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Vulnerability-based seismic resilience and post-earthquake recovery assessment for substation systems

Xiao Liu [a], Siyuan Wu [a], Qiang Xie [a,*], Qiang Li [b]

[a] College of Civil Engineering, Tongji University, Shanghai 200092, China
[b] Dali Bureau, EHV Power Transmission Company of China Southern Power Grid Co., Ltd., Dali 671000, China

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ABSTRACT

The function of substation systems is significantly influenced by earthquakes. To assess the seismic resistance of substation systems and improve post-earthquake recovery efficiency, this study constructs a multi-module framework for seismic vulnerability assessment of substations. Based on the equipment functional status analysis module, a functional network model was established considering the structural function and electrical load of substation systems. The system functional state matrix was obtained through Monte Carlo simulation, and the seismic vulnerability was assessed from the aspects of electrical transmission reliability and the importance of power users. Subsequently, a substation functional index was established based on seismic vulnerability parameters. Post-earthquake functional recovery strategy analysis frameworks were constructed to quantitatively evaluate the recovery process. A stepped functional time-varying function was proposed through iterative analysis, thereby converting the probability parameters of functional status into seismic resilience deterministic indices. Through seismic resilience analysis of a typical 220 kV step-down substation, seismic vulnerability curves for both electrical transmission and power users were obtained. Furthermore, the seismic sensitive intervals of the substation and key equipment for post-earthquake recovery were clarified. Notably, the seismic resilience level and optimal recovery strategy of the typical 220 kV step-down substation were determined.

1. Introduction

In recent years, earthquake disasters have occurred frequently, causing severe damage to urban infrastructure [1,2]. In power systems, substations are vital components of lifeline infrastructure. The functional failure of substations can lead to direct or indirect economic losses [3,4]. This places higher demands on substations, requiring them not only to maintain essential functions during earthquakes but also to have the ability to rapidly recover to normal functionality levels after earthquakes. However, historical earthquake disasters and risk assessment studies reveal that substations suffer severe damage during earthquakes [5–8], resulting in significant economic losses owning to prolonged recovery. Moreover, because comprehensive earthquake early warning systems have not yet been established, it is challenging to provide precise warnings and implement proactive defense measures before an earthquake. Therefore, assessing the seismic resistance of substation systems and expediting post-earthquake recovery processes are the focal points of current research.

Seismic vulnerability is primarily used to measure the probability of exceeding a specified limit under seismic action. It is one of the main methods for assessing the seismic resistance of structures or engineering networks. In the context of substation systems, the United States Federal Emergency Management Agency [9] assessed the seismic damage status of substation systems qualitatively and categorized them into five types: no damage, slight damage, moderate damage, severe damage, and complete damage. Building upon this framework, scholars have conducted further research on the seismic vulnerability of substations using various methods. Hwang et al. [10] regarded substations as combinations of various equipment components, employing fault tree/event tree techniques to analyze the failure probability of substation systems. Li et al. [11] proposed a probability-based method for assessing the seismic reliability of substations. This method constructs a greatly simplified system model using state trees to calculate the failure probability of the entire system while explicitly considering the correlations between components. Liang et al. [12] introduced a system analysis method combining graph theory, fault trees, and success paths, utilizing Monte Carlo simulation to analyze the seismic vulnerability of substation systems at the system level. However, seismic vulnerability studies mainly

* Corresponding author.
E-mail address: qxie@tongji.edu.cn (Q. Xie).

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focus on measuring the seismic reliability of engineering networks. They cannot fully consider the residual functionality and recovery processes after an earthquake. Therefore, research on comprehensive assessment methods for seismic resistance based on seismic vulnerability faces significant challenges.

Ecologist Holling proposed the concept of resilience in 1973 [13], referring to the ability of a system to withstand, maintain, and restore its normal functioning after being subjected to external disturbances [14]. In the field of earthquake engineering, resilience research methods have gradually been applied to various types of infrastructure because resilience can comprehensively assess the seismic resistance throughout the entire process. Cimellaro et al. [15,16] presented a comprehensive model to quantify the disaster resilience of systems. They took a healthcare system as an example to assess resilience from multiple perspectives. Subsequently, Cimellaro et al. [17] argued that resilience is influenced by multiple factors and proposed the PEOPLES framework to evaluate the resilience of community systems in seven dimensions. Hosseini et al. [18] summarized the resilience of various engineering systems in three aspects: qualitative, semi-quantitative, and quantitative. They emphasized that resistance and recovery are the main focus of resilience research. The aforementioned studies emphasize the research focus of resilience assessment and summarize existing research methods. They provide important references for the resilience assessment of engineering networks. Forcellini [19] used seismic resilience to measure the seismic capacity of several isolated bridge configurations. They assessed the efficiency of geotechnical seismic isolation against traditional base isolation. Argyroudis et al. [20] proposed a resilience assessment framework based on well-informed resilience indices to evaluate the seismic capacity of representative bridges. They used two methods to quantify and assess the bridge recovery process and economic losses. In addition, Oboudi et al. [21] proposed a two-stage seismic resilience enhancement method to evaluate distribution systems, and optimized resilience enhancement measures using a particle swarm optimization algorithm. Rahiminejad [22] proposed a resilience-based power network recovery framework. They quantitatively assessed the resilience levels of different response strategies at the power and network levels after network attacks. In terms of substation systems, Li et al. [23] developed a probability-based method for assessing the seismic resilience of substations and quantitatively analyzed post-earthquake repair strategies for substations. Liu et al. [24] conducted research on seismic retrofitting strategies for substation systems based on resilience, and identified key equipment to enhance the seismic robustness of substation systems. Therefore, research on the seismic resilience of substation systems mainly focuses on resistance and post-earthquake recovery. It is an important research issue to accelerate post-earthquake recovery efficiency and reduce recovery time to improve seismic resilience.

Currently, many scholars define and classify the seismic vulnerability and seismic resilience of engineering networks based on different dimensions and attributes. However, knowledge gaps still exist. 1) The seismic vulnerability analysis of power systems mainly focuses on equipment seismic resistance. Therefore, it is urgent to build a seismic vulnerability analysis framework applicable to the network level of power systems based on existing studies. 2) The seismic resilience assessment of substations lacks detailed research. This mainly includes the system's functional state, the functional recovery process, and resource constraints. In addition, external factors such as power users in the surrounding area and engineering requirements need to be considered. Therefore, it is necessary to build a seismic resilience assessment framework that combines the structural and electrical functions and recovery characteristics of substations. 3) A seismic resilience-based post-earthquake recovery analysis framework has yet to be established. In addition, the regularity of post-earthquake functional recovery and the correlation of equipment recovery in substations are insufficiently studied. Thus, key repair equipment and post-earthquake repair sequences in substation systems have not been identified. 4) Current research mainly focuses on the internal aspects of substation systems. It is essential for studying substation system functionality and recovery processes, considering the importance of power users within the regional power grid. Therefore, there is still a vital need to assess the seismic resilience and post-earthquake recovery processes of substation systems.

To address the aforementioned challenges, this study constructs a substation's network functional model, combining functional characteristics and equipment load capacity. It employs a Monte Carlo algorithm to achieve seismic simulation of substation systems. Subsequently, post-earthquake restoration strategies were employed to establish a seismic resilience assessment method. Through the seismic resilience analysis of a typical 220 kV step-down substation, seismic vulnerability curves and post-earthquake restoration strategies were obtained. It demonstrates the applicability of the framework and the effectiveness of the strategies. The main contributions of this study can be summarized as follows:

1) We establish a multi-module seismic vulnerability assessment framework for substations. Compared to [10,11], this framework incorporates the structural and electrical functional characteristics of substation systems. In addition, the seismic vulnerability probabilistic assessment was achieved considering both power users and system-level aspects, thereby addressing the gap in multi-level engineering network seismic vulnerability assessments [9,12].
2) We propose a quantified assessment method for seismic resilience. This method transforms the conditional probabilities of functional states into deterministic parameters, addressing the deterministic analysis of time-varying functions [23]. In addition, the probabilistic seismic performance is upscaled from the local to the global network level. A comprehensive quantitative assessment of the system's seismic resilience is achieved [11,18].
3) We introduce functional restoration strategy frameworks for substation systems. Post-earthquake restoration paths were proposed from three dimensions. The framework clarifies the impact of the importance of power users on functional recovery, thereby enhancing the applicability of recovery strategies under different engineering requirements [23]. The approach addresses the differential assessment of the functional recovery process [21,24].
4) We identify important units and key equipment of the typical 220 kV substation. The interdependencies of equipment repair are clarified, and the optimal restoration strategy for the substation system is determined. The results provide valuable references for practical engineering applications.

2. Seismic vulnerability assessment framework

To assess the seismic vulnerability of substation systems, this section adopts a multi-module seismic vulnerability assessment framework from equipment to system. The framework is mainly divided into three parts, as shown in Fig. 1.

Firstly, an operating status analysis module was established at the equipment level. Based on the seismic vulnerability curves of equipment and the determined seismic intensity, equipment reliability analysis was conducted to clarify the conditional probabilities of electrical equipment operational states. Then, a directed acyclic graph for substations was built based on Simulink modules, and a functional network model was constructed at the system level. Functional state assessments were performed separately from the structure functional module and the power load transmission module. Finally, a seismic vulnerability analysis module for substations was established. By setting criteria for system functional states, the functional state matrix for substation systems was determined, thus obtaining parameters for the system's functional failure probability. The seismic vulnerability curves were fitted and determined.

The seismic vulnerability assessment framework proposed combines

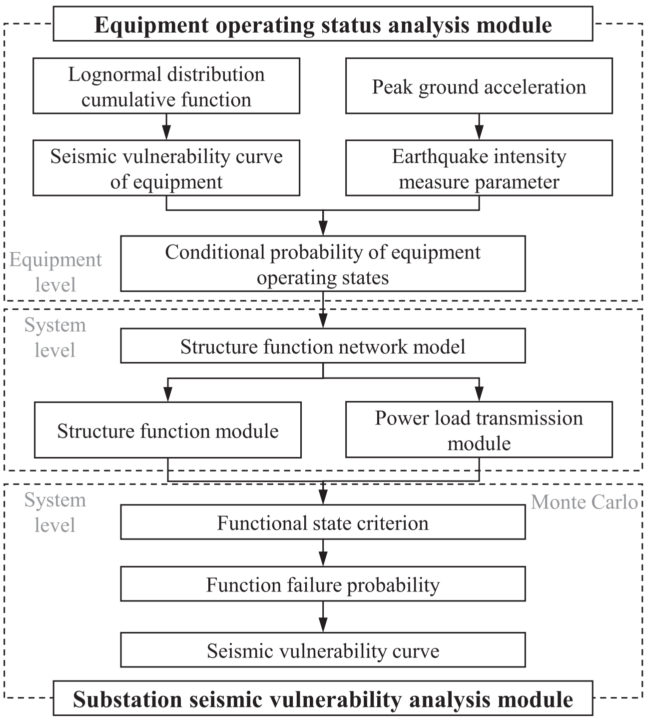


Fig. 1. A multi-module seismic vulnerability assessment framework.

the functional characteristics of substation systems with the importance of electricity users. This satisfies vulnerability analysis from equipment to system, and to community. In addition, the framework obtains the conditional probability parameters of the functional states, thereby laying the foundation for subsequent seismic resilience assessments.

2.1. Substation introduction

Substation systems are an essential infrastructure of the power grid system. They are mainly divided into step-up and step-down substations based on their functional differences in electricity transmission networks. The two types of substations are located at opposite ends of the long-distance electricity transmission network. Therefore, substation systems serve as a crucial hub connecting power users and transmission systems. Within a substation system, a large number of different types of equipment are interconnected via busbars to form the electricity transmission network. Based on the functions of different areas within substation systems, substations can be divided into four functional units: line-in units, busbar units, transformer units, and line-out units. Line-in and line-out units are responsible for transmitting electricity into or out of a substation system, busbar units are responsible for transmitting electricity to different functional zones, and transformer units are responsible for changing voltage levels to meet the electricity transmission needs of power systems. Therefore, seismic activity can impact the functional status of electrical equipment, thereby affecting the overall level of electricity transmission within the substation system.

2.2. Equipment operating status analysis module

Earthquakes significantly affect the functional status of electrical equipment [25], thereby directly impacting the functional level of substation systems. Therefore, this section conducts an analysis of the functional states of equipment. The seismic fragility analysis focuses on identifying the earthquake response and the weak parts of the structures [26], and the seismic vulnerability analysis emphasizes the ease of functional loss and the failure probability under earthquakes [27,28]. This study focuses on the impact of seismic intensity on the functional state of equipment. Therefore, seismic vulnerability curves can determine the probability of equipment functional failure at specific seismic intensities, thus laying the foundation for network vulnerability assessment.

The seismic performance study of equipment can utilize various earthquake intensity measures (IM). However, owing to the structural differences between equipment and engineering networks, the IM suitable for equipment may not apply to substation systems. Considering the widespread application and reliability of IM [23,29–31], this study uses Peak Ground Acceleration (PGA) as the IM. The probability of identified structural responses exceeding a specific IM typically follows a lognormal distribution. According to the literature, the seismic vulnerability curves for various types of equipment follow a cumulative function of log-normal distribution with a median of μ and a logarithmic standard deviation of β, as shown in Eq. (1) [12,32,33].

$$P(\mathrm{IM}|\mathrm{PGA} = x) = \Phi\left(\frac{\ln(x/\mu)}{\beta}\right) \tag{1}$$

To quantitatively assess the operational status of electrical equipment, a device operating status analysis module was proposed, as illustrated in Fig. 2. Structural models were built based on the category and structure of the equipment. Subsequently, N seismic simulations were conducted. Comparing the resulting data with functional failure criteria, the number of equipment functionality loss F is obtained, thereby clarifying the probability of functional failure under specific seismic intensities. Then, the seismic intensity was adjusted, and the data yielded seismic vulnerability curves that were fitted for various types of equipment, thus completing the functional model simulation analysis. Owing to the large number of devices in a substation system, a considerable amount of result data and computation time were required. Therefore, Monte Carlo methods are employed for numerical analysis in this study. It is assumed that electrical equipment exists in two states: normal operation and functional failure, represented by “1” and “0”, respectively. The equipment operating status for a particular sampling instance was determined by randomly sampling x from 0 to 1 and comparing it with P_i.

2.3. Functional network model

2.3.1. Structure function module

This section examines the functionality of the substation system from the perspective of substation structural connectivity, building upon the analysis of electrical equipment functional states. A functional network model of the substation system was constructed using Simulink units. The model was divided into four parts: the input module, the execution module, the logic module, and the output module. Functional states enter the network system from the input module, the execution module assesses node operational states, the logic module determines network connectivity relationships, and the remaining functional states are outputted in the output module. To align with the structural and functional characteristics of the substation, the direction of the arrows indicated the direction of electricity transmission. Nodes in the operation module represent electrical equipment within the substation, and the logic module represents the functional connectivity of equipment in the substation. In the logic module, “AND” represents a series connection. The failure of one set of equipment will result in the failure of the entire line. This means the output is “1” only when all input terminals are “1”. “OR” represents a parallel connection. The failure of one set of equipment does not affect the functional state of adjacent connection lines. In this case, the output becomes “1” if any input terminal is “1”. An example is depicted in Fig. 3. In this example, device A and device C are in normal operational states, while device B and device D are in a state of functional failure. All input terminals maintain normal input electricity. However, owing to the functional failure of some devices, their corresponding output lines are set to 0. Consequently, based on the logic

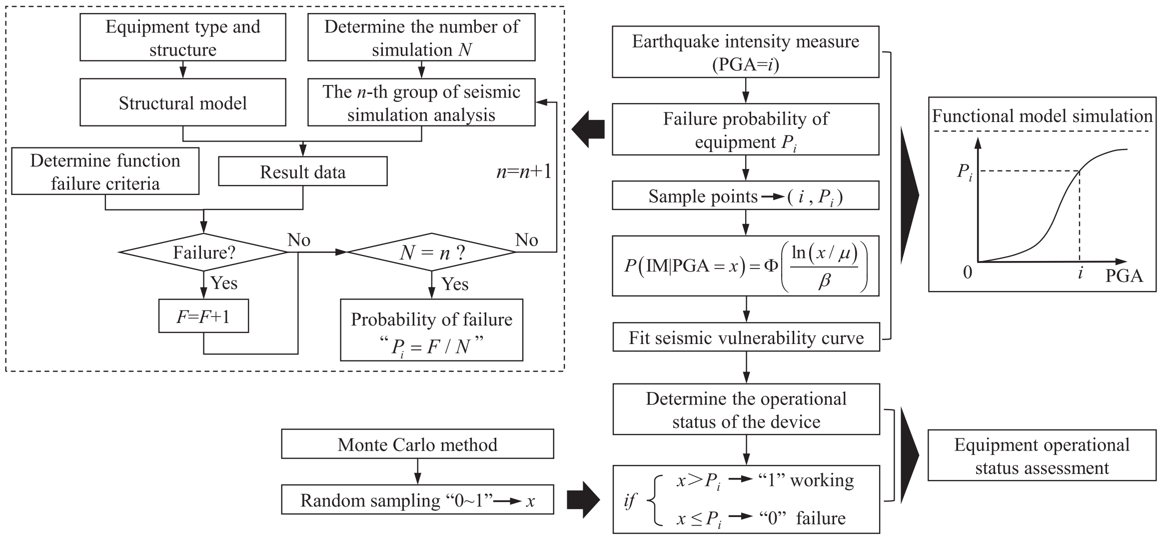


Fig. 2. Equipment operating status analysis module.

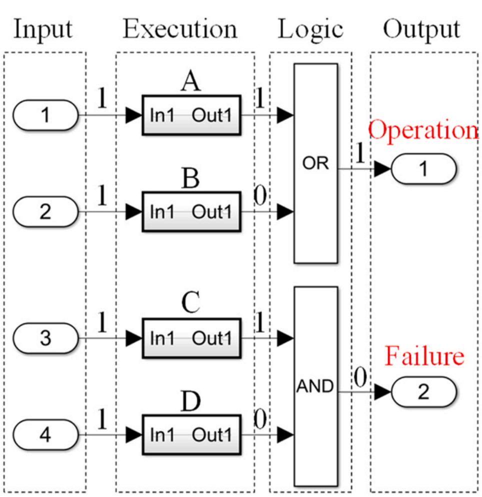


Fig. 3. An example of a structural network functional model.

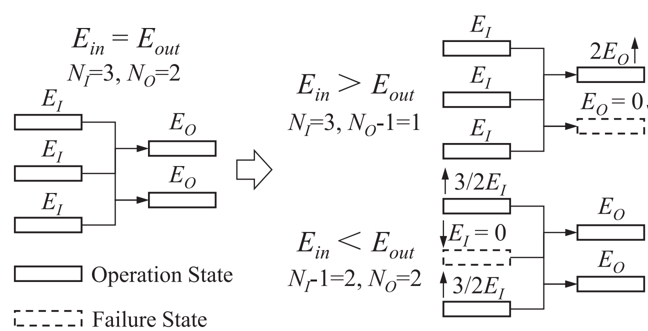


Fig. 4. An example of power load transmission.

module's assessment, the functional states of the output terminals in this example are determined.

2.3.2. Power load transmission module

Some equipment may lose functionality after an earthquake. This will affect the upper limit of the power load for each functional zone. Substations can achieve a rebalanced state of power supply and demand by adjusting the power load levels of other equipment. Therefore, the operational state and power load capacity of equipment are correlated with the functional state of substation systems. This paper proposes that the power load transmission in substation systems needs to adhere to the *N*-1 principle. This means that *N* identical sets of equipment or units are connected in a substation. When any one set of equipment or units loses function and the remaining *N*-1 sets of identical equipment or units can continue to function adequately, the substation can still meet normal operation. Secondly, the operating load of equipment is not at full capacity; it needs to be adjusted based on factors such as equipment importance and quantity. In addition, this approach can enhance the power load redundancy of substation systems, ensuring the supply of electrical power during emergency events. Therefore, it is assumed that the operating load of equipment can be doubled after an earthquake, thereby reducing the probability of functional loss in substation systems. An example of this is depicted in Fig. 4.

Herein, N_I represents the number of input ends, and N_O represents the number of output ends. The power load for each device operating normally at the input end is represented as E_I. The power load for each device operating normally at the output end is represented as E_O. The total power at the input end is represented as E_{in}, and at the output end as E_{out}, as specified in Eq. (2). When one set of output devices fails but the input devices remain operational, the power load level of the remaining N_O-1 output devices is increased to maintain the balance of power supply and demand. When one set of input devices fails, reducing the transmission capacity of the input end, the power load level of the remaining N_I-1 input devices is increased to meet the output power demand. This entire process adheres to the *N*-1 principle of power systems, thereby establishing a new balance between power supply and demand.

$$E_{in} = 3E_I = 2E_O = E_{out} \tag{2}$$

2.4. Substation seismic vulnerability analysis module

Substation systems serve as a critical hub connecting power users and regional power grids. Therefore, seismic vulnerability analysis should consider both the system's electricity transmission and the needs of power users. The system-based seismic vulnerability curve (*C*1) refers to using the post-earthquake power transmission capacity of substation systems as the criterion for functional state assessment. It conducts seismic vulnerability analysis based on the functional zones of substation systems. This effectively reflects their functional connectivity and status, thereby assessing their seismic performance. The power user-based seismic vulnerability curve (*C*2) refers to using the ability to supply electrical energy to power users as the criterion for functional state assessment. It conducts seismic vulnerability analysis based on the importance of power users. This effectively reflects the dependency of different important levels of power users on a substation system, thereby assessing the importance of a substation system in the transmission of power within regional power grids.

Line-out units are crucial functional zones in substations. They represent power transmission to power users. Therefore, this study utilizes the operating status of line-out units to assess the functional state of substation systems. To determine the functional failure probability of substation systems under different conditions, Monte Carlo simulation is employed. To obtain the post-earthquake operational status of line-out units in a substation system, a line-out unit functional state matrix **F** was established to represent the operational status of the line-out units during each Monte Carlo sampling. In addition, a unit electrical energy transmission load matrix **E** was proposed to represent the electrical energy transmission capacity of each functional unit during each Monte Carlo sampling, as shown in Eqs. (3) and (4).

$$\mathrm{F} = \begin{bmatrix} F_1^1 & F_1^2 & \cdots & F_1^L \\ F_2^1 & F_2^2 & \cdots & F_2^L \\ \vdots & \vdots & \ddots & \vdots \\ F_N^1 & F_N^2 & \cdots & F_N^L \end{bmatrix} \tag{3}$$

$$E = \begin{bmatrix} E_1^1 & E_1^2 & \cdots & E_1^U \\ E_2^1 & E_2^2 & \cdots & E_2^U \\ \vdots & \vdots & \ddots & \vdots \\ E_N^1 & E_N^2 & \cdots & E_N^U \end{bmatrix} \tag{4}$$

Where L represents the number of line-out units in the substation system, N represents the number of Monte Carlo samplings, F_N^L represents the operating status of the L-th group of line-out units during the N-th sampling, E_N^U represents the power transmission capacity of the U-th group of functional units during the N-th sampling, and U represents the number of categories of functional units in a substation system. **F** and **E** represent the seismic simulation results of the structure functional module and the power load transmission capacity module, respectively. The result data was processed to obtain the maximum allowable number of operating line-out units L_{Fn} and L_{En} in the substation system, as shown in Eqs. (5) and (6).

$$L_{Fn} = \sum_{l=1}^{L} F_n^l \tag{5}$$

$$L_{En} = \frac{\min\left\{E_n^1, E_n^2, \dots, E_n^U\right\}}{E_{out}} \tag{6}$$

Herein, $\min\{E_n^1, E_n^2, \dots, E_n^U\}$ represents the minimum value of power load transmission capacity of substation systems during the n-th sampling, and E_{out} represents the upper limit of power load for a group of line-out units in substation systems. Considering the structure functional module and the power load transmission module, the functional status L_{Tn} and the functional state matrix **L** of the substation system's functional network model were obtained, as shown specifically in Eqs. (7) and (8).

$$L_{Tn} = \min\left\{L_{Fn}, L_{En}\right\} \tag{7}$$

$$\mathrm{L} = \begin{bmatrix} L_{F1} & L_{E1} & L_{T1} \\ L_{F2} & L_{E2} & L_{T2} \\ \vdots & \vdots & \vdots \\ L_{FN} & L_{EN} & L_{TN} \end{bmatrix} \tag{8}$$

To obtain the seismic vulnerability curve of substation systems, a seismic vulnerability analysis module for substation systems was constructed, as illustrated in Fig. 5. Targeting both internal and external aspects of substation systems, seismic vulnerability curves based on system functional zoning and the importance of power users were proposed and analyzed through seismic simulation. By conducting N Monte Carlo samplings on the functional network model, a functional state matrix was obtained. The functional state matrix includes the functional state of substations after each sampling. Then, the conditional probability $P_{(i,\ q,\ j)}$ of the system's functional state when PGA $= j$ can be obtained. Subsequently, the functional state criteria for the substation system are defined. The states below this standard are considered failure states. The functional failure probability of substation systems is obtained by aggregating the functional conditional probabilities. Through multiple cycles of analysis with varying earthquake intensities and functional state criteria, the functional failure probabilities of substations under different earthquake intensities and functional state criteria are determined. A log-normal distribution cumulative function is used to fit the seismic vulnerability curves of substations for each functional state criterion.

3. Seismic resilience assessment method

The seismic resilience of substation systems is an important parameter for comprehensively assessing the system's ability throughout the seismic process. Therefore, based on the seismic vulnerability curves of substations, a system function index was established to quickly evaluate the residual functionality of substations after an earthquake. Subsequently, post-earthquake restoration strategies were proposed, and a stepped functional recovery function was constructed based on the restoration path, thereby quantifying the post-earthquake functional recovery process. By combining the functional time-varying curves with resilience characteristics, a seismic resilience index was established to achieve a quantitative assessment of system resilience.

3.1. System function index

It is crucial to determine the remaining functional status of substation systems after an earthquake. This reflects the robustness of its seismic resilience, i.e., the system's ability to resist seismic effects. The failure probability for different functional states was determined based on the seismic vulnerability curves of substation systems. A substation system's functional index K was established to assess the functional status of substation systems under different seismic intensities, as shown in Eq. (9).

$$K = \frac{\sum_{q=1}^{Q} L_q \cdot p_{L_q}}{N} \tag{9}$$

Where Q represents the number of system functional state criteria. L_q represents the number of operable line-out units required for the q-th system functional state criterion, p_{Lq} represents the probability of obtaining L_q line-out units after Monte Carlo simulation, and N represents the total number of Monte Carlo samples. A higher value of K indicates that the functional status of a substation system is more intact.

3.2. System recovery process

The speed of functional recovery directly determines the substation system's post-earthquake recovery capability. It reflects the rapidity of seismic resilience. However, owing to the multitude of equipment types and complex structural forms in substations, it is challenging to recover all damages in a short time. In addition, seismic events can lead to traffic congestion and secondary natural disasters, greatly impacting the allocation of manpower, resources, and the efficiency of repair efforts. Therefore, post-earthquake recovery strategies become crucial after seismic events, serving as the primary means to reduce economic losses.

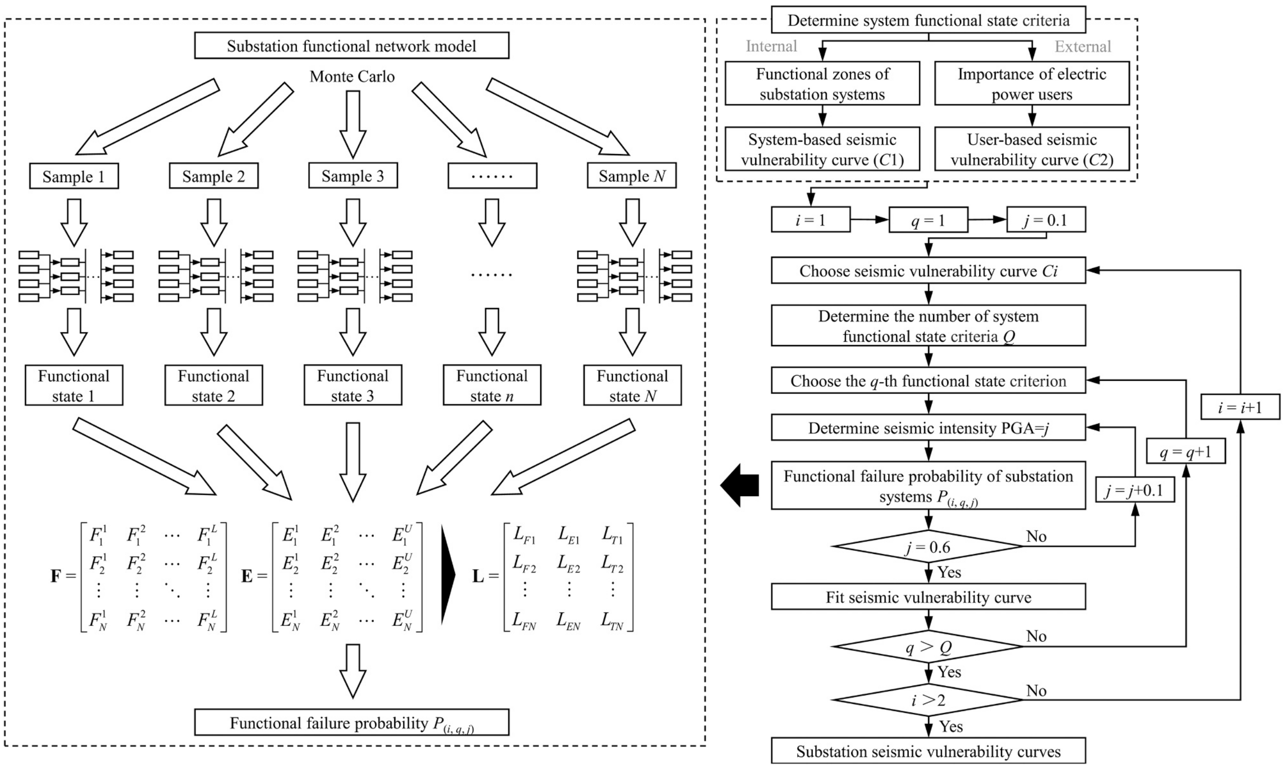


Fig. 5. Substation seismic vulnerability analysis module.

Hence, it is essential to identify the importance of equipment in the post-earthquake recovery from three aspects: equipment types, functional zones, and power users. These three aspects are proposed based on the experience of repair experts and the engineering needs of substations, thus aligning with the post-earthquake repair measures and functional restoration characteristics in actual engineering practice. The equipment-level recovery strategy (S_E) prioritizes the recovery of equipment categories with higher repair efficiency in the substation. The zone-level recovery strategy (S_Z) is prioritized based on the recovery efficiency of various functional zones in a substation. Lastly, the user-level recovery strategy (S_U) prioritizes the recovery of all electrical equipment that supplies power to important users, ensuring a normal power supply to these critical users.

Through communication with maintenance personnel from the power company, we found that the main factors influencing equipment recovery time include the repair experience of maintenance teams, the size and type of equipment, and the lifting environment. Therefore, the recovery time for various types of equipment is uncertain. However, it generally follows a normal distribution function. Consequently, it is assumed that the functional recovery time for each type of equipment follows a normal distribution in subsequent post-earthquake functional recovery analyses. The probability density function $f(T_e)$ for the recovery time of type e equipment is shown in Eq. (10), where θ represents the mean and σ represents the standard deviation.

$$f(T_e) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{T_e-\theta}{\sigma}\right)^2} \tag{10}$$

To establish an analysis method for recovery strategies at the equipment category and functional zone levels, Monte Carlo sampling was employed. Repair efficiency P_e for the equipment-level recovery strategy (S_E) and recovery efficiency P_u for the functional-level recovery strategy (S_Z) were proposed to measure the post-earthquake recovery processes at different levels, as shown in Eqs. (11) and (12), respectively.

$$P_E = \frac{(K_{ae} - K_{be})\cdot I}{\sum_{i=1}^{I} N_{ei} T_{ei}} \tag{11}$$

$$P_Z = \frac{(K_{az} - K_{bz})\cdot I}{\sum_{i=1}^{I} N_{zi} T_{zi}} \tag{12}$$

Where K_{ae} and K_{az} represent the substation functional level after the recovery of the e-th type of equipment and the z-th type of functional zone, respectively; K_{be} and K_{bz} represent the substation functional level before the recovery of the e-th type of equipment and the z-th type of functional zone, respectively; I represents the total number of Monte Carlo samples; N_{ei} and N_{zi} represent the number of functional losses for the e-th type of equipment and the z-th type of functional zone in the substation during the i-th Monte Carlo sample, respectively; T_{ei} and T_{zi} represent the post-earthquake recovery time for a group of e-th type of equipment and the z-th type of functional zone during the i-th sample, respectively.

By identifying the equipment categories or functional zones within the substation, the number of recovery steps required can be determined. After determining the peak ground acceleration (PGA), Monte Carlo simulation was applied to obtain the recovery efficiency for various equipment types or functional zones. The equipment or functional zone with the highest recovery efficiency is prioritized for repair. Subsequently, an iterative simulation is conducted based on the recovery of the first category of equipment, or functional zone. This process is repeated until a final recovery strategy is obtained for the equipment category and functional zone levels. The specific framework for the recovery strategy analysis is shown in Fig. 6.

Governments, hospitals, militaries, and other critical electricity users have significantly higher electricity demand importance compared to commercial and residential users. Therefore, priority should be given to ensuring the electricity supply for critical power users in the event of emergencies. Based on the user-level recovery strategy (S_U), electrical

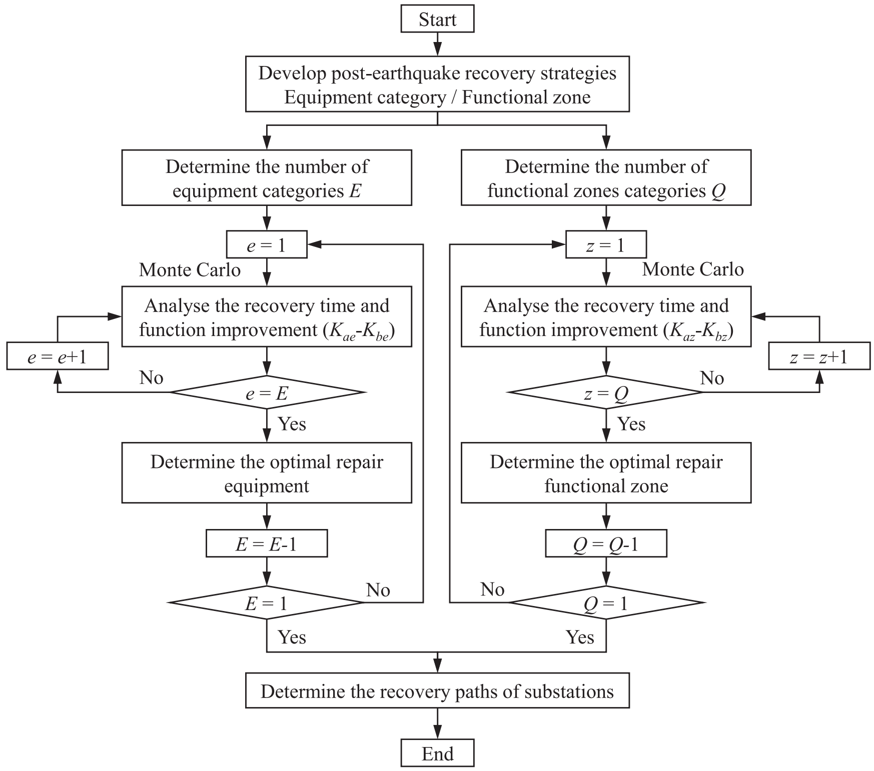


Fig. 6. Recovery strategy analysis framework of S_E and S_Z.

equipment supplying critical users is prioritized for repair according to its importance. Each group of restored line-out units is set as one recovery step to determine the number of recovery steps. Subsequently, the quantity and timing of equipment repairs based on their impact on electricity users need to be determined. Ultimately, the post-earthquake recovery process was determined to minimize the impact of power outages on critical power users in the region. The specific framework for the recovery strategy analysis is shown in Fig. 7.

3.3. System recovery and resilience

Upon establishing recovery strategies, quantitative research on the post-earthquake functional recovery process is essential. A time-varying function $K(t)$ is defined to characterize the process of functional changes over time in the substation system before and after an earthquake. Here, it is assumed that the earthquake occurs at time t_0. To formulate decision-making strategies, an assessment of the damage to the substation system's equipment is necessary. Therefore, t_a is defined as the time when post-earthquake decisions are finalized, and t_r is defined as the time when post-earthquake functionality is fully restored. The expression for the time-varying function $K(t)$ for substation functionality is given by Eq. (13).

$$\begin{array}{ll} K(t) = K_r & t_0 \leq t \leq t_a \\ K(t) = K_r + \sum_{i=1}^{q} \Delta K_i(t) & t_a < t < t_r \end{array} \tag{13}$$

Where K_r represents the residual functional level of substation systems after an earthquake, and $\Delta K_i(t)$ represents the increase in the substation functional level owing to the i-th recovery step after an earthquake. $\sum_{i=1}^{q} \Delta K_i(t)$ represents the total increase in the substation functional level after the q-th recovery step following an earthquake. Owing to the short duration of earthquakes compared to the time required for functional recovery after an earthquake, it is assumed that the earthquake occurs instantaneously. Through discussions with repair staff from power system operation and maintenance units, we found that the decision-making time varies depending on earthquake intensity and damage severity. However, to expedite repairs and restore power supplies, the decision-making time is generally less than two hours. Therefore, we assume the decision-making time is two hours in subsequent case assessments. In addition, if partial line-out units restore power supply after some equipment is repaired in the substation, it is considered that the substation system has partially recovered its functionality. Therefore, the functional time-varying curve of the substation system can be ideally represented as a stepped function, as illustrated in Fig. 8. The resource conditions during the post-earthquake recovery process will be discussed in the subsequent case study.

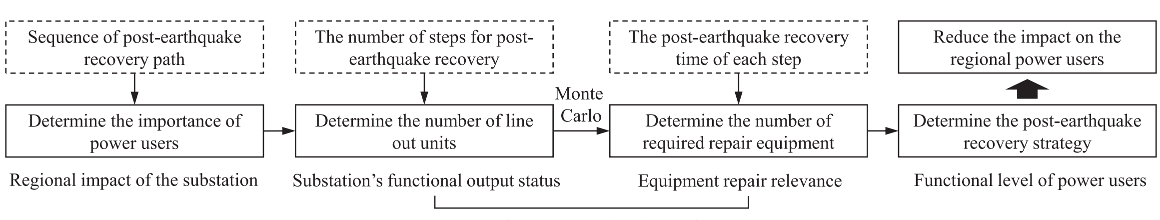


Fig. 7. Recovery strategy analysis framework of S_U.

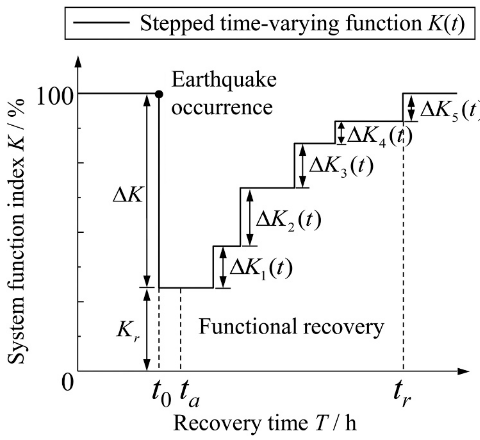


Fig. 8. Stepped functional time-varying curve.

The functional time-varying curve of the substation system can effectively reflect the post-earthquake functional loss and recovery process. Therefore, to quantitatively assess the seismic resilience of a substation system, many researchers have combined the time-varying functional curves of substation systems with resilience characteristics [34–36]. Based on the parameters of functional recovery curves, they have proposed various resilience quantification metrics. Following the above research, the integral of post-earthquake functional loss (robustness) and recovery time (rapidity) is taken as the seismic resilience index. It is used to measure the overall seismic resistance capability of a substation system, as shown in Eq. (14).

$$R = \int_{t_0}^{t_r} (100 - K(t))dt \tag{14}$$

The larger the seismic resilience index R, the greater the post-earthquake functional loss and recovery time of a substation system, indicating weaker seismic resistance of the substation. Conversely, a lower seismic resilience index indicates stronger seismic resistance in the substation.

3.4. Seismic resilience analysis process

Based on the uncertainty of the substation system's seismic vulnerability curves, a quantitative seismic resilience assessment process for substation systems was proposed, as depicted in Fig. 9.

First, it is necessary to convert the failure probability of substation systems into a deterministic assessment of the functional state under specific earthquake intensities. The seismic vulnerability curves of equipment show that the functional state of substation systems is uncertain. The differences in the functional state criteria directly affect the assessment of the system's functional failure probability. Therefore, this paper established a substation functional index K to conduct a deterministic analysis of the system's functional states. The deterministic functional assessment is performed based on the seismic vulnerability curves under Q sets of substation functional state criteria.

Subsequently, a diversity analysis of the post-earthquake functional recovery process of the substation system is conducted based on deterministic functional state parameters. Deterministic functional state parameters aid in quantitatively assessing the recovery process of functionality after an earthquake. However, post-earthquake functional recovery paths are diverse in substation systems. Through iterative simulation of M sets of recovery paths, the differences in various recovery processes and the importance of different types of equipment are clarified.

Finally, the seismic resilience level of the substation system is quantitatively evaluated based on the optimal recovery process. The optimal solution for the M sets of functional recovery processes is identified by analyzing the seismic resilience index. In addition, the probabilistic seismic performance is upscaled from the local to the global scale based on the functional network model and Monte Carlo algorithms. This quantitatively assesses the overall seismic resilience of substation systems and provides an important reference for actual engineering networks.

4. Case study

To validate the applicability and effectiveness of the seismic vulnerability and seismic resilience assessment methods in this study, a typical 220 kV step-down substation is analyzed as a case study. The general layout of this substation system is shown in Fig. 10(a). The substation system is divided into five functional zones according to their functionalities, namely the line-in units, high-voltage busbar units, transformer units, low-voltage busbar units, and line-out units. Each functional zone is interconnected by equipment through busbars. The cross-sectional views of the line-in and line-out units are shown in Fig. 10(b) and (c), respectively. They both consist of disconnecting switches (DS), current transformers (CT), and circuit breakers (CB) of different voltage levels. Busbar units consist of numerous pillar insulators (PI). In contrast, the composition of transformer units is more complex, including three sets of transformer equipment to achieve voltage conversion and distribution. In addition, overhead transmission lines are supported and transmitted by portal frames. However, based on past seismic events and relevant literature [29,30], we found that portal frames have high seismic reliability. Therefore, this study considers that portal frames will not affect the functionality of the substation system.

The step-down substation supplies power to electricity users directly. According to the requirements of reliability of power supply and the degree of harm caused by power interruption, power users are mainly classified as special-level, first-level, and second-level important power users [37]. The substation system has a total of 12 output terminals, assuming that four line-out units supply power to special-level

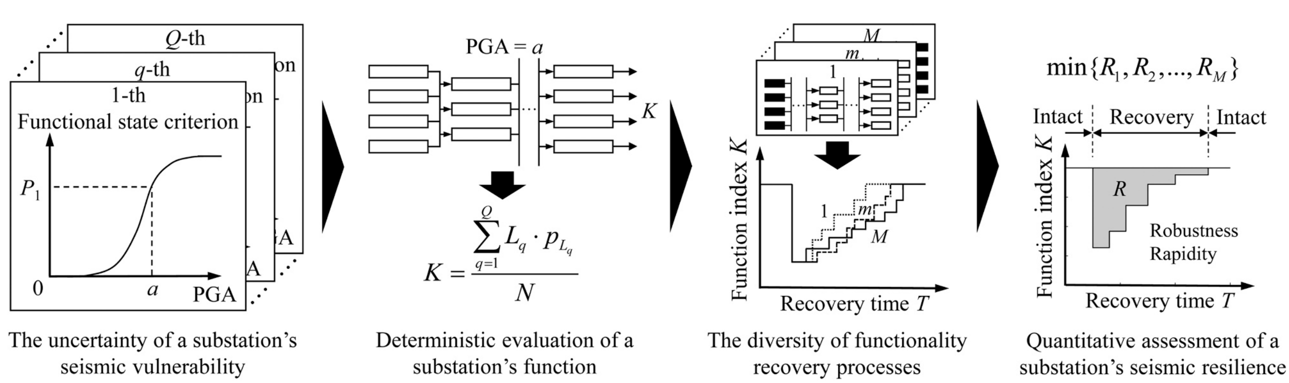


Fig. 9. A quantitative seismic resilience assessment process for substation systems.

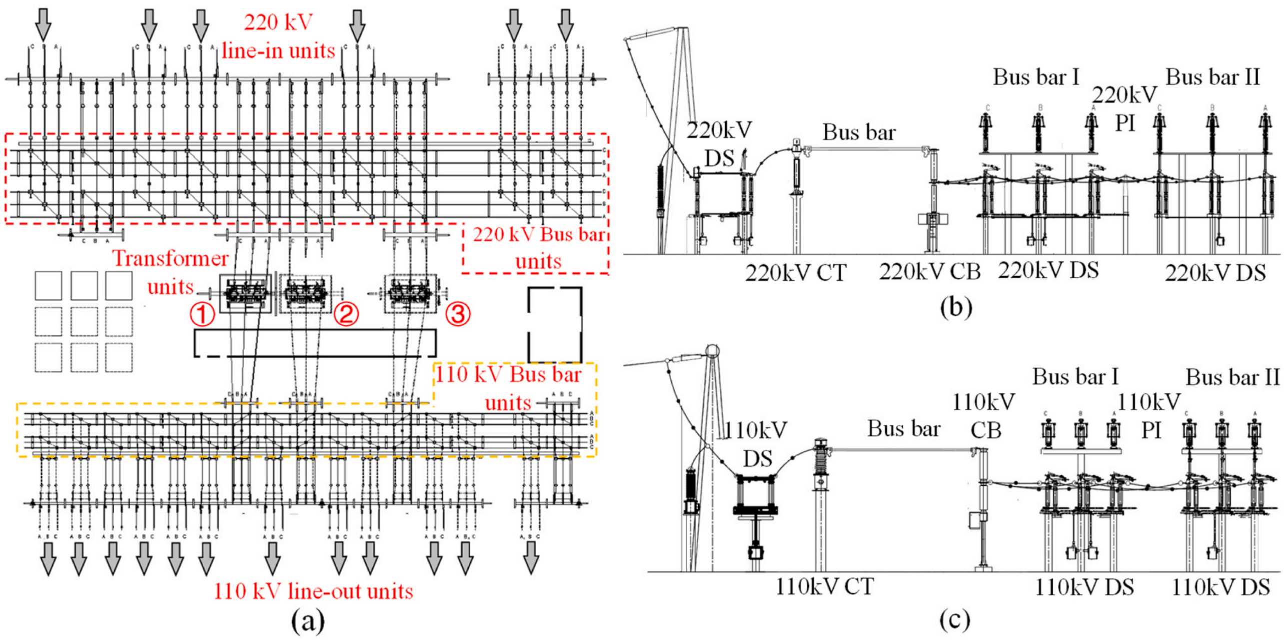


Fig. 10. A typical 220 kV step-down substation, (a) general layout, and (b) cross-sectional views of the line-in units and line-out units.

important users, four line-out units supply power to first-level important users, and four line-out units supply power to second-level important users. When an earthquake causes damage to some electrical equipment in the substation, the electrical load may exceed the specified requirements. Power will be cut off sequentially according to the importance level of power users, starting from the least important. For example, when line-out units supplying power to important power users fail, the line-out units supplying power to non-important users will be redirected to important users to ensure their power requirements.

According to the equipment connection shown in Fig. 10, the typical 220 kV step-down substation includes five types of electrical equipment and two voltage levels: disconnecting switches (220 kV/110 kV DS), current transformers (220 kV/110 kV CT), circuit breakers (220 kV/110 kV CB), pillar insulators (220 kV/110 kV PI), and transformers (TF). To obtain seismic vulnerability curves for each type of equipment, the median values and logarithmic standard deviations of seismic vulnerability curves were obtained from the equipment database referenced in the Pacific Earthquake Engineering Research Center (PEER) [29,38], as shown in Table 1. In addition, Section 3.2 emphasizes the functional recovery characteristics of equipment. The parameters for functional recovery time for each type of equipment were obtained through communication with equipment maintenance and repair personnel, as shown in Table 1.

The post-earthquake functional recovery process of a substation system is quite complex, including factors such as: post-earthquake repair resources (quantity of spare parts and facilities), repair teams, road traffic conditions, etc. These factors will contribute to the delay or disruption of the recovery process. However, these uncertainties are difficult to predict and assess. Because of variations in engineering requirements and resource conditions in substation systems, no literature or report provides explicit statistical data. To meet the requirements for quantifying the functional recovery of substation systems, we assume that the substation has one repair team for restoration work to meet resource constraints and engineering requirements. This allows for the comparison of recovery efficiency under different recovery strategies. In addition, seismic resilience assessments can be conducted based on existing data. Because those uncertain factors are difficult to quantify, and are not the focus of this study, it is assumed that the resource conditions meet the repair needs and that equipment does not need to be allocated from other regions. Therefore, uncertainties related to equipment allocation and transportation networks are not considered.

5. Analysis and discussion

5.1. Seismic vulnerability analysis

Seismic vulnerability was conducted on the typical 220 kV step-down substation system using the proposed framework. We found that performing 1000 Monte Carlo samples has a high degree of convergence. Therefore, subsequent post-earthquake functionality restoration and seismic resilience assessments were analyzed using 1000 Monte Carlo samples. The failure probability parameters of the system-based seismic vulnerability curve ($C1$) and the user-based seismic vulnerability curve (C2) were obtained, as shown in Tables 2 and 3. After fitting the lognormal cumulative distribution function curves, seismic vulnerability curves for both power transmission and power users are shown in Fig. 11.

In the system-based seismic vulnerability curve, the failure probability parameters represent the functional failure probability of the substation under different functional status criteria. For example, 4/12 indicates that the criterion for judging the functional failure of the substation is that only four line-out units can function normally. The

Table 1
Seismic vulnerability curve parameters and recovery time of equipment in the typical 220 kV step-down substation [29,38].

Equipment	DS-220	CT-220	CB-220	PI-220	TF	DS-110	CT-110	CB-110	PI-110
μ/g	0.5	0.5	0.5	0.65	0.55	0.65	0.65	0.65	0.845
β	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
θ/h	3	3	3	2	5	3	3	3	2
σ	1	1	1	1	2	1	1	1	1

Table 2
Failure probability parameters of $C1$.

Functional state	PGA					
	0.1 g	0.2 g	0.3 g	0.4 g	0.5 g	0.6 g
0/12	0 %	0 %	0 %	53 %	100 %	100 %
1/12	0 %	0 %	0 %	88 %	100 %	100 %
2/12	0 %	0 %	0 %	98 %	100 %	100 %
3/12	0 %	0 %	2 %	100 %	100 %	100 %
4/12	0 %	0 %	8 %	100 %	100 %	100 %
5/12	0 %	0 %	21 %	100 %	100 %	100 %
6/12	0 %	0 %	41 %	100 %	100 %	100 %
7/12	0 %	0 %	64 %	100 %	100 %	100 %
8/12	0 %	1 %	83 %	100 %	100 %	100 %
9/12	0 %	7 %	95 %	100 %	100 %	100 %
10/12	0 %	27 %	99 %	100 %	100 %	100 %
11/12	0 %	65 %	100 %	100 %	100 %	100 %

substation is considered to be functioning properly when more than four line-out units can operate normally. Otherwise, it indicates functional failure. In the user-based seismic vulnerability curve, the failure probability parameters represent the failure probability of each line-out unit supplying different importance-level users under earthquakes.

Fig. 11 shows that the substation's functional status remains intact when PGA = 0.1 g, and all line-out units can operate normally. As the seismic intensity increases, the failure probability of equipment and units in the substation gradually increases, leading to a gradual decrease in the substation's electrical output capacity. When PGA $\geq$ 0.5 g, the system's function is completely lost, and it can no longer meet the electricity demand of power users. Table 2 and Fig. 11(a) show that the probability of substation functional failure varies significantly under different judgment criteria. When PGA = 0.2 g, at least eight line-out units can still function normally, but the probability of full function is only 35 %. There is a risk of complete functional failure of the substation when PGA > 0.3 g. Table 3 and Fig. 11(b) show that the seismic reliability of line-out units supplying special level and first-level power users is similar and far higher than that of line-out units supplying second-level power users. This indicates a significant difference in the substation's power supply capacity for various importance of power users, with a higher transmission and survival capacity for supplying important users. In addition, when PGA ranges from 0.2 g to 0.4 g, the seismic sensitivity of the substation's function is higher, and attention should be paid to the seismic resilience of equipment and units under this seismic intensity.

5.2. Post-earthquake function recovery analysis

To explore post-earthquake functionality restoration strategies for the substation system, simulation analyses were conducted using equipment-level recovery strategies (S_E), zone-level recovery strategies (S_Z), and user-level recovery strategies (S_U). In this typical 220 kV step-down substation, five types of equipment (DS, CT, CB, TF, and PI) impact the system's functionality. Different post-earthquake recovery strategies under various seismic intensities were obtained, as shown in Table 4.

Table 4 shows the direct impact of seismic intensity and the substation's structure on the recovery efficiency of equipment. Furthermore, the importance of the busbar gradually rises as the seismic intensity increases. When PGA $\geq$ 0.4 g, the recovery efficiency of the busbar is the highest. This indicates that the busbar gradually becomes the most critical piece of equipment as seismic intensity increases. This aligns with the requirement in electrical design that busbars need to be fortified to the highest standards. In addition, the recovery efficiency of the transformer decreases as PGA increases. It indicates that transformers, as crucial equipment in substations, have high reliability and redundancy.

The 220 kV substation comprises five functional zones: 220 kV line-in units, 220 kV busbar units, transformer units, 110 kV busbar units, and 110 kV line-out units. Following the principle of priority repair for the units with the highest recovery efficiency, zone-level recovery strategies (S_Z) were obtained, as shown in Table 5.

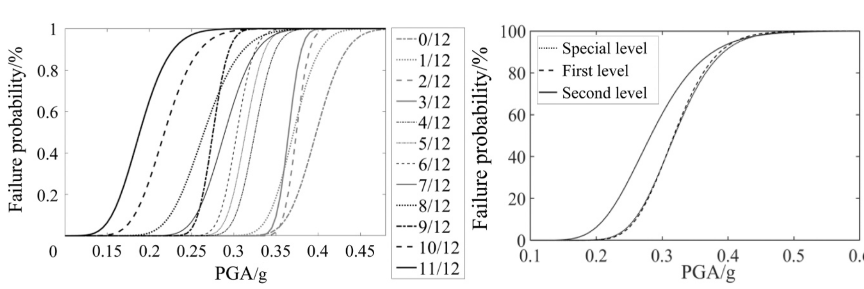
Table 5 shows that the recovery efficiency of busbar units and transformer units is significantly higher than that of line-in units and

Table 4
Recovery strategies of S_E.

PGA	Recovery path
PGA$\leq$ 0.1 g	No need repcovery
PGA= 0.2 g	TF / CB / CT / DS / PI
PGA= 0.3 g	TF / DS / CB / PI / CT
PGA= 0.4 g	PI / TF / CB / CT / DS
PGA= 0.5 g	PI / DS / TF / CB / CT
PGA$\leq$ 0.6 g	PI / DS / CB / CT / TF

Table 3
Failure probability parameters of $C2$.

Power user classification	PGA					
	0.1 g	0.2 g	0.3 g	0.4 g	0.5 g	0.6 g
Special level	0 %	7.51 %	35.39 %	92.07 %	99.99 %	100 %
First level	0 %	7.51 %	35.41 %	93.44 %	100 %	100 %
Second level	0 %	10.14 %	57.46 %	99.25 %	100 %	100 %



(a) (b)

Fig. 11. Seismic vulnerability curves for the typical 220 kV step-down substation, (a) system-based seismic vulnerability curve ($C1$), and (b) user-based seismic vulnerability curve (C2).

Table 5
Recovery strategies of S_Z.

PGA	Recovery path
PGA≤ 0.1 g	No need repcovery
PGA= 0.2 g	Transformer/110 kV busbar/220 kV busbar/110 kV line out/220 kV line in
PGA= 0.3 g	Transformer/110 kV busbar/220 kV busbar/110 kV line out/220 kV line in
PGA= 0.4 g	110 kV busbar/220 kV busbar/Transformer/220 kV line in/110 kV line out
PGA= 0.5 g	220 kV busbar/ Transformer/110 kV busbar/220 kV line in/110 kV line out
PGA≤ 0.6 g	220 kV busbar/110 kV busbar/Transformer/220 kV line in/110 kV line out

line-out units, indicating a higher priority for the recovery of these units in the substation. Under minor seismic activity, the recovery efficiency of the 110 kV line-out units is higher than that of the 220 kV line-in units. However, when PGA $\geq$ 0.4 g, the importance of the 220 kV line-in unit surpasses that of the 110 kV line-out units. This illustrates that the redundancy of the substation's line-in units ensures its functionality intact under minor seismic activity, allowing the prioritization of the recovery of the line-out units to maximize meeting the electricity demand of users. As seismic intensity increases, the functionality of the line-in units becomes insufficient to meet the users' electricity demand, and prioritizing the repair of line-out units has little impact on improving the substation's function. In addition, owing to the relatively higher reliability of various electrical equipment at lower voltage levels, prioritizing the repair of the 220 kV line-in unit has a better effect on improving the substation's function.

The 220 kV substation supplies special-level users, first-level users, and second-level users. Because the user-level recovery strategy (S_U) requires the recovery of each group of line-out units separately, the recovery process is divided into 12 steps. The specific recovery efficiency for each step is illustrated in Fig. 12.

Fig. 12 shows that the repair efficiency among the steps has little difference under the same seismic conditions. However, as seismic intensity increases, the recovery efficiency of equipment has a decreasing trend. When PGA $\geq$ 0.6 g, the recovery efficiency of equipment almost drops to zero. Therefore, this scenario is not further investigated.

5.3. Seismic resilience assessment

Through the seismic resilience assessment of the typical 220 kV step-down substation, the time-variant curves $K(t)$ and the seismic resilience index R under different recovery strategies were obtained, as shown in Fig. 13.

Fig. 13 shows that the early recovery efficiency of the equipment-level recovery strategy is very low under severe earthquakes. Significant improvement in the substation's functionality occurs only in the

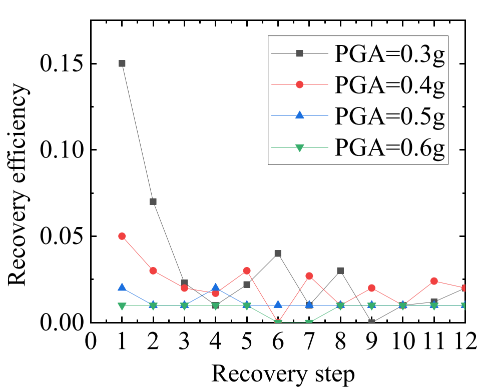


Fig. 12. Recovery efficiency at each step of S_U.

last two recovery steps. In contrast, the recovery efficiency of the zone-level recovery strategy remains relatively stable. The substation's system functionality is steadily increasing with the recovery process. The user-level recovery strategy significantly improves the substation's functionality in the early stages, and the functionality of the substation also recovers rapidly in the later stages. The seismic resilience index R for the three recovery strategies is summarized in Fig. 14.

Fig. 14 shows that the differences in the seismic resilience index among different recovery strategies gradually increase as the seismic intensity increases. When PGA $\geq$ 0.4 g, S_U gradually surpasses the other two strategies, thus being the optimal recovery strategy. Furthermore, adopting the S_U can significantly enhance the post-earthquake rapid recovery capability of the substation while reducing substantial human, material, and economic losses, demonstrating the feasibility and effectiveness of the optimal recovery strategy.

The structure and functional characteristics of substation systems differ from those of other infrastructures. To validate the accuracy of the analysis results, we compared them with related studies in the power systems field. The results show that transformers are critical components in substation systems [24,39,40]. In addition, according to "Q/CSG 110022–2012 Technical Specification for 220 kV Bus Bar Protection in Substations," it states that bus bar units should be fortified to the highest standards. Moreover, in current power enterprises, transformers and bus bars are also regarded as crucial components of substation systems after considering various engineering factors. These findings are consistent with the key repair components identified in this manuscript. To analyze the differences in the post-earthquake recovery process, Li et al. consider important power users. They found that the weighted optimal (OPW) recovery strategy is highly applicable [23]. This aligns with the post-earthquake recovery strategies proposed in this manuscript. Therefore, the framework is correct, and the results are valid.

6. Conclusions

This study established a multi-module framework for assessing the seismic vulnerability of substations. Based on the equipment functional status analysis module, a functional network model considering the structural functionality and the electrical load capacity was constructed. The functional state matrix of substations was determined through Monte Carlo simulation. Considering the reliability of power transmission and the importance of electricity users, the conditional probability parameters of multi-level functional status assessment criteria were explicitly defined, thereby achieving seismic vulnerability analysis from equipment to system and electricity users. Subsequently, a vulnerability-based seismic resilience quantification assessment method was proposed. A substation functional index was established to evaluate the functional states. Three-dimensional analysis frameworks for post-earthquake recovery strategies of substations were constructed. The stepped time-varying function of substations was obtained by simulating iterative analysis. The seismic resilience level of substations was quantitatively assessed through functional loss integration.

Based on the seismic vulnerability and resilience assessments of a typical 220 kV step-down substation, seismic vulnerability curves based on power transmission and electricity users were obtained, clarifying the seismic-sensitive intervals of the substation system. Then, resilience quantification assessments were conducted for post-earthquake recovery strategies. The important units and key equipment in the substation were identified. Notably, the optimal recovery strategy was determined. The proposed seismic vulnerability assessment framework provides a significant reference for seismic risk and reliability analysis of substation systems. The resilience-based post-earthquake recovery strategies provide a data foundation for repair plans under different engineering demands and resource constraints. In addition, the established functional network model can be improved to suit various engineering networks. The functional time-varying function can be adjusted based on the functional recovery characteristics, thereby meeting the requirements

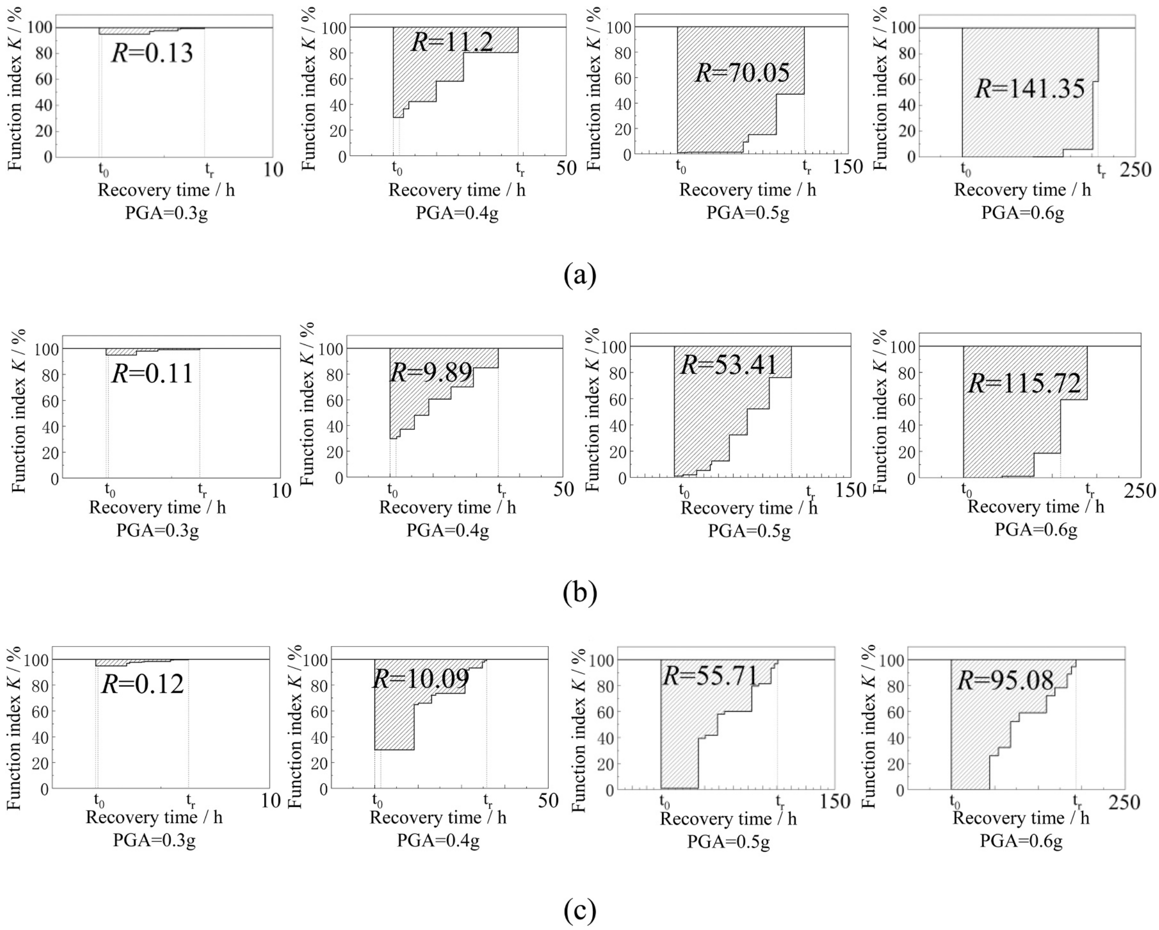


Fig. 13. Time-variant curves $K(t)$ and seismic resilience index R, (a) S_E, (b) S_Z, and (c) S_U.

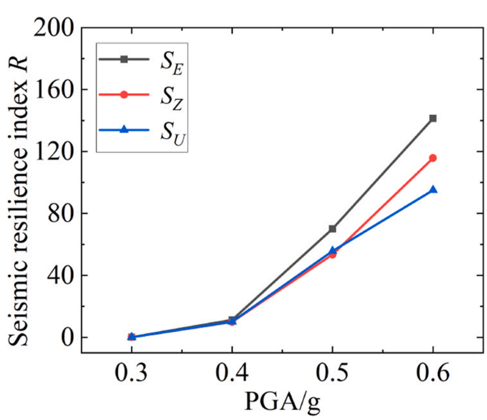


Fig. 14. Seismic resilience index of different recovery strategies.

for post-earthquake recovery and seismic resilience assessments.

However, it is important to note that PGA was used as the sole earthquake intensity parameter in vulnerability and resilience assessments. We did not consider other dimensions of seismic intensity parameters or combinations of intensity measure vectors. In addition, certain limitations and assumptions were proposed for the functional recovery process. Furthermore, the deterministic analysis of the functional restoration resulted in the loss of some quantified information on uncertainties. These lead to a lack of consideration for uncertainties in functional status and resource conditions. These aspects lead to certain limitations for this study. In future research, multi-uncertainty parameters need to be integrated and constrained. It is essential to conduct a resilience uncertainty assessment based on multidimensional seismic intensity parameters. Moreover, we plan to extend the resilience assessment framework to regional power grids based on the importance of power users. Assessing critical infrastructure and restoration strategies under different demands will be an important research focus.

CRediT authorship contribution statement

Siyuan Wu: Formal analysis, Methodology, Software, Validation, Writing – original draft. **Xiao Liu:** Formal analysis, Investigation, Methodology, Resources, Software, Writing – original draft, Writing – review & editing. **Qiang Li:** Data curation, Resources. **Qiang Xie:** Conceptualization, Formal analysis, Funding acquisition, Resources, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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