

Failure characteristics of rainfall-induced shallow landslides in granitic terrains of Shikoku Island of Japan

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Abstract Soil slips, debris slides, and flow occurrences on hill slopes of particular areas are closely related to the mode of rainfall. Because of geological, geomorphological, and climatic settings, Japan is highly prone to rainfall-induced landslides. In 2004, Shikoku, the smallest island of Japan, faced extreme events of typhoon rainfalls and suffered huge losses of life and property because of floods and landslides. This paper deals with the synoptic descriptions of failures that occurred in the granitic terrain of northeast Shikoku Island, Japan, along with rainfall and failure relationships during the typhoon 0423 (Tokage) of 2004. Examples of typical failures that occurred in Moriyuki and Monnyu of northeast Shikoku are taken into consideration in this study. Data from laboratory and field were used to perform sensitivity and stability analyses with respect to varying slope angles, strength parameters, and thicknesses of saturated residual soil. This study attempts to employ a standard method of stability analysis of translational slides, which are very common in masa soil (weathered granite) during extreme rainfall. Average rainfall intensities and

duration during typhoon Tokage were also used to interpret landslide-triggering thresholds for the study area.

Keywords Rainfall-induced landslides · Typhoon · Stability analysis · Rainfall intensity · Triggering threshold

Introduction

Shikoku is the smallest of the four main islands of Japan (total area: 18,800 km²), situated south of the island of Honshu and east of the island of Kyushu, between Seto Inland Sea and the Pacific Ocean. 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. It has a few plain areas along the coastal lines and elevated peaks in the central part. The highest peak of Shikoku is Mount Ishizuchi (1,982 m). There are small villages on the mountains, but the mountain bases are considerably populated. The mountains are almost completely covered with thick forests of subtropical broadleaved trees, Japanese cedars, and Japanese bamboos. The mean annual precipitation of Shikoku ranges from 3,500 to 1,000 mm. Due to the geological and morphological settings, landslides and floods caused by typhoon rainfalls are frequent in Shikoku.

In 2004, Shikoku experienced extreme events of typhoon rainfall and faced huge losses of life and property. Kagawa Prefecture, the northeastern prefecture of Shikoku, was hit by four typhoons (0415, 0416, 0421, and 0423) in 2004 and suffered loss of lives and property owing to the many landslides triggered by the typhoon rainfall. Although the climate of the northern part of Shikoku Island is the inland-type climate, like the Mediterranean region, and subsequently has less rainfall (annual rainfall 1,000 mm only),

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the area sometimes suffers from extreme typhoon-brought rainfall, which sometimes exceeds 750 mm in 1 day.

Moriyuki and Monnyu, situated in the eastern part of the Kagawa Prefecture (Fig. 1), were hardest hit by the typhoon 0423 (Tokage) in 2004. From 19 through 20 October 2004, typhoon 0423 produced 674 and 495 mm of rain in a 48 h period on Moriyuki and Monnyu of eastern Kagawa, respectively. On 20 October, a rain-gauge station in the Kusaka pass (located within 1 km aerial distance from Moriyuki) recorded 582 mm of rain in 24 h with a maximum 116 mm/h rainfall intensity. Likewise, Monnyu area has a reservoir for irrigation water supply in east Kagawa and has a rain gauge station close to the failure sites. In this rain gauge station, on 20 October, 412 mm of rain was recorded in 24 h with a maximum 76 mm/h rainfall intensity (Figs. 1, 2).

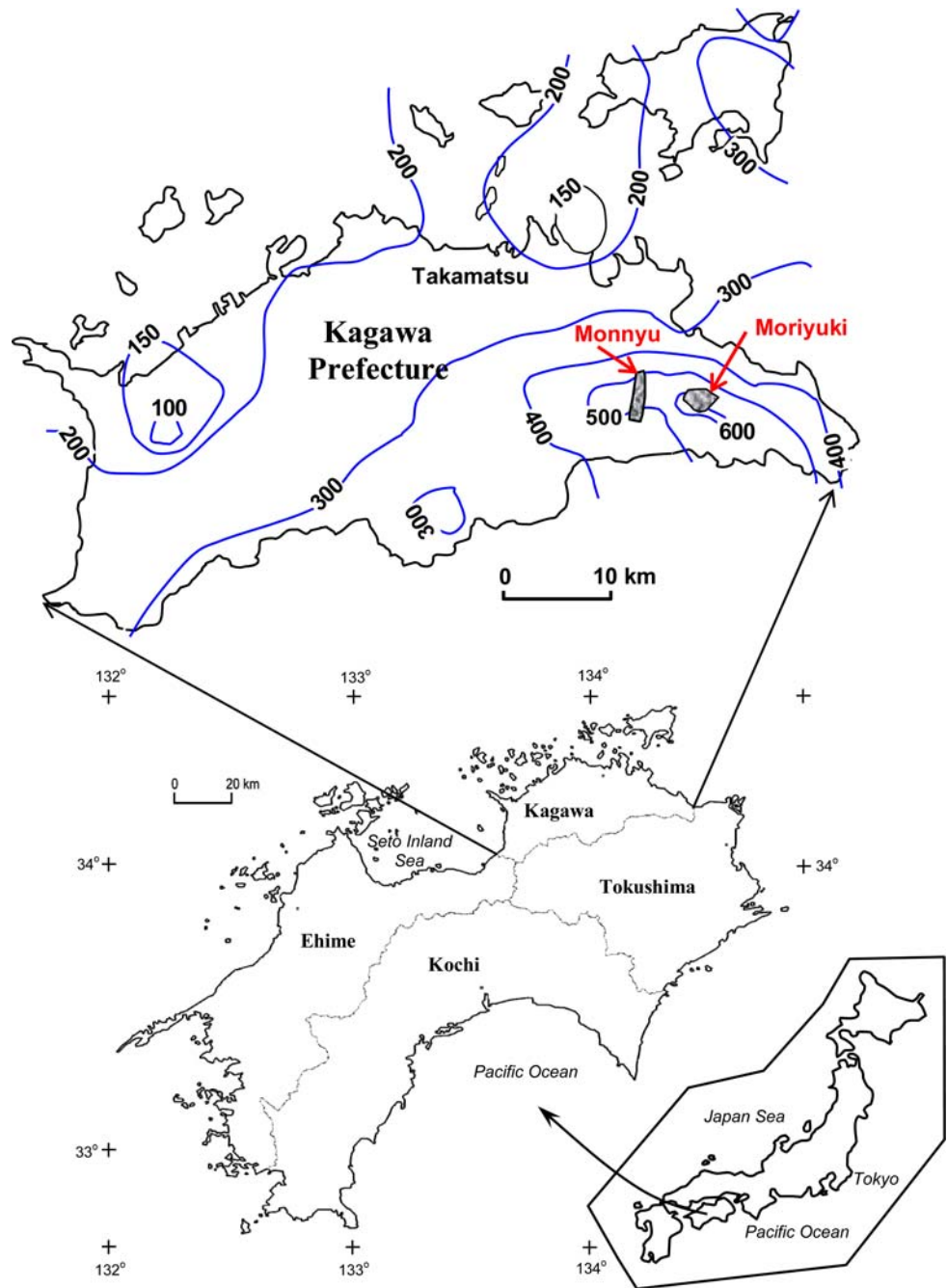
These are the highest precipitations of those areas in the last 30 years. These rainfall events of October 2004 triggered more than 300 landslides in Moriyuki and Monnyu catchment area, and debris flow occurred in the Moriyuki and Monnyu rivers. Field observation indicated that the slides occurred mainly in residual soils that layer forested or partly forested slopes. In both catchments, the basement rock is Cretaceous granite and granodiorite. Few slides were also noticed on weathered colluvium and roadside debris. Most of the slides were shallow and translational in nature, with the failure surface located along the contact between relatively less weathered bedrock in varying depth. In both areas, the granitic bedrock belongs to the Izumi group of Cretaceous age (Hasegawa and Saito 1991). Microscopic and X-ray diffraction studies of granite and granodiorite of the Moriyuki and Monnyu areas show that granite mainly consists of quartz, potassium feldspar, and plagioclase as major mineral constituents along with few amounts of pyroxene, whereas granodiorite is mainly rich in quartz, plagioclase, and potassium feldspar with abundant hornblende. The weathered rock material consists of clay minerals like kaoline, chlorite, vermiculite, lepidolite, and smectite.

The rainfall-induced shallow landslides in both colluvial and residual soils are of great interest to many researchers. Durgin (1977) discussed the relationship between the weathering stages of granite and the occurrence of landslides, and pointed out that shallow landslides or debris avalanches occur distinctively in decomposed, weakly weathered granitic areas. Japan has undergone many recurring disasters in its granitic areas. During such events, landslides and surface erosion injected slugs of weathered granite (masa, in Japanese) into the small rivulets and even in big rivers. Oyagi (1968) reported that numerous shallow landslides occurred in areas of weakly weathered granite after a rainstorm in Shimane Prefecture, western Japan, in 1964. Onda (1992) studied weathering profiles of granite

underlying Obara village, Aichi Prefecture, central Japan, where numerous landslides occurred following a heavy rainfall in 1972. Japan has sustained many recurring disasters in granitic areas following heavy rains, resulting in a total of more than 1,000 casualties over the last 65 years (Chigira 2001). Such recurring disasters are possible because the weathered granite had the potential for repeated landslides since the failures exposed rock having low shear strength and the depth of weathering stages could be related to long-standing erosion base levels (Durgin, 1977). Such fast weathering phenomena and repeated failure mechanism on granitic terrain have been also studied by Chigira and Ito (1999) on artificial cut slope of Japan. Not only in Japan but also in other granitic terrain of the humid and tropical regions, shallow failure phenomena are very common. In the granite and gneiss areas of Rio de Janeiro in 1966 and 1967, severe rainstorms resulted in tens of thousands of landslides and about 1,000 casualties (Durgin 1977). During the main rainfall months of May to September in Hong Kong, numerous landslides occur in cut and natural slopes of soils formed by the residual soils over granite and granodiorite of Jurassic to Cretaceous age (Irfan 1998; Dai et al. 1999, 2003). Moreover, two-thirds of the land area of the Korean peninsula is composed of soils formed by the weathering products of granite and gneiss. During heavy rainfall, many slope failures in these weathered rocks are usually characterized by relatively shallow failure surfaces (typically 2–3 m depth) that develop parallel to the original slope (Kim et al. 2004). Southern Italy also has suffered from landslides in weathered granite (Calcaterra et al. 1996).

Hydrological response of weathered granite during heavy rainfall and occurrences of shallow failure as well as slope stability analysis have been studied by many researchers (e.g., Okimura and Kawatani 1987; Okagbue 1989; Gokceoglu and Aksoy 1996; Dykes and Thornes 2000; Rezaur et al. 2002; Rahardjo et al. 2001; Dykes 2002; Casadei et al. 2003; Vieira and Fernandes 2004; D'Amato Avanzi et al. 2004; Jworchan. 2000; Huat et al. 2005; Mukhlisin et al. 2006). These, as well as other several studies, on rainstorm-related disasters have indicated that shallow landslides in granitic areas are closely related to weakly weathered decomposed granite, rather than to heavily weathered thick saprolite. Moreover, these works also suggested that soil slips on steep hillsides occur after the residual soil over saprolite has reached field capacity (Veihmeyer and Hendrickson 1931), i.e., the moisture at which water flows, under gravity, out of the soil zone as fast as it flows in, followed by intense rainfall that is sufficient to exceed the infiltration rate of saprolite or partially weathered rock material underlying the residual soil. Under this condition, the rainfall intensity exceeds the infiltration rate of the underlying saprolite or partially weathered rock and a perched water table would begin to form inside the

Fig. 1 Location of Moriyuki and Monnyu in northeast Shikoku, Japan and rainfall isohyetal map during typhoon 0423 (19 and 20 October, 2004)

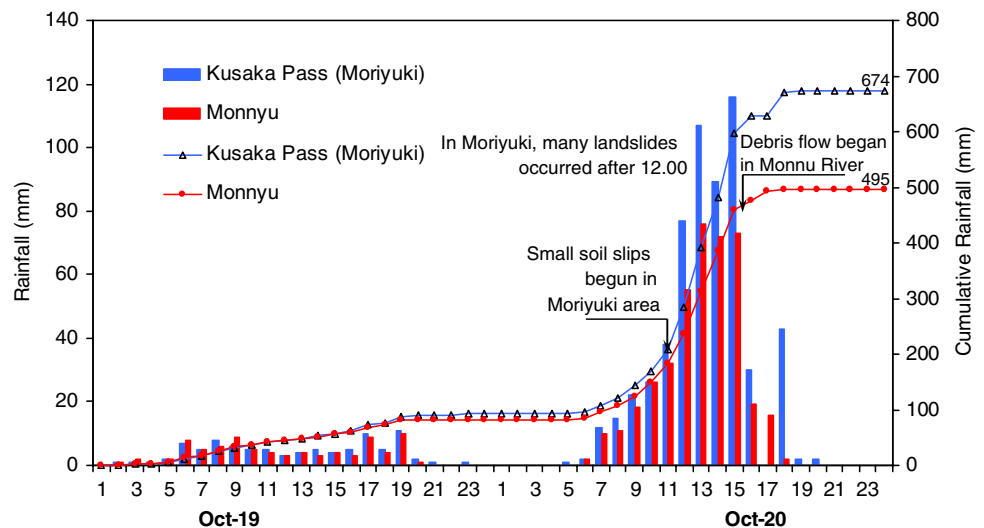


slope layer. The configuration of such water tables has been usually predicted to be parallel to the slope. The longer the heavy rain continues, the higher the piezometric head may rise and greater will be the increase in pore pressure near the base of the residual soil. Failure occurs when pore pressure exceeds some critical value. Rohardjo et al. (2005) discussed about the difficulties that lie in the quantification of the flux boundary condition across the slope surface with respect to rainfall infiltration and its effect on the pore water pressure conditions in the slope. However, they have also mentioned that the response of residual soil slope to

infiltration is still not fully understood. Similarly, some of the research on weathered granite discussed about closely spaced, near-horizontal joints developed by the unloading effect on the granitic body, also responsible for the failure in weathered granite. Chigira (2001) mentioned that the landslides that occurred in the Hiroshima Prefecture in June 1999 were closely related to micro sheeting (closely spaced near horizontal joints) of granite.

A large majority of slope failure are triggered by extreme rainfall, and therefore a number of researchers (Campbell 1975; Caine 1980; Pomeroy 1984; Neary and

Fig. 2 Rainfall pattern and time of failures in Moriyuki and Monnyu catchments during typhoon 0423



Swift 1987; Keefer et al. 1987; Yano 1990; Wilson and Wiczorek 1995; Wiczorek 1996; Terlien 1998; Crosta 1998; Crozier 1999; Glade et al. 2000; Wiczorek et al. 2000; Iverson 2000; Aleotti 2004; Guzzetti et al. 2004; Micos et al. 2004; Zezere et al. 2005; Giannecchini 2006; Guzzetti et al. 2007; Dahal and Hasegawa 2008) have attempted to establish rainfall-intensity thresholds so that predictions about slope failures can be made. A threshold is a defined set of values of rainfall intensity that facilitates slope instability for a given region (Wiczorek 1996). However, previous studies concerning threshold values focused only on the peak rainfall amounts that were considered to have triggered slope instability. From the study of published research works, it is realized that generally two types of thresholds can be established for rainfall (Aleotti 2004), empirical thresholds and physical thresholds. Empirical threshold is based on the statistical analysis of relationship between rainfall and landslide occurrences (Campbell 1975; Caine 1980; Larsen and Simon 1993; Crozier 1999; Guzzetti et al. 2004, 2007; Dahal and Hasegawa 2008), whereas physical threshold is usually described with the help of hydrologic and stability models, which consider parameters like relationship between rainfall and pore water pressure, suction, infiltration, slope morphology, and bedrock structures, etc (Montgomery and Dietrich 1994; Wilson and Wiczorek 1995; Crosta 1998; Terlien 1998; Crosta and Frattini 2003).

Likewise, antecedent rainfall (Wilson 1997; Crozier 1999; Rahardjo et al. 2001) plays an important role in the determination of a rainfall threshold. Rahardjo et al. (2001) found that in residual soil (over sandstone) of Singapore, the antecedent rainfall during the 5 days preceding the main rainfall event was significant in causing landslides, since other rainfall events of similar magnitude (but with less antecedent rainfall) did not cause landslides. With the help

of numerical modeling, they concluded that the antecedent rainfall does play an important role in slope stability.

Keeping these review of previous research in residual soil and threshold rainfall for the failure, the sites of Moriyuki and Monnyu of northeast Shikoku were selected in this study for detailed study of shallow landslides in granitic terrain.

The shallow landslides induced by typhoon-brought rainfall in Moriyuki and Monnyu areas of northeast Shikoku, Japan, were not noticed during the last 30 years of typhoon. Therefore, the study presented in this paper was undertaken to accomplish the following objectives:

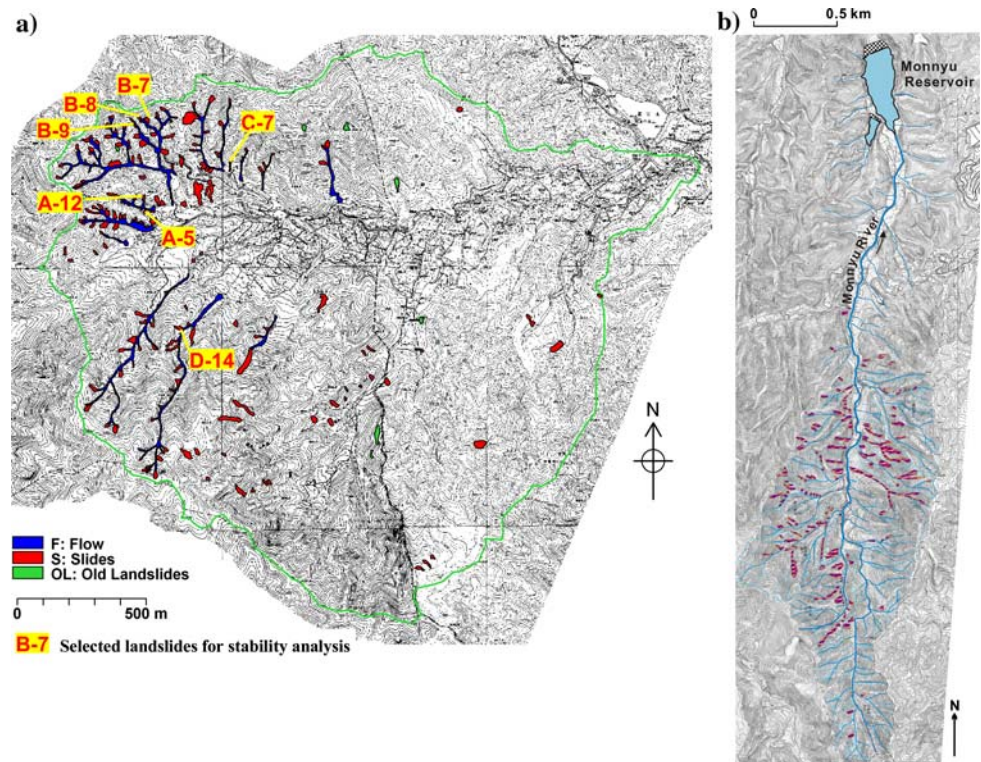
- Investigate the nature (length, height, depth, classification, etc.) of typhoon-brought rainfall-induced landslides at granitic terrains of Moriyuki and Monnyu areas, as well as the relevant slope characteristics such as slope morphology and slope angle.
- Determine the relevant engineering properties of residual soil material from selected landslides of Moriyuki.
- Conduct sensitivity and stability analyses for the selected landslides of the study area and build up an easier technique to analyze stability of residual soil in granitic terrains of Japan.
- Compare the rainfall intensity and duration values that triggered the landslides in the study area with previously established threshold values.

Methodology

Landslide mapping

Detailed field visit has been carried out in the Moriyuki and Monnyu areas after typhoon in order to map the existing

Fig. 3 Landslide inventory maps of (a) Moriyuki and (b) Monnyu catchments



landslides on a 1:2,500 scale topographic map prepared by the Kagawa Prefecture office. All failures, including the flow path of failure materials, were also mapped out during the field visit. Color aerial photographs taken immediately after the events (November 2004) were also studied to check the correct boundary of the landslides. Altogether, 201 small-scale slides were noticed in the Moriyuki catchment and 142 in the Monnyu catchment after typhoon 0423 (Tokage). The total of 76 landslides of the Moriyuki and 40 landslides of the Monnyu area were investigated in field (Fig. 3) for analysis of the nature of the slides (length, height, depth, classification, etc.). These landslides were selected on the basis of the following considerations:

- Variations in landslide size, depth, and relative location with respect to slope face and slope morphology (concave, convex, and planar) among the total sites.
- Variations in slope orientation, slope height, slope angle, extent of vegetation, and thickness of failure.
- Accessibility of slope with respect to investigations and measurements.

Field investigations

Field investigations involved detailed study of failure site geomorphology and landslide characteristics at each site and collection of samples for laboratory investigations from some selected sites. A sheet of data collection prepared for

collection of landslide data and all parameters mentioned in the sheet were collected in the field. The geomorphology of sites included a record of the slope orientation, length, height and angle, and type and extent of vegetation. Description of landslide characteristics consisted of documentation of the landslide dimensions, including length (measured along the strike direction of the slope), height (measured along the dip direction of the slope), depth (measured vertically on slope face), and type of movement according to the classification described by Cruden and Varnes (1996). Additionally, an estimate of the thickness of failed soil mass was made at each site, the presence or absence of groundwater seepage was also recorded, and the location of landslides with respect to slope face and vegetation was also noted. Finally, to understand the geotechnical characteristics of materials involved in slides and to perform stability analysis, samples of the residual soil were collected from 16 sites of Moriyuki and Monnyu.

Laboratory investigations

A series of laboratory tests was conducted to determine the relevant engineering properties of the landslide-prone residual soils. All tests were performed according to the standards of the Japanese Geotechnical Society (JGS) and Japan Industrial Standard (JIS). The soil grain density of residual material at each site was determined with the help of the density tube in accordance with the specifications

outlined in the Japan Industrial Standard (JIS) Procedure A1202. Information on density was used for sensitivity and stability analyses. Other tests performed included the grain size distribution and permeability. Laboratory shear test in remolded soil (JGS 0560-2000) was also performed. Generally, three to five samples were tested from each site to determine a given property and the average values were computed. The falling-head permeability test (JIS A1218) was used to evaluate the drainage characteristics of the residual soils. Permeability is a direct measure of a hydraulic conductivity of soil and it is an important parameter in the evaluation of pore-water pressure rise.

Results of investigation

Characteristics of landslides

To understand the landslides morphology, characteristics, and classification, a total of 76 landslides of Moriyuki and 40 landslides of Monnyu area were investigated and measurements were taken. From the field investigation, it was noticed that more than 70% of landslides were mainly concentrated in the valley or topographic hollow or concave type of slopes. Very few slides were noticed on spur or convex slopes (Fig. 4a). Similarly, the slope angle of failed slopes was also varied in both areas. More than 50% of slides in Moriyuki occurred in slopes having slope angle of 40°–45°, whereas in Monnyu, nearly 80% of slope failures were noticed on the slopes, which had a slope angle of 35°–45° (Fig. 4b). The frequency of occurrences of slides was also investigated with respect to natural and artificially modified slopes. The slopes were artificially modified basically for excavation of road, trails, and tracks, as well as terracing for orange farming after the Second World War. Figure 4c shows the result of field data. More than 70% of slides in Moriyuki occurred on natural slopes, whereas only 5% of slides at Monnyu were on modified slopes.

To classify the slides according to the classification proposed by Cruden and Varnes (1996), detailed longitudinal sections of slopes were investigated in the field. Mainly, translational sense of movement was noticed in all failures (Fig. 5). However, slightly curved failure surfaces were also noticed along with combination of both translational and rotational sense of movements. Thus a total of three categories, translational, semi-translational, and compound, were recognized during investigation. The term “semi-translational” was used to describe translational sense of movement, but having a slightly curved section and not a perfect rotational section as described by Cruden and Varnes (1996).

Figure 4d shows the sense of movements in all slides and more than 50% of slides had a translational sense of

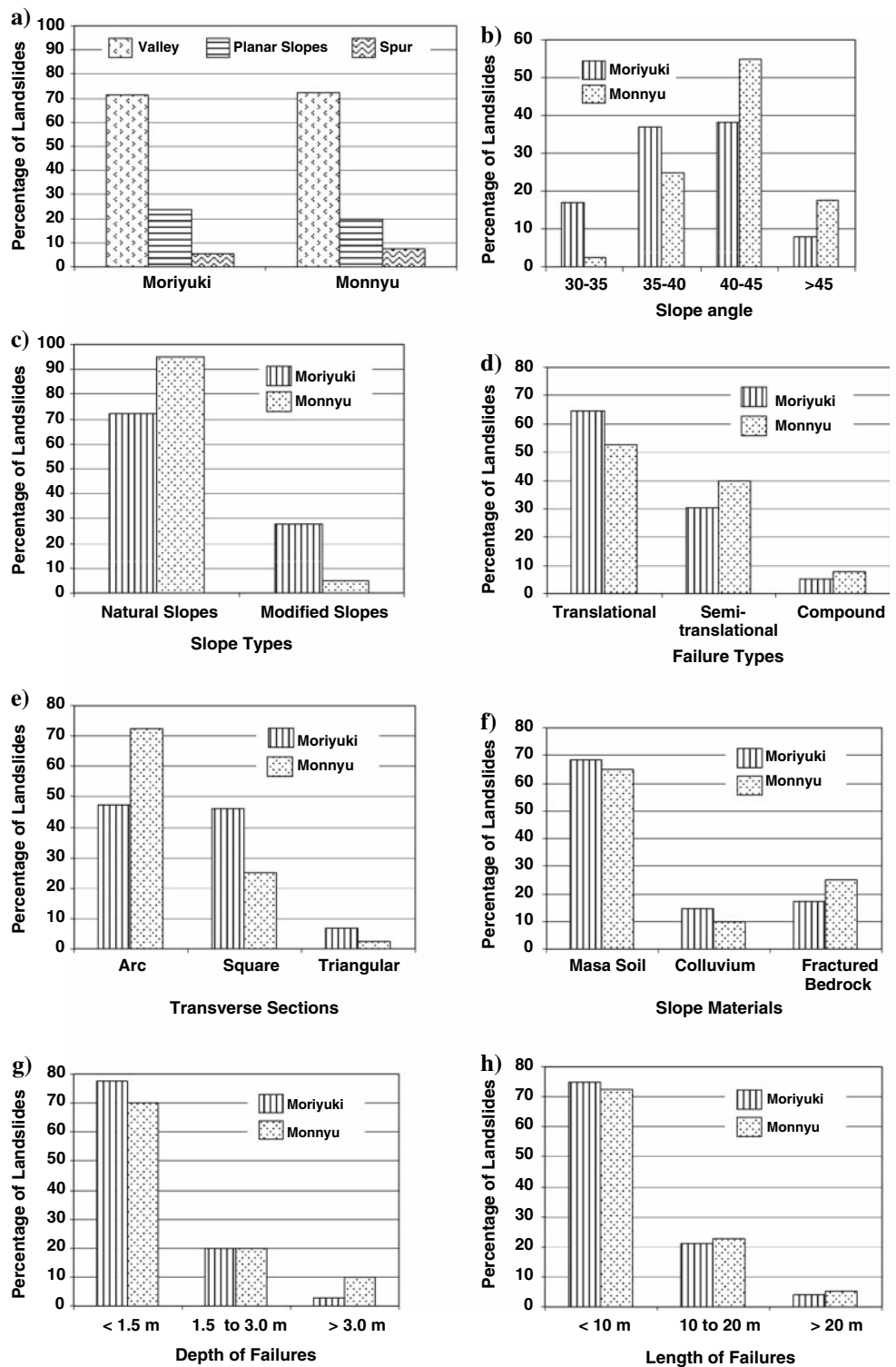
movement. The transverse section of slopes was also investigated. Generally arc, square, and triangular transverse sections of slides were noticed, and arc and square types were more prominent in both areas (Fig. 4e). The material involved in the failure was also evaluated during field investigation (Fig. 4f). More than 60% of the failure occurred within masa soil and at the place of contact of bedrock and masa soil. About 20% of failures were found in fractured bedrocks and few (about 10%) failures were found at the place of contact between bedrock and colluvium and within colluvium. The depth of failure was <1.5 m in more than 70% of slides and more than 70% of slides had a length of <10 m (Fig. 4g, h). A study of the volume of failed materials revealed that 95% of landslides had a volume less than 1,000 m³, whereas in Moriyuki all landslides had a volume less than 1,000 m³. In this area, about 70% of landslides had a volume less than 200 m³. So, the Moriyuki area represents an excellent event of small-scale shallow rainfall-triggered landslides in granitic terrains than Monnyu. Because of this reason also, ideal landslides were selected from Moriyuki for detailed stability analysis.

Vegetation did not appear to play a distinct role in controlling the locations of landslides at Moriyuki and Monnyu areas. Japanese cypress, Japanese cedar, and Japanese bamboos are the main trees in the forest. In the Moriyuki area, more than 82% of the area is covered by dense forest containing these trees. About 6% area is sparse forest and 5% is settlement area. The remaining area is grassland, shrubs, agricultural land, riverbed, and irrigation pond. The role of vegetation in controlling landslides is well described by previous researchers (Gray 1974; Ziemer 1981; Waldron and Dakessian 1981; Gray and Leiser 1982; Greenway 1987; Shields and Gray 1993; Styczen and Morgan 1995; Easson and Yarbrough 2002), but in the granitic terrains of Moriyuki and Monnyu, landslides were noticed in both forested and non-forested areas and it was observed that the occurrence of landslides was mostly controlled by slope morphology, inclination, type of slope (modified or non-modified), and the material involved. Nearly, 70% of slides occurred in the forest area.

Engineering properties of landslide materials

Altogether, 16 samples were collected from various landslide failure zones of both Moriyuki and Monnyu. The main properties determined for the soils included grain-size distribution, soil grain density, and permeability. On the basis of grain-size distribution, the soils from selected sites can be classified as well-graded gravelly sand with little fines. The amount of fines (<0.075 mm) in soils was less than 20% in most of the soils. The fines had low plasticity index and classified as low plastic silt and clay. Chugoko-

Fig. 4 Characteristics of landslides in the study area. **a** Geomorphological location of landslides. **b** Variation of slope angle. **c** Landslides occurrences as per natural and modified slopes. **d** Type of failure. **e** Traverse section of landslides. **f** Type of materials involved in landslides. **g** Depth of failure. **h** Length of slides



Shikoku Agricultural Administrative office (1981) of the Japanese government performed a series of studies in east Kagawa (including the study area) to estimate strength parameters (cohesion and friction angle) of the well-known, weathered granitic layer (masa in Japanese). Thus, for stability and sensitivity analysis, average values of

index parameters were decided as per the work of Chugoko-Shikoku Regional Agricultural Administrative Office (1981) and the present work, and are listed in Table 1. The average friction angle of masa soil in the study area is 31.5° and the average cohesion is 4.9 kN/m² with standard deviation 2.3° and 1.2 kN/m², respectively.

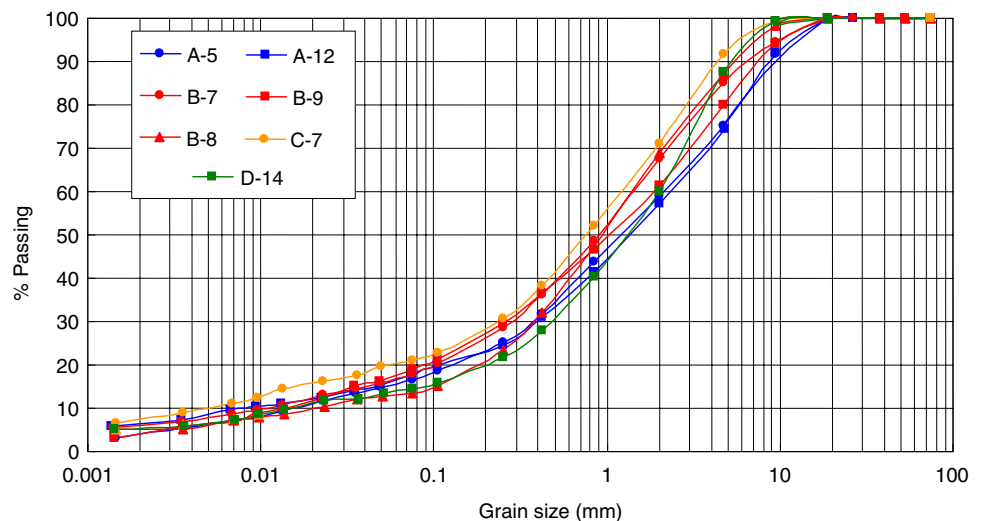
Fig. 5 Translational failure in weathered granite



Table 1 Index properties of masa soil (modified after Chugoko-Shikoku Agricultural Administrative office 1981 and present study)

Parameters	Estimated range value	Used average value	Standard deviation
Unit weight (γ)	17.5–18.9 kN/m ³	18.2 kN/m ³	0.53
Saturated unit weight (γ_{sat})	19.6–20.1 kN/m ³	19.8 kN/m ³	0.16
Dry unit weight (γ_{d})	15.8–16.5 kN/m ³	16.0 kN/m ³	0.28
Specific gravity (G)	2.635–2.700 g/cm ³	2.653 g/cm ³	0.018
Porosity (n)	0.6–0.7	0.6	0.04
Permeability (k)	1.3×10^{-5} to 9.3×10^{-5} m/s	4.86×10^{-5} m/s	3.44×10^{-5}
Cohesion (c)	2.9–6.4 kN/m ²	4.9 kN/m ²	1.2
Effective friction angle (φ)	27.3°–35.3°	31.5°	2.3

Fig. 6 Grain size distribution curve of soils at selected seven landslides



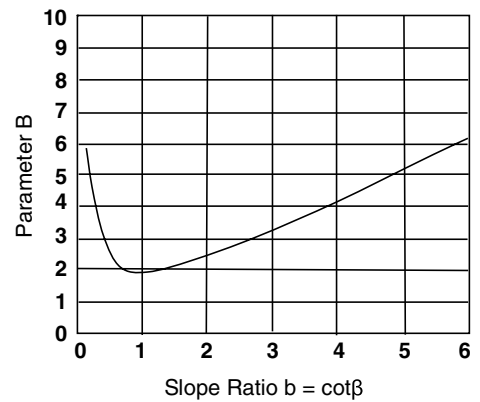
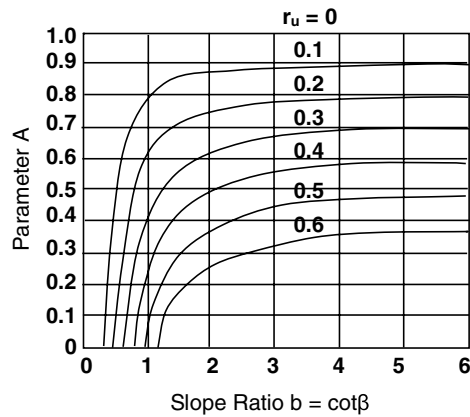
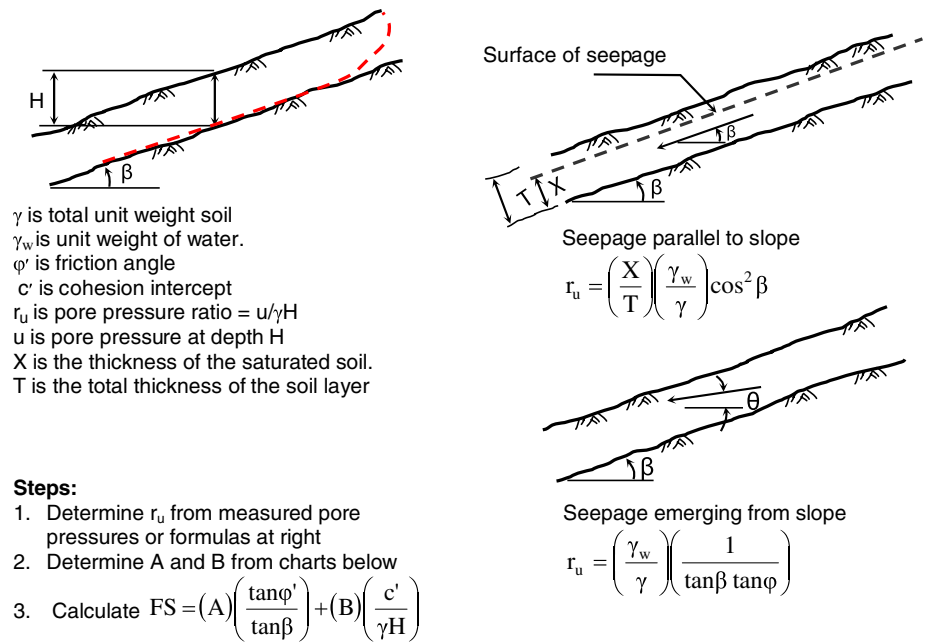
The grain-size distribution curves of samples from the selected seven landslides of Moriyuki are given in Fig. 6. The distribution curve clearly shows the very narrow range of variation in soil types in the selected landslides.

Stability analyses

Stability analyses were carried out to assess the conditions required for initiation of typhoon-brought rainfall-induced

shallow translational slides. Flows after slides were not investigated in this analysis. A total of seven representative translational slides of Moriyuki were taken into consideration for stability analysis. Similarly, sensitivity analysis was also performed to ensure the effectiveness of other parameters used in the stability analysis and the calculated factor of safety. This study attempts to employ a standard method of stability analysis of translational slides, which are very common in masa soil during extreme rainfall. In this study, standard strength parameters of masa soil were

Fig. 7 Infinite slope stability analysis, method described by Duncan (1996), redrawn from Turner and Schuster, 1996



used to make the technique easier and to encourage utilization of the technique in other similar type of granitic terrains of Japan.

The infinite slope stability analysis method developed and described by Duncan et al. (1987) and Duncan (1996) was used for stability and sensitivity analysis. Figure 7 provides the necessary information for the application of this method including the factor of safety equation and the charts for determining parameters A and B used in the factor of safety equation. This method has been already used by some researchers for the stability analysis of translational slides (Shakoor and Smithmyer 2005). In this research, the method is employed on residual soil slopes of granitic terrain.

For this analysis, some considerations were taken into account as per the field observation results. From the analyses of failure type, depth of failure, and material involved (see Fig. 4a–h), it was understood that the failure surface was shallow and located along the contact between

the residual soil and the underlying less weathered granite or granodiorite. Indeed, colluvial materials and fractured bedrocks were also involved in about 20% failure (see Fig. 4f), but for sensitivity and stability analyses, they were excluded in this study and attention given only to the stability of thin residual soils (<1.5 m found in more than 70% of failure) over less weathered granite and granodiorite. For the sensitivity and stability analyses, the residual soil layer was also assumed to be uniform throughout the slope. The depth of soil on each selected slide ranged from 0.7 to 1.1 m. Moreover, investigation of the sense of movement in a total of 116 landslides of Moriyuki and Monnyu showed that more than 60% of the slides had perfect translational sense of movement and about 30% of the slides had semi-translational (having slight curved surface of failure) sense of movement. In this sense, only in Moriyuki, about 90% of slides can be categorized as translational slides. This is another reason that seven landslides of Moriyuki (Fig. 8, Table 2) were taken into

Fig. 8 Photographic representation of selected seven landslides



account for sensitivity and stability analyses. The engineering parameters listed in Table 1 were used for stability and sensitivity analyses. However, when those parameters were used in the stability of slopes, a slope of C-7 was found stable even for completely saturated soil conditions. So, by considering grain-size distribution (see Fig. 6) and amount of fines in soils (Table 2), along with properties of

soil samples of other landslides, the average value of cohesion (4.9 kN/m^2) was considered to be a little dubious for soil materials of sites C-7. So, a back analysis was carried out to obtain more accurate cohesion values corresponding to the average friction angle value of 31.5° . For back analysis, the factor of safety was considered one and the infinite slope stability method developed by Duncan

Table 2 Soil characteristic, depth of failure, and inclination of selected seven landslides

Landslide no.		A-5	A-12	B-7	B-8	B-9	C-7	D-14
Grain size distribution	Gravel	41	43	33	31	39	29	40
	Sand	42	39	49	56	42	50	46
	Silt	10	10	10	7	12	11	7
	Clay	7	8	8	6	7	10	7
Average length, <i>L</i> (m)	33.8	19.4	27.2	47.4	35.6	13.8	35.4	
Average width, <i>W</i> (m)	7.3	5.4	6.2	14.1	6.4	8.7	8.5	
Depth, <i>H</i> (m)	0.8	0.7	0.9	1.1	1.1	1	0.8	
Inclination, β (°)	34	38	44	41	43	32	38	
Permeability <i>k</i> (m/s)		3.6×10^{-5}	2.2×10^{-5}	1.8×10^{-5}	6.9×10^{-5}	1.3×10^{-5}	9.3×10^{-4}	8.9×10^{-5}

(Duncan et al. 1987; Duncan 1996) was employed. New back calculated cohesion for site C-7 was 4.6 kN/m² and it was used in the stability analysis of landslide C-7.

Sensitivity analysis

Sensitivity analysis is a heuristic analysis, which examines the dependency of various parameters used in a calculation. Therefore, before stability analysis, sensitivity analysis was carried out to assess the variations in the factor of safety with respect to changes in engineering parameters such as inclination or slope angle (β), cohesion (*c*), friction angle (φ), and unit weight (γ). The infinite slope analysis method (Duncan 1996) was used for sensitivity analysis by keeping each variable constant, except the input parameter that was needed for estimation. The values of slope angle, unit weight, friction angle, cohesion, and thickness (measured normal to slope) of soil were used for each site as the fixed parameters. This heuristic analysis was carried out using both best (dry condition) and worst (saturated condition) cases of unit weight for failure. Field measurements indicated that the slope angle in seven sites ranged from 32° to 44°. Therefore, a range of 26°–50° was chosen to cover any deviation. Likewise, average friction angle values for the study sites also ranged from 27.3° to 35.3° and thus a range of 25°–40° was used. Value of cohesion ranged from 2.9 to 6.5 kN/m², and so in this analysis, value of cohesion from 2.4 to 7.0 kN/m² with increment of 0.2 kN/m² was used. The value of soil depth was used as per the field measurement (ranged from 0.7 to 1.1 m). Figure 9 shows an example of sensitivity analysis for site A-5. Similar plots were generated for all seven cases.

Stability analysis

The Duncan’s (1996) method quantitatively analyzes the effect of soil saturation on the stability of those slopes,

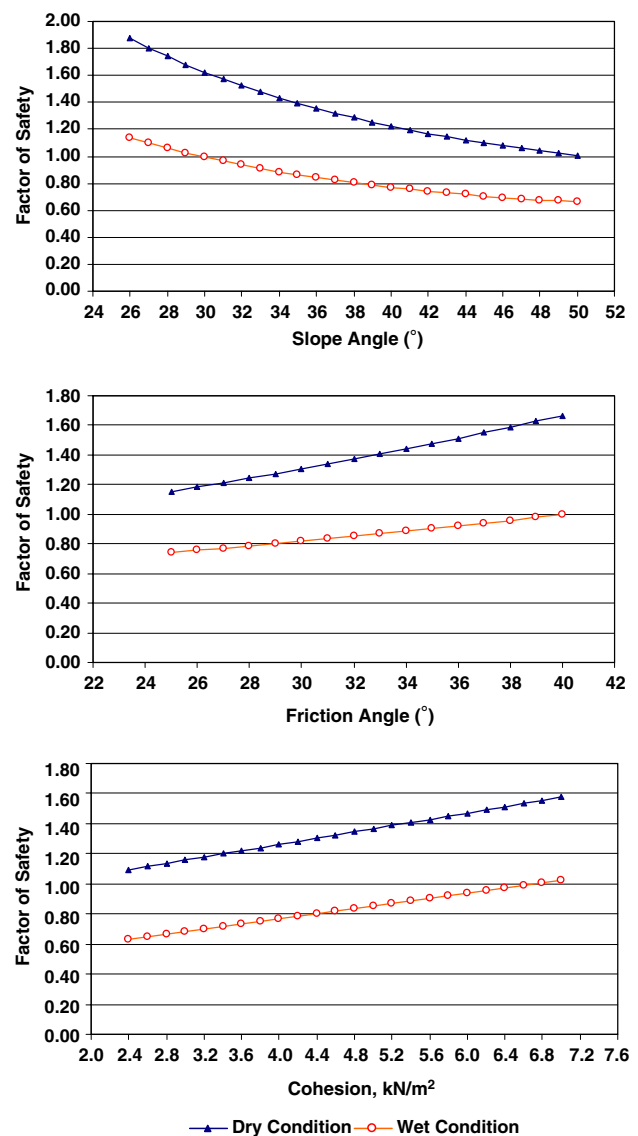


Fig. 9 Variation of factor of safety with respect to slope angle, friction angle, and cohesion for landslide A-5 for both dry and saturated condition of soil

which have high potentiality of translational slides. This method considers that the length of failure surfaces is high in comparison to the depth. It also ignores the driving force at the crown part of the sliding mass and the resisting force at the toe part. In fact, the resisting force is usually high during failure; so, in engineering practice, the infinite slope stability analysis is considered to be slightly conservative (Duncan 1996). Duncan (1996) also described two possible seepage conditions, seepage parallel to the slope face and seepage emerging from the slope (see Fig. 7). In this study, on the basis of field investigation, seepage is considered to occur parallel to the slope face. Duncan (1996) described the following three steps of procedure in the analysis method (see Fig. 7 also).

1. Determination of the pore pressure ratio (r_u), from the following relationship: $r_u = \left(\frac{X}{T}\right) \left(\frac{\gamma_w}{\gamma}\right) \cos^2 \beta$, where X is the thickness of the saturated soil layer. T is the total thickness of the soil layer (measured normal to slope). γ_w is unit weight of water. γ is unit weight of soil. β is the slope angle.
2. Determination of parameters A and B , is necessary for the calculation of factor of safety and can be obtained from Fig. 7. However, the following equation is also useful for estimation of the value of A and B (Duncan 1996). $A = 1 - \left(\frac{r_u}{\cos^2 \beta}\right)$, $B = \frac{1}{\sin \beta \cos \beta}$ where A corresponds to the pore pressure acting normal to the sliding surface, and B corresponds to the shear resistance along the sliding surface.
3. Determination of factor of safety (FS) from the following relationship: $FS = (A) \left(\frac{\tan \phi'}{\tan \beta}\right) + (B) \left(\frac{c'}{\gamma H}\right)$, where, ϕ' and c' are the effective strength parameters; β is the slope angle and γ is unit weight of the soil. H is the depth of soil measured vertically from the slope surface to the surface of sliding.

For infinite slope stability analysis of seven slides of Moriuyuki, the saturated fraction of soil layer, denoted by X in Duncan's (1996) method, was considered to range from

Table 3 Result of stability analysis

Landslide no.	A-5	A-12	B-7	B-8	B-9	C-7	D-14
Existing slope angle (°)	34	38	44	41	43	32	38
Saturated fraction of soil layer	0.8	0.4	0.4	0.8	0.7	1.0	0.6
Factor of safety	1	1	1	1	1	1	1

40 to 100% of soil thickness (T) of each slide. Similar to the process employed in sensitivity analysis, 25 (26°–50° with interval of 1°) slope angle values were examined for each site and plotted. An example of the results of stability analysis for landslides having minimum thickness (A-12) and maximum thickness (B-9) are shown in Fig. 10. It illustrates the relationship between slope angle and factor of safety for various values of saturated fraction of soil layer (X). It is obvious that as soil saturation increases, the factor of safety decreases for a given slope angle. Results of stability analysis are listed in Table 3 and it was understood that masa soil of northeast Shikoku has high potentiality of translational slide even in 40% saturation of soil layer. If soil thickness is high, more saturation is needed.

The calculated factor of safety for each landslide site is illustrated in Table 4. Site B-7, B-8, and B-9 had higher slope angle value and also factor of safety of 1.18, 1.38, and 1.32, respectively for dry conditions. Data show that landslide C-7 failed at 100% saturation during typhoon 0423 (Tokage), whereas the others failed at 40–80% saturation.

The result of stability analysis strongly supports the landslide disaster during typhoon 0423 (Tokage) in granitic terrain of northeast Shikoku, Japan. The soil had relatively high permeability (in the range of 10^{-3}). The amount of rainfall in the Moriuyuki and Monnyu area were 582 and 412 mm, respectively, on 20 October 2004, with antecedent rainfall of 92 and 83 mm on the preceding day.

Fig. 10 Relationship between saturated soil fraction, slope angle, and factor of safety for landslides A-12 and B-9

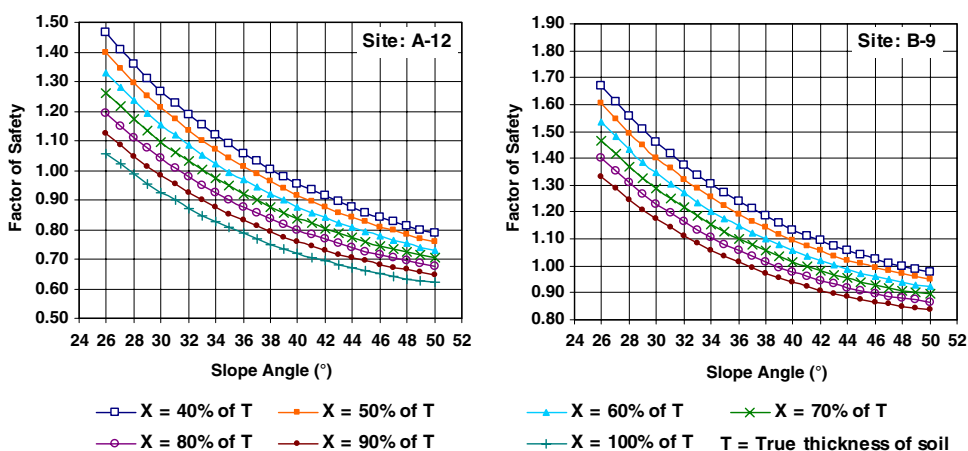


Table 4 Result of stability analyses for different saturated fractions of the masa soil layer

Landslide no.	A-5	A-12	B-7	B-8	B-9	C-7	D-14
Slope angle (°)	34	38	44	41	43	32	38
Factor of safety for dry conditions	1.44	1.22	1.18	1.38	1.32	1.65	1.29
Factor of safety for wet conditions							
Saturated fraction	0.4	–	1.00	1.02	–	–	–
	0.5	1.13	0.96	0.98	1.11	1.07	1.28
	0.6	1.08	0.92	0.95	1.08	1.04	1.23
	0.7	1.03	0.88	0.91	1.04	1.00	1.17
	0.8	0.98	0.84	0.88	1.00	0.97	1.12
	0.9	0.93	0.79	0.85	0.96	0.93	1.06
	1.0	0.88	0.75	0.81	0.92	0.90	1.00

Likewise, the maximum 1 h rainfall in Moriyuki and Monnyu areas on 20 October 2004 was 117 and 76 mm, respectively (see Fig. 2 also). Evaluating from the minimum value of permeability, it was understood that within 5 h of continuous percolation of water into the masa soil of Moriyuki, water could enter more than 20 cm of soil depth. This suggested that extensive failure occurred in masa soil of northeast Shikoku because of a high rate of infiltration and high intensity of rainfall.

Evaluation of rainfall threshold of events

Threshold rainfall for triggering landslides is one of the debatable topics since the last 25 years. N. Caine was the first to publish a paper in 1980 about the threshold rainfall value for the worldwide scenario of landslides. After that, many attempts have been made to establish the threshold value, in a global as well as in a regional context. In Japan, defining the rainfall threshold for failure is basically different from the American and European way of presentation. Various rainfall indexes are used to define the threshold in Japan. Among such rainfall indexes, “effective rainfall” is often used and it can be defined as the summation of rainfall until the occurrence of breakout of the event. Yano (1990) has proposed the use of hourly rainfall as the fundamental unit of rainfall to discuss rainfall threshold for landslide. Effective rainfall, hourly rainfall, and critical line to separate disaster and non-disaster events of rainfall, as well as snake line are used for the prediction of threshold rainfall (Hiura et al. 2005) in Japan.

In this paper, the concept of threshold rainfall intensity proposed by various researchers (Caine 1980; Cancelli and Nova 1985; Wieczorek 1987; Cannon and Ellel 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) is used to describe the rainfall threshold of northeast Shikoku. Figure 11 illustrates the

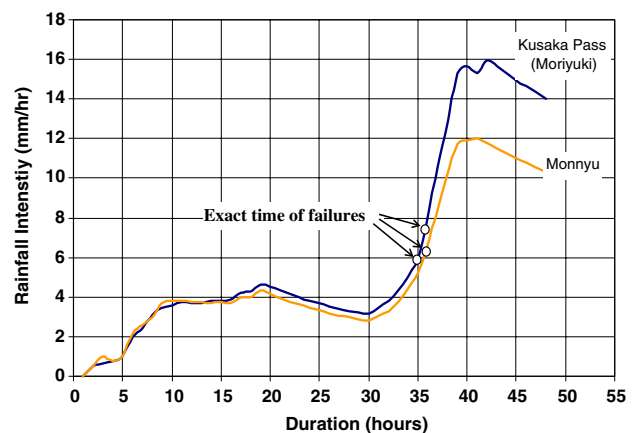


Fig. 11 Temporal pattern of rainfall intensity vs. duration for the 2004 rainfall event of Moriyuki and Monnyu areas. The left of the graphs represent initiation of rainfall. Symbols indicate the occurrence of landslides in Moriyuki and Monnyu during typhoon 0423 (Tokage)

temporal pattern of rainfall intensity vs. duration conditions during the typhoon 0423 (Tokage) in the study areas. The continuous lines represent rainfall intensity vs. duration in Kusaka Pass and Monnyu rainfall gauging stations, whereas the time of occurrence of landslides is shown as circular symbols.

The value of effective temporal rainfall intensity to create landslide was plotted with rainfall duration in a log–log graph to analyze the empirical rainfall thresholds. In the same log–log paper, rainfall threshold curves proposed by various researchers were also portrayed (Fig 12). The plot revealed that the rainfall intensity in northeast Shikoku (Moriyuki and Monnyu) during 2004 typhoon 23 event was slightly higher than the threshold of storm-triggering landslides proposed by Larsen and Simon (1993) for Puerto Rico (humid tropical region) and by Dahal and Hasegawa (2008) for the Nepal Himalaya (tropical monsoon region). Similarly, it is slightly lower than the rainfall threshold of landslides in Portugal, western Europe (Zezere et al. 2005). The curve proposed by Cancelli and Nova

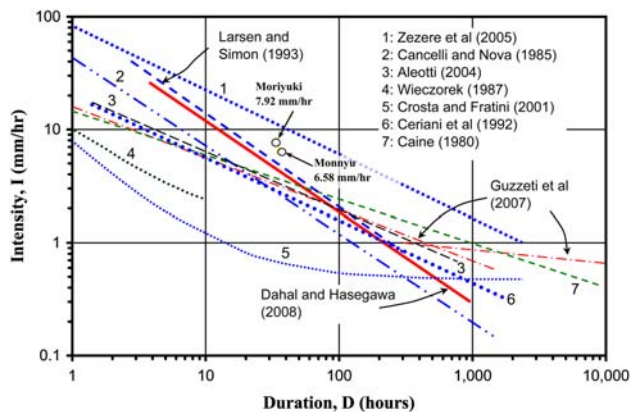


Fig. 12 Rainfall intensity and duration associated with slope failures during typhoon 0423 (Tokage) in northeast Shikoku, Japan, and curves proposed by various researchers for a similar case. From the data of 2004 landslides events, threshold rainfall intensity for northeast Shikoku is slightly higher than the threshold lines for rainfall triggering landslides proposed by Larsen and Simon (1993) for Puerto Rico (humid tropical region) and by Dahal and Hasegawa (2008) for the Nepal Himalaya (tropical monsoon region). Similarly, it is slightly lower than threshold for landslides in Portugal, western Europe (Zeze et al. 2005)

(1985), Ceriani et al. (1994), Crosta and Frattini (2001), Aleotti (2004) and Guzzetti et al. (2007) for the Alps could not cover the average rainfall intensity of the study area. The curves proposed by Wieczorek (1987) and Cannon and Ellel (1985) for the Rockies also do not have any similarity with the data of the study area. However, the full disaster history needs to be understood for more accurate prediction of the threshold. In this study, only data of 2004 failure events were used to correlate threshold with already established threshold curves and to obtain a glimpse of landslide threshold for the granitic terrain of northeast Shikoku.

Conclusions

The conclusions of this study can be explicitly summarized as follows:

1. Typhoon-brought rainfall-induced landslides in the granitic terrain of northeast Shikoku, Japan, in general, can be categorized as shallow, translational slides having failure depth less than 1.5 m. Many slides were subjected to flow down to the slope after sliding.
2. The landslides were initiated when the sandy residual soils of the granitic terrains (masa) were 40–100% saturated, depending on the slope angles and vertical depth of the soil. It was also understood that extensive failure occurred in masa soil of Japan during typhoon

rainfalls, because of a high rate of infiltration and high intensity of rainfall.

3. Temporal rainfall intensity and duration values responsible for failures and calculated from total rainfall events that occurred on 19 through 20 October 2004 were slightly higher than the threshold values established by Larsen and Simon (1993) for humid tropical region and by Dahal and Hasegawa (2008) for tropical monsoon region.

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References

- Aleotti P (2004) A warning system of rainfall-induced shallow failure. *Eng Geol* 73:247–265
- Caine N (1980) The rainfall intensity-duration control of shallow landslides and debris flows. *Geografiska Annaler* 62A:23–27
- Calcaterra D, Parise M, Dattola L (1996) Debris flows in deeply weathered granitoids (Serre Massif-Calabria, Southern Italy). In: Senneset K (Ed) *Proceedings of the 7th international symposium on landslides*, Balkema, Trondheim, 1996, pp 171–176
- Campbell RH (1975) Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, Southern California. *US Geological Survey Professional Paper* 851:1–20
- Cancelli A, Nova R (1985) Landslides in soil debris cover triggered by rainstorms in Valtellina (Central Alps -Italy). *Proceedings of the IV international conference and field workshop on landslides*, Tokyo, August 1985, pp 267–272
- Cannon SH, Ellen SD (1985) Rainfall conditions for abundant debris avalanches, San Francisco Bay region, California. *Geology* 38(12):267–272
- Casadei M, Dietrich WE, Miller NL (2003) Testing a model for predicting the timing and location of shallow landslide initiation in soil-layered landscapes. *Earth Surf Process Landforms* 28:925–950
- Ceriani MS, Lauzi NP (1994) Rainfall thresholds triggering debris flows, in the alpine area of Lombardia Region, Central Alps, Italy. *Man and mountain '94*. First international congress for the protection and development of mountain environment. Ponte di Legno (BS, Italy), June 1994, pp 123–139
- Chigira M (2001) Micro-sheeting of granite and its relationship with landsliding specifically after the heavy rainstorm in June 1999. Hiroshima Prefecture, Japan. *Eng Geol* 59:219–231
- Chigira M, Ito E (1999) Characteristic weathering profiles as basic causes of shallow landslides. In: Yagi N, Yamagam T, Jiang J-C (Eds) *Slope stability engineering*, vol 2, Balkema, Rotterdam, pp 1145–1150
- Chugoko-Shikoku Regional Agricultural Administrative Office (1981) Report on slope stability of weathered granite hills in eastern part of Kagawa Prefecture—engineering properties of “masa soils”. Ministry of Agriculture, Forestry and Fisheries, Japan, pp 6–12 (in Japanese)
- Crosta G (1998) Regionalization of rainfall threshold: an aid to landslide hazard evaluation. *Environ Geol* 35(2–3):131–145
- Crosta G, Frattini P (2001) Rainfall thresholds for triggering soil slips and debris flow. In: *Proceedings of EGS 2nd Plinius Conference 2000, Mediterranean Storms*, Siena, pp 463–488

- Crosta GB, Frattini P (2003) Distributed modelling of shallow landslides triggered by intense rainfall. *Nat Hazards Earth Syst Sci, Eur Geophys Soc* 3(1–2):81–93
- Crozier MJ (1999) Prediction of rainfall-triggered landslides: a test of the antecedent water status model. *Earth Surf Process Landforms* 24:825–833
- Cruden DM, Varnes DJ (1996) Landslide types and processes. In: Turner AK, Schuster RL (Eds) *Landslides: investigation and mitigation*. Sp. Rep.247, Transportation Research Board, National Research Council. National Academy Press, Washington DC, pp 36–75
- D’Amato Avanzi G, Giannecchini R, Puccinelli A (2004) The influence of geological and geomorphological settings on shallow landslides. An example in a temperate climate environment: the June 19, 1996 event in north western Tuscany (Italy). *Eng Geol* 73:215–228
- Dai F, Lee CF, Wang SJ (1999) Analysis of rainstorm-induced slide-debris flows on natural terrain of Lantau Island, Hong Kong. *Eng Geol* 51:279–290
- Dahal RK, Hasegawa S (2008) Rainfall thresholds for landslides in the Nepal Himalaya. *Geomorphology* (in press). doi:10.1016/j.geomorph.2008.01.014
- Dai F, Lee CF, Wang SJ (2003) A characteristics of rainfall-induced landslides. *Int J Remote Sens* 24(23):4817–4834
- Duncan JM, Buchilgnani AL, DeWet M (1987) An engineering manual for slope stability studies. Virginia Polytechnic Institute and State University, Blacksburg, Virginia, p 80
- Duncan MJ (1996) Soil slope stability analysis. In: Turner AK, Schuster RL (Eds) *Landslides: investigations and mitigation*, Transportation Research Board, special report 247, chapter 13. National Research Council, Washington DC, pp 337–371
- Durgin PB (1977) Landslides and the weathering of granitic rocks. *Geol Soc Am Rev Eng Geol* 3:127–131
- Dykes AP, Thornes JB (2000) Hillslope hydrology in tropical rainforest steep lands in Brunei. *Hydrol Process* 14:215–235
- Dykes AP (2002) Weathering-limited rainfall-triggered shallow mass movements in undisturbed steepland tropical rainforest. *Geomorphology* 46:73–93
- Easson G, Yarbrough LD (2002) The effects of riparian vegetation on bank stability. *Environ Eng Geosci* VIII(4):247–260
- Giannecchini R (2006) Relationship between rainfall and shallow landslides in the southern Apuan Alps (Italy). *Nat Hazards Earth Syst Sci* 6:357–364
- Glade T, Crozier M, Smith P (2000) Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical Antecedent Daily Rainfall Model. *Pure Appl Geophys* 157:1059–1079
- Gokceoglu C, Aksoy H (1996) Landslide susceptibility mapping of the slopes in the residual soils of the Mengen region (Turkey) by deterministic stability analyses and image processing techniques. *Eng Geol* 44:147–161
- Gray DH (1974) Reinforcement and stabilization of soil by vegetation. Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers 100(GT6), pp 695–699
- Gray DH, Leiser AT (1982) Biotechnical slope protection and erosion control. Van Nostrand Reinhold, New York
- Greenway DR (1987) Vegetation and slope stability. In: Anderson MG, Richards KS (Eds) *Slope stability*. Wiley, New York, pp 187–230
- Guzzetti F, Cardinali M, Reichenbach P, Cipolla F, Sebastiani C, Galli M, Salvati P (2004) Landslides triggered by the 23 November 2000 rainfall event in the Imperia Province. Western Liguria, Italy. *Eng Geol* 73:229–245
- Guzzetti F, Peruccacci S, Rossi M, Stark CP, (2007) Rainfall thresholds for the initiation of landslides in central and southern Europe. *Meteorol Atmos Phys*. doi:10.1007/s00703-007-0262-7. Accessed 7 Aug 2007
- Hasegawa S, Saito M (1991) Natural environment, topography and geology of Shikoku, Tsushi-to-Kiso (in Japanese). *Jpn Geotech Soc* 39–9(404):19–24
- Hiura H, Kaibori M, Suemine A, Yokoyama S, Murai M (2005) Sediment-related disasters generated by typhoons in 2004. In: Senneset K, Flaate K, Larsen JO (eds) *Landslides and avalanches*. ICFL2005 Norway, pp 157–163
- Huat BBK, Ali FH, Mariappan S (2005) Effect of surface cover on water infiltration rate and stability of cut slope in residual soils. *Electronic J Geotech Eng* 10(G). <http://www.ejge.com/2005/Ppr0614/Abs0614.htm>. Accessed 2 Aug 2007
- Irfan TY (1998) Structurally controlled landslides in saprolitic soils in Hong Kong. *Geotech Geol Eng* 16:215–238
- Iverson RM (2000) Landslide triggering by rain infiltration. *Water Resour Res* 36(7):1897–1910
- Jworchan I (2000) Debris flow initiation mechanism in residual soil. In: Proceedings of the international conference on geotechnical and geological engineering, ‘GeoEng 2000’, Melbourne, pp 2–26
- Keefer DK, Wilson RC, Mark RK, Brabb EE, Brown WM, Ellen SD, Harp EL, Wiczorek GF, Alger CS, Zarkin RS (1987) Real-time warning during heavy rainfall. *Science (new series)* 238(4829):921–925
- Kim J, Jeong S, Park S, Sharma J (2004) Influence of rainfall-induced wetting on the stability of weathered soils slopes. *Eng Geol* 75:251–262
- Larsen MC, Simon A (1993) A rainfall intensity-duration threshold for landslides in a humid-tropical environment. Puerto Rico. *Geogr Ann A* 75(1–2):13–23
- Micos M, Cetina M, Brilly M (2004) Hydrologic conditions responsible for triggering the Stoze landslide. Slovenia. *Eng Geol* 73:193–213
- Montgomery DR, Dietrich WE (1994) A physical based model for the topographic control on shallow landsliding. *Water Resour Res* 30(4):1153–1171
- Mukhlisin M, Kosugi K, Satofuka Y, Mizuyama T (2006) Effects of soil porosity on slope stability and debris flow run out at a weathered granitic hillslope. *Vadose Zone J* 5:283–295
- Neary DG, Swift Jr, LW (1987) Rainfall thresholds for triggering a debris avalanching event in the southern Appalachian Mountains. In: Costa JE, Wiczorek GF (eds) *Debris flows/avalanches: process, recognition and mitigation*. Geological Society of America reviews in engineering geology, vol 7, pp 81–92
- Okagbue CO (1989) Predicting landslides caused by rainstorms in residual/colluvial soils of Nigerian hillside slopes. *Nat Hazards* 3:133–141
- Okimura T, Kawatani T (1987) Mapping of the potential surface-failure sites on granite slopes. In: Gardiner V (ed) *International geomorphology, Part I*. Wiley, Chichester, pp 121–138
- Onda Y (1992) Influence of water storage capacity in the regolith zone on hydrological characteristics, slope processes, and slope form. *J Geomorph NF* 36:165–178
- Oyagi N (1968) Weathering-zone structure and landslides of the area of granitic rocks in Kamo-Daito, Shimane Prefecture. Reports of Cooperative Research for Disaster Prevention, National Research Center for Disaster Prevention (in Japanese with English abstract), vol 14, pp 113–127
- Pomeroy JS (1984) Storm-induced landslides at East Brady, U.S. Geological Survey Bulletin 1618, Northwestern Pennsylvania, p 16
- Rahardjo H, Li XW, Toll DG, Leong EC (2001) The effect of antecedent rainfall on slope stability. *Geotech Geol Eng* 19:371–399
- Rahardjo H, Lee TT, Leong EC, Rezaur RB (2005) Response of residual soil slope to rainfall. *Can Geotech J* 42(2):340–351

- Rezaur RB, Rahardjo H, Leong EC (2002) Spatial and temporal variability of pore-water pressures in residual soil slopes in a tropical climate. *Earth Surf Process Landf* 27(3):317–338
- Shakoor A, Smithmyer AJ (2005) An analysis of storm-induced landslides in colluvial soils overlying mudrock sequences, southeastern Ohio, USA. *Eng Geol* 78:257–274
- Shields FD, Gray DH (1993) Effects of woody vegetation on the structural integrity of sandy levees. *Water Resour Bull* 28(5):917–931
- Styczen ME, Morgan RPC (1995) Engineering properties of vegetation. In: Morgan RPC, Rickson RJ (eds) *Slope stabilisation and erosion control: a bioengineering approach*. E&FN Spon, London, pp 5–58
- Terlien MTJ (1998) The determination of statistical and deterministic hydrological landslide-triggering thresholds. *Environ Geol* 35(2–3):124–130
- Veihmeyer FJ, Hendrickson AH (1931) The moisture equivalent as a measure of the field capacity of soils. *Soil Sci* 32:181–193
- Vieira BC, Fernandes NF (2004) Landslides in Rio de Janeiro: the role played by variations in soil hydraulic conductivity. *Hydrol Process* 18:791–805
- Waldron LJ, Dakessian S (1981) Soil reinforcement by roots: calculation of increased soil shear resistance from root properties. *Soil Sci* 132:427–435
- Wieczorek GF (1987) Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California. *Geol Soc Am Rev Eng Geol* 7:93–104
- Wieczorek GF (1996) Landslide triggering mechanisms. In: Turner AK, Schuster RL (eds) *Landslides: investigation and mitigation*, Transportation Research Board special report 247. National Research Council, Washington, pp 76–79
- Wieczorek GF, Morgan BA, Campbell RH (2000) Debris flow hazards in the Blue Ridge of Central Virginia. *Environ Eng Geosci* 6(1):3–23
- Wilson RC, Wieczorek GF (1995) Rainfall threshold for the initiation of debris flow at La Honda, California. *Environ Eng Geosci* 1(1):11–27
- Wilson RC (1997) Broad-scale climatic influences on rainfall thresholds for debris flows. Adapting thresholds for northern California to southern California. In: Larson RA, Slosson JE (eds) *Storm-induced geologic hazards*. *Geol Soc Am Rev Eng Geol* 11(6):71–79
- Yano K (1990) Studies on deciding rainfall threshold from warning and evacuating from debris flow disaster by improving the decision method of preceding rainfall (in Japanese) *J Jpn Erosion Control Soc* 43(4):3–13
- Zezere JL, Trigo RM, Trigo IF (2005) Shallow and deep landslides induced by rainfall in the Lisbon region (Portugal): assessment of relationships with the North Atlantic Oscillation. *Nat Hazard Earth Sys Sci* 5:331–344
- Ziemer R (1981) Roots and shallow stability of forested slopes. *Int Assoc Hydrol Sci* 132:343–361