Statistical Analysis of Co-seismic Surface Rupture Width and Displacement from Damage Cases

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Abstract: Under specific conditions, strong earthquakes can lead to surface ruptures, forming surface deformation zones. Currently, the assessment of co-seismic surface deformation zones has become a focus in seismic geology and geotechnical earthquake engineering research. This paper employs statistical analysis of co-seismic surface deformation zones to primarily investigate geometric parameters such as zone width and vertical dislocation, and establishes a corresponding database. The results reveal significant correlations between the width of the surface deformation zone and the dislocation amount for different fault types, and establish the following relationships between zone width(W) and vertical dislocation(D): the fitting formula for strike-slip faults is W=16.2+35D; for thrust faults, it is W=14.2+3.7D; and for normal faults, it is W=29.1+4.5D. Furthermore, the feasibility of these fitting formulas for earthquakes of magnitude Ms7.0 to Ms 8.0 was verified based on measured data from historical earthquake surface deformation zones.

Keywords: Strong Earthquake; Surface Deformation Zone; Vertical Displacement; Statistical Analysis

1. Introduction

Surface ruptures, resulting from the uneven surface deformation caused by strong earthquakes rupturing to the surface, induce severe damage to overlying structures. Numerous earthquake cases indicate that events with a magnitude of 6 or higher have the potential to trigger surface rupture deformation, whereas those with a magnitude of 8 or above almost invariably produce surface deformation zones accompanied by severe destruction [1]. Given the frequent occurrence of global seismic activity and the widespread distribution of active faults, the high frequency and intensity of earthquakes render their potential hazards extremely severe. For instance, the Ms7.4 earthquake in Madoi County, Golog Prefecture, Qinghai Province, on May 22, 2021, generated a 150-kilometer-long surface deformation zone with a maximum vertical displacement of 1.2 meters, causing the collapse of the Yema Tan Bridge on the Yugong Expressway and the Changma River Bridge on the Huajiu Expressway, as well as damage, deformation, and uplift of national and provincial highways.

Therefore, assessing the potential impact zone of surface ruptures is crucial for the site selection of major engineering projects and for disaster prevention and mitigation efforts.

2. Statistical Analysis of Surface Deformation Zones Induced by Strong Earthquakes

2.1 Normal Fault

Wu [2] conducted a detailed investigation and study of the surface deformation zone in Wangjiagou, collecting a total of 39 data points. Statistical analysis was performed on the field measurement data, generating Figure 1 and Figure 2, which present the relevant data for the intense geological deformation zone of the Wangjiagou fault set. The data reveal that the deformation zone width has a maximum of 82 m, a minimum of 20 m, an average of 41.1 m, and a standard deviation of 13 m. The vertical displacement has a maximum of 5.2 m, a minimum of 0.4 m, an average of 2.6 m, and a standard deviation of 1.2 m.

Based on this analysis, a fitting curve for the width (W) of the surface deformation zone versus the vertical displacement (D) was plotted

(Figure 3):

$$Wn = 29.1 + 4.5D \quad (1)$$

An in-depth analysis of the statistical data for the width of the Wangjiagou surface deformation zone reveals a mean (μ) of 41.1 m and a standard deviation (σ) of 13 m. Using (μ + σ) as the reference value for the setback width yields 54.1 m, indicating that within a 68.2% confidence interval, the surface deformation zone width is less than 55 m. Using (μ+2σ) as the reference value results in 67.1 m, demonstrating that within a 95.4% confidence interval, the surface deformation zone width is less than 70 m.

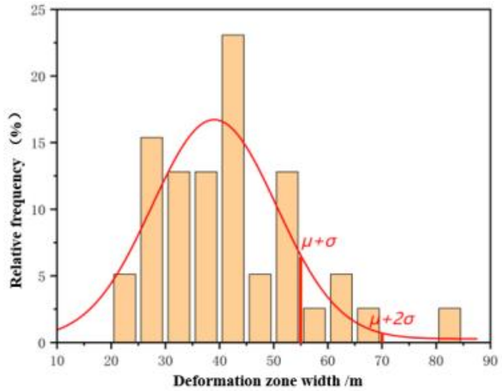

Figure 1. Analysis Diagram of the Deformation Zone Width in Wangjiagou

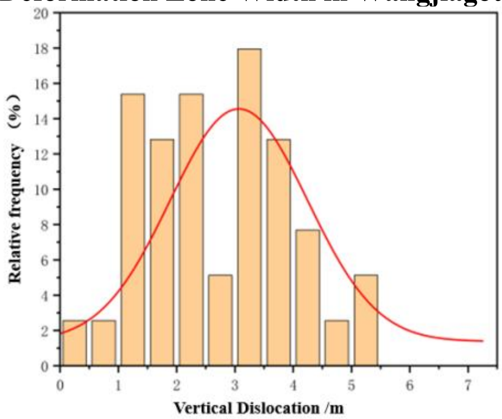

Figure 2. Analysis Diagram of Vertical Dislocation in the Wangjiagou Deformation Zone

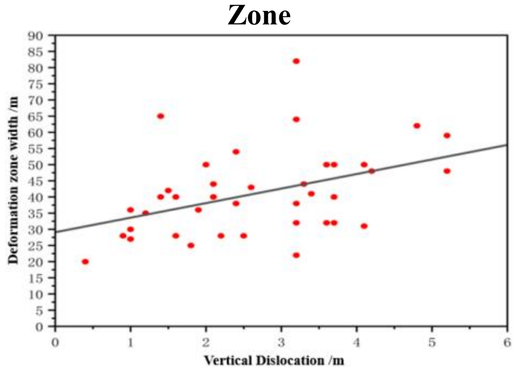

Figure 3. Fitting Curve of the Wangjiagou Deformation Zone

2.2 Reverse Fault

During the scientific investigation of the Wenchuan earthquake (Ms 8.0), the team led by Xu [3] conducted detailed surveys and studies on the Beichuan-Yingxiu deformation zone, the Hanwang-Bailu Town deformation zone, and the Xiaoyudong surface deformation zone. During the investigation of the Wenchuan earthquake, Zhao [4,5] also performed comprehensive research on the surface deformation zones and compiled the relevant data. Furthermore, researchers including Zhang [6] provided survey data for the surface deformation zones of the Wenchuan earthquake, which account for the horizontal shortening component.

Following the compilation and analysis of the surface deformation zone data from the Wenchuan earthquake, Figure 4 and Figure 5 were plotted to illustrate the characteristics of these deformation zones. The analysis reveals that the width of the surface deformation zones has a maximum of 84 m, a minimum of 2 m, with a calculated mean width of 23.1 m and a standard deviation of 15 m. The vertical displacement has a maximum of 6.1 m, a minimum of 0.2 m, with a mean displacement of 2.1 m and a standard deviation of 1.2 m; Figure 4 indicates that the frequency peak of vertical displacement is concentrated between 0.5 m and 4 m. To gain a deeper understanding of the relationship between the surface deformation zone width and the vertical displacement, a fitting curve for the two parameters was derived based on the data (Figure 6). The correlation can be intuitively understood through the fitting formula, which is:

$$Wr = 14.2 + 3.7D \quad (2)$$

A further in-depth analysis was conducted on the statistical data pertaining to the width of the surface deformation zones. For the Wenchuan earthquake, the mean width (μ) of the surface deformation zones is 23 m, with a standard deviation (σ) of 15 m. If the mean plus one standard deviation (μ + σ) is adopted as the reference value for the setback width, the calculated value is 38.1 m, indicating that within a 68.2% confidence interval, the surface deformation zone width is less than 40 m. If we further adopt the mean plus two standard deviations (μ+2σ) as the reference value, the calculated result is 53.1 m. This demonstrates that within a 95.4% confidence interval, the surface deformation zone width is less than 55m.

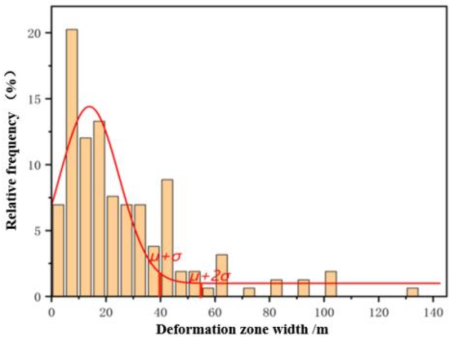

Figure 4. Analysis Diagram of the Deformation Zones from the Wenchuan Earthquake

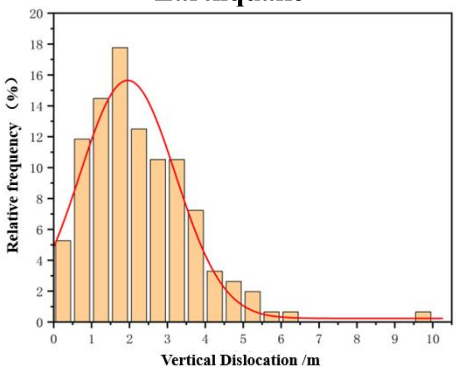

Figure 5. Analysis Diagram of Vertical Dislocation in the Deformation Zones from the Wenchuan Earthquake

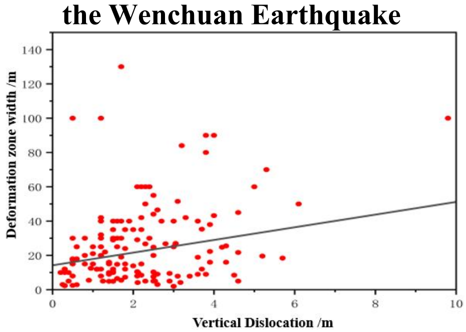

Figure 6. Fitting Curve for the Compiled Data of Surface Deformation Zones from the Wenchuan Earthquake

2.3 Strike-slip Fault

Niu [7,8] and his research team conducted a field investigation of the surface deformation zone resulting from the 2022 Qinghai Menyuan earthquake (Ms6.9), and their findings are documented in detail. After excluding six data points exceeding 100 m, the maximum width of the surface deformation zone was 96.89 m, the minimum width was 5.86 m, the average width was 35.7 m, and the standard deviation was 18 m. Regarding the frequency distribution of the deformation zone widths, the peak frequency falls within the range of 10 m to 60 m, as shown in Figure 7.

A statistical analysis was performed on the surface deformation zone data from the Qinghai Menyuan Ms6.9 earthquake, and Figure 7 was plotted to show the width distribution. The calculated mean width (μ) of the surface deformation zones is 36.7 m, with a standard deviation (σ) of 18 m. Using μ+σ yields 54.7 m, indicating that within a 68.2% confidence interval, the width is less than 55 m. Using μ+2σ as the reference value gives 72.7 m, meaning that within a 95.4% confidence interval, the width is less than 75 m.

Statistical analysis was performed on the vertical displacement data and Figure 8 was plotted. The data show a maximum vertical displacement of 0.49 m, a minimum of 0.08 m, a mean of 0.24 m, and a standard deviation of 0.12 m, with the peak frequency concentrated between 0.1 m and 0.3 m. Based on these data, a fitting curve (Figure 9) and its corresponding formula for the relationship between the surface deformation zone width (W) and the vertical displacement (D) were derived.

$$Ws = 16.2 + 35D \tag{3}$$

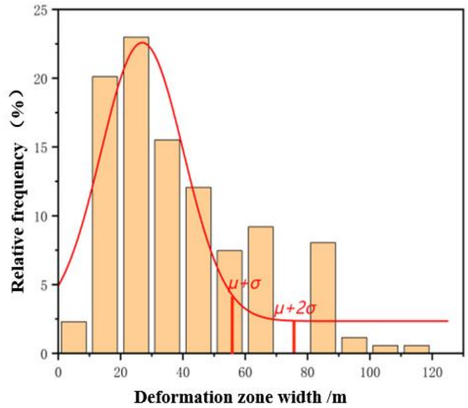

Figure 7. Analysis Diagram of the Deformation Zone Width from the Qinghai Menyuan Earthquake

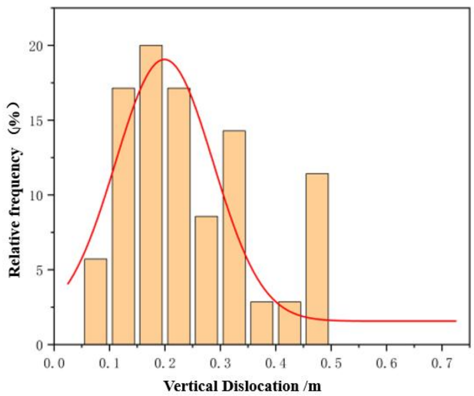

Figure 8. Analysis Diagram of Vertical Dislocation in the Qinghai Menyuan Deformation Zone

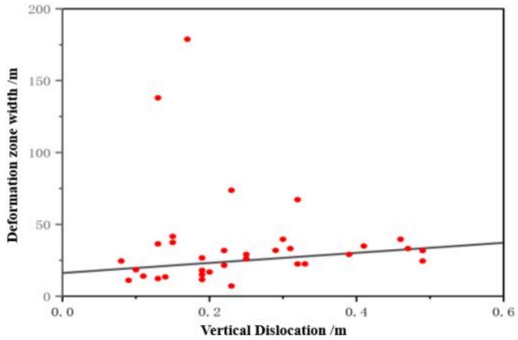

Figure 9. Fitting Curve for the Surface Deformation Zone Data from the Qinghai Menyuan Earthquake

3. Fitting Formula Verification

Based on the parameters of co-seismic surface deformation zones, the characteristics for strike-slip, thrust, and normal fault earthquakes were summarized, and relational formulas between the surface deformation zone width (W) and the vertical displacement (D) were established (Table 1). This chapter will utilize actual surface deformation zone data from earthquakes to verify the feasibility of the derived fitting formulas and to calculate and analyze their error ranges. The error calculation formula is:

$$\delta = [(W - W_O\ )/W]\% \tag{4}$$

Wo-- Field-measured width of the surface deformation zone (m);
W-- Calculated width of the surface deformation zone (m);
δ-- Error (Positive value: calculated deformation zone width is greater than the measured data; Negative value: calculated deformation zone width is less than the measured data).

Table 1. Formula for the Relationship between Surface Deformation Zone Width and Vertical Displacement

Fault type	Formula
Normal fault	Wn=29.1+4.5D
Reverse fault	Wr=14.2+3.7D
Strike-slip fault	Ws=16.2+35D

3.1 Normal Fault

An Mw 6.8 earthquake occurred in Tingri County, Shigatse City, Xizang Autonomous Region, China, on January 7, 2025. Shi [9] and Liu [10] conducted field seismic investigations, performing on-site surveys of the surface deformation zone caused by the earthquake. Their survey results are shown in Figures 10 and Figures11.

The surface deformation zone data recorded by Shi [9] are presented in Figure 10. They measured a vertical displacement of 0.8 m and a deformation zone width of 35 ± 2 m. The measured values were substituted into the fitting formula for calculation. The calculated deformation zone width obtained was 32.25 m. Compared with the actual measured value, the error is -8.5%. The error value indicates a certain deviation between the theoretical calculation and the actual measurement, but overall, the fitting formula can reasonably reflect the actual situation.

Figure 10. Surface Deformation Zone of the Nixia Cuo Segment, Xizang Tingri Earthquake [9]

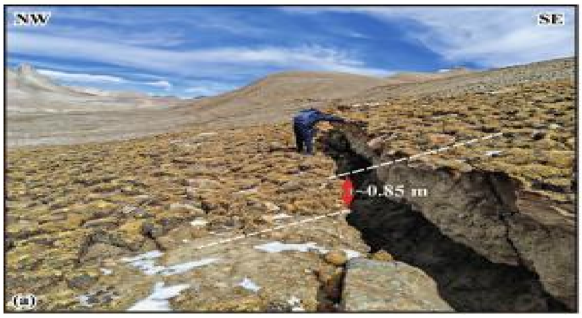

Figure 11. Scarp of the Xizang Tingri Earthquake [10]

Liu [10] also recorded relevant data of the deformation zone caused by this earthquake, as shown in Figure 11. They measured a vertical displacement of 0.85 m and a deformation zone width of 30 ± 2 m. Similarly, substituting the measured values into the fitting formula yielded a calculated deformation zone width of 32.925 m. Comparison with the actual measured value revealed an error of -8.9%. This error value indicates a certain deviation between the theoretical calculation and the actual measurement, but overall, the fitting formula can reasonably reflect the actual situation.

During the field investigation of the surface deformation zone along the Xiadian Fault (Ms 8.0) in Pinggu District, Beijing, data such as the vertical displacement and width of the deformation zone were recorded, as shown in Figure 12. Field measurements indicated a vertical displacement of 1.8 m and a deformation zone width of 35 ± 2 m. Substituting the values into the formula yielded a calculated deformation zone width of 37.2 m. Comparing the calculated result with the actual measured data gives an error of 5.9%.

Figure 12. Scarp of the Xiadian Fault

3.2 Reverse Fault

An Ms 7.1 earthquake occurred in the Wushi area on January 23, 2024. Zhang [11] conducted field geological investigations of this earthquake. During the investigation, they identified significant geological phenomena at the Qialemati Gully road, conducting detailed measurements and recordings which yielded a series of valuable data. As shown in Figure 13, the research team recorded a vertical displacement of 1 m for this surface deformation zone, while measuring its width as 20 ± 2 m. Substituting the data into the fitting formula for calculation resulted in a computed deformation zone width of 17.9 m. Comparison with the actual measured data revealed an error of 11.7%. Although this error exists, it falls within an acceptable range for geological surveys, thus indicating that the fitting formula is effective to a certain extent.

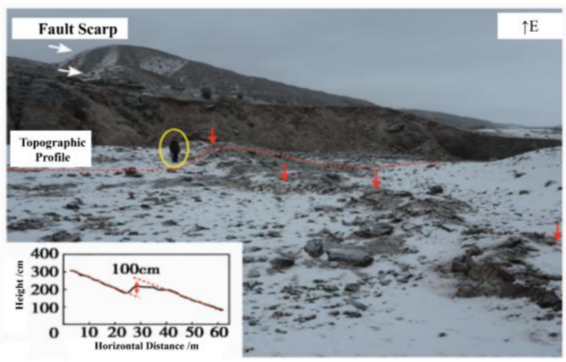

Figure 13. Mole Tracks within the Qialemati Gully, Wushi Earthquake [11]

Zhang [11] recorded another deformation zone (Figure 14), measuring a vertical displacement of 0.66 m and a deformation zone width of 15 m. Substituting these values into the fitting formula for calculation yielded a computed deformation zone width of 16.6 m. After comparing the result with the actual measured data, an error of -9.6% was found. This result indicates that the fitting formula also possesses a certain degree of accuracy in this instance, with the error value falling within an acceptable range.

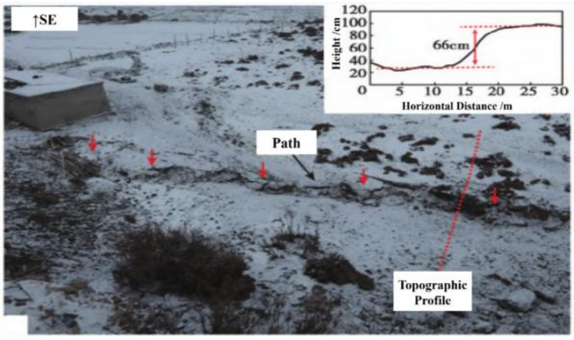

Figure 14. Scarp within the Qialemati Gully, Wushi Earthquake [11]

Chen [12] conducted detailed measurements and research on the surface deformation zone of the Eastern Yumu Shan Fault (Ms7.5). Through field surveys and data collection, they documented scarp geomorphic features within this area at the Heihekou segment (labeled F1-1), as shown in Figures 15 and 16.

In Figure 16, Profile L1 shows a vertical displacement of 3.3 ± 0.2 m for this deformation zone, while the width of the deformation zone was measured as 25 ± 1 m. Substituting the vertical displacement value into the fitting formula yields a calculated deformation zone width of 26.41 m. Comparing the calculated result with the actual measured data reveals an error of 5.3%.

Similarly, Profile L2 in Figure 16 also exhibits comparable measurement results. In this area, the research team measured a vertical displacement of 2.6 ± 0.2 m and a deformation zone width of 22 ± 1 m. Similarly, substituting these values into the fitting formula for calculation gives a computed deformation zone width of 23.82 m. Comparison of this calculated result with the actual measured data shows an error of 7.6%, which further confirms the applicability and reliability of the fitting formula.

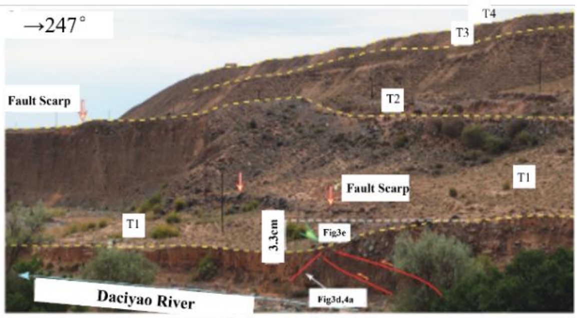

Figure 15. Yumu Shan Fault [12]

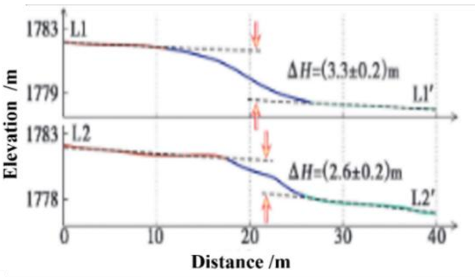

Figure 16. Scarp Profile [12]

3.3 Strike-Slip Fault

On May 22, 2021, an Ms 7.4 earthquake struck the Madoi area in Qinghai Province, China. Yao [13] conducted a detailed geological survey near Xuema Village and created a profile map of the surface deformation phenomena, as shown in Figure 17. Through field measurements, she determined that the vertical displacement of this surface deformation zone reached 1.2 m, and its width was 55 ± 2 m. Substituting these data into the pre-established fitting formula yielded a calculated deformation zone width of 58.2 m. To evaluate the accuracy of the calculation result, the error was computed using the error formula, ultimately yielding a fitting formula error of 5.4%.

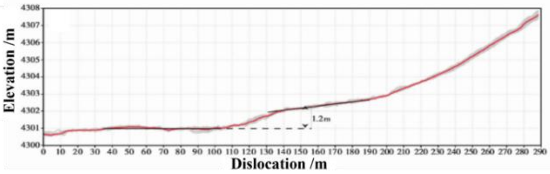

Figure 17. Co-seismic Surface Deformation Zone near Xuema Village [13]

For the surface deformation zone at the Ngoring Lake segment (Figure 18), Yao [13] measured a vertical displacement of 0.4 m and a deformation zone width of 40 ± 2 m. These measured values were substituted into the corresponding fitting formula. The calculation yielded a computed deformation zone width of 43.1 m. Comparing this result with the actual measured data revealed an error of 7.1%. This result indicates that the fitting formula possesses a certain degree of accuracy in predicting surface deformation zone width.

Figure 18. Co-seismic Surface Deformation Zone at the Ngoring Lake Segment [13]

Pan [14] conducted a detailed field investigation of the western segment of the surface deformation zone from the Qinghai Madoi earthquake. During this investigation, they documented specific features of the surface deformation zone (Figure 19). Measurements revealed a vertical displacement of 0.5 m and a deformation zone width of 50 ± 2 m at this location. The measured values were substituted into the pre-established fitting formula for calculation. This yielded a calculated deformation zone width of 46.6 m. A comparative analysis was performed between this theoretical calculated value and the actual measured data. The results show an error of 7.3% between the theoretically calculated value and the actual measured value. This result indicates that the fitting formula can, to a certain extent, relatively accurately reflect the actual width of the surface deformation zone.

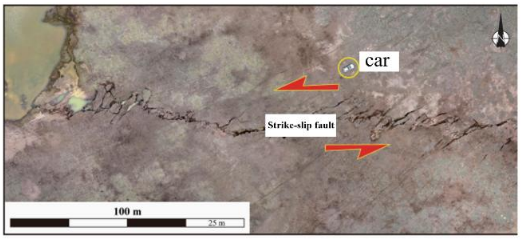

Figure 19. Western Segment of the Surface Deformation Zone, Madoi Earthquake [14]

4. Conclusion

This study employs a statistical analysis of earthquake cases, collecting geometric parameters and deformation mode data of surface rupture phenomena induced by earthquakes with magnitudes less than or equal to Ms 8.0. Based on this, a database was constructed, which includes the geometric parameters (width, vertical displacement) of deformation zones caused by strike-slip, thrust, and normal fault earthquakes. Through in-depth analysis of the database, the characteristics of the deformation zones for strike-slip, thrust, and normal fault earthquakes were discussed in detail. Their respective deformation zone widths and vertical displacement characteristics were determined, confidence intervals for the deformation zone widths were calculated, and empirical relationships between the surface deformation zone width and the vertical displacement were established, leading to the following conclusions:

(1) Strike-slip faults: Analysis of the surface deformation zone from the Qinghai Menyuan

earthquake indicates that the width is less than 55 m within a 68.2% confidence interval and less than 75 m within a 95.4% confidence interval. The relationship between the surface deformation zone width (W) and the vertical displacement (D) was established as:

$$Ws = 16.2 + 35D \tag{5}$$

(2) Reverse faults: Analysis of the surface deformation zones from the Wenchuan earthquake shows that the width is less than 55 m within a 68.2% confidence interval and less than 55 m within a 95.4% confidence interval. A relational model between the surface deformation zone width (W) and the vertical displacement (D) was constructed, with the formula:

$$Wr = 14.2 + 3.7D \tag{6}$$

(3) Normal faults: Analysis of the Wangjiagou surface deformation zone reveals that the width is less than 55 m within a 68.2% confidence interval and less than 70 m within a 95.4% confidence interval. The relationship between the surface deformation zone width (W) and the vertical displacement (D) was established as:

$$Wn = 29.1 + 4.5D \tag{7}$$

(4) The formulas proposed in this study were validated using historical earthquake data. The results demonstrate a significant correlation between the width of the surface deformation zone and the displacement amount. Furthermore, the feasibility of the relational formulas for deformation zones induced by strong earthquakes of Ms 7.0 to Ms 8.0 was verified through cases such as the Qinghai Madoi and Wushi earthquakes, with the prediction error being controlled within ± 15%.

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