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Test of PSHA Map of China -- A Case Study of Sichuan Region

Xiaxin TAO [a, 1], Zhengru TAO [b], Liyuan WANG [c] and Ming ZHANG [a]
[a] *School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China*
[b] *Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, CEA, Harbin 150080, China*
[c] *Heilongjiang university of science and technology, Harbin 150022, China*

Abstract. The PSHA map must be tested, since hypothesis testing is the heart of a scientific method, and it is inappropriate to adopt the map as the basis of seismic fortification in whole country without any test. Two paths of testing are suggested in this paper. The test result by counting up positive intensity difference shows that up to 2015 the percentages of total underestimation areas on 1990 and 2001 maps of China are equivalences of 5.6% and 6.0% in 50 years, both less than the exceeding probability 10% adopted in the map compiling procedure. The result of a case study of the common buildings with brick-concrete structure and frame structure in Sichuan region by evaluating the benefit of seismic fortification according to the two maps shows that the PSHA maps contribute benefits as economic loss reduction 67.9 and 79.7 billion RMB, death reduction 19439 and 17504 persons, and serious injury reduction 42632 and 37700 persons respectively during 2008 great Wenchuan Earthquake.

Keywords. PSHA, seismic zoning map, test, positive intensity difference, cost-benefit analysis

1. Introduction

Seismic zoning map is one of the most important countermeasures against earthquake disaster in many earthquake countries worldwide. In China, seismic zoning map plays a role of state standard, is the basis for all kinds of structures taking engineering measures and for all cities/regions planning for earthquake prevention and disaster reduction. Probabilistic seismic hazard assessment (PSHA) has been developed [1] and widely adopted in compiling of hazard maps and in evaluating sites of major projects for more than 50 years. The zoning maps of China issued in 1990, 2001 and 2015 were developed by means of the PSHA approach, so called as PSHA maps [2-4].

However, PSHA has been queried and debated unceasingly, especially after some highly destructive earthquakes occurred in areas with relative low hazard on the maps. In the criticisms, it was asked “where does probability come in to play?”, even “is PSHA science?” [5-7]. For example, the famous PSHA map, global seismic hazard map issued in 2000, and all 12 earthquakes caused greatest population losses from 2001 to 2011 were mentioned as the difference of epicenter intensity with the one on

[1] Xiaxin Tao, Corresponding author, School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China; E-mail: taoxiaxin@aliyun.com.

the map is usually quite large [8], even if the exceeding probability of the map is only 10% in 50 years. Among all debates and queries on PSHA, the demand to test hazard map cannot be ignored, since hypothesis testing is the heart of a scientific method. Obviously, it is inappropriate to adopt the map as the basis of seismic fortification, even a national standard, without any test.

If we believe that the PSHA map can be tested, how to test it, is still a problem without international common view. Ideally, people hope to examine the difference between happened intensity and that on the map repeatedly for many periods of 50 years, and then get a ratio to see if it is comparable with 10%. However, hazard maps in most earthquake countries are generally renewed in every 10 years or so, people cannot wait so long after the map taken out of service. It is meaningless, to test PSHA map with a synthetic catalogue covering thousands of years, even it is suggested by a famous scientist [9], and to test a PSHA map from 500 years of recorded Intensity data in Japan [10] too, since earthquake disaster could be reduced from building fortification according to a kind of forecasting on the PSHA map for the next 50 years instead of the mean in a long time period [11].

2. Path 1: To Count up Positive Intensity Differences

With the similar idea of the area-based test of long term seismic hazard prediction [12], the authors of this paper suggest a path to take the all destructive earthquakes occurred after the map issued as the objective criterion for testing a PSHA map, to see statistically if the ratio of total area with happened intensities to the entire area of the whole country larger than those on the map is greater or less than the exceeding probability 10% in 50 years adopted in the map compiling procedure [13-14]. In practice, the map is zoned from the hazards assessed at a lot of ground points distributed almost uniformly in a grid [2-4]. The hazard at an individual point, could be considered as a Bernoulli trail with the same assumption, the same method, and the same data, especially at points a few hundred or even a thousand Km away. The test at one point in many time periods and test at many points in one period could be considered as the same in probabilistic meaning, therefore the PSHA map could be tested by statistics of the percentage of the areas with actually suffered intensity larger than the corresponding fortification intensity on the map in an expanded quite large spatial area to make up for the shortage of time period at one point. As examples, the tests of maps issued in 1990 and 2001 are presented, the one on 2015 map is not included since the time period is too short up to now.

Isoseismals of all destructive earthquakes actually occurred after the two PSHA maps released to 2015 are overlaid one by one on the corresponding map managed by GIS, those intensities on 2001 PSHA map are converted by the relation between basic peak ground acceleration and intensity in table 1 of the map, and the maximum intensity difference is kept for each area by spatial analysis operations and table analysis of GIS. The example of the great Wenchuan earthquake is shown in figure 1. In the figure, upper-left picture shows the corresponding part of 2001 PSHA map, the upper-right picture shows the isoseismals of the Wenchuan quake, the lower-left one shows the table calculating of the intensity difference as the attribute, and then the lower-right is the overlaid result [11].

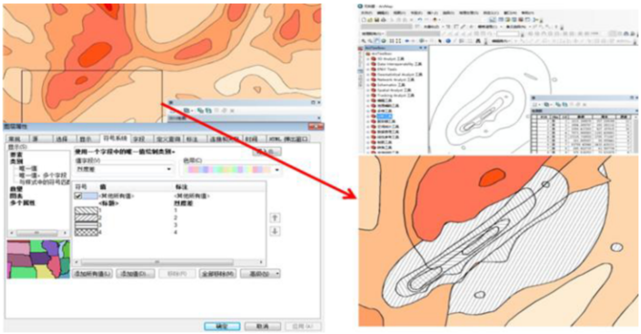

Figure 1. Isoseismals of the 2008 Wenchuan earthquake overlaid on the 2001 PSHA map.

Positive intensity difference is defined as underestimation with the actual happened intensity larger than the intensity at the same location on the hazard map, finally the maximum positive intensity difference map is worked out. The areas with positive intensity difference are counted up, and the percentage of the sum to the entire area of the China mainland are calculated. The results of the tests of the two PSHA maps of China show that the percentages of underestimation areas are 2.9% and 1.8%. Since Poisson model is adopted in development of PSHA map, the hypothesis of the model is the independency between earthquakes in the given future time period, and the seldom nature of earthquake occurrence, thus it is not only impossible but also unnecessary to take into account the correlation between earthquakes, the exceeding probability in 50 years can estimated from the probability in any time period t, by the following equation [11].

$$P_{50} = 1.0 - (1.0 - P_t)^{\frac{50}{t}} \tag{1}$$

Then the corresponding values of the exceeding probabilities in 50 years are 5.6% and 6.0%, both less than the exceeding probability 10%adopted in the map compiling procedure. It is of little significance to pursue the statistical strictness in test the PSHA map, since the disaster must be very difference if the same underestimation occurs in sparsely populated areas such as desert Gobi and high mountains, or in densely populated and wealth-intensive urban areas. So we try the following path 2.

3. Path 2: To Evaluate the Benefit of Seismic Fortification According to the Maps

From the point of view to the role of PSHA map in disaster management, it is obvious that the benefit of engineering seismic measures adopted according to the map should be investigated, not only emphasizing the losses and casualties caused by the underestimations, but also paying attention on the additional fortification costs by the overestimations [15]. The fortification cost and the disaster reduction benefit from the prescribed fortification standard should be comprehensively compared, combined with the total amount of construction, and the seismic design and construction technology during the map implement period.

As a case study, we test the fortification economic benefit and safety benefit of the most common buildings with brick-concrete structure and frame structure that well designed and constructed respectively from the 1990 to 2000 and 2001 to 2008 in Sichuan region according to the two PSHA maps of China and the damage caused by the Wenchuan earthquake. From the framework of Life-Cycle Cost Analysis [16-17], the benefit criteria of two indices, economic benefit of loss reduction B_E and safety benefit of casualty reduction B_S, are simplified as in the following formulas.

$$B_E = L_N - L_F - I_F \quad \text{economic benefit} \tag{2}$$

$$B_S = C_N - C_F \quad \text{safety benefit} \tag{3}$$

where L_F is the total expected loss in earthquakes during the life-cycles of the fortified buildings, L_N is the corresponding loss if those buildings without any fortification, I_F is the additional cost for the fortification; and C_F is the total expected casualty in earthquakes during the life-cycles of the fortified buildings, C_N is the corresponding casualty if those buildings without any fortification. The life-cycles of buildings in China are general 50 years, longer than the time periods from 1990 to 2008, or 2001 to 2008. One can see from the equation (2) that the value of L_N-L_F in any longer period must larger than those in the periods taken in this case study, and I_F paid during the construction must not increase with time, therefore the benefits calculated from these two periods must be the minimum estimation during the life-cycles of the fortified buildings.

The data of total amount of the two type buildings constructed in the two time periods in each county/city are collected from the annual yearbooks of Sichuan province. The increasing rates of additional costs of buildings fortified with intensity VI, VII, VIII and IXto the costs without fortification are estimated for the typical buildings with the two type structures in the region, by software PKPM and GLD [18], as 2.23, 5.43, 10.85 and 17.37 for the brick-concrete structure and 2.18, 4.87, 8.54 and 12.75 for frame structure. The total fortification costs of the two type buildings constructed in the two periods in Sichuan are estimated, as 10.2 and 12.7 billion RMB respectively.

The formulas to assess the loss L and casualty C by earthquake are modified to take into account the fortification intensity [15] as follows respectively.

$$L = \sum_h \sum_i \sum_j \sum_k S_{hik} R_{hijl} D_{hj} Q_h \tag{4}$$

$$C = \sum_h \sum_i \sum_j \sum_k S_{hik} R_{hijl} Z_{hj} P_h \tag{5}$$

where S_{hki} is the total overall floorage of h type buildings fortified by intensity i and suffered intensity k, R_{hijk} is defined as the percentage in the jth damage rank of h type buildings fortified by intensity i and suffered intensity k, so called fortification intensity related vulnerability matrix as a whole, D_{hj} is the loss ratio of h type building suffered jth rank damage, and Q_h is the reset unit cost of h type building; Z_{hj} is the death or serious injury ratio in h type building suffered jth rank damage, and P_h is the expected persons in unit area of h type building.

A set of fortification intensity related vulnerability matrices of the two type buildings are worked out from the damage data in Wenchuan quake [19]. The values of the D_{hj} and Z_{hj} in equation (4) and equation (5) adopted in the case study are listed in table 1, they mainly depend on damage rank j, the effect of structure type and the contribution of the fortification are contained in R_{hijk}. The values of Q_h are taken as 850 RMB and 1300 RMB for the building with brick-concrete structure and frame structure respectively.

Table 1. The values of the other three parameters in equation (4) and equation(5) adopted in the case study.

Damage j	Almost intact	Slightly damaged	Moderately damaged	Severely damaged	Collapsed
D_{hj}(%)	2.5	7.5	25	73	91
Death Z_{hj}(%)	0.00	0.00	0.00	0.08	2.69
Serious injury Z_{hj}(%)	0.00	0.01	0.08	0.40	10.1

The loss of indoor property is estimated by the same way with loss ratio 0.00, 0.03, 0.13, 0.30 and 0.90. Input the suffered intensity in each county/city during the Wenchuan earthquake, the indirect loss is estimated by a ratio of 1.33 to the direct one, since the official report mentioned that the direct economic loss is 771.6 billion RMB and indirect loss is 1030.0 billion RMB in Sichuan region during the earthquake. The total losses and the deaths and serious injuries from the damaged two type buildings are calculated as 114.1 billion RMB, 28076 and 10910 persons; 106.7 billion RMB, 28340 and 10999 persons, respectively.

The seismic fortification benefit of the two type buildings constructed according to the two PSHA maps is then calculated by comparing with the corresponding values estimated if no fortification measures were adopted, as economic loss reduction 67.9 and 79.7 billion RMB, death reduction 19439 and 17504 persons, and serious injury reduction 42632 and 37700 persons respectively. The result shows that the implement of the two PSHA maps contributed a lot to reduce the earthquake disaster, with much less loss and casualty during the Wenchuan earthquake.

4. Conclusion

The significance of the test of PSHA map is emphasized and two paths to test the map are suggested in this paper. The result of our test path 1 by counting up the positive intensity differences shows that the ratio of total underestimation areas on 1990 and 2001 maps to the entire area of China mainland are 2.9% and 1.8%, corresponding exceeding probabilities 5.6% and 6.0% in 50 years, both less than the exceeding probability 10% adopted in the map compiling procedure. The result of our test path 2 by evaluating the benefit of seismic fortification according to the maps in a case study in Sichuan region shows that the fortification benefit of two most common buildings with brick-concrete and frame structures constructed according to the two PSHA maps by comparing with the corresponding values estimated if no fortification measures were adopted, is economic loss reduction 67.9 billion and 79.7 billion RMB, death reduction 19439 and 17504 persons, and serious injury reduction 42632 and 37700 persons respectively during Wenchun earthquake.

The seismic fortification economic benefit and safety benefit are both very good comparing with total fortification costs of the two type buildings in the regions, 10.2

billion and 12.7 billion RMB in the two time periods. The fortification benefit must increase with time to the end of life-cycles of the buildings, since fortification cost paid in the construction never increase any more, and further fortification benefit may generate in the future earthquake in the life-cycles. It is obvious that fortification benefit must be much bigger, if much more buildings with other types, other structures besides buildings, and if more earthquakes in longer time period, are taken into account in the test. The result of our path 2 test demonstrates that implement of the two PSHA maps of China contributes a lot to reduce the earthquake disaster in Sichuan region.

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