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Seismic Risk Probability Assessment of Frame Structures Based on Incremental Dynamic Analysis

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Abstract. To assess the seismic risk probability of frameworks in different seismic fortification intensity zones in China, three fortification intensity framework models-specifically, 6 (0.05 g), 7 (0.1 g), and 8 (0.2 g)-were established as the research objects. The incremental dynamic analysis method was used to conduct a structure seismic fragility assessment, in which the fragility curves as well as the damage probabilities under certain peak ground accelerations were obtained. The risk probabilities of all the seismic damage levels of the frameworks in the next 50 years were calculated using the Monte Carlo method based on a study of the seismic hazard of different fortification intensity zones. The results indicate that, in the next 50 years, the risk probabilities of fortification intensity framework models 6, 7, and 8 exceeding “serious damage” were 1.92, 4.25, and 8.28%, respectively. Additionally, the risk probabilities of the models having a damage degree of “collapse” were 0.14, 0.43, and 1.07%, respectively. Based on the risk probability of the structure, the risk level is classified. This study forms the basis for the comprehensive evaluation of building seismic damage risk and can be used as a reference for the development of building seismic disaster prevention countermeasures.

1. Introduction

An earthquake is a type of extremely destructive disaster that results in significant economic and social losses in earthquake-prone countries all over the world, threatening the safety of people’s lives and property [1]. Adopting seismic fortification for building structures is a fundamental means to reduce the loss caused by building seismic disasters. However, in preparing such fortifications, high-intensity earthquakes that exceed the fortification intensity are often not considered. For example, in many earthquakes, such as the Tangshan (1978) and Wenchuan earthquakes (2008) in China, the fortification intensity was exceeded by the high-intensity earthquake [2], which caused widespread building collapses and displaced millions of people. Therefore, it is crucial to conduct a seismic risk assessment and consider corresponding disaster prevention measures for buildings before the disaster occurs. Conventional seismic fragility analysis is predominantly conducted by analyzing the possibility of different damage grades of structures under specific seismic actions, which ignores the uncertainty of earthquake actions, making it difficult to properly reflect the potential seismic risk. Seismic risk probability assessment considers both the seismic hazard as well as the structural vulnerability [3] and represents the probability of the structure exceeding or reaching a certain earthquake damage state in a certain period in the future. Seismic risk assessment can provide clear measurements of the possible seismic risk level of buildings in the future, scientific basis for decision-making regarding disaster prevention beforehand, earthquake emergency preparedness, and post-disaster rescue work. Further, it can provide an invaluable paradigm shift from the idea of disaster loss reduction to that of disaster risk reduction [4].

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In the long-term practical exploration, various scholars worldwide have conducted studies that have provided valuable insights into structural damage seismic risk. For example, Melani et al. [5] conducted incremental dynamic analysis (IDA) on a low-rise reinforced concrete frame structure, plotted its vulnerability curve, and evaluated the possible economic loss from seismic damage. Berto et al. [6] analyzed the time-varying characteristics of the seismic vulnerability of a steel reinforced concrete structure and conducted seismic risk assessment based on the whole life cycle of the structure. Gu et al. [7] developed a 3D finite element model of a typical low-tower cable-stayed bridge with OpenSees software, performed IDA analysis on the transverse and longitudinal directions of the bridge, and calculated the risk probability of each seismic hazard level of a typical low-tower cable-stayed bridge based on the Monte Carlo method. Lü et al. [8] summarized the general methods of seismic risk assessment from the two aspects of site seismic hazard and seismic vulnerability, analyzed the impact of essential uncertainty and knowledge uncertainty on the structural seismic risk assessment results, and derived relevant formulas. However, the majority of these studies focused on structural vulnerability; there are few reports on the seismic risk probability of frame structures in different seismic fortification intensity zones. To this end, this study focuses on establishing a framework structure for different seismic fortification intensity zones.

Earthquakes in China are characterized by wide distribution, high frequency, high intensity, and shallow source. According to the fifth China ground motion parameter zoning map [9], 84.4% of the 2,860 cities and towns at or above the county level are located in regions with fortification intensities 6, 7 (0.1 g), and 8 (0.2 g). Considering this fact, in this study, three structural models in accordance with the 6, 7 (0.1 g), and 8 (0.2 g) fortification intensity requirements were established as the research objects, and seismic fragility and probability analysis of different seismic actions were conducted on the models based on the IDA and Monte Carlo methods, respectively. On this basis, the seismic risk level was classified into three grades, and the risk level of the frame structure evaluated to reflect its earthquake damage risk degree in different fortification intensity zones. Thus, this study can provide a basis for the formulation of earthquake disaster countermeasures.

2. Materials and Methods

2.1. Incremental Dynamic Analysis Method

Based on the differences between the influence areas of seismicity, seismic damage data acquisition and calculation methods and earthquake fragility evaluation methods primarily consist of empirical and theoretical methods [10]. Theoretical methods reflect the probability relationship between the damage states of the structure and the ground motion by numerical calculation. They include damage condition determination, structural model determination, select and input ground motion, IDA analysis, and fragility curve production. Currently, the IDA method is one of the most commonly used theoretical methods to evaluate structural seismic responses and predict structural damage in performance-based earthquake engineering [11-13]. This method can analyze the entire process of the structure from elasticity to elastoplasticity to collapse, and it can better reflect the change rule of the seismic capacity of the structure under different earthquake actions in the future. Therefore, in this study, the IDA method is used to analyze structural vulnerability. Considering that the reinforced concrete frame structure is the most important structural form in China, a multi-story frame structure is considered as an example in this study.

2.1.1. Selection of IDA Indicators In this example we can see that there are footnotes after each author name and only 5 addresses; the 6th footnote might say, for example, 'Author to whom any correspondence should be addressed.' In addition, acknowledgment of grants or funding, temporary addresses etc might also be indicated by footnotes.

2.1.2. Classification of Damage States For seismic damage prediction, HAZUS [15] has classified the damage status of buildings into five levels: nearly intact, minor damage, moderate damage, serious damage, and collapse. In accordance with the code [16], the relationship between $\theta_{\max}$ and the seismic damage degree is presented in Table 1.

Table 1.

Damage degree	Nearly intact	Minor damage	Moderate damage	Serious damage	Collapse
θ_{max}	θ_{max}<1/400	1/400≤θ_{max}<1/250	1/250≤θ_{max}C1/125	1/125≤θ_{max}<1/50	θ_{max}≥1/50

2.1.3. Model Information In comparison with the uncertainty of the ground motion, the uncertainty of the structural model has little influence on the analysis results [17]. In accordance with the relevant Chinese codes [18-19], three frame structures with three spans and 10 floors with seismic fortification intensities of 6 (0.05 g), 7 (0.1 g), and 8 (0.2 g) were established. The height of the first layer of the structure was 4.5 m, and the height of each of the other layers was 3.6 m. The standard value of the constant load was 4.6 kN/m2, and the standard value of the live load was 0.5 kN/m2 for an unoccupied roof and 2.5 kN/m2 for the floor. The site classification was class II and the classification of the design earthquake was group II. The characteristic period of the site (T\-g) was 0.4 s. The frame structure plan is shown in Figure 1.

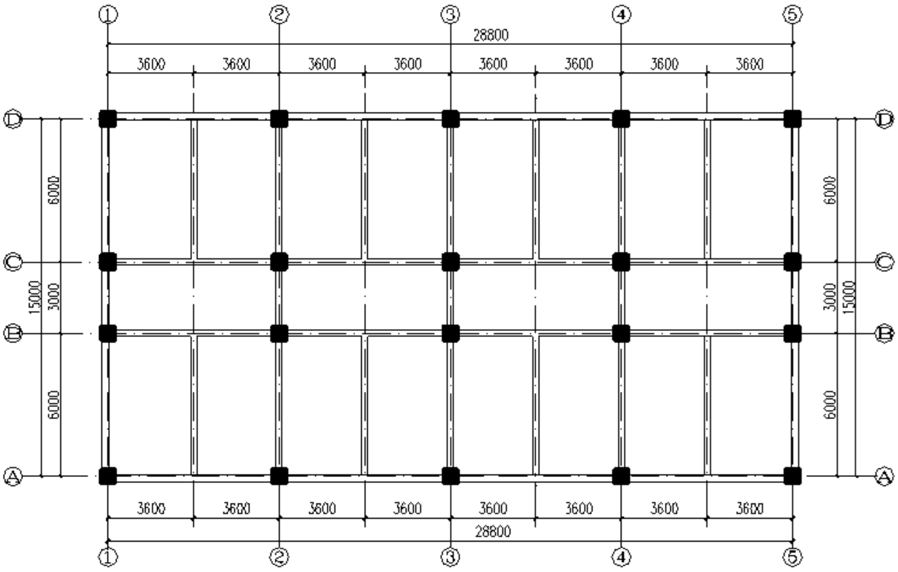

Figure 1. Frame Structure Plan (Unit: mm)

2.1.4. Select and Input Ground Motion Different ground motions have different earthquake effect values, which can differ by up to a factor of ten [20]. To reduce the uncertainty of ground motion on the structure, in this study, 30 seismic waves (more than 20 suggested by FEMA) suitable for the structure were selected from the earthquake ground motion database of the Pacific earthquake center of the United States in accordance with the IDA method requirements. The PGA amplitude modulation was used as the ground motion input for the structural analysis. The selected partial seismic records are listed in Table 2.

Table 2. Ground Motion Records

Number	Name	Time	Station	PGA (g)
1	Livermore-02	1980	San Ramon - Eastman Kodak	0.191
2	Westmorland	1981	Parachute Test Site	0.219
3	Imperial Valley-02	1940	El Centro Array #9	0.341
4	Imperial Valley-06	1979	Delta	0.284
5	Northridge-06	1994	LA - Century City CC North	0.123
6	Whittier Narrows-01	1987	Downey - Co Maint Bldg	0.177
7	Whittier Narrows-01	1987	Brea Dam (Downstream)	0.231
8	Whittier Narrows-02	1987	LA - 116th St School	0.157

2.1.5. Fragility analysis After the IDA analysis of the structure, the corresponding relationship between θ_{max} and PGA can be obtained. The probability function of the structural reaction can be obtained by considering the logarithms of θ_{max} and PGA [21]:

$$\ln\theta_{max} = a + b\ln PGA, \tag{1}$$

Where a and b are constants, which can be obtained by fitting the results of the structural IDA analysis. It is assumed that the probability function of the structural response D and structural capability parameter C all follow lognormal distribution [22], i.e.,

$$D \sim \ln(\hat{D}, \beta_d), C \sim \ln(\hat{C}, \beta_c), \tag{2}$$

Where

$\bar{D}$ represents the values of the structural responses, $\bar{C}$ indicates the structural capacity parameter, β_d is the logarithmic standard deviation of the structural response, and β_c is the logarithmic standard deviation of the structural capacity.

The fragility curves represent the conditional probability that the response of the structure under different ground motions exceeds the capability parameter defined in a damage level, namely, structural failure probability P_f:

$$P_f = P(C/D \le 1) \tag{3}$$

According to Equation (2), both parameters are known to follow a lognormal distribution. Equation (3) for failure probability can be expressed as follows:

$$P_f = \Phi[\frac{(\ln(D/C)}{\sqrt{\beta_c^2 + \beta_d^2}})], \tag{4}$$

By substituting the fitting result of Equation (1) into Equation (4), the failure probability of the structure can be represented as

$$P_f = \Phi[\frac{(\ln(e^a(PGA)^b/C)}{\sqrt{\beta^2{}_c + \beta^2{}_d}})], \tag{5}$$

Where

e is the base of the natural logarithm, HAZUS99 [23] when the structural fragility curves take PGA as the independent variable, set to 0.5; here $\sqrt{\beta_c^2 + \beta_d^2} = 0.5$. $\Phi(\cdot)$ is the standard normal distribution function.

2.2. Seismic Hazard Analysis Method

The earthquake intensity of a zone in the next 50 years obeys the extremum Ⅲ type distribution in accordance with Gao's [24] results for his seismic risk analysis of 45 cities in North, Northwest, and Southwest China. The distribution function is as follows:

$$F(x) = \exp[-(\frac{\omega - x}{\omega - \varepsilon})^K] \tag{6}$$

The derivative of the distribution function is considered and the probability density function is obtained, which represents the probability density of the earthquake intensity occurring at a certain site in the next 50 years:

$$F(x) = \frac{K(\omega - x)^{K-1}}{(\omega - \varepsilon)^K} \exp[-(\frac{\omega - x}{\omega - \varepsilon})^K] \tag{7}$$

Where x represents the seismic intensity and is a discrete variable in the range 1–12;ω is the upper limit of intensity, which is 12 in this case, according to the current common seismic intensity division method in China; ε represents a "multi-value strength" earthquake, the seismic intensity with a probability of exceeding 63.2% in the next 50 years; K is the shape parameter, which is related to the basic design intensity.

According to Lv [25], the value of shape parameter K is presented in Table 3. The seismic probability density curve drawn by Equation (7) is depicted in Figure 2.

Table 3. Value of Shape Parameter K

Basic intensity	6	7	8
K	9.7932	8.3339	6.8713

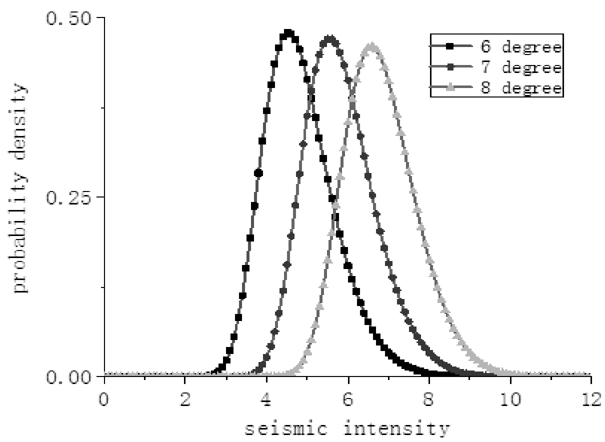

Figure 2. Probabilistic Density of Seismic Intensity in Different Seismic Fortification Zones

2.3. Seismic Risk Analysis Method

The structural seismic risk can be defined as the possibility of various damage degrees of the structure based on the site seismic hazard. The structural seismic risk is numerically equal to the convolution of the site hazard and seismic fragility. The calculation formula is as follows:

$$\mathbf{P} = \sum_{all,m_i} P(C \leq D|PGA = x_i)P(PGA = x_i), \tag{8}$$

In the formula, x_i is the intensity of the earthquake that may occur in the future. As the value of PGA is continuous, Equation (8) can be written as

$$\mathbf{P} = \int P(C \leq D|PGA = x_i)f(x_i)dx, \tag{9}$$

Where f(x_i) is the probability density function of PGA, which is consistent with the probability density function of seismic intensity.

2.4. Monte Carlo Method

The Monte Carlo method can generate a large number of random numbers in line with the probability density of earthquakes to simulate the earthquake intensity that the site may encounter in the future. Considering the accuracy of the integral calculation, the seismic intensity is taken as a continuous variable, and the Monte Carlo method is adopted to sample seismic events in accordance with Equation (7). If the sampling number is n, then the probability of each seismic event is 1/n. The larger the sampling number is, the closer the result is to the real value, and here we consider n=50000.

The seismic intensity obtained after sampling is converted into PGA, according to the formula proposed by Liu [26], as follows:

$$\mathbf{PGA} = \mathbf{10}^{(I \cdot \mathrm{lg}2 - 0.01)} \tag{10}$$

According to the law of large numbers, Equation (11) can be written as

$$\mathbf{P} = \frac{1}{n}\sum_{i=1}^{50000} P(C \leq D|PGA = x_i) \tag{11}$$

The risk probability of the structure exceeding all degrees of damage is

$$\mathbf{P} = \frac{1}{n}\sum_{i=1}^{50000} P(C \leq D|PGA = x_i) \tag{12}$$

Where j=1, 2, 3, 4, 5 represents the damage degrees, namely nearly intact, minor damage, moderate damage, serious damage, and collapse, respectively.

Similarly, the risk of structural damage at all degrees is as follows:

$$\mathbf{C}_j = \begin{Bmatrix} P_j - P_{j+1} & j \leq 4 \\ P_j & j \leq 5 \end{Bmatrix} \tag{13}$$

3. Seismic Risk Probability Assessment

3.1. Vulnerability Analysis Results

After the IDA analysis of the structural model, the fragility curves can be plotted according to the above calculation, as shown in Figures 3–5.

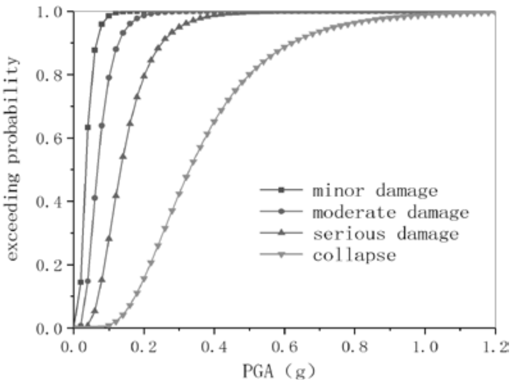

Figure 3. Fragility Curves of a 6-degree Fortification Frame Structure

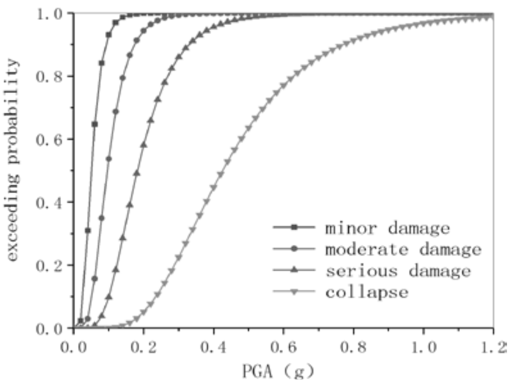

Figure 4. Fragility Curves of a 7-degree Fortification Frame Structure

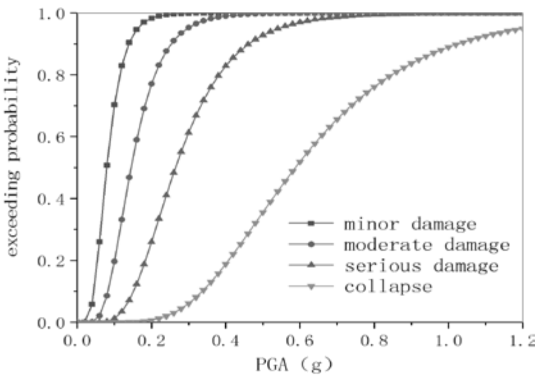

Figure 5. Fragility Curves of an 8-degree Fortification Frame Structure

As can be seen from Figures 2–4, the probability cumulative curves of various damage degrees exhibit an upward trend with the increase of PGA. The larger the PGA is, the more severe the structural damage is. For the probability cumulative curves of the same damage degree, the fragility curve of the 8-degree fortification structure exhibits the slowest rising trend. Under an action of the same seismic intensity, the probability of serious damage and collapse of the 8-degree fortification structure is lower. This indicates that the 8-degree fortification structure has better seismic resistance than the 6- and 7-degree fortification structures.

3.2. Seismic Risk Results

According to the above analysis model, the results of the seismic risk analysis for the next 50 years with different fortification intensity frameworks are calculated as presented in Tables 4–6.

Table 4. Risk Probability Assessment of 6-degree Fortification Frame Structure

Risk probability	Nearly intact	Minor damage	Moderate damage	Serious damage	Collapse
Exceeding probability	100%	29.04%	8.91%	1.92%	0.14%
Occurrence probability	70.96%	20.13%	6.99%	1.78%	0.14%

Table 5. Risk Probability Assessment of 7-degree Fortification Frame Structure

Risk probability	Nearly intact	Minor damage	Moderate damage	Serious damage	Collapse
Exceeding probability	100%	42.34%	16.09%	4.25%	0.43%
Occurrence probability	57.66%	26.25%	11.84%	3.82%	0.43%

Table 6. Risk Probability Assessment of 8-degree Fortification Frame Structure

Risk probability	Nearly intact	Minor damage	Moderate damage	Serious damage	Collapse
Exceeding probability	100%	55.20%	25.64%	8.28%	1.07%
Occurrence probability	44.80%	29.56%	17.36%	7.21%	1.07%

As can be seen from Tables 4–6, the risk occurrence probability of the structure having a damage degree of “nearly intact” and “minor damage” is relatively high at 91.09%, 83.91%, and 74.36%, respectively. The risk occurrence probability of a structure having a damage degree of “serious damage” and “collapse” is relatively low. Through the seismic risk occurrence probability comparison of the 6-, 7-, and 8-degree seismic fortification frameworks, it can be seen that the 8-degree fortification framework’s occurrence probabilities of “serious damage” and “collapse” are the largest, with values of 7.21% and 1.07%, respectively. The 7-degree fortification framework’s occurrence probabilities of “serious damage” and “collapse” are 3.28% and 0.43%, respectively. The 6-degree fortification framework’s occurrence probabilities of “serious damage” and “collapse” are the lowest, with values of 1.78% and 0.14%, respectively. The results of the comprehensive seismic fragility of structures also demonstrate that the seismic risk factors of the seismic damage are related to the seismic fortification area in addition to the seismic capability of the structures.

3.3. Seismic Risk Level Classification

Risk acceptability is a scale that measures whether a certain type of risk is acceptable or not; it is also the basis for formulating risk management countermeasures and schemes. Generally, the risk acceptability is subjective and is based on the public’s opinions. If the risk level of a building is “High”, it is considered to exceed that of public expectations, and effective measures should be taken to reduce the risk until it is at a level that is accepted by the public.

According to the risk probability of the “collapse” damage in the next 50 years, this study classifies the risk level into three levels, namely high risk, medium risk, and low risk. The risk levels are listed in Table 7.

Table 7. Risk Grade Classification

Risk level	Exceeding collapse damage probability (%)	Risk acceptability
High	[2,100)	Unacceptable risk
Medium	[1,2)	Nearly acceptable risk
Low	[0,1)	Acceptable risk

In urban planning, according to the principle of “priority first, then general, then serious, then light,” the countermeasures of seismic strengthening, reconstruction, or demolition of buildings must be formulated based on the principle of “gradual improvement in stages and batches combined with urban reconstruction.” For buildings with a low risk level, the construction risks can be ignored. Buildings with a medium risk level must weigh the costs and benefits of risk management measures. If increased investment does not contribute significantly to risk reduction, risks are allowed. Buildings with a high risk level must take certain measures to reduce risks, such as seismic reinforcement, seismic transformation, demolition, and reconstruction, until the risks are acceptable. According to Table 7, combined with the seismic risk assessment results of buildings from Tables 4–6, it can be seen that the risk probabilities of frame structures fortified in degrees 6, 7, and 8 exceeding “collapse damage” are 0.14%, 0.43%, and 1.07%, respectively. The risk level of frame structures fortified in degrees 6 and 7 are both “Low” and within the acceptable risk range. The risk level of the frame structure fortified in degree 8 is “Medium.” We recommend that further consideration should be given in the formulation of urban disaster prevention planning.

4. Conclusions

In this study, the IDA and Monte Carlo methods were used to systematically analyze the seismic risk of frame structures with different fortification intensities. The main conclusions of the effort in the realm of seismic risk assessment can be outlined as follows:

·Considering the seismic fragility and seismic risk of buildings, the risk level can be quantified and evaluated to reflect the potential seismic disaster risk of buildings in the future. Thus, this study can be used as a reference for earthquake disaster prevention planning and risk level classification in different cities.

·Through the seismic risk assessment of frame structures with different fortification intensities, the risk levels of structures with fortification intensities 6, 7, and 8 were preliminarily discussed, and it was found that the risk levels of structures with a fortification intensity of 8 were higher than those of structures with fortification intensities 6 and 7. Therefore, in urban disaster prevention planning, high-intensity zones need to pay additional attention to risk prevention.

·This study only considers a typical framework as an example. Owing to the lack of sample adequacy and representativeness and the different construction ages in cities, the evaluation results of this study are still limited. The uncertainties in the building model, seismic event, and cognition, and the influence of other factors on the risk need to be investigated in a future study. The first paragraph after a section or subsection heading should not be indented; subsequent paragraphs should be indented by 5 mm.

5. Acknowledgments

Authors wishing to acknowledge assistance or encouragement from colleagues, special work by technical staff or financial support from organizations should do so in an unnumbered Acknowledgments section immediately following the last numbered section of the paper.

6. Appendices

Technical detail that it is necessary to include, but that interrupts the flow of the article, may be consigned to an appendix. Any appendices should be included at the end of the main text of the paper, after the acknowledgments section (if any) but before the reference list. If there are two or more appendices they should be called appendix A, appendix B, etc. Numbered equations should be in the form (A.1), (A.2), etc, figures should appear as figure A1, figure B1, etc and tables as table A1, table B1, etc.

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