Study on Substation Seismic Resilience Evaluation Index and Resilience Matrix

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Abstract. This paper proposes a seismic resilience grading method for 110Kv and above high-voltage substations, and establishes a quantitative index for evaluating the substation seismic resilience -- seismic resilience index, presents a calculation formula for substation seismic resilience index which takes the respective weight coefficients and seismic damage indexes of buildings and high-voltage electrical equipment as the parameters, determines the relationship between the resilience index and the resilience grade, and establishes the substation resilience matrix through making statistics of actual seismic damage and recovered samples of the substations. The results show that with the decrease of resilience index, the resilience of substation becomes worse and worse. When the resilience index is lower than 0.45, the substation reaches the threshold of extremely difficult to recover. The higher the seismic intensity is, the lower the resilience is, and the longer the recovery time is. In 9 degree seismic intensity region, the substation resilience index begins to decrease rapidly, most substations are recoverable and difficult to recover, and the substations in 10 degrees and above seismic intensity region are extremely difficult to recover.

1. Introduction
The substations are important nodes that constitute the power system, and their damage degrees under the action of the earthquake and the progress of the post-earthquake substation functional recovery have a crucial impact on the emergency rescue, residential resettlement and post-disaster reconstruction in the disaster area. Substations have suffered a lot of damages in major earthquakes at home and abroad, and the recovery time is long because of the large amount of resources required for recovery and the great recovery difficulty, which brings great inconvenience to the earthquake relief and reconstruction work. In recent years, with the development of economy and science and technology, the construction of modern cities puts higher demands on the seismic safety and the lifeline system resilience. Therefore, studying the seismic resilience of substations and assessing the resilience capacity and recovery time of the substation after the earthquake can provide reference for decisions on allocation of resources such as power facilities and equipment after earthquakes and accelerating the power restoration and power facility reconstruction in post-earthquake areas, thus effectively reducing the direct and indirect economic losses caused by the earthquake.

Resilience has the meaning of elasticity and tenacity, and it was originally proposed by Holling [1] in the study of the ecosystem in the 1970s, he defined resilience as a characteristic or ability of a system to remain stable and persistent after a brief period of fluctuation due to disturbance or absorption variation. Thereafter, Timmerman [2] applied the concept of resilience to social systems, defining it as the ability of a system or part of a system to suffer and recover from a disaster. Brenuan [3] [4] proposed the concept of earthquake resistance and hazard mitigation of cities with recoverable
function, hoping to reduce the occurrence possibility of the disaster, reduce losses and shorten recovery time. Thornley [5] explored the concept of resilience by analyzing the seismic damage in Canterbury and proposed how to build resilient communities in the earthquake. David Elms et al [6] studied how to improve the resilience of communities in response to natural disasters, and pointed out that there are two factors influencing the resilience in response to natural disasters: One factor is the degree of disturbance on a system caused by the outside world, and second factor is the ability of a system to recover from the disturbance. Guo Xiaodong [7] proposed the concept of building disaster-resistant resilient cities, explored the connotation of resilient cities, and provided a quantitative method for assessing the urban resilience capability for disaster prevention. Qi Chun [8] analyzed the resilience of buildings from both structural and non-structural parts, and divided the seismic resilience of buildings into five grades according to the damage degrees of different components. Although scholars at home and abroad have tried to understand and explain resilience from different angles in recent years, there are few literatures on the seismic resilience of power systems or substations. Many scholars have studied the resilience from the aspects such as damage assessment, vulnerability analysis, damage mode and functional failure mode and post-earthquake recovery time. Rachel A. Davidson [9] established a post-earthquake recovery model of the power system and thus obtained its recovery skeleton curve, including obtaining the uncertainty boundary of the curve and the key variables affecting the shape of the curve. Thereafter, Zehra Cagnan [10] applied a discrete event simulation model to simulate the power recovery condition in the Los Angeles area after Northridge earthquake. Liu Rushan et al [11] made a statistical analysis of the damage frequencies of transformers and other high-voltage electrical equipment, substation shutdown status and functional recovery time in substations with different seismic intensities. Wang Lihua et al [12] analyzed the influences of equipment types and installation modes on the seismic damage degree of the power system, and sorted out the contents of post-earthquake recovery works such as mode type, basic principles and working sequence. According to the damage situation of the power system in recent earthquakes, Yu Wen [13] summarized its damage characteristics, and analyzed the seismic damage causes and mechanisms of various power facilities, and put forward the countermeasures against earthquake and disaster for the power system from two aspects of engineering measures and non-engineering measures on this basis.

At present, the concept of resilience has been introduced in many fields such as ecological environment, community construction, emergency management and urban water supply system. Especially in recent years, “resilient cities” have attracted more and more attention from researchers, while few achievements have been made in in-depth studies on the seismic resilience of the power transmission and transformation facilities of the power system and components, and a set of scientific and specific methods for evaluating the resilience capability of substations during earthquakes have not been formed. In view of this, in this paper, the seismic resilience of the substation was firstly explained, and then the index and its calculation method for quantitatively evaluating seismic resilience of substation were put forward, and the probabilities of occurrences of different resilience grades of substations under different seismic intensities, namely the resilience matrix, were calculated through the actual seismic damages and recovery samples of substations, which provided a reference for the rapid assessment of the resilience capabilities of substations in the affected areas and the allocation of resources required for the recovery based on the intensity after the earthquake.

2. Substation Seismic Resilience

Although there are different understandings and interpretations of resilience at home and abroad, they all emphasize the ability of the system to “accept or absorb disturbances and recover from them”. The substation seismic resilience is defined as an attribute of the substation, this attribute indicates that the substation is hit by an earthquake, which leads to the fact that when the components are damaged and the power supply function is decreased, the power supply function can be basically recovered to the normal state before the earthquake and kept stable in a certain period of time, as shown in figure 1. The substation seismic resilience has the following characteristics: (1) The substation is different from the natural environment and ecosystem, and its internal system cannot be adjusted and recovered when it is disturbed and destroyed, it can only be recovered by relying on the power of the power industry. (2) Recovery means that the substation can operate normally and stably. However, during the
earthquake, the power supply in some substations can only be temporarily recovered through alternative equipment, some electrical equipment, building structures and civil engineering facilities still need further maintenance or repair and recovery, which is not a true full recovery; (3) The recovery is a process. From the seismic damage to the investment of human and material resources, the state level of the substation will gradually increase, and its resilience is also changing.

The resilience study is mainly performed to quickly assess the resilience of substations in the disaster area after the earthquake, including recovery time and resources required for recovery, meanwhile unrecoverable boundaries are delineated to determine the fact that the substations with what extent of damage needs to be reconstructed.

Substation seismic resilience is divided into functional resilience and physical resilience. Functional resilience refers to recovering the power supply volume and the range of power users. Functional resilience does not require all equipment or buildings to be intact. Physical resilience refers to the repair or reconstruction of buildings and the repair or replacement of electrical equipment in the substation to achieve the normalized level before the earthquake in both functional and physical states. The resilience of the substation described in this paper referred the fact that the physical resilience was taken as the basis and the seismic damage performance of buildings and high-voltage electrical equipment (the decreasing degree of state in figure 1) was taken as the study objects.

![Figure 1. Seismic resilience schematic diagram of substations](image)

### 3. Substation Resilience Grading

In terms of the substation resilience grading, Qi Chun [8] divided the resilience of teaching buildings into five grades. These five grades were: intact, easy to recover, recoverable, difficult to recover, and unrecoverable. In fact, the number of grades and the definition of each grade are related to the purpose, understanding and actual needs of the people and the operability. In terms of the seismic damage grading, the seismic damage grades of buildings in China are divided into five grades: basically intact, slightly damaged, moderately damaged, seriously damaged and destroyed. The seismic damage grades in lifeline engineering are also divided into five grades [14]. In order to make the substation and the building structure consistent in terms of the resilience grade, this paper also divided the seismic resilience of the substation into five grades: basically intact, easy to recover, recoverable, difficult to recover, and extremely difficult to recover. According to the actual damage situation and recovery situation of substation sites in several earthquakes since the Wenchuan earthquake in China, the seismic damage, power failure mode and recovery time corresponding to the five resilience grades of the substations were shown in table 1.
Table 1. Resilience grades of substations

| Resilience grade | Seismic damage state, functional failure mode and recovery time |
|------------------|---------------------------------------------------------------|
| Basically intact | The transformers were intact, and very few other high-voltage electrical equipment were damaged, and the buildings were basically intact. The substations had no power failure or power failure due to upstream power failure, occasionally had power failure due to trip out and malfunction of the main transformer or equipment damage, and they could be repaired in a few hours. The weak parts of the transformers were damaged, a small amount of other high-voltage electrical equipment were damaged, and the buildings were basically intact or slightly damaged. The substations had power failure, which could be repaired within half a day to two days. |
| Easy to recover  | The transformers were damaged, with base displacement or tilting, some other high-voltage electrical equipment were damaged (the damage rate was less than 30%), the buildings were slightly damaged or moderately damaged. The substations had power failure, which could be repaired within 2-5 days. |
| Recoverable      | The transformer body was seriously damaged, accompanied by cracks and tilting displacements on the foundation. Many other high-voltage electrical equipment were damaged (the damage rate was less than 60%), and the buildings were seriously damaged. The substations had power failure, which could be repaired within one to two weeks. |
| Difficult to recover | Multiple parts of the transformer were damaged, and the damage rate of other high-voltage electrical equipment exceeded 60%, and the buildings were seriously damaged or destroyed. The substations had a long duration of power failure, which could be repaired within at least 15 days. |

4. Substation Resilience Index

4.1. Resilience Index and Calculation Formula

When the quantitative analysis and judgment of resilience are performed, it is necessary to find quantitative indexes that can mark resilience. The main factors affecting the recovery time of the substation after the earthquake are the substation seismic damage degree (building damage degree, electrical equipment damage rate), the importance degree of the substation, the sufficiency of human resources and the availability of material resources (spare parts and auxiliary facilities) in the recovery work. The above mentioned latter three factors have certain randomness and are difficult to control. It may be assumed here that the importance degrees, the resource condition, spare parts and auxiliary facilities required for recovery are the same in all substations, and the seismic resilience of the substation is only correlated with the seismic damage degree of the substation, and its resilience can be expressed by the seismic damage index.

The substation is mainly composed of outdoor high-voltage electrical equipment such as transformers, circuit breakers, isolating switches, lightning arresters, CT and PT and the house buildings such as main control room and indoor monitoring equipment. Since the damage degrees of the indoor equipment of the substation are generally closely related to the damage rate of the building, the indoor equipment are included into buildings, and their damage is equivalent to damage degree of the buildings; the transformer is the key equipment in the whole substation, and its value accounts for a large proportion. The research results [15] also showed that the transformers are significantly different from other high-voltage electrical equipment. Therefore, outdoor high-voltage electrical equipment can be divided into two categories such as transformers and other high-voltage electrical equipment. Therefore, the substation facilities were divided into three categories such as house building (including indoor equipment, the same below), transformers and other high-voltage equipment, and it was defined that the substation resilience index was expressed by the weight and the seismic damage degree of these three categories of facilities, as shown in equation (1).
In equation (1), $I_r$ is the substation resilience index, $i$ is the substation facility category, and $i = 1, 2, 3$ represent the house buildings, transformers and other high-voltage electrical equipment in the substations. $w_i$ is the weight coefficient of various facilities, $D_i$ is the seismic damage index or the damage ratio of transformers and other high-voltage electrical equipment. The damage ratio of transformers to other high-voltage electrical equipment can also be seen as the "the seismic damage index" of the equipment. 

Comprehensively considering the construction cost ratios of various facilities [16], the difficulty of recovery and the importance degree of the substation, the weight coefficients of house buildings, transformers and other high-voltage electrical equipment in the substations could be set as 0.4, 0.3, and 0.3 respectively. The seismic damage index is an index for assessing the seismic damage degree of house buildings [17]. The selection method of the seismic damage index of house buildings in substations can refer to provisions on the loss ratio of reinforced concrete to masonry buildings in the national standard “Seismic Field Work Part 4: Assessment of Direct Loss” [18]. Considering that the damage mode of other high-voltage electrical equipment is mainly cracks in porcelain components or direct truncation of porcelain columns, once being damaged, they cannot be repaired, so their damage ratio is the ratio of the number of damaged other high-voltage electrical equipment to the total number of other high-voltage electrical equipment in the substation. The transformer damage is usually the damage in local areas such as porcelain casing, oil conservator and air fan. The substation body is extremely difficult to damage [15], and it still can be repaired and used after suffering from seismic damage. Therefore, the damage ratio when it is damaged can be set as 0.2, so as to more accurately characterize the true damage situation of the transformers.

### 4.2. Relationship between Resilience Index and Resilience Grade

The substation resilience index could be calculated from equation (1) according to the damage situation, and it was necessary to establish a substantial congruent relationship between the resilience index and the resilience grade for evaluating the resilience grade of the substation. The resilience index values of 102 substations with voltage grades of 110kV-330kV in Mianyang, Deyang, Guangyuan, and Chengdu (partial areas) were calculated after Wenchuan earthquake, and they were divided into several ranges with intervals of 0.025-0.15. The damage degrees of the substation electrical equipment and house structure and the substation recovery time in the range of each resilience index were statistically analyzed, and the results were shown in table 2. The relationship between the resilience index and the recovery time was shown in figure 2. The blue line in figure 2 was the fitting curve, and the red dotted line was obtained through appropriate extension on the fitting curve due to the fact that there were 6 reconstructed substations without specific recovery time and this was not reflected in the fitting curve. The recovery boundary in the figure was the dividing line for whether the substation could be recovered in time. The data points on the right side of the recovery boundary indicated that the substations could be recovered. The data points on the left side of the recovery boundary indicated that the substation were extremely difficult to recover or needed to be reconstructed.
Figure 2. Relationship between resilience index and restoration time

Table 2. Statistics of substations damage and resilience index

| Resilience index | Basic situation of substation damage degree                                                                 | Average recovery time (day) | Sample No. |
|------------------|----------------------------------------------------------------------------------------------------------|----------------------------|------------|
| (0.97, 1.00)     | The transformers were almost intact, other high-voltage electrical equipment were nearly intact, the buildings were basically intact, and most of the substations had no power failure. | 0.31                       | 27         |
|                  | A small part of the transformers were damaged, and other high-voltage electrical equipment were almost not damaged. Most of the buildings were basically intact, and individual buildings were slightly damaged. About half of the substations had no power failure. |                            |            |
| (0.95, 0.97)     | Most of the transformers had different degrees of damage, other high-voltage electrical equipment were less damaged, most of the buildings were basically intact, some substations were slightly damaged, and some substations had no power failure. | 0.61                       | 22         |
|                  | Most transformers had different degrees of damage, other high-voltage electrical equipment were less damaged, the buildings were slightly damaged, and individual buildings were basically intact. |                            |            |
| (0.90, 0.95)     | Most transformers had different degrees of damage, other high-voltage electrical equipment were less damaged, some buildings were slightly damaged, and some substations had no power failure. | 1.11                       | 19         |
|                  | Most transformers had different degrees of damage, other high-voltage electrical equipment were less damaged, the buildings were slightly damaged, and individual buildings were basically intact. |                            |            |
| (0.85, 0.90)     | Most of the transformers were damaged, other high-voltage electrical equipment were less damaged, some buildings were slightly damaged, and some buildings were moderately damaged. | 1.34                       | 7          |
|                  | Most of the transformers were damaged, other high-voltage electrical equipment were damaged, some buildings were moderately damaged and individual buildings were damaged. |                            |            |
| (0.80, 0.85)     | Most of the transformers were damaged, other high-voltage electrical equipment were damaged, some buildings were moderately damaged and individual buildings were damaged. | 1.98                       | 10         |
|                  | Some transformers were damaged, more other high-voltage electrical equipment were damaged, but the buildings were seriously damaged or even destroyed. |                            |            |
| (0.65, 0.80)     | The transformers were damaged, most other high-voltage electrical equipment were damaged, the buildings were seriously damaged, and they needed to be reconstructed. | 3.44                       | 5          |
| (0.45, 0.65)     |                                                                                                         | 7.00                       | 7          |
| (0.00, 0.45)     |                                                                                                         | >15                        | 5          |
According to table 2 and figure 2, it could be seen that: (1) In terms of the overall trend, as the seismic damage of the substation became heavier and heavier, the average recovery time was longer and longer, and the resilience index value was getting smaller and smaller. (2) When $I_r$ was within the range of 0.975-1.000, the high-voltage electrical equipment and buildings in the substation were basically intact, and the substation had almost no power failure, and the recovery time was within a few hours, so it could be set as the boundary value of easy to recover; When $I_r$ belonged to the range of 0.900-0.975, a small number of transformers were damaged, a few other high-voltage electrical equipment were damaged, the building were basically intact or slightly damaged, and the recovery time was about 1 day. The substations were easy to recover; When $I_r$ belonged to several small investigation ranges of 0.650-0.900), when the statistics on substation damage degree and recovery time was performed, it was found that the transformers in these substations had different degrees of damage, and other high-voltage electrical equipment were also damaged. The average recovery time of the substations was about 1-3 days, and the substations could be recovered; when $I_r$ belonged to the range of 0.450-0.650, the damage rate of high-voltage electrical equipment in the substations was obviously increased, and the damage of buildings was more serious. The average recovery time of the substations was about 7 days, and the longest recovery time was 13 days.

When $I_r$ was lower than 0.45, recovery and reconstruction measures had basically been taken for all substations because they were extremely difficult to recover. There were a total of six substations that needed to be reconstructed due to severe disasters. The resilience indexes were shown in table 3. Among them, although the damage degrees of the houses and equipment themselves were not very prominent in Chuanxindian substation, because it was built on the mountain ridge and the foundations of the houses collapsed seriously, it was listed as a reconstruction substation after the earthquake. The substation with the largest resilience index among other reconstruction substations was Maoxian substation with a resilience index of 0.43. Combined with table 2 and figure 2, it can be seen that the resilience index threshold value of the substation which is extremely difficult to recover can be set as 0.45.

| Substation name | Intensity | Resilience index |
|-----------------|-----------|------------------|
| Chuanxindian    | 9         | 0.59             |
| Yuanmenba       | 9         | 0.28             |
| Anxian          | 9         | 0.28             |
| Maoxian         | 9         | 0.43             |
| Xiaoba          | 10        | 0.28             |
| Hanwang         | 10        | 0.37             |

Based on the above analysis, the boundary values of resilience indexes corresponding to substations of five grades such as basically intact, easy to recover, recoverable, difficult to recover and extremely difficult to recover were set as 0.97, 0.90, 0.65 and 0.45, respectively. The congruent relationships among different resilience grades and indexes were shown in table 4.

Since the seismic damage index of the houses is above 0.7, the stage of severe damage or destruction will arrive, and the recovery and reconstruction need to be generally considered. In calculating examples of this paper, the maximum transformer damage ratio was selected as less than 0.2, which didn’t reach 1.0, so even if the substation damage was quite serious and reconstruction was needed, according to the algorithm proposed in this paper, the substation resilience indexes basically didn’t reach the lower threshold value of 0.0. In addition, there is no approximate linear congruent relationship between the resilience grade and index resilience value.
### Table 4. Congruent relationship between resilience index and resilience grades

| Resilience grade     | Basically intact | Easy to recover | Recoverable | Difficult to recover | Extremely difficult |
|----------------------|------------------|-----------------|-------------|---------------------|-------------------|
| Resilience index     | (0.97,1.00]      | (0.90,0.97]     | (0.65,0.90] | (0.45,0.65]         | [0.00,0.45]       |

4.3. The Analysis on Characterization of Damages of Three Categories of Facilities in the Resilience

The recovery time can reflect the resilience capability of the substation to a certain extent. The shorter the recovery time is, the stronger the resilience is. In order to quickly evaluate the post-earthquake recovery time required for a single substation according to on-site seismic damage investigation data, the characteristic factors of the substation recovery time were studied, and the seismic damage performances of buildings, transformers and other high-voltage electrical equipment were analyzed, it was also analyzed which factor could better reflect the post-earthquake recovery time and was more suitable for assessing the length of recovery time. Here we studied the situation that the substation recovery time varied with the seismic damage performances of three categories of facilities, that was the characterization capability of damage rates of transformers and other high-voltage electrical equipment or the building loss ratio in the recovery time.

Taking into account the differences among individual substation samples and the particularity of the recovery time of a few substations, the average recovery time was used in this study to sort out the substation data and perform function fitting, as shown in figure 3. In figure 3, the abscissa seismic damage index was for buildings, and the damage rate was for transformers and other high-voltage electrical equipment.

It can be seen from figure 3 that when the seismic damage index was high, the average recovery time was sequentially decreased according to other high-voltage electrical equipment, buildings, and transformers, indicating that other high-voltage electrical equipment can best characterize the recovery time, followed by the buildings, and the transformers are the weakest. That is, when the damage degree of other high-voltage electrical equipment reaches a high level, it can be considered that the recovery time of the substation is often very long, and when the damage degree of transformers reaches a high level, the recovery time of the substation may be very long or very short, this provides a basis for us to quickly evaluate the recovery time of other high-voltage electrical equipment based on their seismic damage performances at the earthquake site. When the damage degree is low, the recovery time of the substation will gradually increase as the damage degrees of three facilities deepen. When the damage degree reaches a certain level, the recovery time of the substation will increase dramatically, but the recovery time sensitive boundaries of three facilities are different. Other high-voltage electrical equipment can reach the sensitive boundary as soon as possible, and the buildings reach the sensitive boundary at the latest, that is, the average recovery time increases sharply with the deepening of the damage degree of other high-voltage electrical equipment in the region with a lower damage degree, at this time, the recovery time still increases steadily with the deepening of transformer damage degree, and the recovery time begins to increase sharply until it reaches the sensitive boundary of the transformer, and the substation recovery time increases sharply only when the damage degree of the building reached the level of severe damage or complete destruction.
5. Relationship between Substation Resilience and Seismic Intensity

5.1. Relationship Among Resilience Index, Recovery Time and Seismic Intensity

The epicenter intensity in Wenchuan earthquake reached 11 degrees, and there were abundant substation samples in the low, medium and high intensity regions. These samples were used to calculate the relationship among resilience index, recovery time and seismic intensity of the substation, see the three-dimensional scatter figure 4. The relationship between the intensity of the substation site and the resilience index was shown in figure 5. It could be seen from figure 4 and figure 5 that the points with higher resilience index and shorter recovery time were concentrated in the lower intensity region (the upper left corner area of the coordinate system); the points with lower resilience index and longer recovery time were concentrated in the higher intensity region (the lower right corner area of the coordinate system), and the resilience index and recovery time gradually decreased as the intensity increased; the substation resilience index decreased rapidly when the intensity increased from 8 degrees to 9 degrees, it suddenly decreased from 0.88 to 0.54, which was caused by the apparent increase in the damage degree of the substations in the 9 degree region.

5.2. Substation Resilience Matrix

The resilience indexes of 102 substations in Wenchuan earthquake were calculated, the resilience grade of each substation was determined according to table 4, and combining the intensity of each...
substation site, the proportion of 6-10 degree in seismic intensity substations under each resilience grade was calculated, so as to establish a substation resilience matrix, see table 5. According to table 5, it is possible to quickly infer the most likely resilience state of a substation in a seismic intensity region after an earthquake and the probabilities of occurrences of different resilience states.

| Intensity | Basically intact | Easy to recover | Recoverable | Difficult to recover | Extremely difficult to recover |
|-----------|------------------|----------------|-------------|----------------------|--------------------------------|
| 6         | 100              | 0              | 0           | 0                    | 0                              |
| 7         | 40.0             | 43.6           | 16.4        | 0                    | 0                              |
| 8         | 9.1              | 48.5           | 30.3        | 12.1                 | 0                              |
| 9         | 0                | 0              | 33.3        | 33.3                 | 33.3                           |
| 10        | 0                | 0              | 0           | 0                    | 100                            |

It can be seen from table 5 that when the intensity was 6 degrees, the substations were basically intact, and individual substations might be slightly damaged but would not have power failure; when the intensity was 7 degrees, the damaged substations were easy to recover, the substations were mainly basically intact and slightly damaged, and a small number of substations had certain damages; when the intensity was 8 degrees, the substations were mostly easy to recover and recoverable, and individual substations had the possibility of difficult to in recover; in the 9 degree seismic intensity region, most substations were recoverable and difficult to recover, and some substations reached the stage of extremely difficult to recover; in the 10 degree and above seismic intensity region, the substations were almost extremely difficult to recover.

It should be pointed out that this statistic is specific to Wenchuan earthquake. At that time, most 110kV substations in this area were unguarded and seven-degree guarded substations, and the main control rooms were basically brick-concrete structure houses, with ordinary outdoor porcelain column type high voltage electrical equipment, and thus the seismic capacity was weaker. In the past ten years, many new substations have adopted reinforced concrete houses, and a large number of new GIS substations have emerged, these substations have greatly improved the seismic capacity. The substation resilience matrix in this paper is not applicable to these newly built steel-concrete substations and GIS substations with high seismic capacity.

6. Conclusion

Destructive earthquakes at home and abroad show that the substations, as important nodes of the power grid, are vulnerable to a large number of damages, causing huge economic losses and seriously hindering the reconstruction works in the disaster area. Therefore, it is necessary to carry out in-depth studies on the seismic resilience and post-earthquake recovery efficiency of the substations. This paper proposes an index for quantifying the substation seismic resilience - resilience index, and establishes its calculation method based on seismic damage performance, analyzes the effects of houses, transformers and other high-voltage electrical equipment on substation recovery time, calculates the relationship among resilience index, recovery time and seismic intensity of the substation, and establishes the substation seismic resilience matrix, which provides scientific reference for quick assessment of post-earthquake substation seismic resilience, command and deployment of power system emergency work and distribution of power facilities and relief materials.

The power supply recovery of the substations is a complex task, which depends not only on the integrity of the buildings and equipment of the substation themselves, but also on the functional level of the upstream part of the power grid. When an earthquake occurs, only the power supply is recovered and equipment and buildings are sometimes not completely repaired in some substations. In addition, the factors that determine and affect the seismic resilience of substations are complex and diverse. At present, there is not much accumulation of high-intensity seismic damage samples. In the future, more substation seismic damage data should be collected with the accumulation of earthquake data.
cases, and the resilience of substations should be restored. The index and resilience matrix are further tested and revised. The resilience index and resilience matrix of substation are further tested, amended and perfected.

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