Research and Application of Methods for Estimating Setback Distance of Buildings on Active Fault Sites

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Abstract: From the perspective of earthquake disaster reduction planning and earthquake resilience of urban buildings, the earthquake damage and disaster reduction analysis of buildings on the surface track line of strong earthquakes are mainly concentrated in the aspect of building setback distance. Based on the examples of surface rupture damage caused by strong earthquakes, statistical analysis of the length and width of the surface rupture zone, the failure rate of structure collapse under different setback distances and the probability of surface rupture of the main fault rupture in strong earthquakes, this paper gives the relevant contents of the building setback distance estimation methods: one is the deterministic setback distance analysis method, the other is the probabilistic setback distance analysis method. The two methods are compared, and combined with the importance classification of civil structures, and a comprehensive method for estimating building setback distance is given. This method is an operable and practical building setback distance estimation method.

Keywords: Fault; Building Structures; Setback Distance; Disaster Reduction; Method

1. Introduction

Under appropriate conditions, the dislocation of active faults can lead to surface rupture, which often causes significant damage to buildings near the rupture zone[1,2]. The purpose of the research on the problem of building structure avoidance on the project site with active faults is to determine the setback distance reasonably and safely and analyze the anti-collapse or anti-rupture ability of the building structure under a certain value of setback distance[3,4]. The important research direction to solve this problem is the estimation method of setback distance.

The quantitative study of setback distance is complex, involving many influencing factors such as earthquake intensity, fault type (rupture mechanics), rock and soil type (upper and lower walls), multiple (segmented) rupture events, micro topography and landforms near the fault zone, structure (foundation) type, intersection (parallel and vertical) direction of structure and faulting-rupture distribution trace, and surface seismic response near the fault rupture zone. In this article, two estimation methods of setback distance are proposed from the perspective of earthquake disaster reduction planning and earthquake resilience of urban buildings.

2. Deterministic Setback Distance Analysis Methods

The estimation method of setback distance is to determine the width and distribution length of surface fractures, and provide the specific range of the “avoidance zone” of surface ruptures through the analysis of fracture width (horizontal setback distance) and length. The method of deterministic analysis is theoretically easy for people to accept.

2.1 Deterministic Analysis of Rupture Width

For the determination of the surface rupture width, that is, the determination of horizontal setback distance, the setback distance of the site or the engineering area can be determined by comprehensive judgment and analysis of the width of the surface rupture zone, the setback distance of the structure under seismic damage, and the ground motion response near the rupture zone.

For the analysis of the width of surface rupture zones, the width value can be determined by using the formula (1) for surface rupture zone width for the maximum width of surface rupture zone, based on the rupture modes and influencing factors summarized by the author in this article.

$$W = U(14.7 + 3.3D) \quad (1)$$

In the formula, D represents the maximum vertical dislocation of the surface rupture zone, and U represents the safety factor for setback distance. It is recommended to take 2-3.

For the analysis of structural earthquake damage setback distance, the setback distance (width) of the engineering structure[5,6] can be given by combining the recommended value of setback distance Table 1 and considering the seismic damage effect of the single building structure on and near the surface rupture section.

Table 1. List of Setback Distance Statistics

Earthquake events	Suggested setback distance
Jiji earthquake (reverse fault)	100m on the upper plate and 50m on the lower plate
Wenchuan earthquake (reverse fault)	150m, with a ratio of 3:1 between the upper and lower sections
Yushu earthquake (strike slip fault)	Hollow brick (Class D) structure 100-150m, frame structure at least 20m
Darfield earthquake (strike-slip fault)	At least 40m
Izmit earthquake (normal fault)	50m; If the continuity of the foundation stiffness is good, the avoidance distance value can be reduced.

For the analysis of seismic response near the rupture zone, the setback distance value can be comprehensively determined by inputting no less than 3 pulse type seismic waves similar to the site to be avoided (referring to the near fault wave characteristics of the Taiwan Chiji earthquake) and providing the distribution of surface peak acceleration and response spectrum.

2.2 Deterministic Analysis of Rupture Length

How is the length (direction) of the surface rupture of the next strong earthquake distributed along the active fault zone, following the principle of characteristic earthquakes and surface rupture segmentation. This article suggests that: (1) through the study of ancient earthquakes (exploration trenches) in typical exposed areas of surface ruptures, a 1:10000 geological mapping of the vicinity of the rupture zone should be provided. It is recommended that the distance between the mapping survey points should not exceed 1km, and a comprehensive evaluation should be made based on the location of the rupture and its risk (periodicity); (2) In general urban earthquake damage prediction, the relationship table between the parameters of the surface rupture zone (length L, magnitude M, surface dislocation D, fault properties, and direction) of nearly 60 earthquakes that have occurred in China, provided by Deng[7] et al., can be used to determine. Relevant formulas such as the strike slip rupture formula (2) in the Qinghai region and the reverse rupture formula (3) in the Qinghai region are also provided.

$$M = 5.10 + \lg L + \lg D \quad (2)$$

$$M = 5.34 + \lg L + \lg D \quad (3)$$

For each active fault, a more accurate and quantitative determination of the width of surface rupture at a certain location can be made based on the displacement along the length of the surface ruptures that have already been detailed. For example, by combining the horizontal and vertical displacement distribution maps of 17 rupture points of the 1937 Toso Lake M7.5 earthquake provided by Lia[8] et al. (see Figure 1), and using the vertical characteristic displacement and rupture width formula (1) proposed in this paper, the surface rupture width value of a certain point on the map can be obtained. This is basically consistent with the data investigated by Jiaet al. at the Lanzhou Earthquake Research Institute, where the length of the rupture on the surface rupture zone is between 20-60m.

3. Probabilistic Setback Distance Analysis Methods

3.1 Probability Model of Setback Distance

Strong earthquake surface rupture disaster is a low probability event with high harmfulness. Due to the lack of probabilistic meaning, it creates a dilemma for design engineers to make decisions. Setting up defenses may result in investment waste, while not setting up defenses may lead to safety hazards; At the same time, using probability prediction for earthquakes and strong earthquake surface ruptures is in line with the current level of people's understanding and is also necessary for engineering seismic resistance.

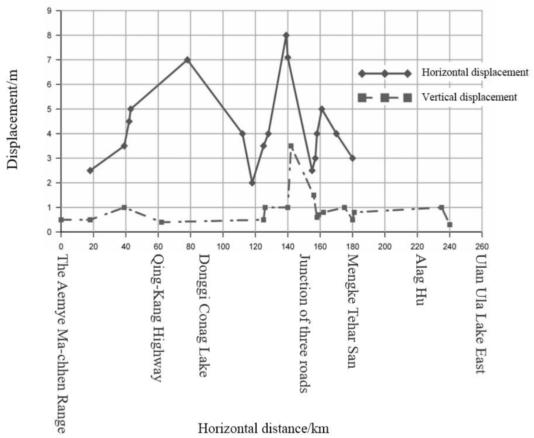


Figure 1. Displacement Curve of Surface Rupture Zone during the Toso Lake Earthquake

There are also many research achievements on the risk or probability analysis methods of surface rupture under strong earthquakes, but their ideas are similar, and some are only theoretical studies. Since it is a probability method, it requires statistical analysis of a certain amount (or even a large amount) of sample data to test.

After comprehensive analysis, this article believes that the hazard analysis of engineering structure setback distance should be considered. Therefore, a probabilistic method model and formula are provided:

$$P = P_R \times P_S \quad (4)$$

Among them, P_R represents the probability of strong earthquake surface rupture occurring on the main fault; P_S is the distribution function of building collapse and damage under avoidance distance.

3.2 Model Parameter

According to formula 4, the model presented in this article involves two parameters: (1) the distribution function P_S of building collapse and damage under avoidance distance; (2) The second is the probability of strong earthquake surface rupture occurring on the main fault, P_R. The following will be discussed separately.

For PS, see Table 2, which is a comprehensive statistical analysis based on the collapse of buildings at a certain distance along the trace line during earthquakes such as Jiji, Wenchuan, and Yushu.

For P_R, Sun and Li[9] believe that in urban seismic disaster prevention planning and seismic safety evaluation of important engineering sites, potential source area division and seismic activity parameter selection are also involved. Therefore, in this inheritance process, favorable conditions have been created for the probability assessment of strong earthquake surface rupture. The idea and probability model can be represented by formula 5.

$$P_R = \sum_{j=1}^{n} \upsilon_{ij} \cdot R_j \quad (5)$$

In the formula υ_{ij} is the average annual occurrence rate of earthquakes, which can be calculated by Equation 6. This is a core derived formula for seismic hazard analysis, and R_j is the frequency of surface rupture caused by earthquakes of magnitude j, which can be calculated[9].

$$\upsilon_{ij} = \upsilon_j \, \omega_{ij} = \upsilon_4 \cdot \int_{M_{j-1}}^{M_j} f(M)dm \cdot \omega_{ij} = \upsilon_4[F(M_j)-F(M_{j-1})] \, \omega_{ij} \quad (6)$$

Table 2. Table of Structural Collapse and Damage Rates

Setback distance	S＞150	150≥S≥100	100＞S≥50	50＞S≥25	S＜25
Probability assignment (%)	10	20	35	60	85

Note: If the building is on the upper wall, the probability assignment in the table will be uniformly increased by 10%.

It should be emphasized here that, ω_{ij} is a spatial distribution function, not derived from seismic data, but from empirical values determined by expert judgment. Although it contains uncertainty in the subjective will of experts, it reflects the current level of cognitive ability and is still acceptable. Because spatial distribution functions generally scientifically consider the influence of factors such as the activity level of active structures in the source area, the probability of recurrence of earthquakes with magnitude 6, the actual frequency of earthquakes occurring in the source area, the area of the source area, the seismic activity within the source area, and the long-term forecast results within the source area.

This article believes through the study of the repeated analysis of surface ruptures in strong earthquakes that the repeated occurrence of surface fractures in situ generally follows the "characteristic earthquake model" and "rupture segmentation model". Therefore, in formula 6, "[$F(M_j)$-$F(M_{j-1})$]" and "υ_4" are actually b and υ_4. Because the minimum magnitude of surface rupture is generally above 6, it should be strengthened Research on υ_6.

3.3 Probability Method

Based on the above analysis, this article combines the probability analysis method of surface rupture and the probability analysis method of surface fault deformation to provide a hazard analysis method for setback distance in engineering sites, as shown in formula 7.

$$\mathrm{P} = \left(\sum_{j=1}^{n} \upsilon_{ij} \cdot R_j \right) \cdot P_S \qquad (7)$$

4. Setback Distance Estimation Method

The setback distance or "avoidance zone" in this article is based on a systematic analysis of deterministic and probabilistic methods, and is given according to the following principles:

(1) This article proposes a preliminary method for analyzing the damage caused by surface ruptures during strong earthquakes: For the distribution length of surface ruptures, quantitative analysis can be conducted using the relationships between magnitude M, distribution length L, and seismic fault dislocation D, which have been studied by many predecessors; For the width of surface ruptures along the distribution length, a comprehensive analysis can be conducted using general width, the characteristic dislocations and width relationship equation provided in this article, etc The specific distribution form of rupture length on active fault zones is whether it is distributed along the original location of the rupture or on another segment of the active fault zone that does not overlap or partially overlaps with it. This article suggests that through the study of ancient earthquakes (exploration trenches) in typical exposed areas of surface ruptures, the location of surface ruptures and their risk (periodicity) can be comprehensively evaluated.

(2) For the seismic damage analysis of engineering structures near the fracture trace, a two-step method was adopted: in the horizontal distribution direction of the rupture trace, the "line" method, that is, the (possible) geometric distribution of the rupure trace, is used to analyze the risk of existing buildings, so as to quantify and locate the risk, which is sufficient for land planning or (and) earthquake damage prediction in urban areas. On the basis of completing the "line" analysis, the "point" analysis of the buildings adjacent to the trace line or on it is best assisted in the probe section to further determine the possible position of the trace line to complete the determination of the setback distance value of the monomer structure. Generally, for the intersection problem of the structural plane and trace line, if the trace line and the structural plane are parallel, the setbak distance can completely use the given value, such as the strike-slip fault setback distance is 50m, if the structure and the rupture trace are perpendicular or intersect, a certain safety factor needs to be given, and 2 is recommended. The type of structural foundation is recommended to adopt a continuous foundation, or even a "flat thin" small box foundation, and it is not recommended to use an independent foundation under the column or even a pile foundation. The influence of the height of steep or anti-steep (graben) on foundation deformation should be estimated.

(3) For Class C and above projects required by the Chinese seismic design code, seismic impact analysis can be considered under a certain seback distance. Numerical simulation analysis of seismic motion on the site that needs to be analyzed can be directly carried out, and the parameters of setback distance and design response spectrum can be provided.

(4) For the possibility of surface rupture setback distance, that is, risk analysis, the probability model and its formula in this paper can be used for preliminary discrimination.

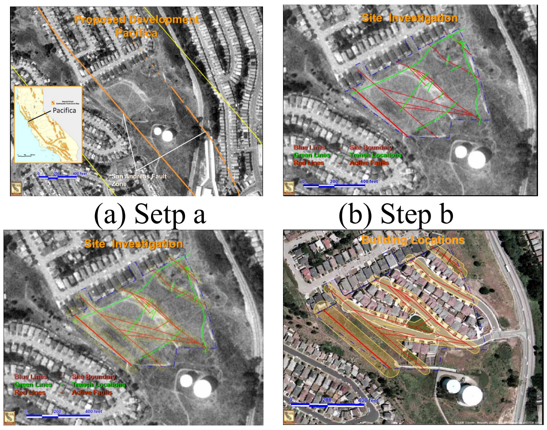
It can be seen that the method proposed in this article is an avoidance area estimation method that considers the risk of surface rupture.

Of course, the determination of the specific range of the "avoidance belt" also needs to consider the accuracy of surface rupture positioning. The reliability of positioning accuracy is one of the important foundational works for achieving the feasibility and economic benefits of building setback distance in reality. In the case that the current fault location and identification methods are not perfect, in order to consider the existing uncertainties as much as possible, this paper believes that the comprehensive application of multiple technical methods should be advocated and emphasized to improve the recognition and credibility of the final results, so as to do a good job in the assessment of surface dislocation risk and rupture hazard. This paper suggests that at the present stage, the best way is to excavate the trough, which can make the positioning accuracy within 1m; If there is no trough, the surface rupture zone (trace line) can be inferred in China's fault strip geological geomorphology map (scale 1:25,000-1:10,000), and the accuracy of the "identified" active fault is at least ±20m. If a satisfactory positioning method and means such as shallow seismic exploration is used, the accuracy caused by inaccuracy and deviation is ±25m. For other large-scaled mapping active faults exposed or surface ruptures, the positioning accuracy analysis method combining the complexity classification of ruture trace and scale accuracy can be referred to.

The following is a practical case analysis and application provided by the California Fault AP Act, as shown in Figure 2.

Step a: The approximate location of the San Andreas active fault in the Pacifica region on the 1:24000 geological map; Step b: The blue boundary represents the red line area of a construction site in the Pacifica region. The red line represents the possible active faults and their traces given by seismologists, while the green line represents the location and length of the exploration trench arranged according to this trace; Step c: The horizontal avoidance distance on the trace line provided after completing excavation discrimination according to step b (i.e. the planning basis diagram of the building layout design scheme within the red line); Step d: Follow the C steps to guide the design and construction of the actual location map of the building.

Based on this, combined with the importance classification of civil structures, this paper preliminarily suggests a comprehensive selection list of setback distance estimation methods, as shown in Table 3.



(a) Setp a (b) Step b

(c) Step c (d) Step d

Figure 2. California Fault AP Act Application Case[10]

Table 3. Options for Building Setbak Distance

Method classification \ Building Type		A	B	C	D
Deterministic analysis methods	Statistical analysis of rupture zone width	√	√	√	√
	Suggested distance for avoiding structural seismic damage and analysis of seismic damage to individual structures	√	√	×	×
	Numerical simulation analysis of seismic motion near the rupture zone[11]	√	√	√	×
Probability analysis method		√	√	×	×
Model testing methods		√*	×	×	×

5. Conclusion

This article proposes an operable and practical method for estimating fault setback distance of building structure.

This method mainly involves deterministic analysis based on the width and length of surface ruptures, as well as probabilistic analysis of the probability of surface ruptures and the collapse density function of structures at different distances from ground ruptures. Combined with the accuracy results of fault rupture localization, it provides a more systematic method that can specifically divide avoidance areas or zones of fault dislocation.

At the same time, it is recommended to further study and determine the selection method of building setback distance considering active fault in combination with the importance classification of civil structure in China building seismic design code.

In the future study, the process of comprehensive determination of building setback distance is given to make up for the shortcomings in the selection of methods. In conclusion, this method can bring good economic and social benefits to urban safety considering the influence of active faults in the aspects of earthquake disaster reduction planning of urban buildings, soil utilization planning and urban disaster prevention resilience assessment.

Acknowledgments

This paper is supported by National Natural Science Foundation of China (No. 51608118) and Hebei Key Laboratory of Earthquake Disaster Prevention and Risk Assessment Open Foundation (Grant No. FZ223201).

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