Typhoon Rainfall and Landsliding in the Pacific Ocean Side of Japan

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ABSTRACT

Japan is an island chain located off the north-western rim of the Pacific Ocean. Generally, in Japan, precipitation occurs mostly during typhoon seasons on the Pacific Ocean side, and in winter (heavy snow) on the Japan Sea side. This paper deals with synoptic descriptions of failures that occurred in various areas, along with rainfall and failure relationships during the typhoons of 2004 in Shikoku. In this paper, the effective amount of rainfall that triggered landslides in the Shikoku Island during these typhoons was identified along with information of occurrence time and landslide-triggering thresholds for Shikoku Island were interpreted.

KEY WORDS: Typhoon; Shikoku, rainfall induced landslides; debris slides; debris flows; triggering thresholds.

INTRODUCTION

Experience shows that landslide occurrences on hill slopes have very close relationship with availability of water. As a result, many types of landslides occur after heavy rainfall in tropical and temperate climatic zones (Jakob and Weatherly, 2003). Landslides triggered by rainfall occur in most mountainous landscape of the world. They pose a significant natural hazard and they have a high damage potential. Many statistically meaningful analyses have been published to demonstrate threshold values of rainfall and landslide triggering (e.g., Caine, 1980; Wilson and Wieczorek, 1995; Crozier, 1999; Aleotti, 2004; Guzzetti et al., 2007). Within the last few years, many studies focusing on rainfall thresholds for triggering landslides with hydroclimatic condition, antecedent rainfall (Crozier, 1999; Glade et al., 2000), and hydraulic conductivity (Terlien, 1998) were conducted. In this context, this paper describes some scenarios of rainfall-triggered landslides that occurred in Shikoku Island, Japan (north western Pacific Ocean side) during various typhoon events in 2004.

It is 225 km long and 50-150 km wide, with more than 80% of land consisting of steep mountain slopes. It is a heavily forested mountainous region of Japan. It has a few plain areas along the coastal lines and elevated peaks in the central part. There are only small villages on the mountains but the mountain bases are considerably populated. The mean annual precipitation of Shikoku ranges from 3,500 to 1,000 mm. Shikoku Island can be roughly divided into three geological zones: Ryoke, Sambagawa-Chichibu, and Shimanto belts from north to south (Fig. 1).

The three zones are bounded by two northerly dipping major faults, the Median Tectonic Line (MTL) and the Butsuzo Tectonic Line (BTL) from north to south, respectively. The Ryoke Belt consists of late Cretaceous granitic rocks, late Cretaceous sedimentary rocks (Izumi Group), and Miocene volcanic rocks (Samuki Group). Cretaceous granite is widely distributed in the north of Seto Inland Sea. The MTL topographically marks a distinct sharp boundary for Shikoku Range. This range, with a maximum altitude of nearly 2,000 m, is occupied by the Sambagawa-Chichibu Belt. The Sambagawa Belt is composed of low-grade metamorphic rocks. The southern Chichibu Belt is mainly composed of carboniferous to Jurassic sedimentary rocks and low-grade metamorphic rocks. The Shimanto Belt consists of Cretaceous and Palaeogene sedimentary rocks and this belt occupies the two southern peninsulas protruding into the Pacific Ocean. The middle Miocene granitic and partially gabbroic rocks are sporadically distributed along the axes of Muroto and Ashizuri peninsulas.

Owing to the geological and morphological settings, landslides and floods caused by typhoon rainfall are frequent in Shikoku. Also, in 2004, Shikoku experienced extreme events of typhoon rainfall and faced huge losses of life and property. In this paper, rainfall events due to typhoons of 2004 are critically evaluated and landslide events during the rains are also described. The main objectives of this paper are (a) to document the pattern of landslides in response to the typhoon rainfall events of 2004, (b) to derive the intensity-duration relation of rainfall that triggered the landslides during the typhoons of 2004, and (c) to determine the effect of typhoon rainfall on the different geological and physiographical terrain of Shikoku Island.

TYPHOONS IN JAPAN AND SHIKOKU

Typhoons are the most significant meteorological events for natural disasters on earth, which are caused by strong winds, heavy rains, river floods, storm surges, and high waves. It is noticed that the horizontal scale of a typhoon ranges from several 100 km to a few 1,000 km, while that of the cumulonimbus clouds is in the order of 10 km (Tsuboki, 2005). The heavy rain is usually localized in the eye wall and spiral rainbands. From 1951 to 2005, there were 1,468 typhoon events in the northern part of the Pacific Ocean, 163 of which hit the Japanese archipelago. In 2004, Japan was hit by 10 typhoons which are the maximum annual typhoon events within the last 55 years (Fig. 2) and the lowest number of typhoons occurs in February, whereas the highest number is in August (Fig. 3).
Fig. 1. Geological map of Shikoku Region (modified after Hasegawa and Saito, 1991), location of Shikoku in Japan is shown in inset.

Fig. 2. Number of typhoon events in Japan during last 55 years (source: Digital Typhoon, 2006 and JMA, 2005)

Fig. 3. Total typhoon events in North Pacific Ocean, Japan and Shikoku during last 55 years (source: Digital Typhoon, 2006 and JMA, 2005)

But, in Japan, the months of January, February, March, and December do not have any typhoon records and it is most abundant in months of August and September. Similarly, there were some records of typhoon in June and July to October. As seen in the isohyetal map of Shikoku, the island usually gets more extensive typhoon rainfall in its southern part than in its northern part (Fig. 4). The last 30-year rainfall pattern (Fig. 4) shows that mostly Kochi and Tokushima as well as the southern part of Ehime receive extreme rainfall. High-intensity rainfall is concentrated over most parts of Kochi and Tokushima prefectures. The elevated peaks in central Shikoku Island are the main cause of rainfall concentration in these two prefectures. Rainfall-related slope failure phenomena are very common in central and southern Shikoku. However, north Shikoku (Kagawa) has also been suffering from some events of failure. Fig. 5 illustrates the condition of rainfall-related disasters in four prefectures of Shikoku. In 2004, 10 typhoons hit the Japanese archipelago and nine of these affected Shikoku Island (Table 1). Storm and flood damages in 2004 resulted in a total of 227 persons killed and missing in the whole of Japan, which is the highest number since 1984 (JMA, 2005). Ehime, Kochi, and Kagawa prefectures were mostly affected by typhoons 23 and 21 whereas typhoons 4, 6, 10, 11, 15, 16, and 18 resulted in extensive damage and loss of lives in Kochi, Tokushima, and Ehime. The number of typhoon events and the damage outlines are given in Fig. 6. In 2004, rainfall intensity was abnormally greater than those of previous typhoon events.

DATA COLLECTION

In this paper, presenting data of all landslide events is almost impossible; however significant events were documented using sources such as field visits, government records, scientific publications, and technical notes. One interesting feature of the landslide data is good information about rainfall and timing of landslides for nearly 20 landslide events.
Table 1. Typhoon in Shikoku Island in 2004, rainfall values are taken from AMeDAS, JMA, 2005.

<table>
<thead>
<tr>
<th>Name of Prefecture</th>
<th>Typhoon No.</th>
<th>Date</th>
<th>Name of Typhoon</th>
<th>Min. Pressure (hPa)</th>
<th>Maximum Values</th>
<th>Cumulative (mm)</th>
<th>Rain gauge Station</th>
<th>Number of Places</th>
</tr>
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</tr>
<tr>
<td>Kochi</td>
<td>4</td>
<td>6/11</td>
<td>Conson</td>
<td>960</td>
<td>Kochi</td>
<td>118</td>
<td>Saga</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6/19-6/21</td>
<td>Dianmu</td>
<td>915</td>
<td>Tokushima</td>
<td>138</td>
<td>Asahimaru</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7/31-8/2</td>
<td>Namtheun</td>
<td>935</td>
<td>Tokushima</td>
<td>124</td>
<td>Sawadaani</td>
<td>900</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8/3-5</td>
<td>Malou</td>
<td>996</td>
<td>Tokushima</td>
<td>188</td>
<td>Asahimaru</td>
<td>800</td>
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<tr>
<td></td>
<td></td>
<td>8/17-18</td>
<td>Megi</td>
<td>970</td>
<td>Tokushima</td>
<td>386</td>
<td>Ikegawa</td>
<td>700</td>
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<td></td>
<td></td>
<td>8/29-30</td>
<td>Chaba</td>
<td>910</td>
<td>Tokushima</td>
<td>507</td>
<td>Jojusha</td>
<td>600</td>
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<td></td>
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<td>9/7-8</td>
<td>Songda</td>
<td>925</td>
<td>Kochi</td>
<td>536</td>
<td>Kamihayashi</td>
<td>500</td>
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<td></td>
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<td>9/29-30</td>
<td>Meari</td>
<td>940</td>
<td>Ehime</td>
<td>168</td>
<td>Tomisato</td>
<td>400</td>
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<tr>
<td></td>
<td></td>
<td>10/19-21</td>
<td>Tokage</td>
<td>940</td>
<td>Ehime</td>
<td>542</td>
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</tr>
</tbody>
</table>

Therefore, such data were used to do a representative analysis of rainfall and failure relationship. Aerial photographs taken after the event, maps, and personal and public documentation were also considered to enable landslide inventory maps of some representative areas to illustrate the problem.

In 2004, Shikoku Island faced one of the worst disaster events in the history of Japan. A scenario of occurrences of landslides in Shikoku Island after the 2004 typhoons is shown in Fig. 7. Although nine typhoons affected the island, the more effective typhoons were only six (Typhoons No. 10, 11, 15, 16, 21, and 23).

But all six typhoons did not bring torrential rainfall in the whole island. Some typhoons 10, 11, 15, 16, and 21 were more aggressive in Tokushima, Kochi, and Ehime, whereas typhoons 15, 21, and 23 were most troublesome for Kagawa Prefecture. A greater concentration of landslides was noticed mainly in Kagawa Prefecture, that year’s third most disaster-affected prefecture in the whole Japan. Based on available information, the different typhoons hit various places and significant damage was observed in areas of maximum rainfall concentration. Example of such events within each prefecture is described in the following sections.

**Landslides in Tokushima**

From late July to early August, typhoon 10 brought heavy rainfall (more than 2000 mm) to the southern part of Shikoku. This typhoon rainfall created four huge landslides around the Kisawa village of Nakagawa, occurring mainly in the Ooyochi, Kashu, Azue, and Shiraishi area (Fig 8).
In Kaminaka, data recorded by Shikoku Electric Power Co. Inc. showed hourly rainfall reaching more than 120 mm; the highest daily precipitation (1,317 mm) was on 1 August 2004 (Fig. 9). It is believed that this value surpassed the previous record held by Kito (1,114 mm). This village is 16 km southwest of Kisawa village and was visited by Typhoon Fran on 11 September 1976 (Wang et al., 2005). Similarly, typhoons 6, 11, 16, 18, and 23 also hit Tokushima Prefecture and small- to medium-scale landslides were reported along national and express highways and also in the Naka River catchments. The failure areas of Kisawa and Kaminaka area were more affected by rainfall from typhoons 11, 16, 18, and 23. Some 550 mm of rain fell in Uekatsu, Tokushima during typhoon 16. Likewise, a daily rainfall of more than 300 mm was recorded in the southwestern part of Tokushima.

Fig. 9, Rainfall pattern in Kaigawa area during Typhoon 10 (31-Jul to 2 Aug, 2004), this hyetograph represent one day maximum precipitation ever recorded in Japan (source: Shikoku Electric Power Co. Inc.)

The Ooyochi landslide occurred at 20:00-23:00 h of 1 August and Azue was advanced (2300 h, 2 August) after a total relaxation of typhoon rainfall around 16:00 h of 2 August (Fig. 10).

The area mainly consists of Palaeozoic greenstone, Palaeozoic and Mesozoic pelite and greywacke, and serpentinite of the Mesozoic Kurosegawa terrain, as well as scarce limestone and chert. On the landslide area, cedars are the main species in the forest. The river valley is steep and most of the settlements are located on gentle slopes formed by past landslide materials and on narrow riverside terraces.

Fig. 10, Rainfall pattern and time of landslide in Kisawa area during typhoon 10

**Landslides in Ehime**

Ehime prefecture also suffered tremendous losses due to debris flows and flooding induced by the typhoon rainfall of 2004. Typhoons 15, 16, 18, 21, and 23 affected Ehime in 2004. In these typhoon events, hourly rainfall exceeding 50 mm and total rainfall of more than 400 mm were recorded in many stations. Rainfall due to typhoons 15 and 21 triggered many landslides at different locations in northeast Ehime. The hardest hit area was Niihama City (Fig. 11). The debris flows near the hill base of this city took the lives of some 25 people and destroyed property worth 40 billion yen (Bhandary and Yatabe, 2005). Geologically, Niihama consists of green schist of the Sambagawa Belt in the south and sandstone and shale of the Izumi Group in the north. The area that suffered extensive failure during the disaster is part of the Izumi Group. This geological belt is primarily made of sedimentary deposits of sandstone with frequent intercalation of shale. Most of the failed slopes consist of decomposed sandstone, either stiff clay resulting from weathering of shale or less disintegrated rock mass. For many landslide researchers, the Izumi Group used to be little known in relation to debris flow or landslide disaster. But, in 2004, during typhoons 15 and 21, the intensity of rainfall was so high that hundreds of landslides and debris flows occurred. Typhoon 23 also triggered many landslides in Ehime. Slope failure events in Ibukimachi (Uwajima City), Kawanouchi (Touon City), and Shingumachi (Shikoku Chuo City) are some other examples (see Fig. 7).

Fig. 11, Landslides in Takamatsu-Matsuyama Express Highway at Niihama, Typhoon 21, September 29, 2004 (source: MLIT, 2004)
Landslides in Kagawa

Kagawa Prefecture was hit mainly by four typhoons (15, 16, 21, and 23) in 2004 and suffered loss of lives and property because of many landslides triggered by typhoon rainfall. Although mean annual rainfall of Kagawa is less than 1000 mm, it was the most affected prefecture in 2004. It was observed that hourly rainfall exceeding 50 mm and total 24-h rainfalls of more than 200 mm were the main causes of slope failure at different locations in Kagawa. The hardest hit areas were Moriyuki and Monnyu of Kagawa Prefecture. There was localized damage in the highway and forest area also around Takamatsu City (Fig. 12). Central Kagawa is also affected by many landslides occurred in the forest.

In Toyohama and Onohara, west Kagawa, a heavy rain in the afternoon of 17 August due to typhoon 15 killed five persons despite a few landslides and debris flow events. The rainfall that started only from 11:00 h of that day was enough to create failure in both towns during the typhoon. In the case of typhoon 21, extensive damage was observed in the whole area. During typhoon 15, a total of 246 mm of rainfall was recorded in 24 h, with maximum hourly rainfall of 54 mm. Similarly, during typhoon 21, 249 mm of rainfall occurred with a maximum 1-h rainfall of 65 mm. Almost all streams coming from the mountain slopes brought a huge pile of debris. During typhoon 23, in east Kagawa, hourly rainfall reached 125 mm in Maeyama. Likewise, Kusaka Pass received a maximum of 116 mm h\(^{-1}\) and Yodayama received 107 mm h\(^{-1}\). This extreme rainfall created many landslides and debris flow in the Shiratori, Moriyuki, Minamigawa, and Monnyu area (Dahal et al., 2008).

The Okawa area mainly consists of crystalline green schist of the Sambagawa Belt, which includes pelitic schist, psammitic schist, and siliceous schist. There are thin to thick deposits of quaternary colluvium on the mountain slope of the Yoshino River Valley. The crystalline schist is usually well known for landslide hazard and the sliding mass mainly consists of weathered and jointed schist (Hong et al., 2005).

Landslides in Kochi

In 2004, typhoons 4, 6, 10, 11, 15, 18, and 23 hit Kochi Prefecture. Rainfall caused by typhoon 15 (Megi) induced many landslides in the Yoshino River basin of Shikoku on 17-18 August. Reihoku District in Kochi Prefecture was greatly affected by typhoon 15. Okawa and Uwezugawa villages were severely damaged. Many landslides occurred along the roadside slopes too. As a result, Okawa was isolated from the other parts of the prefecture (Yatabe and Hasegawa, 2004). Rainfall data recorded in the Komatsu rain gauge station showed hourly precipitation exceeding 100 mm at 1600-1800 h of 17 August and total 24-h rainfall was 205 mm. Cumulative rainfall from 01:00 h to 18:00 h reached 518 mm with maximum rainfall intensity of 104 mm h\(^{-1}\). Total precipitation reached 1,000 mm in 3 days. Many landslides and debris flow occurred during 17:00-18:00 h of 17 August (Fig. 13).
Toyohama, Okawa, and Kisawa) were translational debris slides occurring first on steep zero-order valley or concave slope and debris materials were run down through first-order stream channel. Commonly, the slides are several to tens of meters wide and tens to hundreds of meters long. The slip surface, 0.3-2 m deep, was near the irregular contact between the colluvium and decomposed or fresh bedrock. All of these initial soil slides were mobilized completely to form debris flows and the liquefied debris also scraped off the saturated soil of the first-order gully and the whole mass of the channel began to flow, like a liquid following the liquefaction flow rule (Darve, 1996). The flow continued to erode its route and either piled up huge debris on the mouth of the stream or continued traveling through the second-order stream to a considerable distance on the sloping terrain. Therefore, during a field visit, the first-order streams were noticed as totally cleaned up (Fig. 15).

- In some cases, the down-to-top failure was also noticed and it was exactly like the headward erosion of the first-order stream onto the zero-order stream by extremely high rate of erosion. The Kashu landslide of Kisawa area is a suitable example of such failures.
- In addition, field observations pointed out that landslides were occurred both in natural and man-made slopes having thick residual or colluvial deposits.

Rainfall Intensity

The rainfall intensity threshold for triggering landslides is one of the debatable topics in the last 25 years. Caine first published a paper in 1980 about the threshold rainfall intensity for landslide triggering. After that, many attempts were done to establish the threshold rainfall intensity in the global and in the regional context. In the case of Shikoku, data of rainfall amount and exact landslide timing were collected from 18 major and minor landslide events. Although there were hundreds of landslides, only 18 landslide events were standardized with the exact time of occurrence. In terms of classification, all these 18 rainfall-triggered landslides were either debris slides or debris flows (Curden and Varnes, 1996) or flow-like landslides (Hung, 2001; Hung, 2003; Jakob and Weatherly, 2003). Fig. 16 illustrates the temporal pattern of rainfall intensity vs. duration conditions during the various typhoons of 2004. The continuous lines represent rainfall intensity vs. duration, whereas time of occurrence of landslides is shown as circular symbols. The upper graph (i) corresponds to rainfall recorded at the different rain gauge stations during typhoon 10 and the time of landslides are shown using circle symbols. Likewise, graphs (ii), (iii), and (iv) represent rainfall and times of occurrence of landslide during typhoons 15, 21, and 23, respectively, in different places of Shikoku. The data of effective temporal rainfall intensity for producing landslide vs. rainfall duration are also plotted in log-log graph to analyze the empirical rainfall thresholds (Fig. 17). It was noted that the intensity of rainfall to produce landslides around the Shikoku mountain range was higher than that in northeast Shikoku (area highly affected by typhoon events of 2004). Similarly, all failure events during various typhoons began only after a minimum of 10 h of continuous rainfall. However, during typhoon 23, the many failures began only after 35 h of continuous rainfall.

The threshold line of rainfall intensity proposed by various researchers (Caine, 1980; Cancelli and Nova, 1985; Wieczorek, 1987; Cannon and Ellen, 1985; Larsen and Simon, 1993; Ceriani et al., 1994; Crosta and Frattini, 2001; Zezere et al., 2005; Guzzetti et al., 2007; Dahal and Hasegawa, 2008) area also plotted in Fig. 17. A comparison of the curves showed that threshold rainfall to produce landslides for Shikoku (as per data on rainfall intensity of 2004 events) follows the threshold line for storm-triggering landslides proposed by Dahal and Hasegawa, (2008) for Himalaya (tropical monsoon region) and Larsen and Simon (1993) for Puerto Rico (humid-tropical region). The curve prepared by Dahal and Hasegawa (2008) using the 55-year data of the Nepal Himalaya showed relatively better congruence for the Shikoku data than the curve proposed by others for different part of world. The curve proposed by Caine (1980), Cancelli and Nova (1985), Ceriani et al. (1994), Crosta and Frattini (2001), and Alcotti (2004) for the Alps could not cover up the average rainfall intensity of Shikoku during failures due to the extreme rainfall events of 2004. The curves proposed by Wieczorek (1987) and Cannon and Ellen (1985) for the Rockies also do not have any similarity with the Shikoku data.

CONCLUSIONS

Based on the above observations, analyses, and discussion, the following conclusions are drawn.

- A study of the last 55-year of typhoon data shows that Japan is very susceptible to typhoon-brought rainfall disasters. Shikoku Island (northeast Pacific Ocean side) also has a severe problem of typhoon-brought, rainfall-triggered landslides.
The number of debris slides and debris flows of 2004 in Shikoku Island results from severe rainstorms brought by various typhoons, along with the presence of unstable colluviums, moderately to highly weathered rocks, and steep mountain terrains.

- Most of the slope failures are normally shallow and consist of translational slides, rotational slides, and combination of both. The flow of materials after failure along the first-order stream on steep mountain slopes (30°–45°) is a common scenario in many events.

Fig. 16, Temporal pattern of rainfall intensity vs. duration condition for the 2004 rainfall events. The left of the graphs represent initiation of rainfall. Symbols indicate the occurrence of landslides in Shikoku during various typhoon events of 2004.

- The rainfall pattern and failure process in central Shikoku and northeast Shikoku are entirely different because of bedrock geology, thickness of colluvium, permeability contrast between colluvium and bedrock, slope gradient, and average rainfall intensity.

- A study of average rainfall intensity during failure helps to gain an understanding, to some extent, of threshold rainfall intensity behind slope failure in Shikoku Island. When various threshold curves for rainfall-triggering landslides as proposed by different researchers are compared with Shikoku data, the curve proposed by Larsen and Simon (1993) for Puerto Rico (humid-tropical region) and Dahal and Hasegawa (2008) for the Nepal Himalaya (tropical monsoon region) more or less reflect the data of average rainfall intensity during failure in Shikoku due to the 2004 extreme rainfall events. However, historical average rainfall intensity and failure data of Shikoku need to be analyzed in detail to understand the threshold curve for Shikoku. The 2004 data certainly give some helpful insights. Shikoku has very similarly in geological settings with Himalaya (Kikkawa, et al., 2003) and rainfall threshold also shows such similarity in some extent.

- Further studies to investigate hydrological responses of mountain slopes and mechanical behaviour of soils from major to minor catchments scale are essential to understand the local variation in rainfall intensity thresholds. The influence of antecedent rainfall, if there is any, should also be incorporated in such a study.

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REFERENCES


