Original Article

Collapsed material movement of deep-seated landslides caused by Typhoon Talas 2011 on the Kii Peninsula, Japan

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Extensive research on landslide susceptibility and landslide-affected areas has been conducted, but many technologies still lack sufficient accuracy and information to predict the movement of collapsed material. Adequate disaster mitigation requires prediction of the movement type and travel distance of collapsed material from deep-seated landslides. This research aims to classify the movement type of collapsed material from deep-seated landslides and to clarify the topographic conditions that influence it. The research area is the Kii Peninsula, south-western Japan, which was severely damaged by sediment-related disasters triggered by Typhoon Talas in 2011. A digital elevation model and aerial photographs were used in ArcGIS analysis, and topographic characteristics were examined to find significant factors that influenced the movement of collapsed material. Collapsed material of deep-seated landslides formed two main outcomes, debris flows and landslide dams. Debris flows were likely in catchments of streams with gradient $> 10^\circ$ and inflow angle $< 60^\circ$. Landslide dams were likely in catchments of streams with gradient $< 10^\circ$ and inflow angle $> 60^\circ$. Landslide dams with an upstream watershed exceeding 100 km² tended to remain for much shorter periods than those with smaller watershed. The equivalent coefficient of friction, representing the travel distance and degree of fluidization of collapsed material, could be used for predicting the deposition zone of collapsed material.

Key words: deep-seated landslide, landslide dam, debris flow, stream gradient, inflow angle

1. INTRODUCTION

Sediment disasters—events emanating from debris flows and landslides, for example—occur with disturbing frequency around the world, taking lives and damaging property. Restoring affected areas often requires great amounts of time and money. Large-scale disasters are notable not only for their heavy death tolls, but also for the way in which they can disrupt communities, delaying recovery and, in some cases, assuring their decline. However, the relative infrequency of large-scale sediment disasters has resulted in comparatively little research on them, resulting in little progress in developing countermeasures against them. A distinction is made between shallow-seated and deep-seated landslides, depending on factors such as scale, slip-surface depth, geology, and root-system resistance [Baron *et al.*, 2005; Bruckl and Parotidis, 2005; Klimes *et al.*, 2009; Uchida *et al.*, 2011]. In shallow-seated landslides, a

slip surface is formed either within the surface soil or near the boundary between the surface soil and the bedrock [MLIT, 2013]. In deep-seated landslides, the slip surface is formed deep within the bedrock [MLIT, 2013; Uchida *et al.*, 2011]. Thus, the scale of deep-seated landslides tends to be larger than that of shallow-seated landslides and, accordingly, the amount of transported collapsed material tends to be larger as well.

A deep-seated landslide transfers material down a slope. Such events can be classified on the basis of characteristics such as slope morphology and transported material mobility (Fig. 1). Figure 1 summarizes landslides recorded on the Kii Peninsula, with additional information from one in Sichuan, China. (1) If there is a direct connection to a river or stream, the material may flow down there. The flow characteristic is influenced by the water content. If the material contains a large proportion of water, it will descend as debris flow, but if it contains little water, it

Fig. 1 Types of collapsed material movement from deep-seated landslides on the Kii Peninsula (1, 3, 4) or in Sichuan, China (2)

will descend as a debris avalanche. (2) If a large volume of material flows down or across the river or stream and accumulates at some point along the stream channel, it can form a landslide dam. This is a special case which commonly occurs when collapsed material from several landslides unites while flowing down the stream and forms a large deposition downstream, such as the large landslide dam in Sichuan, China [Ou, 2012]. (3) If the terrain towards the bottom of the slope is only moderately inclined or flat, material tends to deposit over a broad expanse. An example of this type of movement was found in Fudono, Wakayama Prefecture (**Fig. 2**), where the material spread over a flat area but was not a landslide dam because no river existed. In other cases, if there is a wide flat river or stream at the bottom of the slope, the material might flow along the river bed. (4) When there is a stream channel at the bottom of the slope, the material might block the channel, resulting in a landslide dam. This is defined as natural blockage of a river channel caused by slope movement, having significant height and potentially causing inundation behind it [Canuti *et al.*, 1998; MLIT, 2006]. In any of these situations, material travels downward, sometimes damaging or even burying houses and other structures, and even causing fatalities.

Swanson *et al.* [1986] classified material movement into three types of landslide dams: minor damming, single impoundment, and extensive damming. Landslide-dammed lakes may last from several minutes to thousands of years. Of 73 examples of landslide dams worldwide, most failed quickly after

Fig. 2 Uncommon collapsed material movement in Fudono, Tanabe-shi, Wakayama Pref. [Sediment Disaster Prevention Publicity Center, 2011]

formation, half failed within 10 days, and only 15% lasted longer than 1 year [Costa and Schuster, 1987]. Historical documents and topography reveal the formation of many landslide dams, some of which broke and caused major damage in Japan [Tabata *et al.*, 2002]. Debris flow from deep-seated landslides can have serious impacts on human life and infrastructure [Nishiguchi *et al.*, 2012]. However, landslide dams holds further threats: back-flooding threatens upstream areas, and when the dam breaks, commonly owing to overflow of backed-up water, large surge and debris flows threaten downstream areas [e.g., Ermini and Casagli, 2003; Inoue *et al.*, 2012].

Active and passive countermeasures are widely used for mitigating disasters caused by deep-seated landslides. It is difficult to prevent or alleviate debris-related damage through active countermeasures. Instead, passive countermeasures require the development of methods for inferring likely failure locations, scale, and area of flooding and deposition, as well as a good understanding of landslide and debris transport mechanisms. Predictions should then be made publicly available in the form of hazard maps.

Estimating hazard areas and the deposition zone of collapsed material for prevention and mitigation requires knowledge of whether collapsed material will form a landslide dam or debris flow when a deep-seated landslide occurs. To this end, this research used the topographic characteristics of disaster areas to classify material movement and to clarify characteristics that influenced the movement. This research focused on deep-seated landslides on the Kii

Peninsula due to Typhoon Talas in 2011, omitting deep-seated landslides of coherent material (slow movement type).

2. RESEARCH AREA

The Kii Peninsula is a large peninsula located between $33^{\circ}43'N$ and $34^{\circ}78'N$ and between $134^{\circ}99'E$ and $136^{\circ}98'E$ in the south-western part of Honshu Island, which includes Osaka, Wakayama, Nara, and Mie Prefectures. This area commonly experiences severe damage when typhoons hit. In addition, it receives high rainfall during the early summer and is known for its extremely high annual rainfall of about 3000 mm [MLIT, 2013]. The Kii Peninsula has an elevation of over 1000 m at the centre and a maximum elevation of 1915 m [Nonomura and Hasegawa, 2014]. It is about 150 km wide and 150 km long. Topographically, it features steep mountains that extend from north to south. Thus, when typhoons or heavy rains hit, landslides and floods occur in many locations and cause severe damage. Geologically, the Kii Peninsula consists mainly of an accretionary complex in the Shimanto Belt, which generally has a north-east-south-west strike and a north-westward dip [Saito and Matsuyama, 2012]. The accretionary complex consists of foliated mudstone, sandstone, acid tuff, chert, and greenstone, and contains a small amount of Miocene granite and sedimentary rocks [Chigira *et al.*, 2013]. The Shimanto Belt is highly folded and faulted, with steeply dipping, vertical, and overturned strata and much strike faulting [Taira *et al.*, 1982]. The research area is located in Wakayama and Nara prefectures, in part of the Totsukawa Stream watershed, and has total area of about 1110 km² (Fig. 3).

The Kii Peninsula was catastrophically damaged by typhoons in 1889 and 2011. The 1889 typhoon brought over 1000 mm of rainfall from 18 to 20 August over an extended area from Nara to Wakayama prefectures [MLIT, n.d.; Tabata *et al.*, 2001]. It triggered deep-seated landslides at more than 1000 sites in the Totsukawa region, formed 53 landslide dams with total of 20 million m³ of material, most of which collapsed, caused flooding to a depth of 190 m, and created immense damage [Inoue and Doshida, 2012; MLIT, n.d., 2013].

Typhoon Talas (Typhoon No. 12) was formed on 24 August 2011 near the Mariana Islands, reached Japan on 3 September, and continued to move northward [JMA, n.d.]. It moved very slowly and caused heavy rainfall especially on the Kii Peninsula, where record-breaking rainfall of over 1600 mm in 72 h was recorded at Kamikitayama Village in Nara Prefecture, with total precipitation of 1805.5 mm, and over 2000

Fig. 3 Research area on the Kii Peninsula, Japan

mm estimated in some areas [JMA, n.d.]. The typhoon killed 72 people (with another 16 listed as missing) and injured 31 in Mie, Nara, and Wakayama Prefectures [MLIT, 2013]. It also completely destroyed 369 houses, partially destroyed 2901, and caused inundation of more than 7000 [MLIT, 2013]. The heavy rainfall induced many sediment-related disasters in Mie, Nara, and Wakayama Prefectures, including 58 debris flows, 33 deep-seated landslides, 30 rock falls, and 21 stream blockages, with a total of approximately 100 million m³ of sediment [MLIT, 2011, 2013].

3. METHODS

Two main data sets were used in this research, namely digital elevation model (DEM) data and aerial photographs. The 10-m resolution DEM data were obtained from the Geospatial Information Authority of Japan at 1:25 000 scale. Aerial photographs were obtained from the MLIT, Kinki Regional and Development Bureau, at 1:20 000 scale; they were taken on 7 September 2011 over most of the research area, on 10 September 2011 in Kitamata, Nara Prefecture, and on 13 September 2011 in Iya, Wakayama Prefecture. A national municipal boundaries map from ESRI Japan was also used.

The landslide studied here was deep-seated landslide (defined as downward movement of material with a sliding surface mostly in bedrock, which commonly occurs owing to long-term or heavy rainfall, in a short time, with collapsed material moving at high speed, most of it moving outside the source area [MLIT, 2013]). Generally, landslides with collapsed material volume exceeding 100 000 m³ are classified as deep-

seated [Ishikawa, 2014]. However, the volume of collapsed material is difficult to calculate in ArcGIS, so the volume boundary was converted to landslide source area by using Guzzetti's [2009] empirical equation and an empirical equation derived from data published by Chigira *et al.* [2013]. There are many proposed empirical equations for the relationship between landslide area and volume [e.g., Guzzetti *et al.*, 2009; Haflidason *et al.*, 2005; Imaizumi and Siddle, 2007; Imaizumi *et al.*, 2008; Uchida *et al.*, 2014]. Guzzetti's equation was chosen owing to its wide range of failure zone area ($2 \times 10^0 - 1 \times 10^9 \text{ m}^2$), covering all landslides found in the research area. Chigira *et al.*'s [2013] published data relate to volume and area of 14 deep-seated landslides obtained by lidar on the Kii Peninsula. From the published landslide area and volume, an empirical equation was derived and was used with Guzzetti's. As the conversion result, landslides with a failure zone of $> 16\,000 \text{ m}^2$ were classified as deep-seated landslides and were studied further.

Deep-seated landslides were classified by the travelling coefficient (Tr) and by the type of collapsed material movement (Fig. 1). $Tr (= l_2/l_1)$, defined as the ratio between travelling length of collapsed material (l_2) and failure zone length (l_1) [Usuki *et al.*, 2006], was used for initial identification of the movement (Fig. 4). Landslides with $Tr \geq 2$ were labelled as long-travelled landslides, and those with $Tr < 2$ as short-travelled landslides. Statistical analysis of 75 landslides induced by earthquakes in Japan showed that about 80% of all landslides have $Tr < 2$ [Ishii and Sugimoto, 2015].

Generally, determination of failure zone and deposition zone from aerial photographs is difficult, because they can overlap. Here, failure zones were determined by comparing aerial photos and Google Earth images from before the disaster with aerial photos from MLIT and Google Earth 3D images after the disaster and a 1:25 000-scale topographic map before the disaster. After a failure zone was determined, the rest of the collapsed material movement was considered as the deposition zone. The type of collapsed material movement (Fig. 1) was then determined, with the support of information from Nara Prefecture [2012], Chigira *et al.* [2013], and MLIT [2013].

The topographic characteristics of each landslide were obtained from DEM data analysis as described below:

- 1) **Area of failure zone** (Fig. 5) was obtained by comparing aerial photos and Google Earth images from before and after the disaster and the topographic map before the disaster.
- 2) **Width (w) and length (l_1) of failure zone**

(Fig. 5): the largest value was taken, not the average. The length of the failure zone was measured from its top to its bottom. In some cases the width was larger than the length.

- 3) **Failure zone inclination (θ)** (Fig. 4) was calculated by simple trigonometric calculation of the top and bottom of the failure zone, the coordinates of which were obtained by ArcGIS analysis.
- 4) **Distance to stream (d)** (Fig. 5) was measured from the bottom of the failure zone to the centre of the adjacent stream, and was an averaged value. It was assumed that the closer the failure zone was to the stream, the easier it was for the collapsed material to form a landslide dam.
- 5) **Slope height (h)** (Fig. 4) was measured from the top of the slope where the landslide occurred to its streambed. Higher slopes implied more

Fig. 4 Measurements for calculation of travelling coefficient and equivalent coefficient of friction

Fig. 5 Example of topographic characteristics measurement

collapsed material and thus a higher possibility of landslide dam formation, so this characteristic had to be confirmed.

- 6) **Stream order.** A stream (a body of running water flowing downhill under the influence of gravity) can be recognized from a pattern of lines on a contour map that forms a chevron shape pointing upstream. Stream order classifies or measures the relative size of a stream according to its hierarchical position in the drainage network. The *Strahler* [1957] method was used, by which all headstreams without tributaries were assigned an order of 1. The stream order increases when streams of the same order intersect, but not when two streams of different orders intersect [Strahler, 1957].
- 7) **Failure zone watershed (Fig. 6)** represents the area of drainage that potentially triggers a landslide.
- 8) **Upstream watershed (Fig. 6)** represents the amount of water flow that could erode collapsed material deposited in the stream, and was measured upstream from the intersection point between the failure zone and the adjacent stream.
- 9) **Stream gradient (i)** was measured from a 1-km stream section adjacent to the failure zone (Fig. 5). Stream gradient tends to be higher for low-order streams than for high-order ones. A landslide located on a gentle stream gradient (high-order stream) was assumed to have a larger watershed area, which might collect more water discharge to erode any collapsed material, thus making the stream order and stream gradient

important factors for understanding their influence on landslide dam formation.

- 10) **Inflow angle (α)** was expected to significantly influence landslide dam formation. It was measured as the angle between an imaginary line along the failure zone showing the inflow motion of material into the stream and upstream (Fig. 5).
- 11) **Equivalent coefficient of friction (ECF)** is widely used as an indicator of travel distance [Dahl *et al.*, 2010; Finlay *et al.*, 1999; Hsu, 1975; Nishiguchi *et al.*, 2012; Okura *et al.*, 2003; Rickenmann, 2005; Scheidegger, 1973; Usuki *et al.*, 2006], and is greatly influenced by topographic factors [Hattaji and Moriwaki, 2009; Okura *et al.*, 2003]. ECF ($= \Sigma H / \Sigma L$) is the ratio between relative height (ΣH) and total travel length (ΣL) from the top of the failure zone to the end of the deposition zone (Fig. 4). Here, the ECF for a landslide dam was measured from the top of the failure zone to the end of the main body of collapsed material deposition, and did not consider material flows after the landslide dam collapse. In situations other than a landslide dam, the ECF was measured from the top of the failure zone to the end of spreading (fanning) of the collapsed material, or to the end of material deposition at the stream curve when no spreading could be found.

4. RESULTS AND DISCUSSION

4.1 Types of collapsed material movement

In total, 33 deep-seated landslides were found in the research area, with a total failure zone area of 2.8×10^6 m². By travelling coefficient, they consisted of 10 long-travelled ($Tr \geq 2$) and 23 short-travelled landslides ($Tr < 2$) (Fig. 7). By the characteristics of material movement, among the 10 long-travelled landslides, all collapsed material was deposited either on stream curves or on flat streams. While among the 23 short-travelled landslides, 2 formed depositions in a wide stream and 21 formed landslide dams. The former 2 cannot be classified as landslide dams since the collapsed material volume was small compared with the width of stream and the material deposition was insignificant. This characteristic corresponds to the first type of landslide material movement defined by Swanson *et al.* [1986], where the collapsed material is small compared with the valley width, partially crosses the valley floor, and causes only minor impoundment.

The 21 landslide dams were sub-categorized as 14 long-term landslide dams, 5 short-term landslide dams, and 2 landslide dams in reservoirs (Fig. 8). Long-term landslide dams were those in which (1) the material deposition (dam) and/or water inundation remained

Fig. 6 Example of failure zone watershed and upstream watershed measurement

Fig. 7 Travelling coefficients of deep-seated landslides

several days or more after formation; (2) if the dam had already breached, the river was still mostly covered with material; and (3) based on the information obtained, a landslide dam occurred. Short-term landslide dams were those in which (1) the dam and water inundation were not visible on the aerial photographs several days after formation; (2) traces of deposition were found (e.g. material deposition and fallen trees on the opposite slope and upstream area); and additionally (3) based on the information obtained, a landslide dam occurred.

As judged from the aerial photographs, the approximate time boundary between long term and short term was 4 days. Some of the short-term

landslide dams might have collapsed within a day, but we had no data to support this. Landslide dams occurred in reservoirs where the landslide was adjacent to the reservoir, so the collapsed material entered the reservoir and was presumably deposited there (Fig. 9).

4.2 Landslide dam formation

Among 11 topographic characteristics analysed (Table 1), only 5 were considered effective: inflow angle, stream gradient, upstream watershed, area of failure zone, and ECF. Surpassing all other characteristics, the relation between inflow angle and stream gradient formed a clear distinction between landslide dams and debris flows (Fig. 10). Collapsed material was likely to form a landslide dam if the landslide occurred in catchments of streams with gradient $< 10^\circ$ and inflow angle $> 60^\circ$. Debris flow was likely to be formed by landslides in catchments of streams with gradient $> 10^\circ$ and inflow angle $< 60^\circ$.

The likelihood that collapsed material from a landslide will form a dam depends on the topographic factors involved in the interaction between river and slope dynamics [Dal Sasso *et al.*, 2014; Stefanelli *et al.*, 2015]. Collapsed material due to slope failures in Miyagi Prefecture caused by the 2008 Iwate-Miyagi earthquake easily formed landslide dams in areas where the streambank slope had large relative height and the streambed had a relatively gentle inclination (third- to fifth-order streams) [Ishikawa and Ishikawa, 2012]. Furthermore, among 110 landslides in Japan, the USA, Canada, Peru, New Zealand, and Pakistan, no landslide dam was formed on streams with gradient $> 15^\circ$ [Ministry of Construction, 1987].

Fig. 8 Classification of collapsed material movement types found in the research area

Fig. 9 Examples of collapsed material movement: (a) debris flow in Nagatono, Nara Pref. (landslide no.27); (b) long-term landslide dam in Nagatono, Nara Prefecture (no. 5); (c) short-term landslide dam in Uguwara, Nara Pref. (no. 18); (d) landslide dam in reservoir in Kawatsu, Nara Pref. (no. 21); and (e) deposition on relatively wide stream in Kashiwara, Nara Pref. (no. 23)

Fig. 10 Formation of landslide dam and debris flow

At a large inflow angle, the collision of the material with the stream expended a large amount of energy wherein the collapsed material overflowed to the opposite slope, knocked down trees, and scraped the soil in most cases. This large energy loss stopped the further movement of the overflowed material, and thus a landslide dam formed. In addition, a low stream gradient promoted the formation of landslide dams owing to the gentle streambed and slow water flow, which could carry only small amounts of very fine sediment.

At a small inflow angle, collapsed material could flow easily into a stream, losing little energy on

collision with the opposite slope. In conjunction with a high stream gradient (rapid water flow), collapsed material would flow downstream easily to form a debris flow. This process of formation agrees with the results of *Ikeya* [1989], who stated that, in general, debris flows initiate in streams with gradients of 15° - 30° and deposit on stream beds when the gradient falls to 3° - 10° .

4.3 Landslide dam duration

Generally, most debris flows in the catchments of first-order streams had small upstream watershed, while most landslide dams in catchments of high-order streams had larger upstream watershed. The area of upstream watershed is inversely correlated with the duration of landslide dams: the duration is likely to be short when a small landslide mass blocks a river or stream with a large watershed area [Swanson *et al.*, 1986].

Landslide dams with an upstream watershed of $> 100 \text{ km}^2$ had very large flood discharge which increased the water inundation height rapidly, overtopped the dam, and quickly caused its failure (**Fig. 11**). Those short-term landslide dams commonly left traces of dam formation upstream and on the opposite slope, such as fallen trees, scraped soil, and material deposition. Landslide dams with an upstream watershed of $< 100 \text{ km}^2$ had a small flood discharge, and thus the dam was harder to erode. Most long-term landslide dams and inundation were still evident 4 to 10 days after the typhoon.

Topographic characteristics influence dam stability and duration: dam volume stabilizes the dam, while

Fig. 11 Duration of landslide dam, influenced by upstream watershed

catchment area destabilizes it [Canuti *et al.*, 1998; Casagli and Ermini, 1999; Ermini and Casagli, 2003; Swanson *et al.*, 1986]. Further, Ermini and Casagli [2003] considered landslide dam height an important variable in relation to overtopping and piping failure, and proposed a dimensionless blockage index as an indicator of landslide dam stability, based on landslide dam volume, watershed area, and landslide dam height. Since all data on landslide dam heights could not be obtained, the dimensionless blockage index in the research area could not be clarified.

Nevertheless, the size of the upstream watershed influences flood discharge, which influences the failure time of landslide dams. According to the Ministry of Construction [1987], the higher the flood discharge is, the shorter the failure time of landslide dam will be.

4.4 ECF

The ECF of a landslide represents the travel distance and the degree of fluidization of collapsed material, and is an important point for assessing deep-seated landslide hazards. The ECF in this research area was 0.1–0.5; generally it was < 0.25 for debris flows and > 0.25 for landslide dams (Fig. 12). The small ECF of a debris flow implied that collapsed material flowed far downstream, was deposited further from the failure zone, and created a hazard over a large area. This extent was influenced not only by topography, but also by the characteristics of the collapsed material, as debris flow material is commonly fluid enough to travel long distances in streams with modest slopes and to inundate vast areas, as do water floods [Iverson, 1997].

An ECF of > 0.25 indicated that collapsed material

Fig. 12 Equivalent coefficient of friction

did not flow far from the failure zone, and that it tended to be deposited adjacent to the failure zone, possibly forming a landslide dam. Having a larger ECF, a landslide dam created a hazard over a smaller area than a debris flow, but the threat of dam failure and a following flood cannot be disregarded. $ECF = 0.25$ is a threshold between landslide dam and debris flow. However, this value is not universal and represents the condition only in this research area. Different areas with different topography, geomorphology, geology, and rainfall will generate different values.

In previous studies, ECF decreased with increasing landslide volume [Hattaji and Moriwaki, 2009; Hsu, 1975; Scheidegger, 1973; Takahashi, 2007]. The collapsed material volume in Fig. 13 was estimated by using an equation derived from data published by Chigira *et al.* [2013]. Divided into short-travelled and long-travelled landslides, ECF values in this research corresponded with previous research. However, unlike Takahashi [2007], a clear trend between ECF and volume could not be found, because the collapsed material volumes in this research were smaller than in Takahashi [2007]. Further, most of the deep-seated landslides analysed here formed landslide dams with a large failure zone but a short total travel length, which significantly affected the ECF and volume correlation. The landslides on the Kii Peninsula were caused by heavy rainfall, and thus the ECF was more strongly influenced by topography than by the area of the failure zone. Movement of collapsed material in unsaturated conditions is different from that of collapsed material in saturated conditions following heavy rainfall.

To predict landslide hazards in downstream areas,

Fig. 13 ECF of deep-seated landslides compared to data of Takahashi [2007]

factors critical to travel distance are needed. Topography influences the ECF or travel distance of a landslide [Hattaji and Moriwaki, 2009; Okura *et al.*, 2003]. Both stream gradient and inflow angle influenced ECF (Fig. 14), in agreement with Ishikawa's [1998] observation that the angle between a slope and a lower channel influences the formation of debris flows significantly. Debris flows can be separated from landslide dams with a stream gradient of about 10° and an inflow angle of about 60° . It is necessary to analyse the correlation of stream gradient and inflow angle with ECF for hazard evaluation downstream of deep-seated landslides. If ECF can be estimated from stream gradient and inflow angle, the hazard area of a landslide-prone slope can be predicted.

5. CONCLUSION

Topographic characteristics of the Kii Peninsula were used to classify material movement and to clarify characteristics that influence the movement of collapsed material from landslides. Thirty three deep-seated landslides were found, classified into 10 long-travelled and 23 short-travelled landslides. The 23 short-travelled landslides consisted of 21 landslide dams and 2 depositions in wide streams. Collapsed material of landslides in catchments of streams with gradient $< 10^\circ$ and inflow angle $> 60^\circ$ were likely to form landslide dams. Collapsed material of landslides in catchments of streams with gradient $> 10^\circ$ and inflow angle $< 60^\circ$ were likely to flow downstream as debris flows. Debris flows can be separated from landslide

Fig. 14 Stream gradients and ECF of deep-seated landslides

Table 1 List of topographical characteristics analysed

Landslide no.	Location	Type	(1) Area of failure zone (m^2)	(2) Width of failure zone (w , m)	(2) Failure zone length (l_1 , m)	Travel length (l_2 , m)	Travel ratio ($Tr = l_2/l_1$)	(3) Failure zone inclination (θ , °)	(4) Distance to stream (d , m)	(5) Slope height (h , m)	(6) Stream order	(7) Failure zone watershed (m^2)	(8) Upstream watershed (m^2)	(9) Stream gradient (i , %)	(10) Inflow angle (α , °)	Relative height (ZH , m)	Total travel length (ZL , m)	(11) ECF ($= ZH/ZL$)	Estimated collapsed material volume (m^3)
1	Kiamata, Nara Pref.	Long-term landslide dam	49,700	210	330	510	1.53	31	70	180	2	104,700	486,000	10.0	61	240	840	0.29	444,000
2	Akadani, Nara Pref.	Long-term landslide dam	293,000	440	1,000	970	0.97	42	110	640	3	482,300	13,703,000	2.5	89	660	1,970	0.33	8,316,000
3	Tsubonouchi, Nara Pref.	Long-term landslide dam	71,500	350	320	220	0.69	34	80	270	5	285,000	107,801,000	0.5	108	170	550	0.31	763,000
4	Tsubonouchi, Nara Pref.	Long-term landslide dam	24,700	140	250	140	0.54	38	70	230	3	91,400	5,489,000	2.2	95	210	390	0.53	171,000
5	Nagatono, Nara Pref.	Long-term landslide dam	169,200	330	670	370	0.55	40	50	430	2	332,300	4,611,000	4.7	83	450	1,030	0.44	3,127,000
6	Kuridaira, Nara Pref.	Long-term landslide dam	382,900	660	780	500	0.64	35	50	460	4	464,700	9,016,000	3.0	85	430	1,280	0.33	13,626,000
7	Iya, Wakayama Pref.	Long-term landslide dam	155,200	460	510	750	1.46	26	90	290	2	342,800	1,514,000	6.9	67	330	1,260	0.26	2,694,000
8	Hongucho Kamikiribara, Wakayama Pref.	Long-term landslide dam	30,200	190	280	220	0.76	36	70	220	2	122,300	663,000	10.1	77	240	500	0.48	222,000
9	Hongucho Mikoshi, Wakayama Pref.	Long-term landslide dam	45,500	200	300	300	1.01	35	80	180	4	142,800	20,008,000	1.1	79	180	600	0.30	391,000
10	Shirakawa, Nara Pref.	Long-term landslide dam	43,500	190	370	410	1.11	33	170	360	3	189,600	5,243,000	6.8	61	350	780	0.45	367,000
11	Akaki, Nara Pref.	Long-term landslide dam	22,800	150	200	130	0.62	41	30	150	3	68,700	3,789,000	4.3	80	140	330	0.43	154,000
12	Takahara, Nara Pref.	Long-term landslide dam	26,300	150	260	210	0.74	36	30	260	3	133,600	4,117,000	4.5	91	180	500	0.37	204,000
13	Taketsu, Nara Pref.	Long-term landslide dam	16,700	150	200	130	0.65	45	20	170	3	116,800	2,531,000	5.6	82	160	330	0.48	121,000
14	Yamashiki, Nara Pref.	Long-term landslide dam	22,200	130	210	130	0.64	30	10	200	3	168,000	4,413,000	3.6	88	130	340	0.38	149,000
15	Minamihara, Nara Pref.	Short-term landslide dam	22,000	150	210	260	1.26	37	170	190	5	209,000	101,292,000	0.4	76	170	460	0.36	147,000
16	Ootcho Shimizu, Nara Pref.	Short-term landslide dam	66,500	250	370	210	0.56	42	40	510	5	191,900	218,932,000	0.2	78	250	570	0.43	684,000
17	Akadani, Nara Pref.	Short-term landslide dam	240,700	470	870	360	0.41	35	80	460	5	336,900	153,993,000	0.7	68	460	1,230	0.57	5,827,000
18	Uguwara, Nara Pref.	Short-term landslide dam	173,500	320	1,170	320	0.28	34	110	640	6	496,000	447,602,000	0.8	121	590	1,490	0.40	3,332,000
19	Nijiri, Nara Pref.	Short-term landslide dam	173,300	360	910	800	0.88	30	610	270	6	260,500	731,530,000	0.3	83	570	1,700	0.34	3,458,000
20	Sako, Nara Pref.	Landslide dam inside reservoir	81,600	220	600	360	0.60	32	250	270	5	286,500	248,577,000	0.1	93	380	970	0.39	937,000
21	Kawatsu, Nara Pref.	Landslide dam inside reservoir	147,900	390	890	400	0.45	36	630	450	6	336,700	658,047,000	0.0	99	590	1,280	0.46	2,483,000
22	Uguwara, Nara Pref.	Dep. on relatively wide stream	35,400	160	300	240	0.78	53	80	310	6	158,700	448,133,000	0.7	95	260	540	0.48	276,000
23	Kashihara, Nara Pref.	Dep. on relatively wide stream	19,100	130	220	130	0.60	51	40	170	6	46,100	842,396,000	0.1	86	170	350	0.50	124,000
24	Tochio, Nara Pref.	Debris flow	17,700	110	220	1,470	6.75	40	50	160	1	58,700	109,000	14.3	20	410	1,680	0.24	112,000
25	Oiocho Tsujido, Nara Pref.	Debris flow	19,000	120	250	1,310	5.29	32	180	150	1	62,600	590,000	27.8	19	330	1,560	0.21	123,000
26	Oiocho Tsujido, Nara Pref.	Debris flow	19,900	170	160	1,390	8.49	47	10	160	1	78,400	524,000	25.1	33	340	1,550	0.22	130,000
27	Nagatono, Nara Pref.	Debris flow	24,900	160	250	1,410	5.58	46	40	210	1	89,700	108,000	16.4	15	410	1,660	0.25	173,000
28	Tanabe, Nara Pref.	Debris flow	17,600	130	230	1,760	7.69	35	40	180	1	129,700	723,000	11.5	31	350	1,980	0.18	112,000
29	Asahi, Nara Pref.	Debris flow	86,400	280	600	2,290	3.84	34	120	340	1	316,700	377,000	14.3	24	710	2,880	0.25	1,026,000
30	Takaki, Nara Pref.	Debris flow	56,000	280	440	2,210	5.06	30	120	310	1	165,200	632,000	14.7	35	550	2,550	0.21	527,000
31	Akaki, Nara Pref.	Debris flow	44,600	170	560	1,930	3.34	36	40	230	1	191,600	234,000	14.7	40	570	2,510	0.23	380,000
32	Imanishi, Nara Pref.	Debris flow	134,400	280	880	3,310	3.71	32	60	420	2	264,200	720,000	14.2	37	830	4,200	0.20	2,112,000
33	Uchino, Nara Pref.	Debris flow	23,400	100	420	2,460	5.82	37	60	170	1	53,300	89,000	26.3	4	570	2,990	0.20	159,000

dams at an ECF of 0.25. It is necessary to analyse the correlation of stream gradient and inflow angle with ECF for hazard evaluation downstream of deep-seated landslides and for prediction of deposition zones.

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