Characteristics of Sediment-Related Disasters Triggered by the Wenchuan Earthquake

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The “5.12” Wenchuan earthquake not only had catastrophic primary effects, but also triggered many major secondary effects in mountainous regions including collapse (rock fail, slide, and so on), landslides, debris flows, and the formation of barrier lakes. These secondary disasters had a major influence on the areas affected by the earthquake, as they resulted in significant blocks to aid and seriously slowed the rescue process. Furthermore, huge amounts of uncompacted debris created by collapse and landslides continue to pose a substantial long-term risk to the safety of the people and to their property as it can form powerful debris flows with strong rains. In this study, the distribution characteristics and physical status were investigated through field surveys and image interpretation. The features and distribution of future sediment disasters were estimated, and suggestions for corresponding mitigation measures were proposed. These will play an important role in protecting the safety of the people and in facilitating the reconstruction of disaster areas.

1. BRIEF INTRODUCTION TO SEDIMENT DISASTERS TRIGGERED BY THE WENCHUAN EARTHQUAKE

At 14:28 Beijing time on 12 May 2008, a devastating earthquake of magnitude 8.0 on the Richter scale hit Wenchuan County in the Sichuan Province of southwestern China. By 10:00 am on 25 May 2009, 69,227 people had died, 374,643 people had been injured and 17,923 people were declared missing as a direct consequence of the earthquake. The area affected by the disaster covers over 100,000 km², and the breadth of the sweeping region and the scale of the damage are apparently without precedent in the recorded history of this area. The earthquake exerted great damage to Wenchuan, Beichuan, Dujiangyan, Pengzhou, Mianzhu, Shifang, Anxian, Qingchuan, Pingwu, Lixian, Maoyian and Wenxian, all of which lie along the Longmen Fault.

Since the most-seriously affected areas lie in the western mountain regions of Sichuan Province, which contain high mountains, deep valleys, complicated geological structures, and fault development, the earthquake induced many disastrous sedimentary effects, such as slope collapse, landslides, and barrier lake formation. These major secondary sedimentary effects caused great damage to mountain towns, villages, roads, hydroelectric engineering, and communication facilities, which not only aggravated the disaster, but also presented major obstacles to disaster relief, seriously delaying its progress. The main shock of the Wenchuan earthquake was very strong, with an epicentral intensity of up to XI on the Mercalli scale, causing great damage to the mountain surface (Fig.1). Before 12:00 am on 1 August 2009, 303 aftershocks over Ms = 4.0 occurred in the area. Among these aftershocks, 258 were between Ms = 4.0 and 4.9, 37 were between Ms = 5.0 and 5.9, and eight were over Ms = 6.0 (Fig. 2, data from China Earthquake Networks Center). Frequent and strong aftershocks caused reciprocating damage to mountain surfaces. In summary, many sediment-related disasters, such as collapse and landslides, were triggered, and a large amount of loose solid material was created. According to field
investigations and interpretations of remote sensing data, the total amount of soil and water loss in the area most seriously affected by the Wenchuan earthquake was about 56 billion tons [Chen et al., 2009].

The sedimentary disasters caused by the Wenchuan earthquake have already caused great damage, and it is estimated that about one-third of the recorded deaths, missing persons, and property losses can be attributed to these secondary sedimentary effects. For example, the intense rainfall on 24 September 2008 initiated widespread debris flows in the epicenter of the Wenchuan earthquake, Beichuan. These debris flows greatly impacted the community of Beichuan County and caused 42 fatalities. Between June and July 2009, the Sichuan Basin area experienced frequent rainstorms, and in the major disaster areas such as Doujiangyan, Pingwu, Pengzhou, and Qingchuan, serious landslides and debris flows occurred, jeopardizing the safety of local people and the post-disaster reconstruction efforts.

The “5.12” Wenchuan earthquake occurred in the structural belt of the Longmen Mountains on the eastern edge of Tibetan Plateau. Intensively squeezed by the Tibetan Plateau and the Sichuan Basin, the Longmen structural belt was in a continuously active state before the earthquake. This region includes one of the steepest mountain slope areas in China. A 5500-m change in elevation occurs over a distance of 100 km. This region also encompasses the headwaters of many rivers in the upper Yangtze River catchment [Yin, 2009].

Therefore, this area always has a high incidence of sediment disasters. Before the earthquake, sediment disaster investigations identified 5184 hidden hazardous mountain locations in the 44 counties within the serious disaster area. Among these, 3300 landslides, 492 collapses, 604 debris flows, and 751 unstable slopes were recorded before the earthquake. After 20 July 2008, 9671 additional hidden trouble spots were added in the 44 disaster counties (cities). Among the 8627 statistically identified hazardous spots with a certain scale, 3627 landslides, 2383 collapses, 837 debris flows, and 1694 unstable slopes were recorded [Huang, 2008]. The change in sediment disaster occurrence caused by the Wenchuan earthquake can be illustrated by the statistical data of collapse, landslide, and debris flow before and after the earthquake in the serious disaster area (Table 1).

The data in Table 1 show that the Wenchuan earthquake induced a large number of collapses, landslides, and debris flows. Before the earthquake, 1013 sediment disaster spots were identified in 10 of the counties (cities), whereas after the earthquake, sediment disaster spots increased by a factor of 8.82 to a total of 8933 occurrences. Among the secondary sedimentary effects, the increase in the occurrence of collapses was perhaps the most remarkable; 1855
collapses were recorded after the earthquake, which is 12.28 times the number before the earthquake. The second most dramatic difference was seen in landslide occurrence, with 6785 landslides occurring after the earthquake, 9.57 times the number before the earthquake. Two hundred ninety-three debris flows were recorded after the earthquake, 1.92 times the occurrence before the earthquake. Therefore, the dramatic increase in the occurrence of collapses represents the biggest effect, and it shows that the destructive effect of the earthquake on steep slopes is especially great. According to the relative proportions of the occurrence of different sediment disasters, before the earthquake, collapse accounted for 14.9%, landslides accounted for 70.0%, and debris flows accounted for 15.1%. After the earthquake, collapse accounted for 20.8%, landslides accounted for 76.0%, and debris flows accounted for 3.2%. This shows that landslides represented the most common effect of the earthquake, followed by collapse, and debris flow.

2. SEDIMENTARY DISASTER CHARACTERISTICS ANALYSIS OF THE WENCHUAN EARTHQUAKE

2.1 Distribution characteristics and damage

2.1.1 Distribution characteristics

(1) Wide distribution area

According to the investigation of sediment disasters associated with the Wenchuan earthquake carried out by the Ministry of Land and Resources P.R.C, preliminary results show that the sediment disasters induced by the Wenchuan earthquake have a very wide distribution. They cover three provinces and 84 counties (cities), with a total area of 48 × 104 km² [Wu et al., 2008]. Over the larger area, sediment disasters occur to different degrees. No other external force can result in such a large number of simultaneous sediment disasters and over such a wide area.

(2) High density of sediment disasters

Another characteristic of the sediment disasters triggered by this earthquake is the very high number of resultant mountain hazards in the unit area (Fig. 3). The 5.12 Wenchuan earthquake induced 18,997 collapses and landslides. The average county had 142 disasters, the county with the highest number of disasters (Qingchuan) had 989 disasters, and Wenchuan had 474 disasters. Along the 213 national highway from Zipingpu Power Station to Wenchuan County, 351 sediment disasters developed, with a density of 3.28/km [Yan et al., 2009].

(3) Concentrated distribution along the two sides of the Longmenshan Fault

The distribution of sediment disasters triggered by the Wenchuan earthquake was mainly determined by the location of fault movement that triggered the seismic activity, and the sedimentary effects are distributed along those faults like a ribbon. Because the faults that triggered the earthquake were reverse faults, the distribution of the sediment disasters showed a clear “Upper plate/lower plate effect.” That is, the upper plate had a higher distribution density of sediment disasters than did the lower plate, and these events were also characterized by a wider scope and larger scale [Huang et al., 2009]. Through analysis of the relationships between the locations of the mountain hazards after the earthquake and the fault that caused the earthquake, it was shown that the farther an area was from the fault, the smaller was the distribution density of mountain hazards. The region of highest intensity of mountain hazards was between 0 and 7 km away from the fault in the upper plate; the region of moderate hazard development was between 7 and 11 km from the fault in the upper plate and between 0 and 5 km from the fault in the lower plate. The vast majority of larger-scale landslides were about 5 km away from faults [Huang, 2008].

2.1.2 Damage Characteristics

Unlike other strong earthquakes in China, the Wenchuan earthquake induced a large number of landslides, collapses, debris flows, and barrier lakes. With the added occurrence of rainstorms, many sediment disasters occurred, causing major injuries and fatalities among local populations as well as a high degree of property loss and much damage to traffic arteries in and around the affected villages, towns, and cities.
Table 1: Comparison of collapse, landslide, and debris flow occurrence before and after the Wenchuan earthquake in the most serious disaster area.

<table>
<thead>
<tr>
<th>Region</th>
<th>Collapse Before earthquake</th>
<th>Landslide Before earthquake</th>
<th>Debris flow Before earthquake</th>
<th>Total Before earthquake</th>
<th>Collapse After earthquake</th>
<th>Landslide After earthquake</th>
<th>Debris flow After earthquake</th>
<th>Total After earthquake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wenchuan</td>
<td>7</td>
<td>43</td>
<td>71</td>
<td>121</td>
<td>1379</td>
<td>1181</td>
<td>125</td>
<td>2685</td>
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<tr>
<td>Beichuan</td>
<td>21</td>
<td>211</td>
<td>23</td>
<td>255</td>
<td>42</td>
<td>1124</td>
<td>38</td>
<td>1204</td>
</tr>
<tr>
<td>Mianzhu</td>
<td>35</td>
<td>47</td>
<td>17</td>
<td>99</td>
<td>11</td>
<td>993</td>
<td>24</td>
<td>1028</td>
</tr>
<tr>
<td>Shifang</td>
<td>21</td>
<td>57</td>
<td>13</td>
<td>91</td>
<td>70</td>
<td>733</td>
<td>6</td>
<td>809</td>
</tr>
<tr>
<td>Qingchuan</td>
<td>18</td>
<td>76</td>
<td>5</td>
<td>99</td>
<td>5</td>
<td>432</td>
<td>6</td>
<td>443</td>
</tr>
<tr>
<td>Maoxian</td>
<td>8</td>
<td>91</td>
<td>16</td>
<td>115</td>
<td>72</td>
<td>647</td>
<td>34</td>
<td>753</td>
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<tr>
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<td>2</td>
<td>29</td>
<td>25</td>
<td>686</td>
<td>10</td>
<td>721</td>
</tr>
<tr>
<td>Dujiangyan</td>
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<td>29</td>
<td>1</td>
<td>49</td>
<td>38</td>
<td>93</td>
<td>17</td>
<td>148</td>
</tr>
<tr>
<td>Pingwu</td>
<td>12</td>
<td>60</td>
<td>5</td>
<td>77</td>
<td>43</td>
<td>528</td>
<td>19</td>
<td>590</td>
</tr>
<tr>
<td>Pengzhou</td>
<td>8</td>
<td>70</td>
<td>0</td>
<td>78</td>
<td>170</td>
<td>368</td>
<td>14</td>
<td>552</td>
</tr>
<tr>
<td>Lixian</td>
<td>/</td>
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<td>/</td>
</tr>
<tr>
<td>Jiangyou</td>
<td>73</td>
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<td>39</td>
<td>452</td>
<td>26</td>
<td>106</td>
<td>0</td>
<td>132</td>
</tr>
</tbody>
</table>

(1) Threat to villages, towns, and cities, and resultant injury and death

It is estimated that the sediment disasters induced by the earthquake were the direct cause of 20,000 deaths. About one third of the fatalities can be attributed to the sediment disasters in the major disaster area. Thirty-one disastrous landslides caused 4996 fatalities in Sichuan Province. The landslide with the most disastrous results was the Wangjiayan landslide in Beichuan County, which caused 1600 deaths. Debris flows also caused great damage in the major affected area. For example, the earthquake area experienced debris flows during 22–24 September 2008, leaving 14 people missing and many people injured in the Maliuwan village of Leigu Town. A debris flow also buried many prefabricated houses, and a set of infrastructures were damaged (Fig. 4). On 23 July 2009 a debris flow suddenly broke out in the Xiangshui gully of Kangding County in Sichuan Province causing 15 fatalities and leaving 39 people missing (Fig. 5).

(2) Threat to main traffic arteries

As a direct result of the earthquake, many collapses, landslides, debris flows, and barrier lakes developed, which blocked the roads by which rescue services might reach the disaster area and significantly delayed rescue progress (Fig. 6). These sediment disasters threatened the safety of the important traffic artery during the time of earthquake relief. For example, the pier of the Chediguan Bridge on the 213 National Highway was smashed by large rocks, causing the death of six people and injury to 12.

The 213 National Highway was interrupted for 7 days as a result (Fig. 7). On 25 August 2009, many debris flows developed along the section of the 213 National Highway from Yingxiu to Wenchuan, again causing interruption of traffic on the 213 National Highway.
(3) Threat to people’s livelihoods and living quarters

The secondary sediment disasters washed away and submerged many houses and made many villagers homeless again. In addition, these secondary processes destroyed much cultivated land along the river banks, rendering them unsuitable for future cultivation, or at least making it very difficult to re-convert them to land that could be easily cultivated (Fig. 8). People’s livelihoods and living quarters were thus seriously threatened. In addition, the secondary sediment disasters induced by the earthquake washed much sand into the main river (Fig. 9) as well as causing violent uplift of the main river, causing serious damage to the ecological environment along the river banks.

2.2 Change in conditions of occurrence of sediment disasters

Precipitation is a very important condition that induces the occurrence of sediment disasters. After an earthquake, the critical rainfall required to trigger sediment disasters decreases. For example, the hourly rainfall intensity and the critical accumulated precipitation that induced debris flow after the Chichi earthquake in Taiwan decreased by one-third compared to that before the earthquake [Lin et al., 2003]. Taking the “9.24” debris flow in Beichuan County as an example, Tang and Liang [2008] analyzed the changes in occurrence conditions of debris flows after the earthquake. The antecedent precipitation (accumulated during the prophase of the debris flows) was 320–350 mm, and the critical
rainfall intensity required for the occurrence of debris flow was 55–60 mm/h in Beichuan County.

Based on the rainfall records of the Tangjiashan rainfall station (Fig. 10), the antecedent precipitation accumulated during the prophase was 272.7 mm, and the critical rainfall intensity inducing debris flows was 41 mm/h. Therefore, the prophase precipitation and critical precipitation for the occurrence of debris flow change considerably from before to after an earthquake. The prophase precipitation and the critical precipitation required for the occurrence of debris flows after the earthquake were smaller than those before earthquake. Taking Beichuan county as an example, the prophase antecedent precipitation necessary to initiate debris flow decreased by about 14.8–22.1%, and the hourly rainfall intensity decreased by about 25.4–31.6%.

3. TENDENCY PREDICTION AND COUNTERMEASURES

This large-scale earthquake resulted in dramatic changes to the landscape in the affected area, with major increases in the reserves of loose solid material and a much-enhanced threat of sediment disasters. Major earthquakes in history have caused large debris flows, landslides, and other sediment disasters for decades or even centuries after the main earthquake occurred. For example, in the case of the earthquakes that occurred in the Xiaojiang fault zone, Yunnan Province, in 1733 and 1833, sediment disasters such as collapse, landslides, and debris flows have continued during the 200–300-year period following the earthquakes and have occurred frequently up to the present time. Among the major effects triggered by Xiaojiang Earthquake, 15 debris flows have been reported in the Jiangjia gully, with about 3,000,000 tons of sand transported per year into Xiaojiang River, often blocking Xiaojiang and causing considerable damage. The Zayu M8.5 earthquake that occurred in Tibet on 15 August 1950 was followed by an outbreak of nearly 1000 debris flows in the 40 years after 1953. More than 600 debris flows occurred in the 20-year interval from 1953 to 1973, and an estimated total of up to 1.5 × 108 m3 of solid material was transported [Zhu et al., 1999]. Debris flows occurred in belts and groups after the Luhuo M7.9 earthquake in 1973 [Tian, 1986], and they have continued to occur frequently to the present day. Therefore, the development of sediment disasters in the Wenchuan area is worrying, and to protect people’s lives and property, as well to allow restoration and reconstruction work to be carried out smoothly, the need for reliable sediment-disaster forecasting is urgent.

3.1 Prediction Method
3.1.1 Monitoring of temporal and spatial variation in mountain surfaces

Fast and effective means of monitoring the dynamic changes underlying sediment disasters in affected area are available using GIS and remote sensing technology. Topographic changes in mountain surfaces and spatial distribution characteristics and changes in sediment disasters after earthquakes can be determined macroscopically. Such data combined with the information on the distribution of aftershocks allows for effective prediction of the development tendencies of sediment disasters. On the basis of this, the entire earthquake disaster area can be divided into zones according to the hazard levels, providing crucial information for choosing the location of reconstruction sites after the disaster and for designing major infrastructures.

3.1.2 The prototype observation of typical disaster spots

On the basis of temporal and spatial variations in the mountain surface, as determined by monitoring, along with additional knowledge about the distribution and occurrence of disasters, the prototype observation of a typical collapse and landslide can be carried out. By choosing typical disaster spots, the deposition of solid matter, the change of physical and mechanical properties, water content, displacement, and groundwater level can be monitored. The mechanism by which these sediment disasters occurred following the Wenchuan earthquake, given the conditions of a new underlying surface and the characteristics and development tendency of the disasters, can be determined, providing a basis for future disaster prevention and reduction.
3.1.3 Experimental and theoretical research

On the basis of surface monitoring and prototype observation, experiments (field experiments, indoor simulation experiments) and theoretical research examining the mechanical problems of sediment disasters after a major earthquake should be carried out. Using with remote sensing and prototype observations, models can be developed to estimate the likelihood of occurrence and the dynamics of sediment disasters in the Wenchuan earthquake disaster area. A model for evaluating the danger of sediment disasters in the Wenchuan earthquake disaster area can also be developed.

Research into how to predict the tendency for sediment disasters in the Wenchuan earthquake disaster area, as well as adoption of the methods of surface monitoring, placement observation, and pertinent research, should also include analysis of and comparisons with the research achievements in other areas with long observation histories and rich research data (such as the Xiaojiang watershed in Yunnan Province, Tibet, and Yakedake in Japan). Using this information combined with the specific details of the geological environment in the Longmen Mountains region, a model for the prediction of sediment disasters following the Wenchuan earthquake can be developed to provide a scientific basis for disaster prevention and reduction and to guarantee successful reconstruction in the disaster area, thereby preserving people’s lives and property.

3.2 Predicting the tendency of sediment disasters in the emergency phase

The establishment of a reliable model that can predict sediment disasters following an earthquake represents a long-term and continuous research challenge.

Focusing on the need for immediate post-disaster reconstruction and victim resettlement, attention should be paid to existing information from related areas, combined with data on the geographical characteristics of the Longmen Mountains derived from remote sensing data. These sources of information can be combined to yield a preliminary prediction of the tendency for sediment disasters during the emergency phase after an earthquake. The model results can provide the necessary basis for the enacting particular emergency measures while considering the potential for sediment disasters.

![Diagram of debris flow forecast](image)

The major earthquake destroyed the weak mountain surface in the Wenchuan earthquake disaster area. Because of the earthquake load, the integrity of the mountain surface was destroyed, and the shear strength decreased so that the slope became unstable. Rain causes a decrease in slope stability once it infiltrates the surface. Therefore, the secondary sediment disasters, such as collapse, landslides, and debris flow are likely to be very active for a long time in the earthquake area.

The occurrence of debris flows after the earthquake shows a strong hysteretic quality. The movement of the abundant solid materials loosened by the earthquake was determined mainly by rainfall, which led to the debris flows observed in this region. After an earthquake, debris flows will increase in occurrence as the rainfall threshold needed to trigger a debris flow decreases (Fig. 11). For example, in the region of Hongkou in Dujiangyan and in Yinchang Gully in Penzhou, no occurrences of debris flows had been recorded in a very long time before the earthquake. However, following the earthquake, many debris flows have occurred.
3.3 Countermeasures

3.3.1 Emergency measures

To ensure the smooth progress of post-disaster reconstruction and resettlement work, it is essential to take appropriate countermeasures to prevent more damage from being caused by sediment disasters after the Wenchuan earthquake.

(1) Disaster investigation and risk assessment

Through systematic field investigation and discovery of previously hidden areas at risk for sediment disasters and by assessing the risk of future sediment disasters for a particular area, we can select a relatively safe area for the site of post-disaster reconstruction.

(2) Emergency engineering measures

In certain regions where reconstruction is needed but where sediment disasters cannot be avoided, it is essential to identify the characteristics, scale, and potential damage from the sediment disasters through detailed field investigation. In conducting such investigations, we can take appropriate emergency engineering measures to protect reconstruction projects.

(3) Monitoring and warning

As sediment disasters threaten important protection objects, villages, cities, highways, et al., it is essential to establish a comprehensive disaster monitoring and early-warning system to ensure the protection of lives and property.

(4) Treatment of barrier lakes

With respect to the barrier lakes triggered by the earthquakes, we should initially carry out a risk assessment of dam breakage. In terms of high-danger barrier lakes, it is essential to use artificial methods to mitigate any immediate danger from dam breakage, or at least reduce risks and losses as much as possible.

(5) Mass monitoring and prevention

To avoid further loss of life and property, it is essential to establish a mass monitoring and prevention system for timely detection and early warning of potential sediment disasters. In this way, when sediment disasters do occur, we can evacuate people as quickly as possible.

3.3.2 Long-term measures

Due to the hysteretic nature of sediment disasters following an earthquake, we should undertake not only emergency measures, but also long-term measures to protect infrastructures and important sites during post-disaster reconstruction projects.

(1) Regional risk zonation

By using 3S technology, RS, GIS, GPS, combining field investigation and prototype observation, and after analyzing the temporal and spatial distribution characteristics and development potential of sediment disasters, we can establish zoning based on regional risks. The results of such zonation can provide a basis for the general layout for post-earthquake reconstruction.

(2) Developing comprehensive disaster prevention and mitigation programs

Based on the monitoring of typical disaster points, prototype observation, and experimental study, we can develop comprehensive disaster prevention and mitigation programs that combine engineering and ecological measures, monitoring and warning systems, and emergency evacuation measures. We should protect the environment from damage induced by engineering activities and carry out ecological environment-restoration programs during post-earthquake reconstruction to achieve the restoration of the mountain environment, as well as to prevent or mitigate sediment disasters in the long-term.

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