of data for that situation. The results for fortification intensity IX is not presented in the two tables, by the same reason.

5. Conclusion
As number of fortified buildings are designed and constructed more and more, it must be inevitable to adopt fortification intensity related vulnerability matrix in seismic risk analysis, instead of the existing matrix built from data without fortification information. This improvement could provide more realistic base to test and evaluate the benefit of our seismic engineering fortification, and to determine acceptable seismic risk level for city or region.

By means of mining information of construction years of the buildings damaged during the great Wenchuan earthquake, the corresponding fortification intensities are inferred with seismic zoning maps issued for three time periods.

Preliminary results of the vulnerability matrices related with fortification intensity for brick-concrete structure and frame structure building in Sichuan region are presented. The results show clearly decreasing of vulnerability with increasing of the fortification intensity as expected. Further study is going to do with data from more other earthquakes.

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