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Design of Rural Buildings Based on the Theory of Anti-Seismic Design

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ABSTRACT: Current structural seismic fortification criteria can not fully meet the actual development level of rural areas. In order to study rural seismic fortification of rural buildings and hazard characteristic of earthquake in rural areas, this paper introduces the performance-based seismic design theory in research of the design of rural buildings. According to the actual structure type, urban and rural differences between in the aspects of social and economic development, income gap between different classes, as well as damage degree of earthquake on building, the structural type of rural buildings, vulnerability analysis and a series of studies on nonlinear seismic response of masonry structures, this paper provide references for decision making during the rural residential earthquake safety project. This paper focuses on the rural building types and analyzes the response of masonry structure on the nonlinear seismic .According regression analysis on the random sample of ground motion, it is concluded that several models are obtained and analyzed on their vulnerability. It is expected that provide beneficial exploration for the construction of new rural areas and reduce the losses and casualties caused by the earthquake as much as possible.

KEYWORDS: Rural buildings; Performance-based fortification criteria; Seismic vulnerability curves; Generation of ground motion sample.

INTRODUCTION

In recent years, due to the frequent crustal movement, earthquake disasters frequently occur, and the ground motion caused by an earthquake leads to the seismic load on housing structure which results in additional internal force add into housing structure, finally leading to damage and even collapse of the building. Seismic researchers in recent years launch many studies on seismic fortification of the rural building. They carry out the seismic damage prediction, performance test and other studies on existing rural building. Besides they have put forward some advices to the policies and measures of rural anti-seismic. In the seismic design, the designer must first consider the fact that earthquake load will make damage to the house. Because the lack of sufficient understanding of the earthquake, seismic load calculation is very approximate. Thus seismic design of the house must be carried out on the basis of earthquake damage investigation and theoretical analysis. At the same time, calculation of the housing structure and the necessary structural measures must be made, so as to ensure that building structure has certain seismic performance. Buildings in countryside, towns and counties differ from urban buildings on building materials and structure. For example, there are a large number of buildings with the structure of civil engineering and single-storey brick in rural areas. Because anti-seismic problem has been the hot issues around the world, this paper carried out a series of studies on structure type, vulnerability analysis, and seismic response of nonlinear masonry structure in Chinese rural areas.

STRUCTURE TYPE OF RURAL BUILDINGS

The rural buildings are usually built by the local construction workers according to the owner's economic conditions and requirements as well as the local constructional traditions without professional designs. These buildings are characterized by simple structure, low cost, consistent style and easily finding materials. The structural form and architectural style of the house show obvious regional characteristics.

Wooden Framed Load-Bearing Building

(1) Chuan-dou wooden frame. Each frame consists of 3-5 (some 7-9) wooden column the top and middle parts of which are connected by a square wood named Chuan-fang. The short standing columns on the upper part of wooden

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frame are also connected with Chuan-fang, making the whole structure more firmly. The longitudinal frames are connected by the purlins both ends of which are made into dovetail joint on the roof of the house.

(2) Wooden roof truss with wooden column. Wooden column bears the load and the roof truss is triangular. The wooden columns are connected with roof truss by tenons with purlins putting at the joints. Roof is built on the purlin, and adobe or brick are used into walls. This house with is structure can be large and tall, so it has been widely used around the world, as shown in Figure 1.

(3) Wooden column and wooden beam. It includes two types:

- Flat wooden frame (also called portal wooden frame). The column is thin and beam is thick. Wooden column are built into adobe or brick walls. Column and beam are connected by dowelled joints without diagonal brace or other connectivity measures. And there is nothing to connect columns and the wall. Houses with this structure are relatively short and small.

- Hill wooden frame (also called the small wooden frame) The main beam is thick. A short column which is long in the middle part and short on the two sides is put on the beam. A purlin is put on the short column and the roof is made above purlin, leading to slope roof. Adobe walls are widely used. Houses with this structure are relatively short and small.

Figure 1. Wooden Framed Load-Bearing House.

Adobe Wall Load-bearing Buildings

The roof frame, roof and other load are borne by the adobe walls which mainly include:

(1) Adobe wall houses. Adobes are used as the materials of wall. Clay mud masonry are used to build the wall by the method of horizontal or vertical building way. The roof frame and purlin are aside on the adobe wall.

(2) loam wall (commonly known as rammed earth or pile-planking). The semi dry and semi wet clay is placed between the wooden plywood, and is compacted and formed by layer by layer. The thickness of each layer is generally between 30cm-35cm. According to the different local practices, the clay may be mixed with different ratio of lime, sand, shell ash, pebbles, furnace ash and other materials, so as to improve its strength. The main beam is placed on the longitudinal and the purlin is placed on flush gable.

(3) Arch kiln. This is simple civilian housing types which use adobe, stone and brick as the building materials, which can be used as bearing wall and the arc or semicircular vault roof. The seismic intensity and the overall stability of this kind of house differ a lot.

(4) Loess cave. Loess cave is a form of caves, which is characterized by no requirements of wood and cool, being cool in summer and warm in winter, long time to update, and good seismic performance. This type of housing is mainly distributed in the northwest region of China. It is shown in Figure 2.

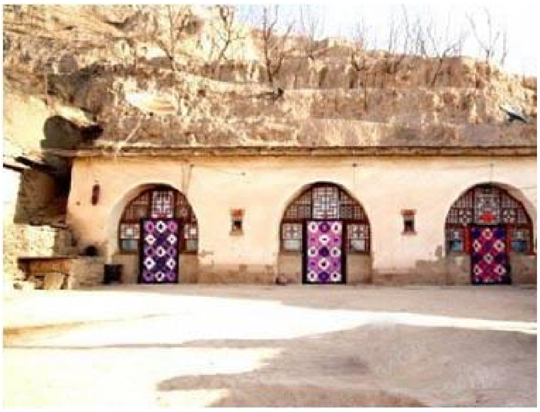


Figure 2. Adobe Wall load-Bearing House.

Masonry Load-bearing House

Masonry load-bearing structure is mainly composed of brick masonry or brick column bearing, which is the most common structure in China's villages and towns. There a lot of this kind of housing. According to the roof structure, they can be divided into brick structure and concrete structure. According to the way of building walls, it can be divided into:

(1)There are single-floor and multi-floor empty bucket wall housing. Most residential houses have one or two floors and are mainly distributed in south of the Huaihe River with a large amount.

(2) There are single-floor and multi-floor solid bucket wall housing. Most rural residential houses have one floor and a pitched roof or dome roof. Most of the former are wooden framed tile roof as shown in Figure 3.

(3) Brick column row frame building. Roof fame and roof load are born by brick row column, so that the house is relatively tall and open. Brick, adobe, fences and other materials are used to build the maintenance wall.

Figure 3. Masonry Load-bearing House.

Stone Wall Load-bearing House

The load of stone structure buildings are born by stone wall. According to the materials of wall, they can be divided into dressed stone houses and raw stone houses. According to the type of building roof, they can be divided into stone-and-concrete structure, stone-and-wood structure and pure stone structure. Stone wall structure is the traditional houses form in stone production area such as Northeast China, eastern and southeast coastal area, the Yunnan Guizhou Plateau, Qinghai Tibet Plateau and other mountainous regions. The house is shown in Figure 4.

Figure 4. Stone Wall Load-Bearing House.

Mixed Load-bearing House

Mixed bearing structure refers to that the buildings have several kinds of bearing systems to share the load of structure:

(1) Brick and clay mixed load-bearing housing: ①there is house with brick column and adobe wall. Roof frame is supported by brick column on the vertical wall; gable and maintenance wall use adobe masonry, purlin is placed on flush gable; the weight of the roof is shared by brick columns and pediment. ② there is house with brick in the lower part and adobe in the upper part. Lower part of the wall is about 1m of the brick wall and the upper part is adobe masonry. The weight of the roof is shared by brick and soil mixed wall. ③there is house with stone in the lower part and adobe in the upper part. The lower part of the wall is made of stone and the upper part is adobe or rammed earth wall; ④ there are also brick outside and adobe inside, brick longitudinal and gable, vertical and horizontal wall with brick outside and gable soil and so on.

(2) This type of structure is characterized by saving woods. However, it only builds simple wooden frame with beam column or purlin in the middle of the house, one framed bend in the middle of the two rooms or two framed bents in the middle of three rooms, or a column to support in the Tong-rang house, which makes poor intensity of the housing structure and uninformed distribution .Most of the front walls and barring walls are adobe masonry, and gable and the walls are rammed earth walls.

(3) The brick masonry load-bearing housing with bottom frame. The first layer is frame bearing structure, and the second layer and above adopts the masonry bearing structure. The type of housing can makes a larger space for the bottom part of the house, which is usually suitable for developing commercial housing at the first floor and residential housing at the second and above floors. The house is shown in Figure 5.

(4) The brick masonry load-bearing housing with partial bottom frame. Most rural buildings are “two floors of brick masonry above one frame” or “three floors of brick masonry above one frame”. The structure arrangement of this type of housing is usually chaotic. Lateral stiffness of frame structure and brick masonry structure is not consistent, especially for the houses whose front part adopts bottom local framework bearing, whose front and backward stiffness are very different. Therefore, the integrity of and seismic performance this type of housing is poor.

Figure 5. Mixed Load-Bearing House with Bottom Frame.

THE NONLINEAR RESPONSE ANALYSIS OF MASONRY STRUCTURE TO THE EARTHQUAKE

Masonry structure is one of the most widely used and largest area covered structures in Chinese village and town buildings. Because of its poor shear strength, masonry structure is easy to be in nonlinear state under the action of earthquake. Therefore, only the nonlinear response analysis can really obtain the vulnerability of masonry structure under earthquake.

Lateral Stiffness of Seismic Wall Section

(1) Non porous and non structural column wall section

When $h/bk < 1$, $K_0 = \frac{GA}{\xi h}$

When $1\langle h/b \leq 4$, $k_0 = \frac{GA_m}{1.2h(1+\frac{h^2}{3b^2})}$

When $h/b > 4$, its stiffness is out of consideration.

In the above equations,

K_0- the initial stiffness of wall section;

h - the calculated height between layers of wall sections;

b - wall width of the wall section;

G - elastic modulus of brick masonry;

G=0.3E (E refers to elastic modulus pf brick masonry);

A-horizontal area of the wall section;

A_m - total horizontal area of wall section;

ξ -influence coefficient of non-uniformity of shear stress and the rectangular can be set as 1.2.

(2) If the wall section has two or more constructional columns or a portal at two ends, $k_0 = \frac{\lambda_0 GA_m}{\xi h}$.

In this equation, λ_0 refers to the updating stiffness coefficient without considering the portal and curve. And according to the following equations, it can be concluded that:

When h/b<1 , $\lambda_0 = \frac{\varphi_0 A_z}{A_m}$.

When 1<h/b ≤ 4 , $\lambda_0 = \frac{\varphi_0}{\left(1+\frac{GA_z}{\xi}\times\frac{h^2}{12EJ_a}\right)}$.

When $h/b > 4$, its stiffness is out of consideration.

In the equation, A_z refers to are of converted horizontal section and according to the following equation it can be obtained that:

$A_z = A_{jz} + \eta_g \frac{E_c}{E} A$ in this equation:

A_e -the sum of horizontal section areas of constructional columns concrete

E_c - elastic modulus of concrete

A_{jz} - horizontal area of brick masonry section deducting the area of portal and constructional columns

η_g -the working coefficient of the main reinforcement in the wall. When $h/b \geq 0.5$, $\eta_g = 0.3$; When $h/b < 0$, $\eta_g = 0.26$.

J_z -the inertia moment of I-shaped cross section of horizontal area of constructional columns after converting together with horizontal area of wall section

φ_0 -influencing coefficient of portal, adopted value shown in Table 1.

Table 1. Influencing Coefficient ϕ_0 of Portal.

Δp	0.9	0.8	0.7	0.6	0.5	0.4
φ_0	0.98	0.94	0.88	0.76	0.68	0.56

(3) Strain hardening stiffness K_1 and softening negative stiffness K_2 . $K_1 = \alpha_i K_0, i = 1, 2$

In the equation, α_1 refers to the strain hardening ratio; α_2 refers to softening coefficient.

When the constructional columns are out of consideration, $\alpha_1 = 0.18, \alpha_2 =$ -0.166 .

When the constructional columns is under consideration, $\alpha_1 = 0.075, \alpha_2 =$ -0.056 .

(4) The unloading stiffness Ku after the deformation exceeding the crack displacement V

$$k_u = (\frac{V}{V_c})^{a_3} K_0$$

In this equation,

V - the interlayer displacement during wall section unloading;

V_c - interlayer displacement during wall segment cracking;

α_3 - unloading coefficient. Without considering the constructional column, α_3 =-0.6; with the consideration of the constructional column, α_3 =-0.53.

Strength of Wall Section

(1) Wall section without or without considering the constructional column

Cracking strength: $Q_c : Q_c = \frac{AR_j}{\xi}\sqrt{1+\sigma_0 / R_j}$

Extreme strength: $Q_u : Q_u = \alpha_u Q_c$

In the above equation, R_i refers to shear strength of brick masonry along the stepped section; σ_0 refers to partial pressure value of upper part of the wall; α_u=1.192 .

(2) Wall section with the constructional column at two ends

Cracking strength: $Q_c : Q_c = \frac{A_z R_i}{\xi}\sqrt{1+\sigma_0/R_j}$

Extreme strength: $Q_u : Q_u = \alpha_u Q_c$

In the equation: α_u=1.11

Dynamic Response Analysis of the Structures

The dynamic analysis equation of masonry structure under earthquake action is as follows:

$$\lfloor M \rfloor \cdot \{u_1\} + \lfloor K \rfloor \cdot \{u_2\} + \lfloor C \rfloor \cdot \{u_3\} = \{p\}$$

In the equation, $\{u_1\}$, $\{u_2\}$ and $\{u_3\}$ respectively refer to the values of displacement, velocity and acceleration of the particle; [M] refers to the mass matrix; [K] refers to stiffness matrix; [C] is the damping matrix. Deformation of masonry structure under seismic load is mainly shear deformation, so in the dynamic analysis, the deformation can be simplified as a shear type multi mass system. And damping matrix is formed by the Rayleigh damping, among which structural damping ratio is 0.05, namely: $C = \sigma_0 M + \sigma_1 K$

Dynamic response numerical analysis uses Newmark-βmethod, with the specific steps shown in the following:

(1) Preparation of basic data and initial conditions for the calculation:

Select the time step and parameters, and calculate the integral constant:

$$a_0 = \frac{1}{\beta.\Delta t^2}; a_1 = \frac{\gamma}{\beta.\Delta t}; a_2 = \frac{1}{\beta.\Delta t}; a_3 = \frac{1}{2\beta} - 1;$$

$$a_4 = \frac{\gamma}{\beta} - 1; a_5 = \frac{\Delta t}{2}(\frac{\gamma}{\beta} - 2); a_6 = \Delta t(1-\gamma); a_7 = \gamma \Delta t$$

Determine the initial values of the movement $\{u_1\}_0$, $\{u_2\}_0$ and $\{u_3\}_0$,

(2) Form the stiffness matrix [K], the mass matrix [M] and the damping matrix [C]

(3) Form equivalent stiffness matrix $\lfloor \hat{K} \rfloor = \lfloor K \rfloor = a_0 \lfloor M \rfloor + a_1 \lfloor C \rfloor$

(4) calculate the equivalent load at the time of t_{i+1}, namely

$$\{\hat{P}\}_{i+1} = \{\hat{P}\}_{i+1} + [M][a_0\{u_1\}_i + a_2\{u_2\}_i + a_3\{u_3\}_i] + [C]a_1\{u_1\}_i + a_4\{u_2\}_i + a_5\{u_3\}_i$$

(5) calculate the displacement at t_{i+1}, namely $\lfloor \mathrm{k} \rfloor \{u\}_{i+1} = \{\hat{p}\}_{i+1}$

(6) calculate the acceleration and speed at the time t_{i+1}

$$\{u_3\}_{i+1} = a_0(\{u_1\}_{i+1} - \{u_1\}_i) - a_2\{u_2\}_i - a_3\{u_3\}_i$$

$$\{u_2\}_{i+1} = \{u_2\}_i + a_6(\{u_3\}_i + a_7(\{u_3\}_{i+1}$$

Cycle step (2) to (6) to carry out the nonlinear calculation on the structure. In the equation, meanings of the symbols are same with the above symbols. According to dynamic equation of the shear-typed multi mass system and the above analysis, the MATLAB language is used to compile the nonlinear analysis program for dynamic analysis to conduct the following calculation.

THE GENERATION OF GROUND MOTION SAMPLES

The Generation of Random Ground Motion Samples

Random factors of ground motion mainly include: Peak Ground Acceleration (PGA), duration T of seismic ground motion, damping ratio, mean response spectrum and etc. This paper mainly considers the randomness of PGA and duration T of seismic peak ground motion which is assumed to obey lognormal distribution. Variation coefficient of duration is 0.678. In this paper, the seismic waves adopt artificial seismic waves, with a total number of 60. Monte Carlo method is used to generate random number of PGA and duration T as shown in Table 2.

Table 2. Random Parameters of Ground Motion.

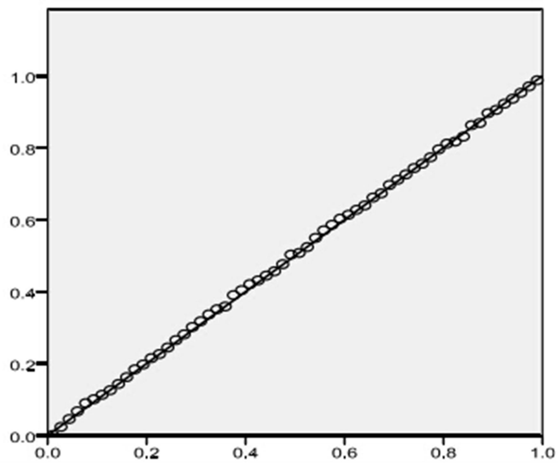
No.	PGA (g)	Duration T (s)
1	0.023	15.48
2	0.034	3.84
3	0.041	13.48
4	0.053	3.96
5	0.065	8.31
6	0.072	3.03
7	0.082	6.32
8	0.089	28.02
9	0.092	8.34
10	0.1	7.76
11	0.105	17.7
12	0.11	6.07
13	0.117	22.34
14	0.124	11.81
15	0.133	4.38
16	0.135	5.02
17	0.148	6.52
18	0.153	5.19
19	0.157	8.48
20	0.163	6.2

SPSS statistical software is used to conduct P-P test on the generated random values, and verify the distribution type. The testing results are shown in Table 3 and Figure 6.

Table 3. Test on the Random Values of Seismic Duration.

Names of Parameters		**PGA**	**T**
lognormal distribution	scale	0.186	7.767
	shape	0.882	0.630

P-P of Lognormal Distribution of T



The Observed Cumulative Probability

Figure 6. The P-P of Random Duration.

Design of Analysis Model of Typical Masonry Structure

At present, masonry buildings in China's rural area are mainly low-layer structured such as cottage, two layers, and three layers. Taking into account of the economic disparity among rural, township and county areas, strength grade of the materials used in building houses and the constructional measures vary to some degree. According to the common village building layout, this paper assumes a design of a bungalow as shown in Figure 7.

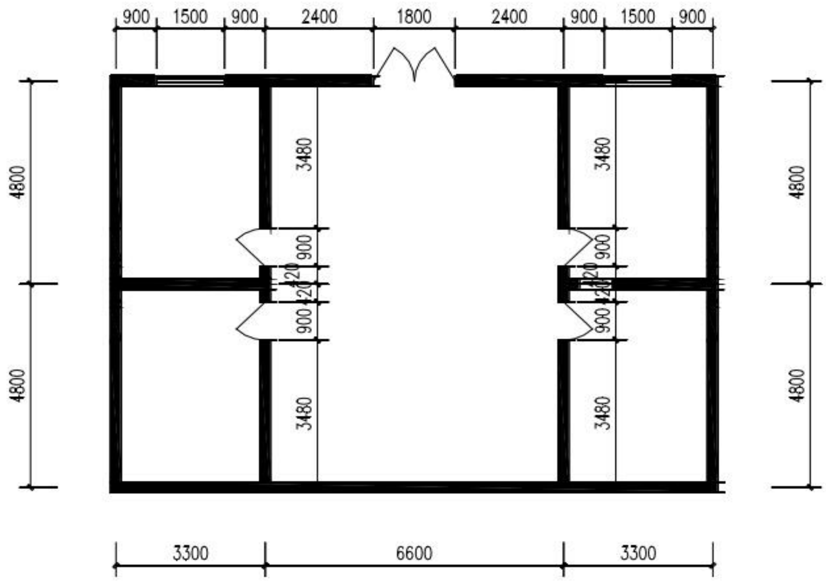


Figure 7. Floor Plan of Bungalow.

There are bungalows in the countryside, towns and counties. The different level of strength of materials and the fact that whether it has constructional columns to masonry structure should be taken into consideration. Eight types of bungalow models have been established in this paper as Table 4 shows.

Table 4. Masonry Structured Bungalow Models based on Different Performance-based Criteria

Locations	Material Model
Countryside	1. Mu10 M2.5 material model without constructional columns and other measures;
	2. Mu10 M2.5 material model with constructional columns and other measures;
	3. Mu10 M5 material model without constructional columns and other measures.
Towns	1. Mu10 M2.5 with constructional columns and other measures;
	2. Mu10 M5 with constructional columns and other measures;
	3. Mu15 M2.5 material model without constructional columns and other measures;
	4. Mu15 M2.5 with constructional columns and other measures.
Counties	1.Mu15 M2.5 material model without constructional columns and other measures;
	2. Mu15 M2.5 with constructional columns and other measures;
	3. Mu15 M5 material model without constructional columns and other measures;
	4. Mu15 M5 with constructional columns and other measures.

Analysis of Seismic Venerability of Masonry Structure

In this paper, the traditional reliable method is used to describe the seismic vulnerability of the structure, namely: the probability of masonry structural seismic demand exceeding its seismic capacity. This failure probability can be expressed in $p_f = p\left[\frac{S_d}{S_e} \geq 1\right]$. P_f is refers to the probability value of exceeding a limit state; S_d is seismic demand of masonry structure; S_e refers to the seismic capacity of masonry structure. When masonry structure is described as obeying the lognormal distribution under the ground motion, the probability of reaching or exceeding a certain limit state will be in a log normal distribution and the probability can be calculated by the following equation:

$$P_f=\Phi\left[\frac{\ln(S_d/S_e)}{(\beta_d^2+\beta_e^2)^{1/2}}\right] \tag{1}$$

In this equation, β_d refers to the standard deviation of seismic demand of masonry structure being in the log normal distribution; β_c Refers to the standard deviation of seismic capacity of masonry structure being in the log normal distribution; meaning of other symbols are same with the above ones.

The Venerability Curves of the Non-structural Model of the Bungalow

There are eight models in the paper. According to the selected 60 earthquake wave, conduct dynamic and time-historical analysis of non constructional model. With the peak ground acceleration (PGA) as independent variables, make regression analysis on the corresponding structural response data (ductility coefficient) and the following formula can be obtained:

$$\ln(\mu)=0.6668\ln(PGA)\ +\ 1.6871 \tag{2}$$

Graph obtained by the regression analysis is shown in Figure 8. It can be seen that most structural response data are distributed around the regression line which takes PGA as the independent variables. Usually, in studies, probability functions of structural response are represented by lognormal distribution function which is defined by the mean response $\hat{\mu}_d$ of the structures and the logarithmic standard deviation β_d, namely $\mu=\ln(\hat{\mu}_d,\beta_d)$. The probability function of seismic bearing ability of the structure is also represented by logarithmic normal distribution function which is defined by the seismic bearing ability mean $\hat{\mu}_c$ of the structure and logarithmic standard deviation β_c, namely $\mu_c=\ln(\hat{\mu}_c\beta_c)$.

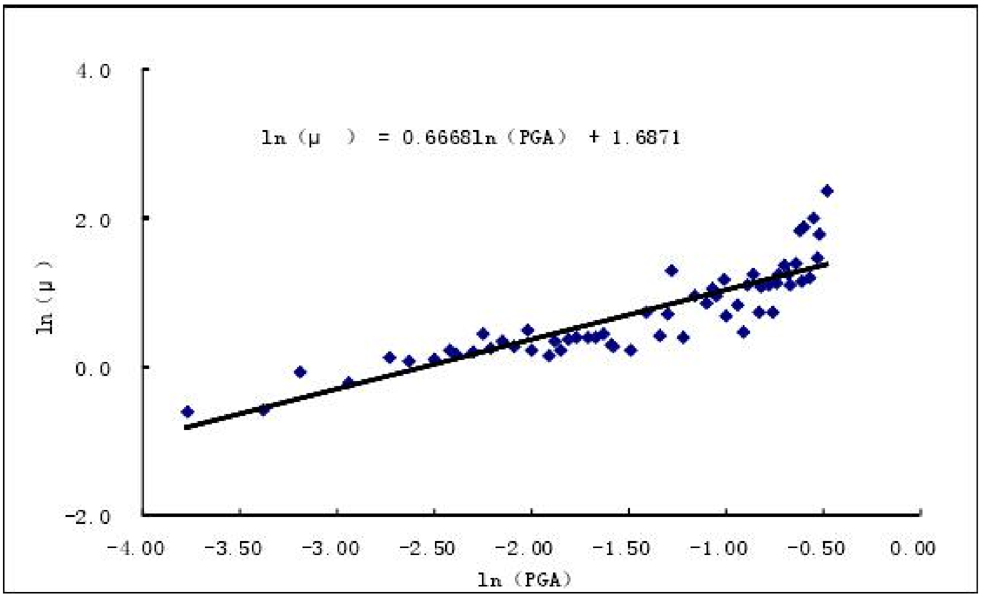


Figure 8. Regression Analysis of the Extension Coefficient of Non Structural Bungalow.

Put formula (2) into the formula (1) and the exceeding probability of non structural bungalow model under specified conditions can be obtained:

$$p_f=\Phi\left[\frac{0.6668\ln(PGA)\ +\ 1.6871-\ \ln(\hat{\mu}_C)}{(\beta_d^2+\beta_c^2)^{1/2}}\right]$$

As a result, the venerability curves of non structural bungalow model can be obtained as shown in Figure 9. The curve in the figure from left to right corresponds to a slight damage, moderate damage, severe damage and collapse state. The abscissa refers to PGA and ordinate refers to the probability of structural response under ground motion exceeding different damage grades.

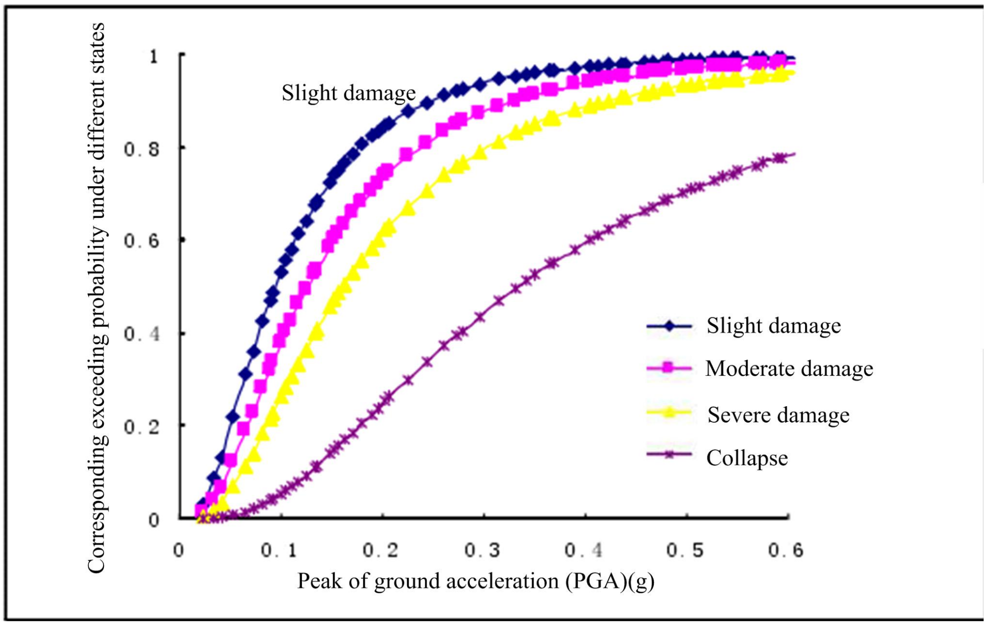


Figure 9. Venerability Curves of Non Structural Bungalow Model.

Through regression analysis of large amounts of data, the seismic venerability curves of masonry structure model of different perform-based criteria. According to the comparison analysis of the venerability curves of each model and that of masonry model under same damage state but different perform-based criteria, it can be known that: 1. the failure probability of the structure under a certain damage degree increases with the peak ground acceleration of PGA; at the same ground acceleration, the probability of slight damage on the structure is larger than other damage grades.2. The structures with different material strength and construction measures, at the same peak ground motion, have different vulnerability.

CONCLUSIONS AND EXPECTATIONS

Based on the fact that present buildings in towns and cities are adopting same seismic fortification criterion without considering the differences of urban and rural areas in seismic risk characteristic, social and economic developing level of rural area, and the income gap between classes, this paper introduces performance-based seismic fortification into the rural buildings, Through the introduction of hierarchical (countryside, township and county) structural type of rural buildings, generation of ground motion random samples, and nonlinear seismic response analysis on masonry structure, this papers draws the conclusions that different damage can happen to the structure which indirectly indicates that the seismic performance of the structure can be different. Adopting different seismic fortification criterion to areas with different economic development levels can fully reflect the wishes of the village people and give full consideration to the practical conditions and the imbalanced economic development among different villages. But there are still a lot of problems to be further studied..Through preliminary consideration, it is believed that the following issues can be further studied and improved: 1 classification of the seismic design of rural buildings needs further detailed division; 2 Conduct investigation on casualties in the villages, towns and counties, thus improving the perform-based seismic fortification criteria of rural buildings; 3 the seismic vulnerability analysis of the other structures in rural areas can also be divided into different levels; 4. In the process of the determination of the earthquake insurance, the determination of the seismic risk characteristics and the loss rate needs to be further studied.

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