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

Ranjan Kumar Dahal . Shuichi Hasegawa . Atsuko Nonomura . Minoru Yamanaka . Takuro Masuda . Katsuhiro Nishino

R. K. Dahal

1 Dept. of Safety Systems Construction Engineering, Faculty of Engineering, Kagawa University, 2217-20, Hayashi-cho, Takamatsu City, 761-0396, Japan

2 Department of Geology, Tri-Chandra Multiple Campus, Tribhuvan University, Ghantaghar, Kathmandu, Nepal

Phone: 0081-87-864-2140

Fax: 0081-87-864-2031

Email: ranjan@ranjan.net.np

URL: http://www.ranjan.net.np

S. Hasegawa . A. Nonomura . M. Yamanaka . T Masuda

Dept. of Safety Systems Construction Engineering, Faculty of Engineering, Kagawa University, 2217-20, Hayashi-cho, Takamatsu City, 761-0396, Japan

K. Nishino

Oyo Corporation, Ichigaya Building, 4-2-6, Kudan North, Chiyoda, Tokyo, 102-0073, Japan

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Abstract

Soil slips, debris slides, and flow occurrences on hill slopes of particular areas are closely related to mode of rainfall. Because of geological, geomorphological, and climatic settings, Japan is highly prone for 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 synoptic descriptions of failures that occurred in granitic terrain of north east Shikoku Island, Japan along with rainfall and failure relationships during the typhoon 0423 (Tokage) of 2004. Examples of typical failures occurred in Moriyuki and Monnyu of north east 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 study area.

Key words: rainfall-induced landslides; typhoon; stability analysis; rainfall intensity; triggering threshold

1 Introduction

Shikoku is the smallest of the four main islands of Japan (total area: 18,800 km^2), 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 covered by 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 typhoon rainfall. Although climate of the northern part of Shikoku Island is the inland type climate like Mediterranean region and subsequently have few rainfall (annual rainfall 1000 mm only), the area sometime suffered by extreme typhoon brought rainfall which some time exceeds more than 750 mm in one day.

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

These are the highest precipitations of those areas in last 30 years. These rainfall events of October 2004 triggered more than 300 landslides in Moriyuki and Monnyu catchment area and debris flow was 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 road side debris. Most of 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). Mircoscopic 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, where as granodiorite is mainly rich with quartz, plagioclase and potassium feldspar with abundant hornblende. The weathered rock material consists of clay minerals like, kaoline, chlorite, vermiculite, lepidolite, and smectite.

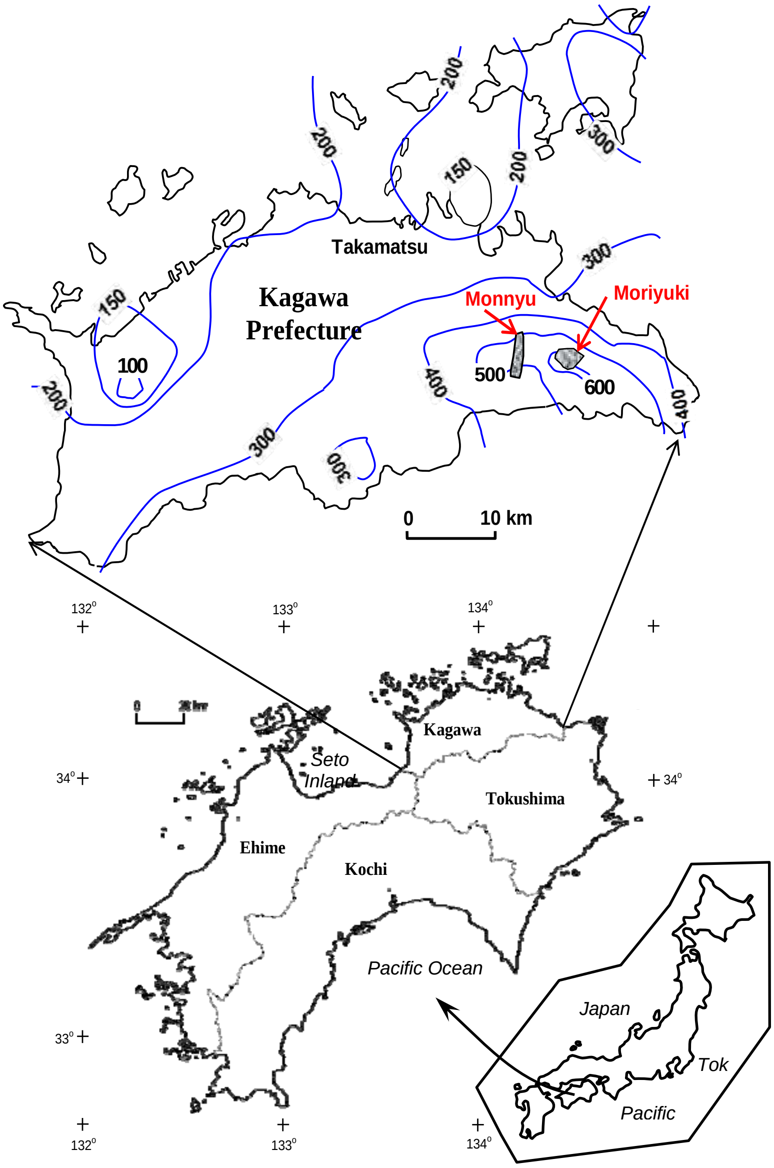


Fig. 1. Location of Moriyuki and Monnyu in north east Shikoku, Japan and rainfall isohyetal map during typhoon 0423 (October 19 and 20, 2004)

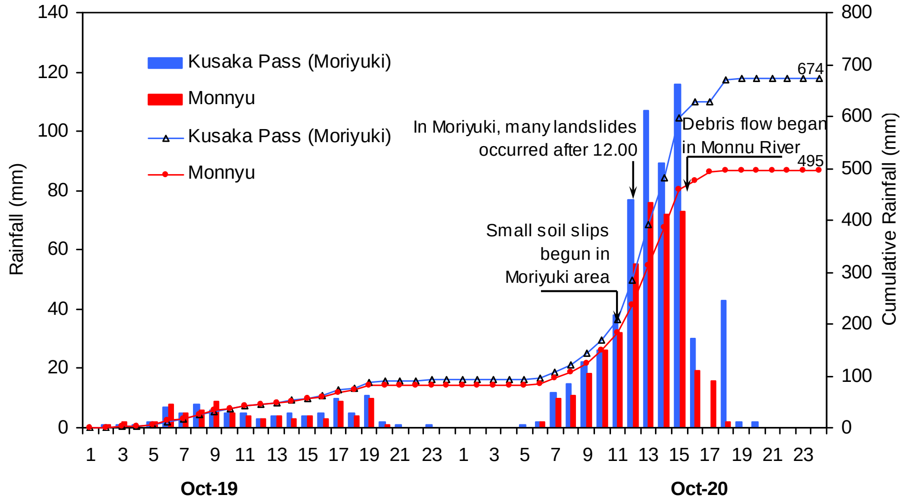


Fig. 2 Rainfall pattern and time of failures in Moriyuki and Monnyu catchments during typhoon 0423

The rainfall-induced shallow landslides in both colluvial and residual soils are great interest of 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 1000 casualties over the last 65 years (Chigira 2000). 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 is 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 1000 casualties (Durgin, 1977). During 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 2003). Moreover, two-thirds of the land area of Korean peninsula is composed of soils formed by weathering product 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, 1987; 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 under gravity water flows out of the soil zone as fast as it flows in, followed by intense rainfall enough 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 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 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 mention that the response of residual soil slope to infiltration still not fully understood. Similarly, some of research on weathered granite discussed about closely spaced, near horizontal joints developed by unloading effect on granitic body also responsible for failure in weathered granite. Chigira (2000) mentioned that the landslides occurring in Hiroshima Prefecture in June 1999 were closely related to micro-sheeting (closely spaced near horizontal joints) of granite.

Because of large majority of slope failure are triggered by extreme rainfall, a number of researchers (Campbell,1975; Caine, 1980; Pomeroy, 1984; Neary and Swift, 1987; Keefer et al., 1987; Yano, 1990; Wilson and Wieczorek, 1995; Wieczorek, 1996; Terlien 1998; Crosta, 1998; Crozier, 1999; Glade et al., 2000; Wieczorek 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) have attempt 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 (Wieczorek, 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 based on statistical analysis of relationship between rainfall and landslide occurrences (Campbell, 1975; Caine, 1980; Larsen and Simon, 1993; Crozier 1999; Guzzetti et al 2004, Guzzetti, et al., 2007) whereas, physical threshold usually described by 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 Wieczorek, 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 five days preceding the main rainfall event was significant in causing the landslides since other rainfall events of similar magnitude (but with less antecedent rainfall) did not cause landslides. By 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 site of Moriyuki and Monnyu of north east Shikoku were selected in this study for detail study of shallow landslides in granitic terrain.

The shallow landslides induced by typhoon brought rainfall in Moriyuki and Monnyu area of northeast Shikoku, Japan were not noticed during period 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 landsides of 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 study area with previously established threshold values.

2 Methodology

2.1 Landslide mapping

Detail field visit has been carried out in Moriyuki and Monnyu area after typhoon in order to map the existing landslides on 1:2,500 scale topographic map prepared by Kagawa prefecture office. All failures including flow path of failure materials were also mapped out during field visit. The colour aerial photographs taken immediately after the events (November 2004) were also studied to check the correct boundary of landslides. Altogether 201 small scale slides were noticed in Moriyuki catchment and 142 in Monnyu catchment after typhoon 0423 (Tokage). Total 76 landslides of moriyuki and 40 landslides of Monnyu area were investigated in field (Fig. 3) for analysis of nature of 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.

2.2 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 mention in sheet were collected in field. Geomorphology of sites included a record of slope orientation, length, height, and angle, 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 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 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.

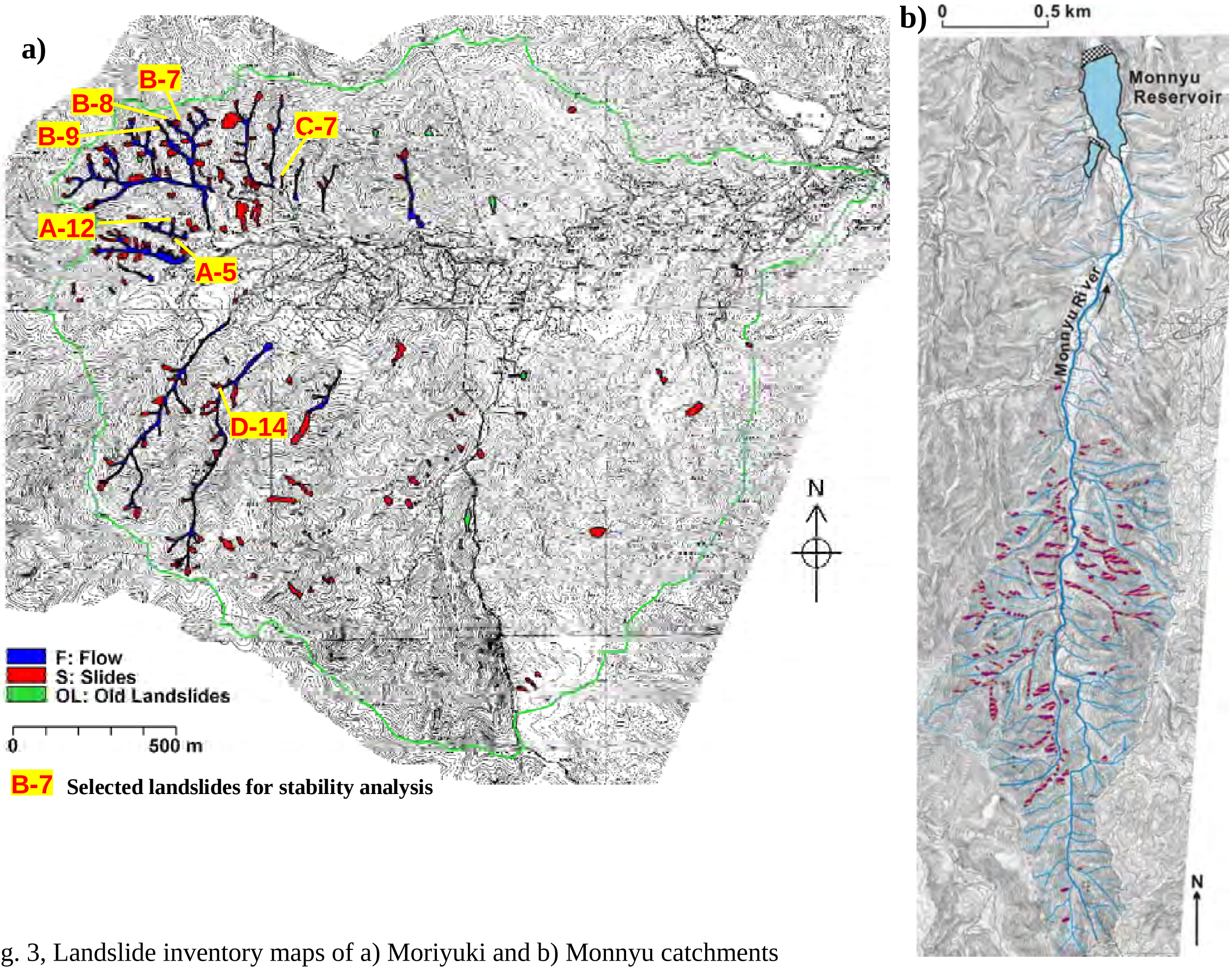


Fig. 3, Landslide inventory maps of a) Moriyuki and b) Monnyu catchments

2.3 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 Standard of Japanese Geotechnical Society (JGS) and Japan Industrial Standard (JIS). The soil grain density of residual material at each site was determined by the help of density tube in accordance with the specifications outlined in the Japan Industrial Standard (JIS) procedure A1202. Information about 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 evaluation of pore-water pressure rise.

3 Results of investigation

3.1 Characteristics of landslides

To understand the landslides morphology, characteristics, and classification, total 76 landslides of Moriyuki and 40 landslides of Monnyu area were investigated and measurement were taken. From the field investigation, it was notice that more than 70 % of landslides were mainly concentrated on valley or topographic hollow or concave type of slopes. Very few slides were noticed on spur or convex slopes (Fig. 4a). Similarly, slope angle of failed slopes was also varied in both areas. More than 50% of slides in Moriyuki were occurred in slope having slope angle 40 to 45 degrees, where as in Monnyu, nearly 80% of slope failures were noticed on the slopes which had slope angle 35 to 45 degrees (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 Second World War. Fig. 4c shows the result of field data. More than 70% of slides in Moriyuki were occurred on natural slopes where as only 5% of slides at Monnyu were on modified slopes.

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

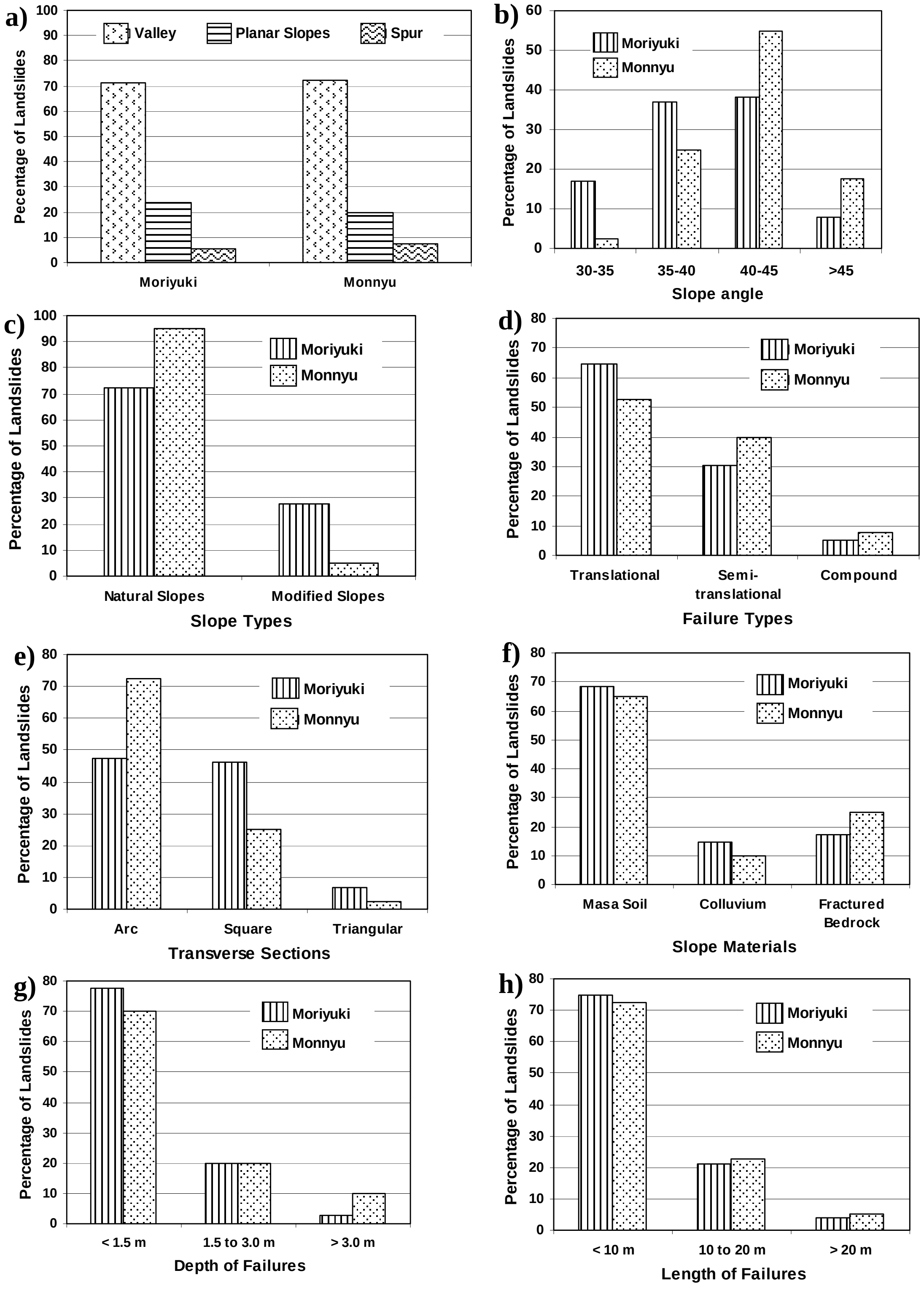


Fig. 4, Characteristics of landslides in the study area, a) Geomorphological location of landslides, b) Variation of slope angle, c) Landslides occurrences as per natural and modified slopes, d) Type of failure, e) Traverse section of landslides, f) Type of materials involved in landslides, g) Depth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

Fig. 5, Translational failure in weathered granite

Fig. 4d shows sense of movements in all slides and more than 50% of slides had translational sense of movement. 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). Material involved in the failure was also evaluated during field investigation (Fig. 4f). More than 60% of failure occurred within masa soil and contact of bedrock and masa soil. About 20% of failures were found in fractured bedrocks and few (about 10%) failures were found on 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 length <10 m (Fig. 4g and 4h). Study of volume of failed materials revealed that 95% of landslides had volume less than 1000 m3, where as in Moriyuki all landslides had volume less than 1000 m3. In this area, about 70% of landslides had volume less than 200 m3. So, the Moriyuki area represents the 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 detail stability analysis.

Vegetation did not appear to play a distinct role in controlling the locations of landslides at Moriyuki and Monnyu area. Japanese cypress, Japanese cedar, Japanese bamboos are main trees in forest. In Moriyuki area, more than 82% area is covered by dense forest of such trees. 6% area belongs to sparse forest and 5% is settlement area. Remaining area belongs to grassland, shrubs, agricultural land, riverbed and irrigation pond. The role of vegetation to control landslides is well described by previous researcher (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 on both forested and non forested area and it was observed that livelihood of landslides were mostly control by slope morphology, inclination, type of slope (modified or non-modified), and material involved. Nearly, 70% of slides occurred in forest area.

3.2 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. Amount of fines (<0.075 mm) in soils was less than 20% in most of soils. The fines had low plasticity index and classified as low plastic silt and clay. Chugoko-Shikoku Agricultural Administrative office (1981) of Japanese Government performed series of study in east Kagawa (including the study area) to estimate strength parameters (cohesion and friction angle) of well known weathered granitic layer (masa in Japanese). Thus, for stability and sensitivity analysis, average values of index parameters were decided as per work of Chugoko-Shikoku Regional Agricultural Administrative Office (1981) and present work, which are listed in Table 1. The average friction angle of masa soil for study area is 31.5° and the average cohesion is 4.9 kN/m^2 with standard deviation 2.3° and 1.2 kN/m^2 respectively.

The grain-size distribution curves of samples from 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 selected landslides.

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

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

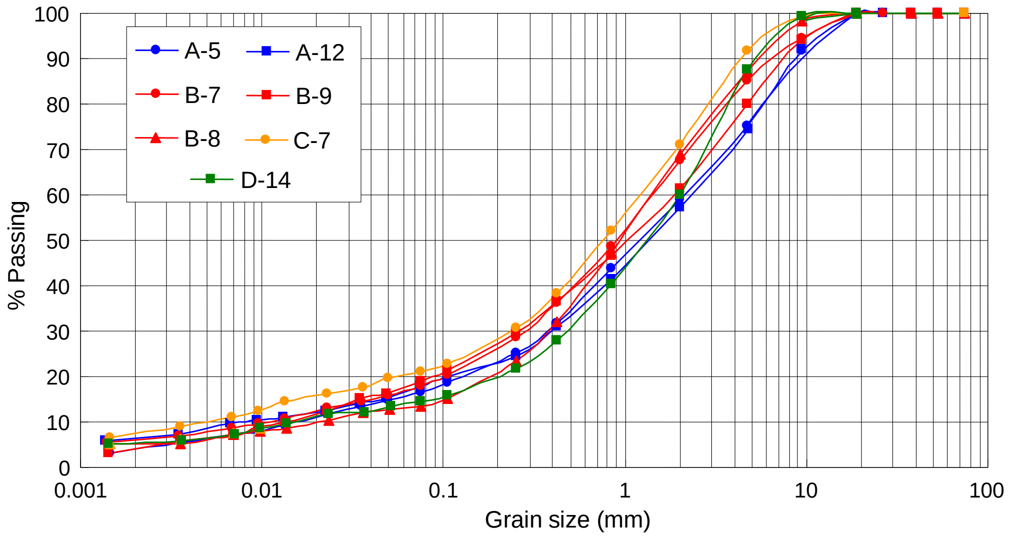
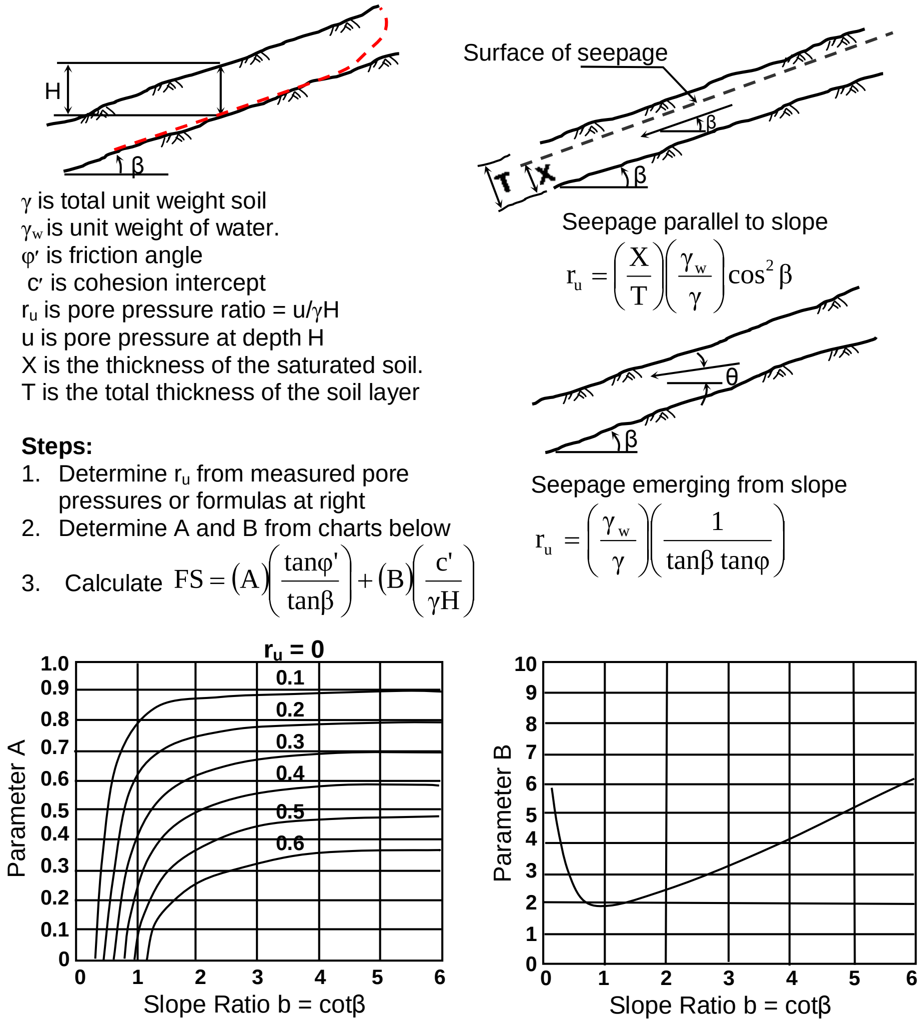


Fig. 6, Grain size distribution curve of soils at selected seven landslides

4 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. Total seven representative translational slides of Moriyuki were taken into consideration for stability analysis. Similarly, sensitivity analysis was also performed to ensure about parameters used in stability analysis and 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 used to make technique easier to attempt and to encourage utilization of 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. Fig. 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 of researchers for stability analysis of translational slides (Shakoor and Smithmyer, 2005). In this research, the method is employed on residual soil slopes of granitic terrain.



γ is total unit weight soil
γ_w is unit weight of water.
φ' is friction angle
c' is cohesion intercept
r_u is pore pressure ratio = $u/\gamma H$
u is pore pressure at depth H
X is the thickness of the saturated soil.
T is the total thickness of the soil layer

Steps:

1. Determine r_u from measured pore pressures or formulas at right
2. Determine A and B from charts below
3. Calculate $FS = (A)\left(\frac{\tan\varphi'}{\tan\beta}\right) + (B)\left(\frac{c'}{\gamma H}\right)$

Seepage parallel to slope

$$r_u = \left(\frac{X}{T}\right)\left(\frac{\gamma_w}{\gamma}\right)\cos^2\beta$$

Seepage emerging from slope

$$r_u = \left(\frac{\gamma_w}{\gamma}\right)\left(\frac{1}{\tan\beta\tan\varphi}\right)$$

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

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 to 4h), 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, there were colluvial materials and fractured bedrocks were also involved in about 20% failure (see Fig. 4f), but for sensitivity and stability analysis, they were excluded in this study and only attention were given 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 slides is ranged from 0.7 m to 1.1 m. Moreover, investigation of sense of movement in total 116 landslides of Moriyuki and Monnyu shows that more than 60% slides had perfect translational sense of movement and about 30% of slides had semi-translational (having slight curve 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 and Table 2) were taken into 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 stability of slopes, 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, average value of cohesion (4.9 kN/m^2) was considered little dubious for soil materials of sites C-7. So, a back analysis was carried out to obtain more accurate cohesion values corresponding to average friction angle value 31.5^{o}. For back analysis, factor of safety was considered one and infinite slope stability method developed by Duncan (Duncan et al 1987; Duncan 1996) was employed. New back calculated cohesion for site C-7 was 4.6 kN/m^2 and it was used in stability analysis of landslide C-7.

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, L, m		33.8	19.4	27.2	47.4	35.6	13.8	35.4
Average width, W, m		7.3	5.4	6.2	14.1	6.4	8.7	8.5
Depth, H, m		0.8	0.7	0.9	1.1	1.1	1	0.8
Inclination, β		34	38	44	41	43	32	38
Permeability k, 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}

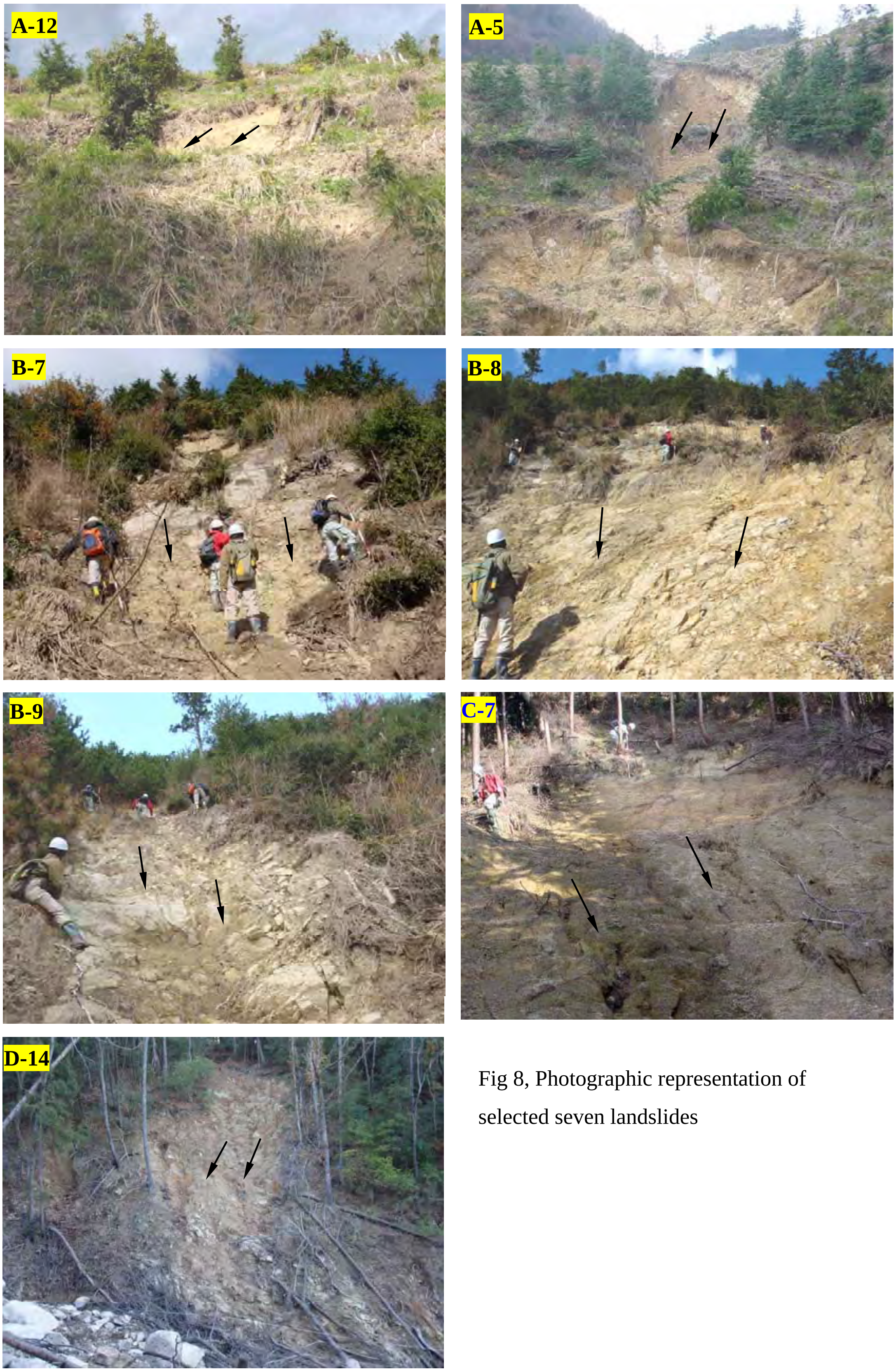


Fig 8, Photographic representation of selected seven landslides

4.1 *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 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 which was needed to estimate. 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^o to 44^o. Therefore, a range of 26^o to 50^o was chosen to cover any deviation. Likewise, average friction angle values also ranged from for the study sites ranged from 27.3^o to 35.3^o; thus, a range of 25^o to 40^o was used. Value of cohesion ranged from 2.9 to 6.5 kN/m^2, so, in this analysis, value of cohesion was used from 2.4 kN/m^2 to 7.0 kN/m^2 with increment of 0.2 kN/m^2. The value of soil depth was used as per the field measurement (ranged from 0.7 m to 1.1 m). Fig. 9 shows an example of sensitivity analysis for site A-5. Similar plots were generated for all seven cases.

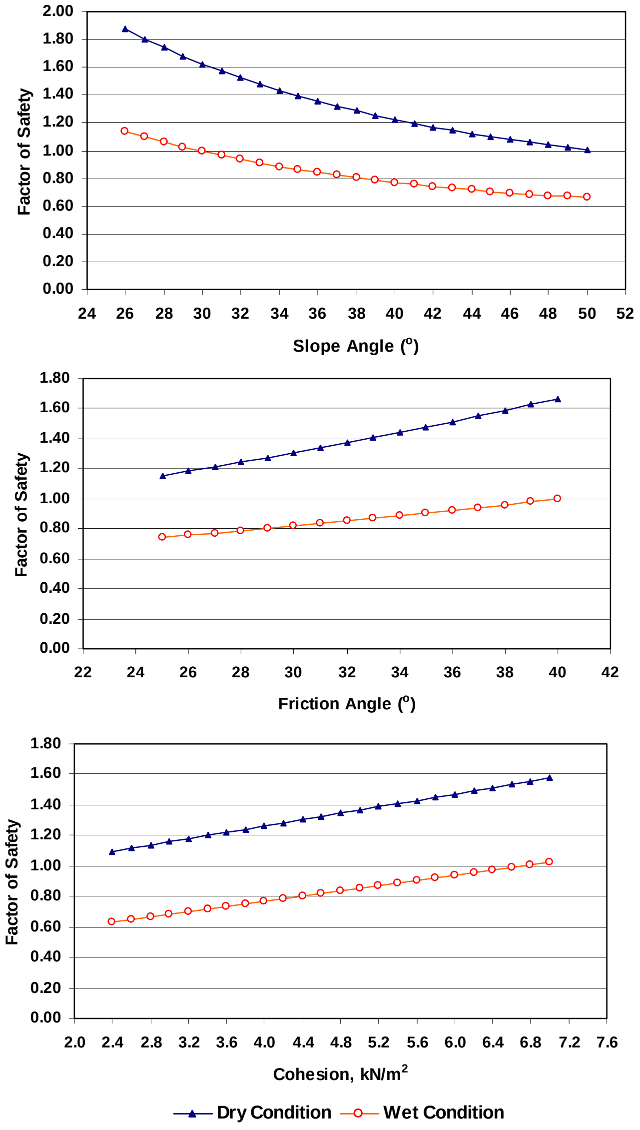


Fig. 9. Variation of factor of safety with respect to slope angle, friction angle, and cohesion for landslide A-5 for both dry and saturated condition of soil

4.2 Stability analysis

The Duncan's (1996) method quantitatively analyzes effect of soil saturation on the stability of those slopes which have high potentiality of translational slides. This method considers the length of failure surfaces is high in comparison to depth. It also ignores the driving force at 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 slope face. Duncan (1996) described following three steps of procedure in the analysis method (see Fig. 7 also).

1. Determination of the pore pressure ratio (r_u), from 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 soil.

   β is slope angle

2. Determination of parameters A and B, these parameters are necessary for calculation of factor of safety and can be obtained by Fig. 7. However 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 B corresponds to the shear resistance along the sliding

3. Determination of Factor of Safety (FS), from following relationship.

   $$FS = (A)\left(\frac{\tan\varphi'}{\tan\beta}\right) + (B)\left(\frac{c'}{\gamma H}\right)$$

   Where,

   φ' and c' are effective strength parameters;

   β is the slope angle.

   γ is unit weight of 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 Moriyuki, the saturated fraction of soil layer, denoted by X in Duncan's (1996) method, was considered to range from 40% to 100% of soil thickness (T) of each slide. Similar to the process employed in sensitivity analysis, 25 (26^o to 50^o with interval of 1^o) 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 that illustrate 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. Result of stability analysis is listed in Table 3 and it was understood that masa soil of north east Shikoku has high potentiality of translational slide even in 40% saturation of soil layer. If soil thickness is high, more saturation is needed.

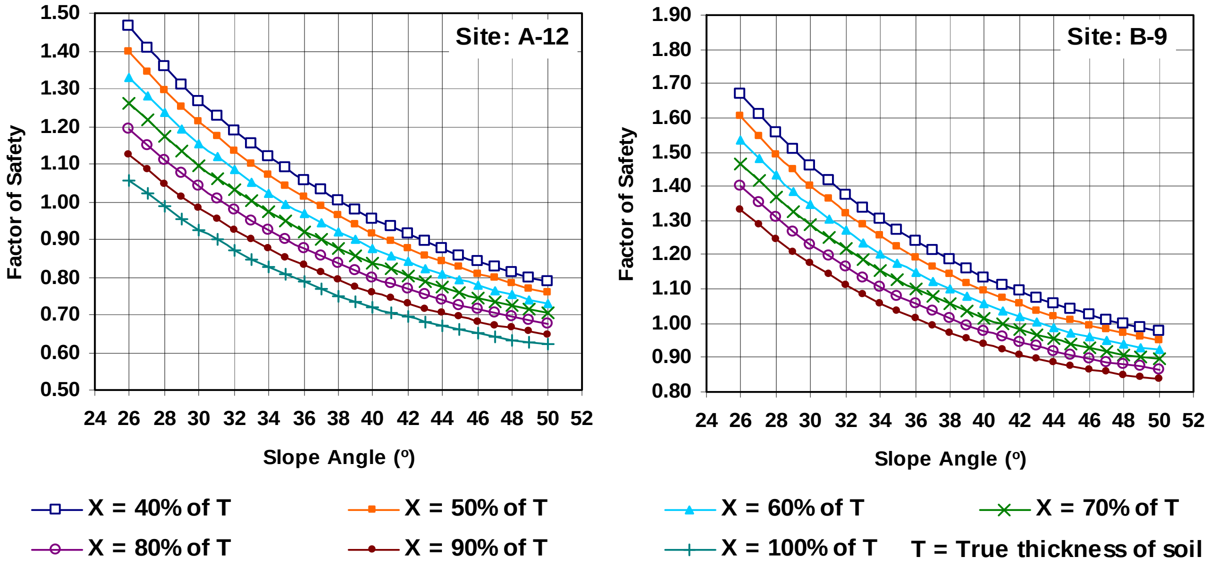


Fig. 10, Relationship between saturated soil fraction, slope angle and factor of safety for landslides A-12 and B-9

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 had factor of safety also 1.18, 1.38 and 1.32 respectively for dry conditions. Data shows landslide C-7 was failed at 100% saturation during typhoon 0423 (Tokage), whereas other were failed at 40% to 80% saturation.

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

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 saftey for dry conditions	1.44	1.22	1.18	1.38	1.32	1.65	1.29
Factor of saftey 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	1.02
0.6	1.08	0.92	0.95	1.08	1.04	1.23	0.97
0.7	1.03	0.88	0.91	1.04	1.00	1.17	0.93
0.8	0.98	0.84	0.88	1.00	0.97	1.12	0.89
0.9	0.93	0.79	0.85	0.96	0.93	1.06	0.85
1.0	0.88	0.75	0.81	0.92	0.90	1.00	0.81

The result of stability analysis strongly supports the landslide disaster during typhoon 0423 (Tokage) in granitic terrain of north east Shikoku, Japan. The soil had relatively high permeability (in the range of 10^{-3}). The amount of rainfalls in the Moriyuki and Monnyu area were 582 mm and 412 mm on the day of 20 October 2004, respectively with antecedent rainfall of 92 mm and 83 mm of preceding day. Likewise, maximum one hour rainfall in Moriyuki and Monnyu area on 20 October 2004 is 117 mm and 76 mm, respectively (see Fig. 2 also). Evaluating from the minimum value of permeability, it was understood that within 5 hour of continue percolation of water into the masa soil of Moriyuki; water can enter more than 20 cm of soil depth. This suggested extensive failure occurred in masa soil of north east Shikoku because of high rate of infiltration and high amount of rainfall intensity.

5 Evaluation of rainfall threshold of events

Thresholds rainfall for triggering landslides is one of the debatable topics since last 25 years. It was N. Caine who first published a paper in 1980 about the threshold rainfall value for worldwide landslides scenario. After that many attempts has been made to establish the threshold value, in global context as well as in regional context. In Japan, defining rainfall threshold for failure is basically different than American and European way of presentation. Various rainfall indexes are used to define 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 break out of the event. Yano (1990) has proposed to use 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 threshold rainfall prediction (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) is used to describe the rainfall threshold of north east Shikoku. Fig. 11 illustrates the 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 time of occurrence of landslides is shown as circular symbols.

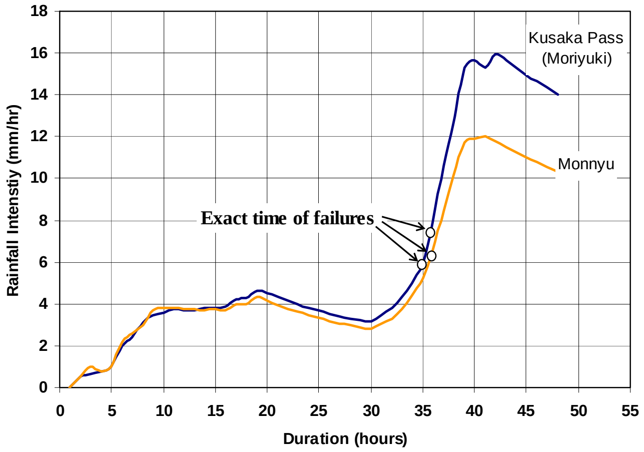


Fig. 11, Temporal pattern of rainfall intensity vs. duration for the 2004 rainfall event of Moriyuki and Monnyu area. The left of the graphs represent initiation of rainfall. Symbols indicate the occurrence of landslides in Moriyuki and Monnyu during typhoon 0423 (Tokage).

The value of effective temporal rainfall intensity to create landslide was plotted with rainfall duration in 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 north east Shikoku (Moriyuki and Monnyu) during 2004 typhoon 23 event slightly higher than the threshold of storm-triggering landslides proposed by Larsen and Simon (1993) for Puerto Rico (humid-tropical region) and slightly lower than rainfall threshold of landslides in Portugal, western Europe (Zezere et al. 2005). The curve proposed by Cancelli and Nova (1985), Ceriani et al. (1994), Crosta and Frattini (2001), Aleotti (2004) and Guzzetti et al. (2007) for the Alps could not cover up the average rainfall intensity of 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 study area. However, the full disaster history needs to be understood for more accurate prediction of 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 granitic terrain of north east Shikoku.

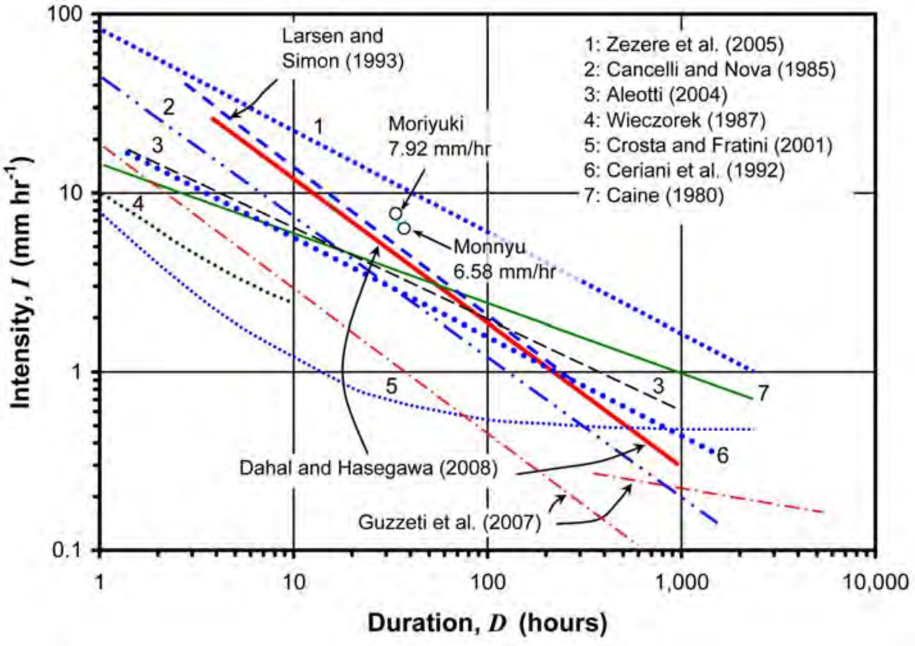


Fig. 12, Rainfall intensity and durations associated with slopes failures during typhoon 0423 (Tokage) in north east Shikoku, Japan and curve proposed by various researchers for similar case. From the data of 2004 landslides events, threshold rainfall intensity for north east Shikoku is slightly higher than the threshold line for storms triggering landslides proposed by Larsen and Simon (1993) for Puerto Rico (Humid-Tropical Region) and slightly lower than threshold of landslides in Portugal, western Europe (Zezere et al. 2005). For north east Shikoku, the curve proposed by Larsen and Simon (1993) is relatively better than line proposed by Caine (1980) from worldwide data.

6 Conclusions

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

1. Typhoon brought rainfall-induced landslides in granitic terrain of north east 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 granitic terrains (masa) were 40% to 100% saturated depending upon the slope angles and vertical depth of soil.

It was also understood that extensive failure occurred in masa soil of Japan during typhoon rainfalls because of high rate of infiltration and high amount of rainfall intensity.

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

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