Rainfall triggered flow-like landslides: Understanding from southern hills of Kathmandu, Nepal and Northern Shikoku, Japan

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Abstract: Flow-like landslides triggered by rainfall are very prominent in Nepal and Shikoku, Japan. In July 2002, many landslides occurred in the southern hills of the Nepalese capital, Kathmandu, because of torrential rainfall. A single flow-like landslide occurred at Matatirtha, a small village situated at the south marginal hill of Kathmandu, killing 18 people who lived at the foot of the hill. Much damage was caused to roads and houses because of landslides and debris flows in small streams.

Similarly, in August, September and October 2004, strong typhoon hit the area of northern Sikoku, Japan and extensive damage occurred on hill slopes and some human casualties were also reported. Field observation showed that in northern Sikoku, many flow-like landslides occur in the thin weathering profile of igneous and sedimentary rocks, as well as in old debris materials. However, in the southern hills of Kathmandu, flow-like landslides occurred in weathered debris.

During the investigation, the geotechnical properties of landslide materials were determined in the laboratory. The volume of material involved in some of the flows was calculated as per average thickness of the soil cover and area of failure. Likewise, rainfall threshold value for Kathmandu and Northern Shikoku is also evaluated. From the field investigations, it is recommended that human habitation at the foot of hills should be legally regulated by the government to reduce death from flow-like landslides triggered by torrential rainfall. It is also recommended that landslide hazard maps need to be quantified to include landslide risk assessment and management for flow like landslide also which help to develop early warning systems for flow-like landslide disasters.

Résumé: Couler-comme des éboulements déclenchés par des précipitations soyez très en avant au Népal et le Shikoku, Japon. En juillet 2002, beaucoup d'éboulements produit dans les collines méridionales du capital népalais, Katmandou, en raison de précipitations torrentielles. Un simple couler-comme l'éboulement s'est produit chez Matatirtha, a petit village situé à la colline marginale du sud de Katmandou, tuant 18 peuplez qui a vécu au pied de la colline. Beaucoup de dommages ont été causés aux routes et maisons en raison des éboulements et des écoulements de débris dans de petits jets.

De même, en août, septembre et octobre 2004, l'ouragan fort a frappé le secteur de Sikoku nordique, le Japon et les dommages étendus se sont produits sur des pentes de colline et quelques accidents humains ont été également rapportés. L'observation de champ a prouvé que dans Sikoku nordique, beaucoup couler-comme des éboulements produisez-vous dans le profil survivant à mince des roches ignées et sédimentaires, aussi bien comme en vieux matériaux de débris. Cependant, dans les collines méridionales de Katmandou, couler-comme des éboulements s'est produit en débris survécus à.

Pendant la recherche, le géotechnique des propriétés des matériaux d'éboulement ont été déterminées dans le laboratoire. Le volume du matériel impliqué dans certains des écoulements a été calculé selon la moyenne épaisseur de la couverture de sol et du domaine de l'échec. De même, seuil de précipitations la valeur pour Katmandou et Shikoku nordique est également évaluée. Du champ des investigations, on lui recommande qu'habitation humaine au pied de collines si est légalement réglé par le gouvernement pour réduire la mort de couler-comme éboulements déclenchés par des précipitations torrentielles. On lui recommande également qu'éboulement des cartes de risque doivent être mesurées pour inclure la évaluation des risques d'éboulement et gestion pour l'écoulement comme l'éboulement également qui aident à développer la détection précoce systèmes pour couler-comme des désastres d'éboulement.

Keywords: Landslide, weathering, failures, igneous rock, soils

INTRODUCTION

Slope failure broadly described as landslide is a consequence of a large mass surges down slope in response to the gravity. The style of mass movement is generally defined according to flow velocity, volume of the material involved, shear rates, and shear strength of the materials. The fluid and its interaction with the solid materials provide broader variations in its style. Experiences show that landslide occurrences on hill slopes have very close relationship with availability of water. As a result, many varieties of landslides occur as a consequence of heavy rainfall in tropical and temperate climatic zones (Jacob and Weatherly, 2003). Flow-like landslides triggered by rainfall occur in most mountainous landscape of the world (Iverson, 2000). They pose a significant natural hazard and they have a high damaged potential (Brenner, 2003). There are many statistically meaningful analysis has been published to demonstrate threshold value of rainfall and landslide triggering (Caine 1980; Keefer et al., 1987; Wilson and Wieczorek 1995; Terlien 1998; Crosta 1998; Pasuto & Silvano 1998; Guzzetti et al., 2000; Crozier 1999; Glade et al., 2000; Wieczorek et al., 2000; Aleotti 2004; Guzzetti et al 2004; Mikos, Cetina & Brilly 2004; Shakoor & Smithmyer 2005; Xie, Esaki & Cai 2005). The first study about rainfall threshold was done by Caine in 1980. In this study, he investigated total 73 shallow landslides of world and by the help of local precipitation records and he postulated a relationship $I = 14.82\ D^{-0.39}$, where I is rainfall intensity (mm/h) and D is rainfall duration (h). But within last few years, there are many works available in relation to threshold rainfall for triggering landslide with hydroclimatic condition, antecedent rainfall (Crozier 1999; Glade, Crozier & Smith 2000) and hydraulic conductivity (Terlien 1998). Keeping view of these contexts, this paper will describe some of scenario of rainfall triggered flow-like landslide occurred in Kathmandu, Nepal and Shikoku, Japan.

RAINFALL TRIGGERED FLOW-LIKE LANDSLIDE IN NEPAL

The Kingdom of Nepal is sandwiched between Peoples' Republic of China in the north and India in the south, east and west. Nepal is situated in the center of the long Himalayan concave chain, and is almost rectangular in shape with about 870 km length in the NWW-SEE and 130 to 260 km in N-S direction. The Himalaya has one of the most dynamic and fragile mountain landscapes. It is a live mountain with active tectonics (Figure 1). The seasonal monsoon rains, intense but improper land use practices both for cultivation and construction ensure that the Nepalese Himalayas are among the most unstable landscapes worldwide. The inherently weak geological characteristics of the rocks and soils have made the Himalaya fundamentally a very fragile mountain (Upreti 2001). The Himalaya is very vulnerable to natural and common hazards such as landslides, debris flows, and soil erosion primarily triggered by extensive rainfall of monsoon (Figure 2 and Figure 3). Moreover central Nepal, including Kathmandu, gets high intensity of rainfall than other part of Nepal. The combination of the weak geology and the monsoon climate makes each physiographic zone of Nepal very hazardous.

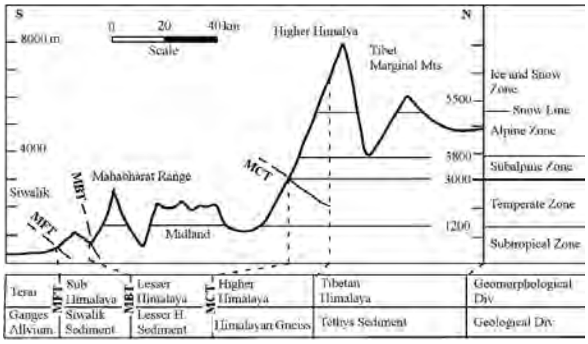

Figure 1. Cross section of Nepal Himalaya, MCT (Main Central Thrust), MBT (Main Boundary Thrust) and MFT (main frontal Thrust) make Himalaya tectonically active and dynamic mountain of world (modified after Upreti and Yoshida, 2005 and Kizaki, 1994).

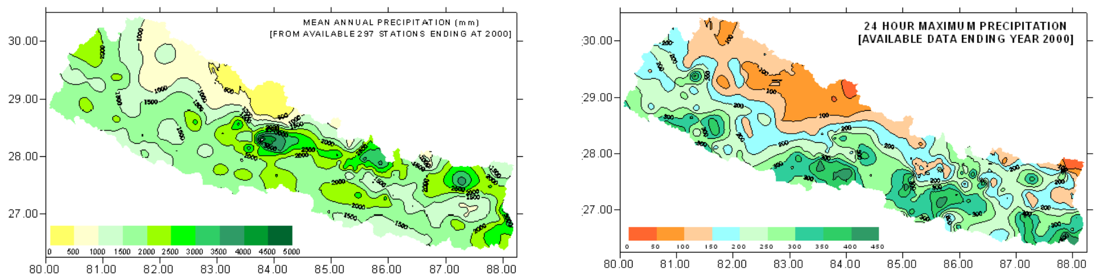

Figure 2. Mean annual precipitation map and highest 24-hour precipitation (mm) Map of Nepal (DHM 2003)

Although, Nepal has problem of rainfall triggered landslide, still there are no any significance works to identify the threshold value of rainfall to create shallow failure. The shallow landslide on slope that generally flows down to slope in very high velocity is found to be most devastating landslide in Nepal. Such landslide is fundamentally debris flow (Hungr et al 1984; Coussot and Meunier 1996; Guadango et al 1999, Hungr 1995; Hungr 2000; Hungr et al 2001; Wen and Aydin 2005; Jacob, Hungr &Thomson 1997) and recently very famous as flow like landslide (Dai, Lee & Wang 1999, Iverson, 2000, Hungr et al 2001, Hungr 2003, Dai, Lee & Wang 2003, Jacob and Weatherly, 2003, Malet et al 2004). Some attempt has been done to describe the threshold value of Himalayan flow-like landslides (Caine &

Mool 1982, Dahal and Kafle 2003, Gabet et al, 2004, Khanal and Watanabe 2005) but it is found to be insufficient because of extremely varied site condition.

In Nepal, on an average 260 people lost their lives every year and about 30,000 families affected annually. In 2002, from mid July to late September, 52 districts affected by landslides and floods, 444 people were killed, about 44 were missed, more than 100 were injured, more than 55,000 families were affected (Dahal and Kafle, 2003). This phenomenon is also experienced in monsoon of the year 2003. In the year 2003, landslides triggered by rainfall extensively damaged the Mugling-Narayanghat road. More than 200 landslides are noticed in this road section. In which more than 60% of landslides belong to flow-like nature.

Flow-like landslide in southern hills of Kathmandu

In Nepal, it is felt that flow-like landslides affect human settlements, bridge and roads by destroying and burying (Figure 3). In the year 2002, many flow-like landslides occurred along southern marginal hills of Kathmandu and damaged many infrastructures. Single flow-like landslide occurred in Matatirtha, a small and beautiful village situated at the south western marginal hill of the capital city Kathmandu killed 18 people inhabiting on the base of the hill (Figure 4 and Figure 5). Although some more flow-like landslides occurred in southern marginal hills, the Matatirtha was most devastating one. Some of flow-like landslides also damaged road of hills (Figure 6) but casualty was not reported.

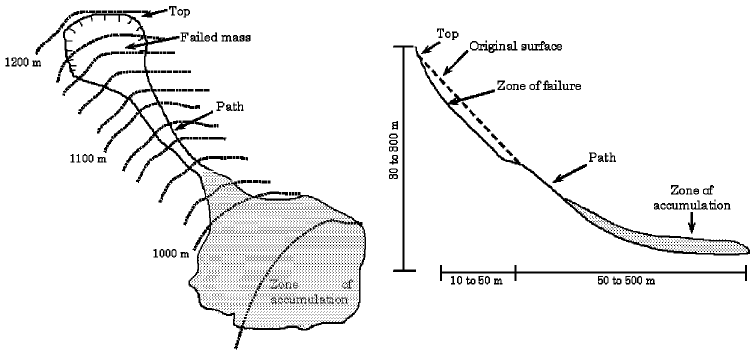

Figure 3. Diagrammatic indication of a typical flow-like landslide feature in Nepal Himalaya

Figure 4. Flow-like landslide of Matatirtha, July 2002, site after 40 hours

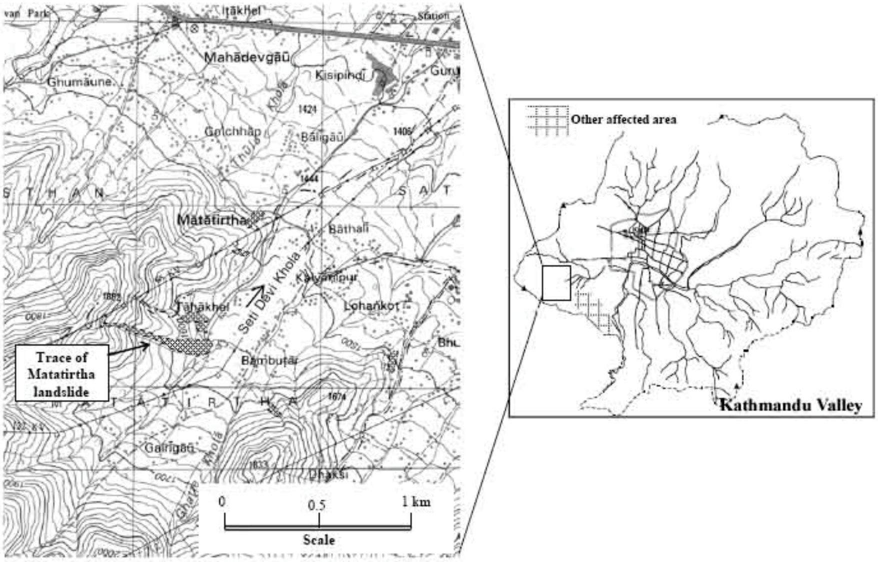

Figure 5. Location Map of Matatirtha flow-like landslide, other flow-like are also shown in map

RAINFALL TRIGGERED FLOW-LIKE LANDSLIDE IN SHIKOKU, JAPAN

Shikoku is the smallest of the four main islands of Japan (18,800 sq km) and situated at south of the island of Honshu and east of the island of Kyushu, between the Inland Sea and the Pacific Ocean. Shikoku is 225 km long and 50 km to 150 km wide. It is a heavily forested mountainous region of Japan. The highest peak of Shikoku is Mount Ishizuchi (1,982 m).

Shikoku can be roughly divided into three geological zones (Figure 7). They are Ryoke, Sambagawa-Chichibu and Shimanto belts from north to south, respectively. The three zones are bounded by the northerly dipping two master faults. These are the Median Tectonic Line (MTL) and the Butsuzo Tectonic Line (BTL) from north to south, respectively. The Ryoke belt in Shikoku topographically divided into three zones: Seto Inland Sea, recent fan and hills having maximum altitude about 1000 m. This belt consists of mainly of the Late Cretaceous Ryoke granitic rocks, the Latest Cretaceous sedimentary rocks (Izumi Group) and Miocene volcanic rocks (Sanuki Group). Cretaceous granite is widely distributed in Chugoku to the north of Seto Island Sea. The Median Tectonic Line (MTL) topographically marks a distinct sharp boundary of Shikoku Range. Shikoku Range having maximum altitude of nearly 2000 m is occupied by the Sambagawa-Chichibu Belt. The Sambagawa Belt is composed of the low-grade Sambagawa metamorphic rocks. The Chichibu Belt is mainly composed of the Carboniferous to Jurassic sedimentary rocks and low-grade Sambagawa metamorphic rocks.

Figure 6. Flow-like landslide on roadside slopes of southern hills of Kathmandu, triggered by Rainfall of July 2002

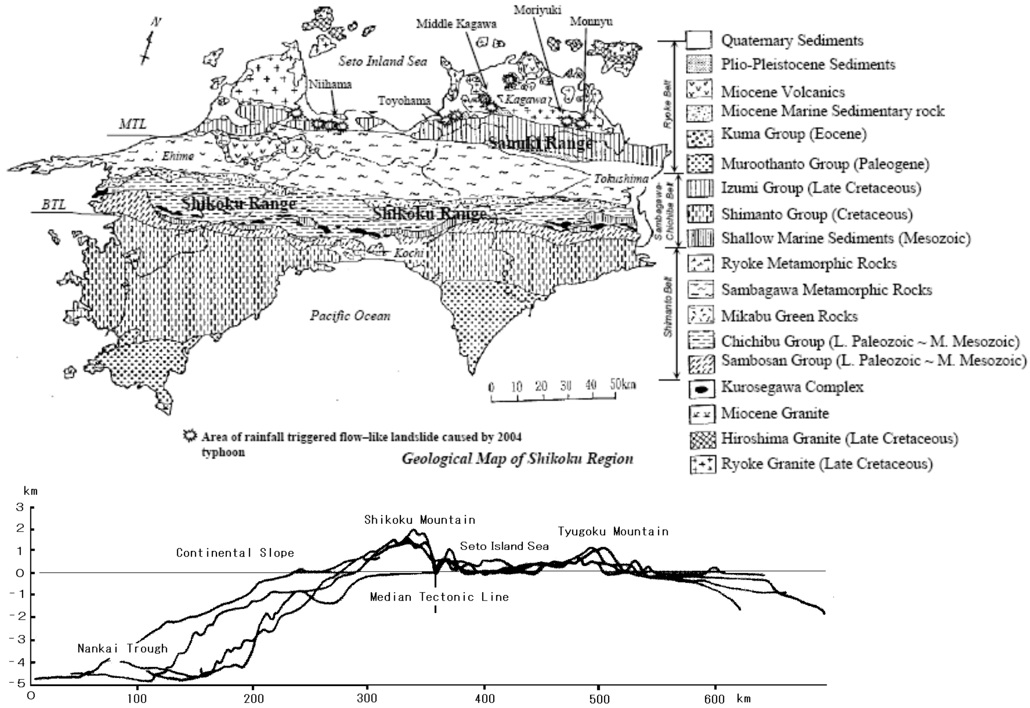

Figure 7. Geological Map of Shikoku Region (modified after Hasegawa and Saito, 1991 and profile of Shikoku Region, modified after Kikkawa et al, 2003)

The Shimanto Belt consists of the Cretaceous and Paleogene sedimentary rocks and this belt occupies southern two peninsulas protruding out into the Pacific Ocean. The middle Miocene granitic and partially gabbroic rocks are sporadically distributed along the axes of Muroto and Ashizuri peninsulas.

There is almost no settlement in hills but hill of base are considerably populated. Hills are almost covered by thick forest of subtropical broad leaf trees, Japanese cedars as well as few Japanese bamboos and all landslides are occurs within the forest and flow-like landslide usually bring not only soil and rock debris but also huge amount of bamboos and cedar tress debris.

Flow-like landslide in northern Shikoku

In the year 2004, Japan was hit by 10 typhoons in a period of 3 months from August to October. The typhoons were very devastating as they bring tremendous rainfall, often exceeding 100 mm in one hour. Previously there are some typhoon events in Northern Shikoku Region and extensively damage the whole area (Table 1).

There is good rainfall measurement system in Shikoku Region and it is available on the internet also. During typhoon of 2004 August to October, there is extreme rainfall occurred in central northern Shikoku and north east Shikoku (Figure 8, Figure 9 and Table 2).

Shikoku Island was hit by six typhoons last year and Northen Shikoku (mainly Ehime and Kagawa) was suffered by loss of lives and property due to many flow-like landslide induced by typhoon rainfall. Because of good rainfall data logging system of Japan, it is noticed that hourly rainfalls exceeding 50 mm and total 24-hours rainfalls as much as 400 mm were main cause of slope failures at different locations in north Shikoku. The hardest-hit area was Niihama of Ehime Prefecture and Moriyama and Monnyu of Kagawa Prefecture (Table 2 and Figure 10). The flows like landslide and debris flows near the densely populated hill bases took lives of more than 30 people.

Table 1. Main events of typhoon in Kagawa, north east Shikoku (Yokihiro, 2005)

S.N.	Year	Date	Name of Typhoon	Death	Missed	Injured	Damaged house	Partly damaged house
1	1899	8/28	Typhoon of 8/28	307	10	955	7015	4286
2	1934	9/21	Moroto Typhoon	18	1	30	938	728
3	1945	9/17-18	Makurazaki Typhoon	13	0	13	2204	380
4	1959	9/26	Toyamaru Typhoon	8	7	5	275	430
5	1974	7/6	Typhoon 8	29	0	27	51	216
6	1976	9/8-9/13	Typhoon 17	50	0	126	287	321
7	2004	10/20	Typhoon 23	11	0	15	49	70

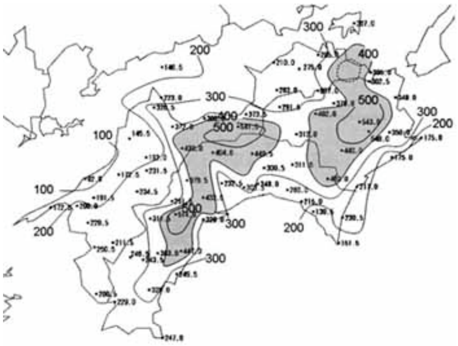

Figure 8. Cumulative Rainfall of October 19 to 21, 2004 in Shikoku Region (Yokihiro, 2005)

Figure 9. Buried village in Moriyuki (see Figure 7 for location)

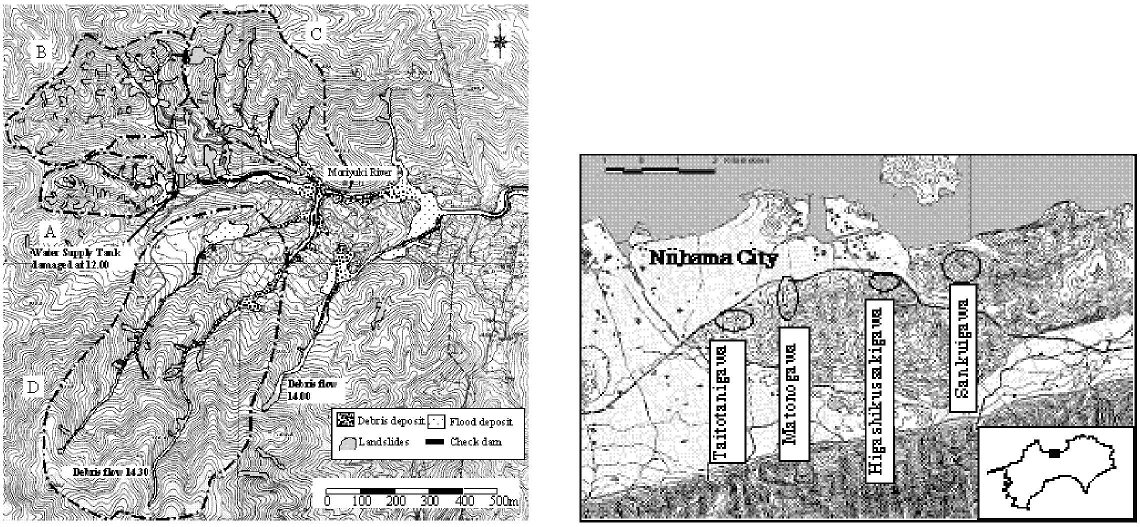

Figure 10. Rainfall triggered debris slide and flow-like landslide in Moriyuki area (north east Shikoku) and Niihama City (middle north Shikoku)

There is much local scale damage in highway and forest areas around Takamatsu City (regional headquarter of Shikoku). Middle Kagawa is also affected by the typhoon and there are many slides in forest area also (see Figure 7). Takamibo forest area and Mineyama landslide near to Central Takamatsu are some examples. Landslides occurred at base of hills in Toyohama city (Figure 11 and see Figure 7 also) are some other examples of flow like landslides of west Kagawa.

Table 2. Four typhoon disasters in Kagawa (north east Shikoku) in the year 2004 (Yokihiro, 2005)

S.N.	Typhoon No.	Date	Death	Injured	Damaged houses	Half damaged house	Partly damaged house
1	Typhoon 15	8/17-18	5	0	0	4	3
2	Typhoon 16	8/30	3	6	1	8	224
3	Typhoon 21	9/29	0	0	1	2	40
4	Typhoon 23	10/20	11	15	49	70	155

Figure 11. Rainfall triggered flow-like landslide and in Kagawa (Takamibo, Mineyama and Toyohama)

NATURE OF SLIDES AND MATERIALS INVOLVED IN SOUTHERN HILLS OF KATHMANDU

Geological characteristics

Kathmandu valley is surrounded by high rising mountain ranges, such as Shivapuri (2732 m) in the north and Phulchauki (2762 m) in the south east and Chandragiri in south west. The Kathmandu valley comprises of quaternary sediments on top of basement rocks. The basement rock consists of Phulchauki Group and Bhimphedi Group of the Kathmandu Complex (Stöcklin and Bhattarai, 1977 and Stöcklin 1980) and is formed by Precambrian to Devonian rocks. The rocks of Phulchauki Group and Bhimphedi Group together form the Kathmandu Complex, and tectonically interpreted as thrust mass (allochthonous). The rocks of Kathmandu Complex along with the underlying autochthonous Nawakot Complex constitute the Mahabharat Synclinorium. The axis of this synclinorium passes along the Phulchowki-Chandragiri Range (southern hills of the Kathmandu valley). The Bhimphedi Group consists of relatively high-grade metamorphic rocks of Precambrian age whereas Phulchowki Group comprises of weakly metamorphosed sediments of early to middle Palaeozoic age. The rock consists of intensely folded and faulted meta-sediments such as phyllites, schists, slates, limestone and marbles. Southern hills of Kathmandu valley mainly consists of limestone rocks of Phulchauki Group (Figure 12).

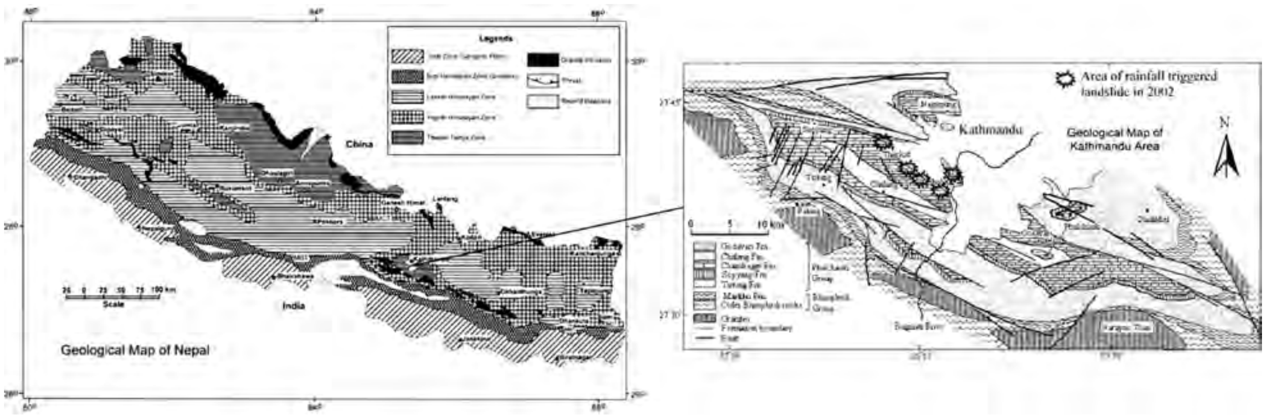

Figure 12. Simplified geological map of Nepal (Dahal, 2005) and Kathmandu area (Stöcklin, 1980)

Precipitation of the area

From the meteorological point f view, the month of July is very critical for the southern hills. There are not much rain gauge station and hourly rainfall data is also not available. Most nearest rain gauge station from the failure area is in Thankot (situated at about 1.5 to 3 km aerial distance from Matatirtha and other slides see Figure 12). Plotting of last 32 years rainfall data of south and south-west Kathmandu reveals that month of July of every year has been facing maximum rainfall (Figure 13). Rainfall data recorded by the Department of Hydrology and Meteorology (DMG) at its Thankot station is 300.1 mm at 24 hr in the day of major failures, i.e. 23 July 2002 (Figure 14).

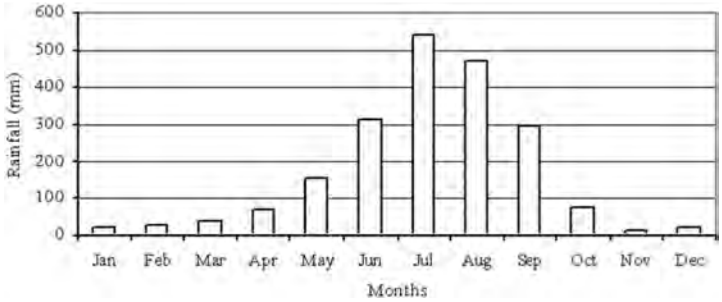

Figure 13. Mean monthly rainfall pattern of Thankot area for a period of 32 years (1971-2002)

Surface geology and geotechnical characteristics of materials

The southern hills are mainly covered by old weathered debris deposit over limestone and thin layer of residual soil on top. Almost all landslides in southern hills were noticed mainly on weathered colluvial materials. The large and most catastrophic Matatirtha landslide was also occurred on weathered debris materials. Geomorphologically, all failure sites were noticed in gullies. The topographical map and aerial photo of the area clearly show typical dry gully having thick weathered colluvium are main failed slopes.

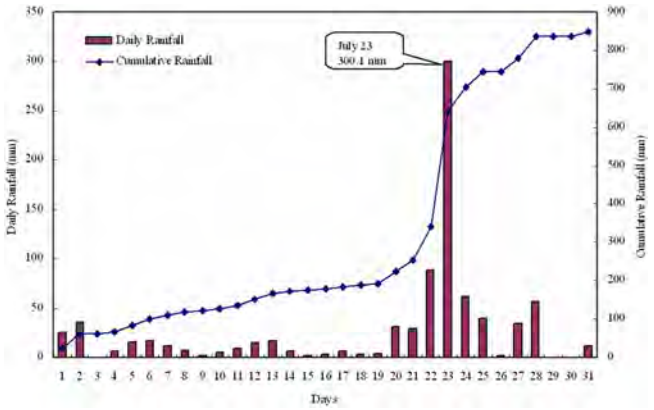

Figure 14. Rainfall pattern of Thankot area in the year 2002

Geotechnical properties of the both deposited debris and colluvial materials of the slope are identified as far as practicable. The altered and reworked soils, which often form the original soil cover at the heads of gullies, have wide grain size distributions (Figure 15) and have significant clay fractions.

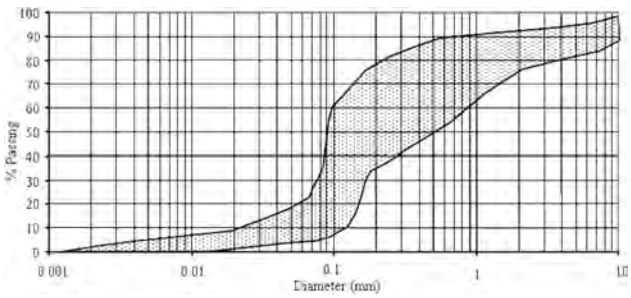

Figure 15. Grain size distribution pattern of debris and undisturbed soil in the Matatirtha area

The thickness of soil is also varied from crown part to lowest part of failure in all failure. At crown part of many failures, the thin veneer of porous silty gravel of thickness 0.5 m to 1.5 m is found over the extensively jointed calcareous rock. In almost all slides, the soil thickness at end of failure zone is 4 to 5.5 m. Unified Soil Classification of soil shows that the soil type of the all failure area ranged between GM-GC to SM-ML with considerable amount of gravel. The plastic limits of the soils from different locations vary from 20% to 35% whereas the liquid limit of the soil generally varied from 20% to 45%. Almost all failure mass plots of liquid limit and plasticity index (Figure 16) lie below the A-Line of Casagrande Plasticity Chart (USBR, 1963). The calculated dry unit weight of the soil is ranged between 15 kN/m^3 to 19 kN/m^3. The shear strength parameters from undisturbed samples were not determinable due to considerable amount of rock fragment in samples. So the shear strength test carried out on reconstituted specimen and variable friction angle value ranged from 25^o to 30^o. The value of apparent cohesion also ranged from 4 kN/m^2 to 7 kN/m^2.

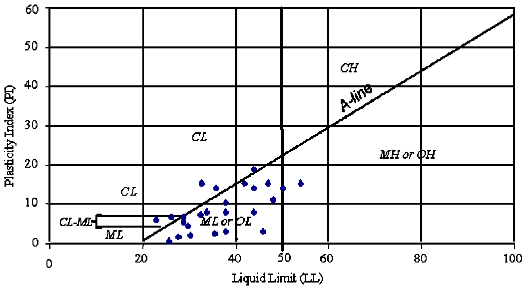

Figure 16. Plot of liquid limit and plasticity index in plasticity chart of Casagrande

Failure processes with example

The steep slope of upper reaches of each landslides containing thin veneer of soil which was almost liquefied during the huge rainfall and plucked from the underlain bed rock. Before failure at crown, the pervious soil continued infiltrating rainwater, also helped to generate almost saturation condition on the thick colluvial soil of down slope. The down slope in each failure has a gully and without any outlet system in lower reaches. As a result, the saturation of slope materials was initiated from down to up. In each slide it is very clearly observed that debris slide first occurred at crown part and it scrape off the almost saturated thick soil of down hill and whole mass of the channel begins to flow like a liquid as per the liquefaction flow rule (Darve, 1996). Such flows continued erode its route down to the deposition area. In case of Matatirtha landslide, debris flow hit the whole settlement of base and killed 18 people. It also dammed the small stream (Seti Devi River, see Figure 7) which was opened after few minutes. The evidence of liquefaction at the site was seen on toe part and cultivated land. The toe and cultivated land were almost cushioned by slurry of debris. The schematic view of the debris flow development pattern is shown in Figure 17.

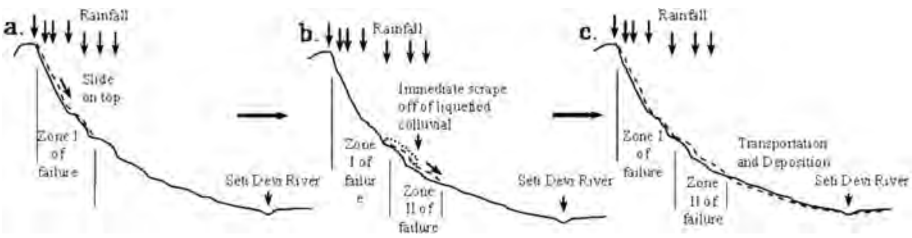

Figure 17. Schematic view of formation of flow at Matatirtha Landslide, an example of flow pattern in of flow-like landslide southern hills of Kathmandu

From the study of flow-like landslides of southern hills of Kathmandu, it is felt that there are some parameters which caused the abrupt loss of shear strength of colluvium deposit and they are listed below.

- High intensity of rainfall
- Steep slope (>60o) of upper reaches covered by thin veneer of silty gravel cover
- High infiltration rate at upper reaches
- Localized slide on the upper reaches of the slope
- Gully with thick clayey and silty gravel deposits
- Encroachment of channel in lower reaches by cultivation practice

Due to large in nature, the flow velocity of Matatirtha landsilde is also approximately estimated by the following equation by considering simple infinite model for liquefied debris and correcting value of g with slope angle (Hungr 2003, Dahal and Kafle 2003 and Poudel 2004).

$$1/2mv^2 \geq m\ g\ \sin\beta\ h$$

where, m is mass, v is velocity, g is gravitational acceleration, β is slope angle and h is height

From the relationship, the minimum flow velocity of the Matatirtha before hitting the settlement was ≥40 m/s. According to Cruden and Varnes (1996) landslide scale, the Matatirtha landslide is Extremely Rapid Landslide. Similarly, time elapsed of flow is also estimated by simple equation of motion. It is predicted that after initiation of slide at upper reaches, minimum time taken to hit the first house settlement was just 8 sec. Interview with the villager who was able to escape from the Matatirtha landslide also confirmed middling accuracy of the timing. The volume of materials displaced in Zone I and Zone II of Matatirtha landslide (see Figure 17) are also calculated during investigation by the help of total area and average depth of failed materials in the channel. In debris slide zone near to crown about 3100 m^3 of the debris was failed whereas materials rolled down from this zone entrained approximately 5860 m^3 of colluvial materials other failure zone of down slope (see Figure 17). In the Zone I, the yield rate (Hungr et al, 1984 and Hungr, 2003) of landslide is 20.6 m^3/m and in Zone II it is 63.6 m^3/m. The yield rates support the quite widen gully resulted after landslide.

NATURE OF SLIDES AND MATERIALS INVOLVED IN NORTHERN SHIKOKU

Geological characteristics

Geologically, northern Sikoku is belongs to Ryoke Belt and Samagawa-Chichiba Belt (Figure 7). It consists of Miocene volcanic rocks, Cretaceous granite, and trough filled turbidites (sandstone and mudstone) of Izumi Group. The Izumi Group is adjacent in south to one of the prominent tectonic lines in the Shikoku Region called Median Tectonic Line (MTL). Middle part of Shikoku consists of green and black schist of Sambagawa-Chichiba Belt. Most of flow-like are found in Ryoke Belt. Surprisingly, in Kagawa area, the landslides are found in volcanic rock and granite except in Toyohama (sandstone with frequent shale layers). Although the rainfall amount is same in southern part of Moriyuki, landslides were not occurred in zone of Izumi Group (Sanuki Range). But, in same zone, there are many landslides in Toyohama and Niihama area (see Figure 7). Basically, landslides are generally noticed on weathered profile of granitic and volcanic rocks. Similalry, most of the failed slopes in Toyohama and Niihama are noticed in thin layers of weathered sandstone or a stiff layer of clay resulted from decomposition of the layers of shale. Although number of landslides occurrences as per rock type are not recorded, the field observation clearly shows that likelihood of rainfall triggered flow-like landslide in northern Shikoku is more in volcanic rock and granitic rock than sedimentary rock. This phenomenon is also well described by Dai et al (1999) for the Lantasu Island of Hong Kong during study of rainfall triggered landslide in igneous rock terrain.

Precipitation of the area

From the meteorological point of view, the month of August, September and October is very critical for the hills of northern Shikoku. There is very good rainfall data recording system in Shikoku in comparison to Nepal. There are many rain gauge stations and hourly rainfall data is also available. Rain gauge station in Moriyuki is 700 m far (Kusaka Pass) from the failure area and Monnyu area has rain gauge station. Thus, rainfall correlation during failure time is possible. Rainfall data of Typhoon 23 are presented in Figure 18 and Figure 19 for Moriyuki and Niihama area respectively.

Surface geology and geotechnical characteristics of materials

The hills of northern Shikoku are mainly covered by thin (<2.0 m) residual soil over igneous rock and sedimentary rock. Almost all landslides in were noticed mainly on residual soils.

The large flow-like landslides in Moriyuki area are also occurred on residual materials. Geomorphologically, the all failure sites are located in gullies or concave slope. Geotechnical properties of the both deposited debris and residual soil materials of the slope are identified as far as practicable. The soils of Monnyu, Moriyuki and middle Kagawa have wide grain size distributions (Figure 20) and have significant sand fractions because of weathering product of igneous rocks. Likewise soils of Toyohama and Niihama are rich with clay fraction because of weathering product of sedimentary rock mainly shale.

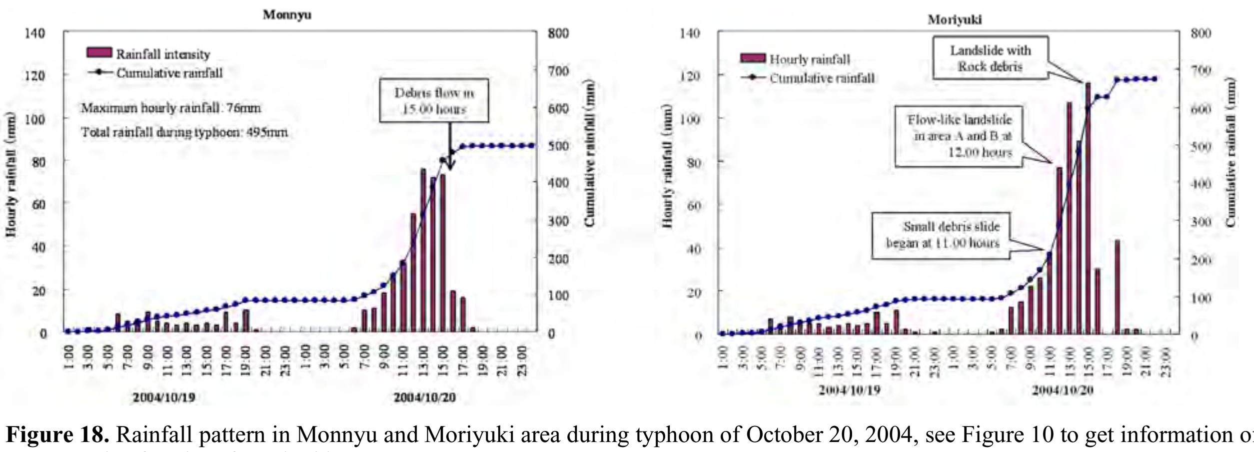

Figure 18. Rainfall pattern in Monnyu and Moriyuki area during typhoon of October 20, 2004, see Figure 10 to get information of area A and B for plot of Moriyuki

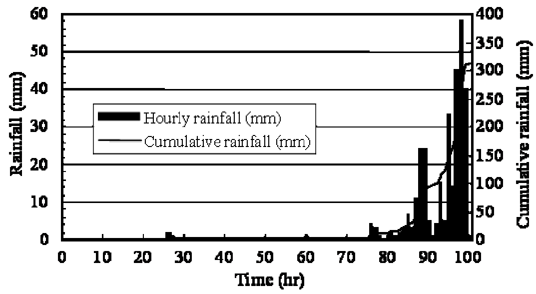

Figure 19. Rainfall in Niihama area during typhoon of September 29 2004 (Modified after Bhandary & Yatabe, 2005)

Failure Processes

There were hundreds of failure spots, most of which were concentrated over the hills near Niihama city, Moriyuki, Monnyu and Middle Kagawa. Similarly, More than 80% of failures have length less than 30 m and more than 50% of slides has width less than 10 m. Likewise more than 60% of failure is occurred in slope angle 30°-40°. The changes in negative pore-water pressures associated with heavy rainfalls are the main causes of numerous slope failures that often turn into debris flows or mudflows during typhoon seasons in the mountains of Shikoku (Bhandary et al 2005).

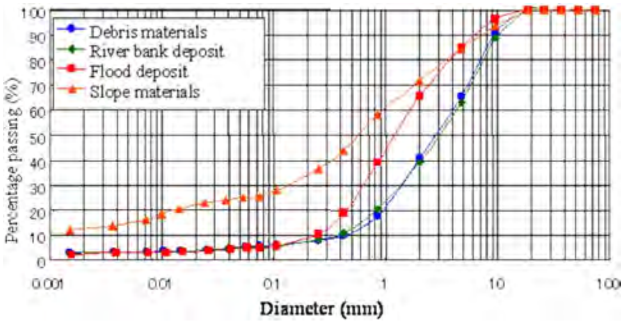

Figure 20. Grain size distribution of slope, debris and deposited materials in Monnyu area and it shows that slope materials has considerable amount of clay.

From the field observation, it is realized that all landslide in igneous and sedimentary terrain are begin first as debris slide and on the route of flow, the failed material scrape off more materials and flow became more energetic and voluminous. Thus, more disasters are seen on settlement of hill base around Niihama and Moriyuki. In all slides, most failures that turned into flow-like landslides are found as surface failure nature with a maximum depth up to 1.5 m (Figure 21 and Figure 22). Some debris slides depth in Moriyuki area is less than 0.5 m (Figure 23). From the field survey, it is also confirmed that the top layer soil is comparatively loose.

Some of landslides in northern Shikoku also are found to be more voluminous and energetic. Some has earth quantity more than 2400 m^3 (in Monnyu area). Because of less height of failure, maximum velocity of flow is calculated as up to 25 m/s. Likewise, it is felt that the failure of surface layers of slopes in northern Shikoku is mainly influenced by the slope parameters such as rock type, depth of loose soil layer, slope inclination, length of slope, etc., and the soil parameters such as coefficient of permeability, water storage capacity, strength parameters.

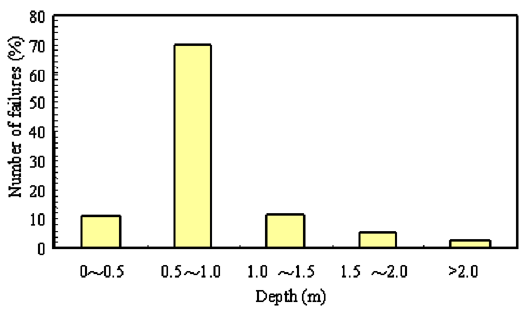

Figure 21. Variation of depth of failure in Niihama area ((Modified after Bhandary & Yatabe, 2005)

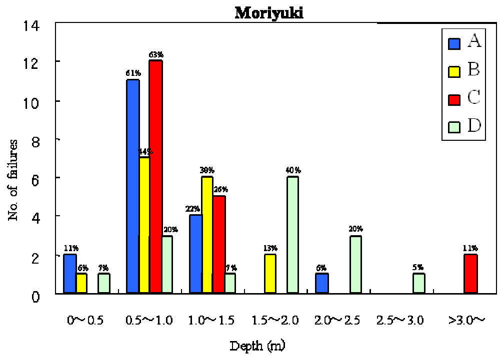

Figure 22. Variation of depth of failure in Moriyuki area (see Figure 7 for reference of area A, B, C and D)

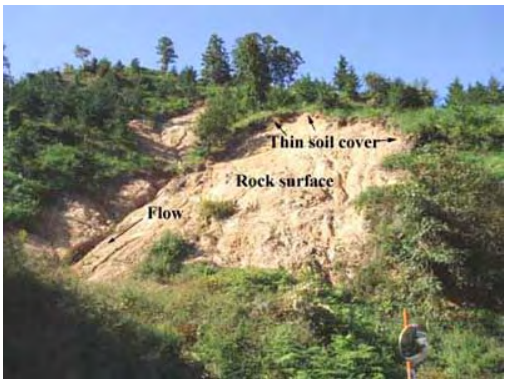

Figure 23. Thin soil cover in one of the debris slides in Moriyuki

CONCLUSIONS

From this comparative study of Kathmandu and northern Shikoku following conclusions are made.

- It is felt that rainfall triggered flow-like landslide is frequent phenomena of Nepal but comparatively Shikoku is not facing the problem time to time.
- Rainfall triggered landslide is more common in terrain of igneous rock in comparison to sedimentary rock. Thus, there is not so much landslide in southern hills of Kathmandu as in northern Shikoku although there is a heavy rainfall event in Kathmandu every year. Same phenomenon is seen in less weathered sedimentary terrain of northern Shikoku.
- From rainfall data of Shikoku, it is felt that generally if the cumulative rainfall of one day is reached near to 120 mm shallow debris slides will be started in terrain of igneous rock and weathered sedimentary whereas flow-like landslides will be began if cumulative rainfall is reached near to 200 mm in a day. Similarly, debris flow as mixture of huge rock boulders start to flow on slope after 600 mm of cumulative rainfall as in Moriyuki. Nevertheless, this value of rainfall is more dependent of antecedent soil moisture condition. Effect of which is clearly seen in failures of Niihama city, where more extensive failure occurred in sedimentary rocks than other parts because of more than 100 mm of previous day rainfall. In the case of southern hills of Kathmandu, major failures occurred in the time between 11 PM to 1 AM, so from rainfall data, it can be predicted that if cumulative rainfall of 24-hours is more than 260 mm, flow like landslide will be occurred and for shallow debris slide, this value can be ranged between 230 to 250 mm. In other part of Nepal, also if the soil is thick colluvium deposit, this value of threshold rainfall is 230 mm (Khanal and Watanabe 2005). It seems that both southern hills of Kathmandu and Northern hills of Shikoku do not agree the rainfall threshold values established by Caine (1980) and it is very clear that the threshold value of rainfall for shallow as well as flow-like sliding is more dependent on antecedent rainfall, soil depth and slope angle.
- Hills of both area (Kathmandu and northern Shikoku) have good vegetation and it is felt that vegetation play an important role in distribution of flow-like landslides. It is observed that on the base of hills at Toyohama , some of flows were stopped only because of forest of bamboo and cedar trees.
- Detail geotechnical study of flow-like landslide events is necessary to evaluate the effects of surface-layer depth, slope inclination, and precipitation pattern on the pore water pressure development, which is responsible for the loss of negative pore-water pressure (or the suction) as well as reduction of effective stress. It is therefore essential to carry out study on various aspects of slope failures as well as rainwater infiltration mechanism that led to destructive debris flows during heavy rainfall.
- It is also felt that human inhabitation practice on old fan deposit and immediate base of hill should be regularized by government through separate law to decrease death from debris flow triggered by torrential rainfall.

- From this study, it is also concluded that landslide hazard map should be quantified towards landslide risk assessment and management for rainfall triggered flow-like landslide also which decisively provides fruitful upshot to early warning system of flow-like landslide disasters.

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