UNRAVELING THE MECHANISM OF MULTIPLE DEEP-SEATED LANDSLIDES FROM THE 2011 GREAT FLOODS IN KII PENINSULA

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In 2011, Typhoon Talas brought record-breaking heavy rain and caused extensive sediment-related disasters, such as deep-seated landslides in Nara, Mie, and Wakayama prefectures. The total rainfall from August 30 had reached 1,808.5 mm in Kamikitayama , Nara Prefecture. The Nara Prefecture, which suffered from significant damage, has been trying to conduct “Research and study to mechanism of deep-seated landslides” while establishing a “Large-scale sediment disasters archive”, which would be an accumulation/use of the results of such research and study, and will be handed down to the next generation. Large-scale sediment disasters, at this point, deal with the three questions “When can it happen?”, “Where can it happen?”, and “How to prepare for it?”

In this report, the question “Where can it happen?” may be answered from the to-be-created “Large-scale sediment disasters archive” and “Deep-seated landslides map in Nara Prefecture” which are prepared from the knowledge gained in unraveling the mechanism of multiple deep-seated landslides.

Key words: deep-seated landslide, landslide, mechanism, archive, Kii Peninsula, Typhoon Talas

1. INTRODUCTION

In 2011, Typhoon Talas brought record-breaking heavy rain and caused extensive sediment-related disasters such as deep-seated landslides across Kii Peninsula in Nara, Mie, and Wakayama prefectures (hereinafter, “The Disaster”). In the Kii Peninsula, it is estimated that about 100 million m^3 of sediment was generated from about 3,000 landslides [Ministry of Land, Infrastructure, Transport and Tourism (MLIT), 2011]. Nara Prefecture was the area most severely damaged by the landslides, which resulted in 86 million m^3 of sediment, which was about 90 % of the total sediment generated in the disaster. 24 dead and missing and 184 damaged houses, was the result in Nara Prefecture. In the southern area of the prefecture, in particular, roads were cut off at many locations, leaving neighborhoods isolated for a long time.

In April 2012, Nara Prefecture, which suffered from significant damage, established the Deep-Seated Landslide Control Office to conduct “Research and study to unravel the mechanism of deep-seated landslides” while establishing a “Large-scale sediment disasters archive”, which would be an accumulation/use of the results of such research and study, and will be handed down to the next generation. Three questions concerning large-scale sediment disasters are, at this point, “When can it happen?”, “Where can it happen?” and “How to prepare for it?” Establishment of an integrated disaster management system as a combination of self-help, mutual-help, and public-help is on the table to improve the community disaster management force.

In this report, “where can it happen?” may be answered from the to-be-created “large-scale sediment disasters archive” and the “deep-seated landslides map in Nara Prefecture”, which are prepared from the knowledge gained from unraveling the mechanism of multiple deep-seated landslides.

2. RESEARCH, STUDY AND UTILIZATION OF THE RESULTS

Fig. 2.1 shows the flow of the research, study, and utilization of the results, initiated by Nara Prefecture.

Knowledge obtained from the "Research and study to unravel the mechanism of deep-seated landslides" is considered to be additional information to be used on the deep-seated landslide map in the Nara Prefecture (on the map or in the material that comes with it).

Data and related materials obtained by the research and study will be recorded in the "Large-scale sediment disasters archive", which is to be used for future research, studies and disaster prevention education, etc.

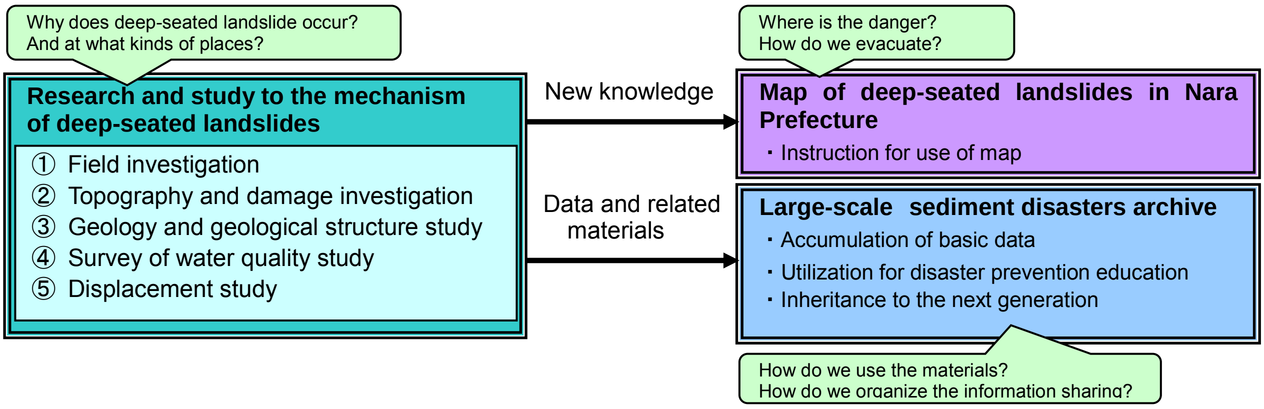

Fig. 2.1 Flow chart of research, study, and utilization of results

3. DEEP-SEATED LANDSLIDES IN THE DISASTER

In Nara Prefecture, a "Deep-seated landslide" is defined as a newly occurred large-scale landslide with a collapsed area of 1ha or more, and exceeding 10 m of collapsed depth occurring in the disaster.

Interpretation of the aerial photographs, taken immediately after the disaster and the site investigation, found 54 locations of deep-seated landslides (**Fig. 3.1**, **Photos 3.1** and **3.2**).

River course blockages were created at 26 locations including temporary blocks caused by deep-seated landslides, resulting in clogging at 15 locations. Breaches occurred at 3 locations, but 12 locations were left without breaches.

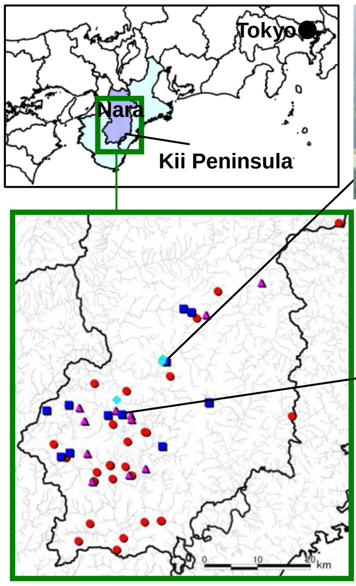

Photo 3.1 Deep-seated landslide (Hiyamizu, Ashinose)

Photo 3.2 Deep-seated landslide (Nagatono-tani)

Legend	Type	Number
● (red circle)	Landslides with no blockage of the river course	28
▲ (magenta triangle)	Landslides with temporary blockage of the river course, and gravity flow	11
◆ (cyan diamond)	Landslides with blockage of the river course, flood, breach	3
■ (blue square)	Landslides with blockage of the river course, flood, no breach. Rocks and earth mass remains	12
	Total	54

Fig. 3.1 Deep-seated landslide and river course blockage locations

4. RESEARCH AND STUDY TO MECHANISM OF DEEP-SEATED LANDSLIDES

Nara Prefecture has been conducting studies on deep-seated landslides followed by river course blockage, with measurement of the shape, and understanding of the geometry and geological features of the landslide locations, and the resulting damage, which are shown in **Table 4.1**.

In addition to 54 locations of deep-seated landslides, landslides causing river course blockages which do not meet the criteria for deep-seated landslides (in 6 locations), and 28 deep-seated landslides which occurred during the Great Flood in Totsukawa Village in the Meiji Period(1889), also have been studied.

Table 4.1 Research to unravel the mechanism of deep-seated landslides conducted by Nara Prefecture

Survey	Details	Publication
Surface survey	In addition to examination of the geometry of the surface of the slopes which suffered from deep-seated landslides, the surface geology and geological structure (dip slope, etc.) of the landslide sections, or of the outcrop locations, were confirmed. The results of the survey were made in a report by landslide location.	Some were published as reports*1
Topographic investigation	Aerial photographs, and the data from airborne laser scanning, before and after the disaster, were used to conduct interpretation of typical topography seen in landslides or surrounding slopes and creates a map of landslide locations. The outcomes were digitized by Geographical Information Systems(GIS) to measure the areas, etc.	Some were published as reports*1
Damage investigation	Interviews of local residents and public office employees were conducted to verify the time of the occurrence of the landslides or the time of breach by river course blockage, and resulting damage, evacuation situation, etc.	Some results were published in the archive *2
Rainfall and hydrologic studies	Data on the rainfall which covered all of Kii Peninsula, mainly in Nara Prefecture (JMA, MLIT and municipalities), was collected and organized, in order to understand the history of rainfall which triggered deep-seated landslides. Snake lines in a hyetograph were created, and probable rainfall was calculated.	Some were published as reports*1
Study of geological features and structures	Drilling data from the study on the geological structure of southern Nara Prefecture (tunnels and dam-related structures, etc.), and strike and dip data were collected and digitized for GIS analysis use. Geological structure of the southern part of Nara Prefecture and future methods for monitoring slopes were examined, based on the data.	Ongoing
Survey of water quality study	In order to have a clear understanding of the circumstances regarding underground water as a trigger of deep-seated landslides, the electrical conductivity, pH and water temperature of the spring water spots, and torrent where landslides occurred, were examined. Six locations were selected to perform the observation continuously, including on the slopes where no slides occurred.	Ongoing
Displacement study	In order to understand the terrain displacement of the slope due to landslides (erosion and silting), aerial photographs and data from airborne laser scanning (1 m x 1 m grid elevation model), before and after the landslides, were used to observe finite differences by comparing the data from these two different times. Terrain displacement of the southern part of Nara Prefecture has been studied based on such data.	Ongoing

*1 Deep-Seated Landslide Control Office of the Infrastructure Management Dept., Nara Prefecture (2013): Report from the research and study to unravel the mechanism of deep-seated landslides in June, 2013.
*2 Deep-Seated Landslide Control Office of the Infrastructure Management Dept., Nara Prefecture: Large-scale sediment disasters archive (http://shinsouhoukai.sakura.ne.jp/index.shtml)

5. CHARACTERISTICS OF THE DEEP-SEATED LANDSLIDE LOCATIONS IN THE DISASTER

Table 5.1 shows the characteristics, revealed from the studies described in 4, of the deep-seated landslides that occurred in the disaster.

Table 5.1 Characteristics of the deep-seated landslides in the disaster

Characteristics			Number (proportion to 54 locations)	Survey methods, etc.
Causative factors	Geology	Many occurred in accretionary prisms	52 (96 %)	Landslides and surface geology were examined in the surface field survey, while using a geological map to confirm the findings.
		Many occurred on dip slope	39 (72 %)	The geologic structure of the locations where outcroppings of collapsed slopes or bare rocks that were spotted in the surface field survey was verified.
	Topography	Many occurred on north facing slope	35 (65 %)	The aspects of the slopes where deep-seated landslides occurred were confirmed in aerial photographs and topographic maps.
		Many occurred on gentle slopes near ridge	36 (67 %)	Aerial photographs and data from the airborne laser scanning before and after the landslides were used to conduct topography interpretation of the locations.
		Many occurred on slopes with old deep-seated landslide scars	41 (76 %)	Aerial photographs and data from the airborne laser scanning before and after the landslides were used to conduct topography interpretation of the locations.
		Many occurred on the slopes of relative height of 150 m above the river bed	52 (96 %)	The height of the slopes where deep-seated landslides occurred from the streambeds to the ridgelines was verified on a 1/25,000 topographic map.
Triggers		Rainfall with accumulations of 600 mm or more	12 *1	To analyze the relationship between the rainfall and landslides, interviews of local residents and public office employees were conducted to verify the time of the occurrence of landslides, while the amount of rainfall at the time of the slides was determined,
Extent of the damage		Maximum height above riverbeds in damaged areas was 40 m at main rivers, and 65 m at tributaries	7 *2	In addition to confirming the sediment movement traces in the field, interviews of local residents were conducted to verify the information.

*1 Locations where the time of the occurrence was verified

*2 Locations where houses were damaged, or where there were casualties

5.1 Many landslides occurred in the accretionary prisms

Surface surveys of geological distribution indicated that most of the slopes, where deep-seated landslides occurred, were in the accretionary prism including the Shimanto Belt. In Nara Prefecture, 52 among 54deep-seated landslides occurred in the accretionary prism (96 %). The other 2 locations of the event were in the Ryoke Belt, which is characterized by volcanic rocks (**Table 5.2**).

On the suggestion of the Japan Society of Erosion Control Engineering [JSECE, 2012], deep-seated landslides in Japan often occur in the areas of specific geological features or structures, and have high frequency of occurrence in the accretionary prism, in particular. Actual events of deep-seated landslides in Nara Prefecture confirmed such a tendency (**Figs. 5.1** and **5.2**).

Table 5.2 Characteristics of the deep-seated landslide locations in the disaster in the southern part of Nara Prefecture by geological zone

Geological zone	Accretionary prism			Volcanic rocks
	Shimanto Belt	Chichibu Belt	Sanbagawa Belt	Ryoke Belt
Number of occurrences	45	4	3	2

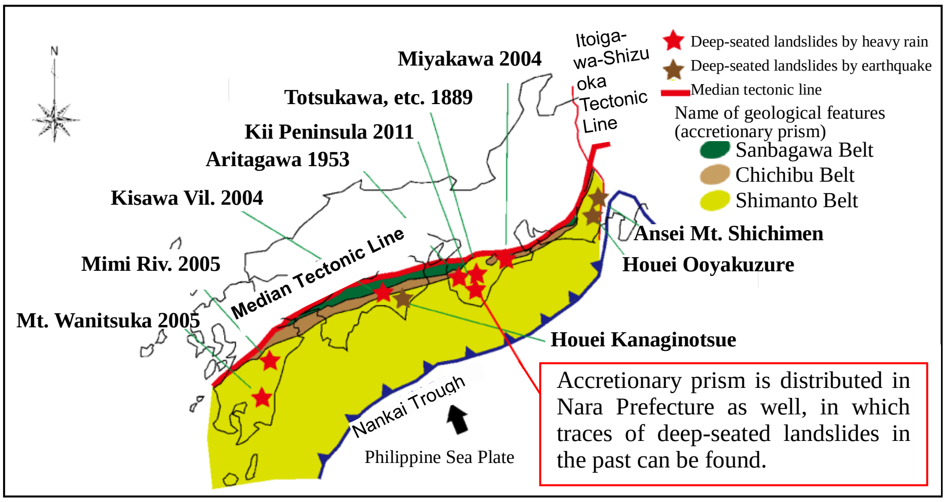

Fig. 5.1 Distribution of accretionary prism and the locations of deep-seated landslides in western Japan

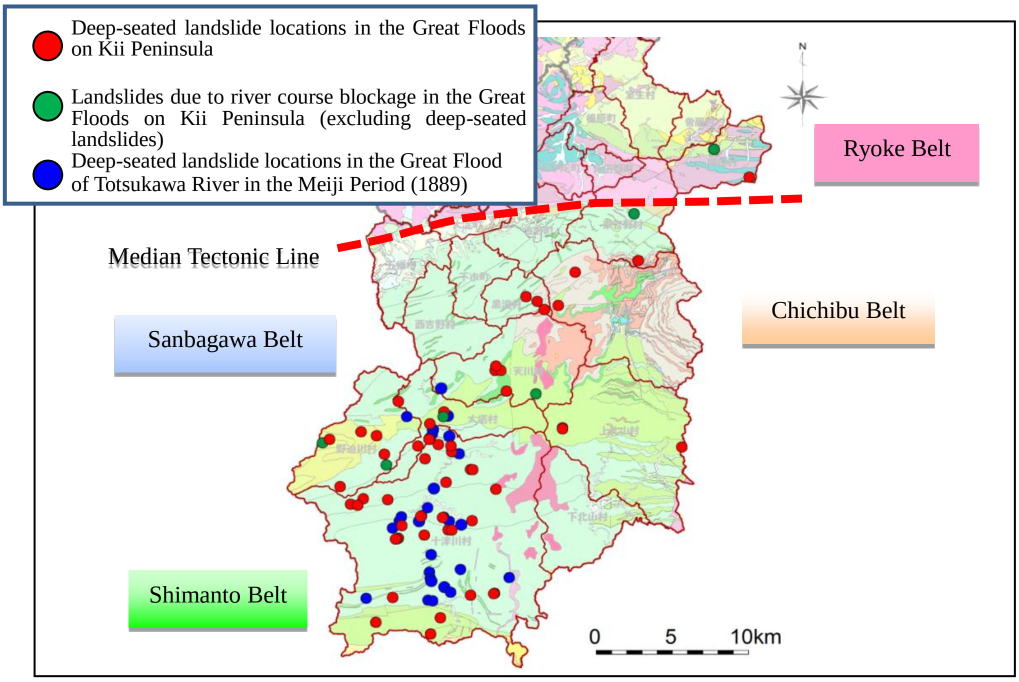

Fig. 5.2 Geology and deep-seated landslide locations in Nara Prefecture
(This geological map based on the“Seamless Digital Geological Map of Japan”, published by the National Institute of Advanced Industrial Science and Technology, revision approval No.: 60635130-A-20130205-001)

5.2 Many landslides occurred on the dip slopes

Surface surveys and studies on landslides, and places where there are outcrops, indicate that most of the slopes where deep-seated landslides occurred were on the “dip slopes”.

In Nara Prefecture, 39 among 54 deep-seated landslides occurred on the dip slopes (**Fig. 5.3**).

The lithology was an alternation of sandstones and mudstones, but after the landslide, bare bedrock with prominent cracks, was observed in many locations.

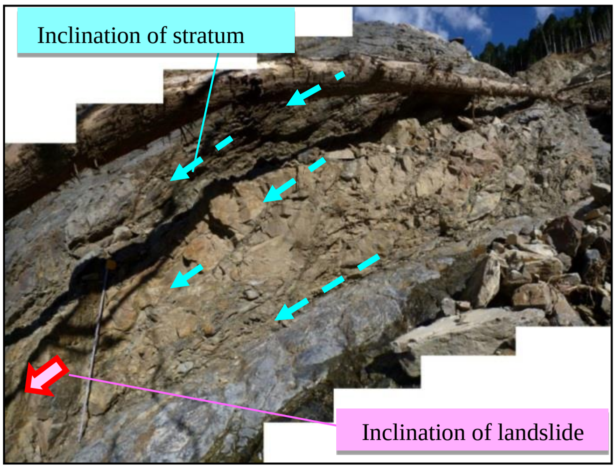

Fig. 5.3 Dip slopes at deep-seated landslide site in Kuridaira

5.3 Many landslides occurred on the slopes exposed to the north

The aspects of the slopes where deep-seated landslides occurred were confirmed in the aerial photographs and the topographic maps in which many of them occurred on the slopes exposed to the north.

In Nara Prefecture, 35 among 54 deep-seated landslides occurred on the north facing slopes (**Fig. 5.4**).

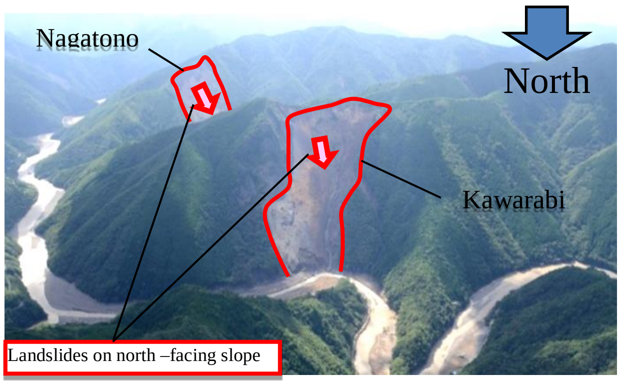

Fig. 5.4 Aerial photograph of the slopes where deep-seated landslides site in Kawarabi and Nagatono

This is largely consistent with the tendency of many landslides on dip slopes shown in Fig. 5.2, indicating the potential of association with the geological structure.

5.4 Many landslides occurred on the gentle slopes near ridges

Aerial photographs, and the data obtained from the airborne laser scanning, before and after the (deep-seated) landslides, were used to conduct topographical interpretation of the slopes. This study found that the landslides occurred frequently on the slopes with gentle sloped summits.

In Nara Prefecture, 36 among 54 deep-seated landslides occurred where there were gentle sloped summits (**Fig. 5.5**).
This is one of the interpretation items listed in the “Draw-off manual of mountain streams likely to cause deep-seated landslides (draft)” [NILIM, 2008] as geomorphic elements found typically in deep-seated landslides, which resulted in supporting the assumption.

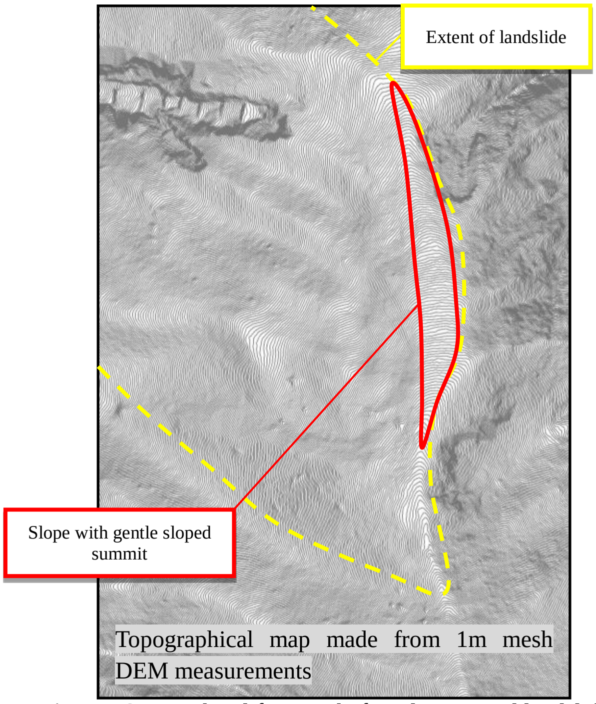

Fig. 5.5 Geographical features before deep-seated landslide in Nagatono

5.5 Many landslides occurred on the slopes with old deep-seated landslide scars

Topographical interpretation was conducted in the same manner as described in 5.4, and revealed that the landslides occurred frequently on the slopes with scars of old landslides.

In Nara Prefecture, 41 among 54 locations of deep-seated landslides occurred on the slopes with scars of past landslides (**Fig. 5.6**).

It has been also pointed out that there is a high risk of deep-seated landslides in the vicinity of scars of past deep-seated landslides [Suzuki T. et al., 2008]. There may be a strong relationship between old deep-seated landslide scars and deep-seated landslides as seen in the disaster.

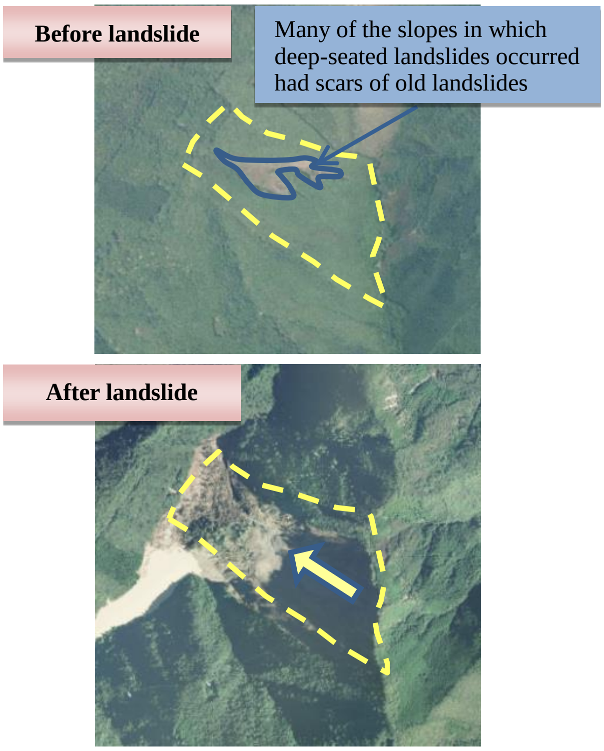

Fig. 5.6 Slope before deep-seated landslide in Nagatono

5.6 Many landslides occurred on the slopes with relative height of 150 m or more from streambeds to ridgelines

The relative heights of the slopes where deep-seated landslides occurred from the riverbeds to the ridgelines were examined on a 1/25,000 topographic map. In the study area, 52 of 54 deep-seated landslides (90 %) had a relative height of 150 m or more. In addition, the relative height of the slopes with old deep-seated landslide scars (1,052 spots) were examined, which generated substantially the same result (**Fig. 5.7**).

Deep-seated landslides are thought to occur on slopes greater than a certain height, and they can be 150 m or more in the case of the southern part of Nara Prefecture

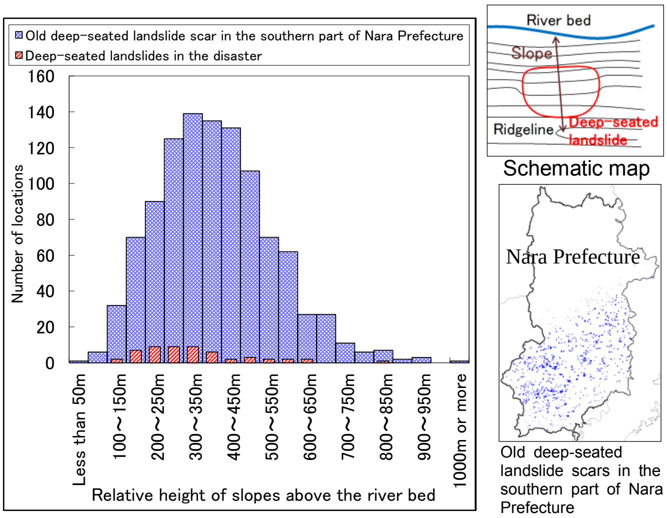

Fig. 5.7 Relative heights of the slopes where deep-seated landslides occurred

5.7 Characteristics of the disaster locations

As characteristics of the areas damaged by deep-seated landslides, “direct hit from the opposite shore”, “ponding damage”, “flood damage” and “abrupt wave” are listed. Examination of the traces of landslide and interviews of local residents revealed that the relative greatest height from the riverbeds where houses were damaged or humans were harmed was 40 m along the main roads (forth – order stream or more), and 65 m at the torrents (third – order stream or less) in the damaged areas in the disaster (Fig. 5.8, Photo 5.1).

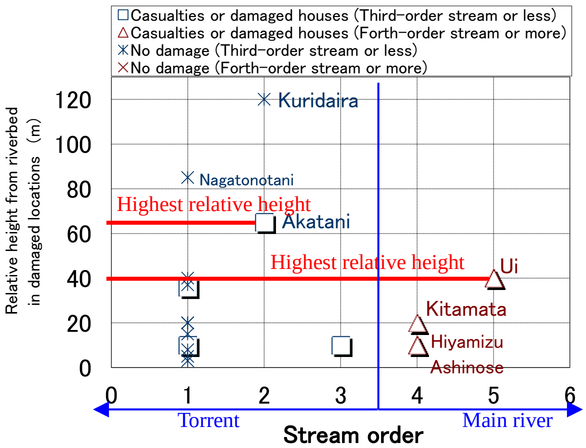

Fig. 5.8 Relative height from the riverbeds in the damaged area

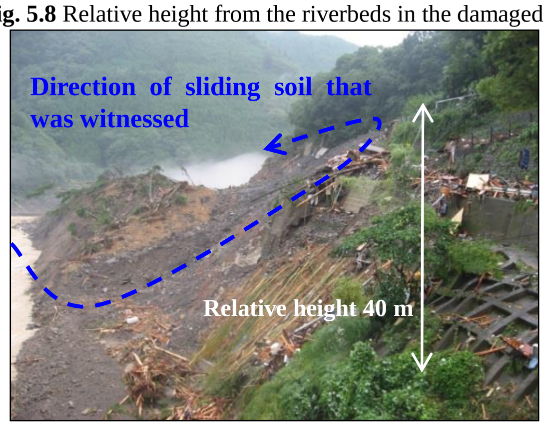

Photo 5.1 Damage from discharged sediment (Ui)

5.8 Cumulative rainfall of 600 mm or more

Among the deep-seated landslides in the disaster, studies were made on the amount of rainfall at the time of the slides (hourly rainfall and the cumulative rainfall from the beginning, **Fig. 5.9**) for 12 locations which were verified at the time of the occurrence of the landslides according to interviews of local residents and public office employees. The rainfall data was based on the data published by rain-gauge stations of Japan Meteorological Agency which are mostly located closest to each deep-seated landslide.

The study found that the deep-seated landslides occurred when cumulative rainfall exceeded 600 mm. On the other hand, hourly rainfall was about 20 to 50 mm, which is intense in this area (maximum hourly rainfall has been 62 mm since 1977: Kazeya Observation Station). Therefore, cumulative rainfall is believed to be the main cause of the deep-seated landslides in the disaster.

In terms of the relationship between rainfall and deep-seated landslides, a recent report pointed out that cumulative rainfall of 400 mm or more had triggered landslides [JSECE, 2011]. However, further discussion based on the results of analysis and data is still needed in the future, because there are only a few cases to study, and they are within a certain area.

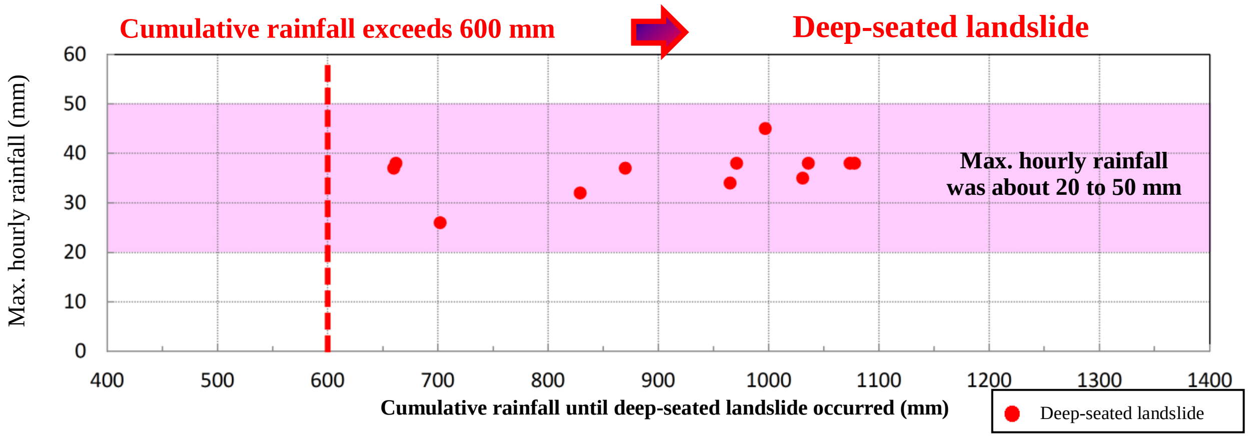

Fig. 5.9 Cumulative rainfall and max. hourly rainfall at the time of landslide

6. ONGOING RESEARCH

Based on the characteristics of the deep-seated landslides in the disaster described in Chapter 5, Nara Prefecture has been conducting the following studies to identify the mechanism of deep-seated landslides.

6.1 Geology

In order to understand the geological structure of the southern part of Nara Prefecture, according to the knowledge that deep-seated landslides frequently occurred on dip slopes, drilling data or strike and dip information was obtained from the outcomes of the existing research on the geological structure of southern Nara Prefecture (tunnels and dam-related) to digitize them for GIS (**Fig. 6.1**).

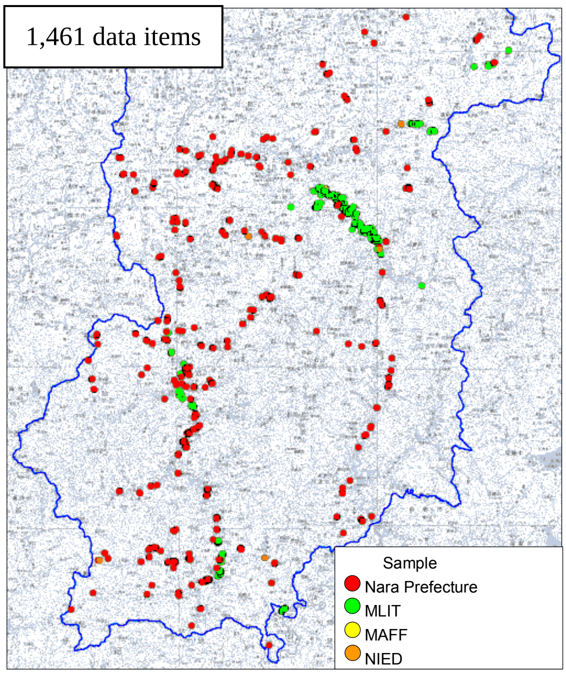

Fig. 6.1 Drilling data locations

6.2 Water quality survey

For the purpose of understanding the ground water which triggers landslides, electrical conductivity, pH, water temperature and the flow rate of the spring water spots and torrent where landslides occurred, were measured. In addition, 6 locations used for the purpose of continued observation were selected to conduct a survey of stream water and spring water including the surrounding undamaged slopes (**Fig. 6.2**).

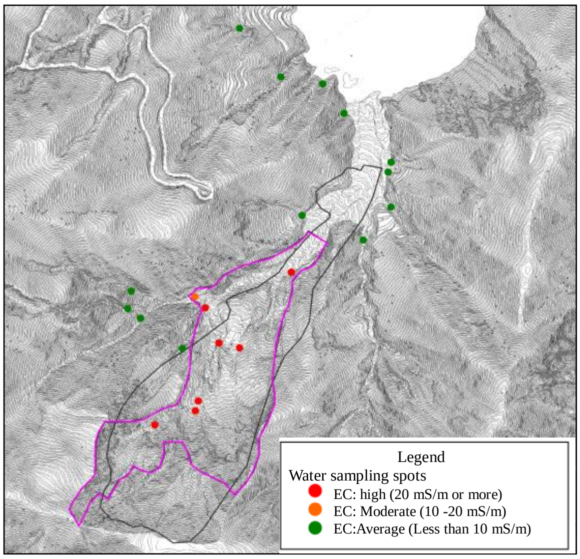

Fig. 6.2 Water quality survey in Kawazu

6.3 Displacement study

In order to find out whether or not there were any areas where micro relief displacement, deeply related to deep-seated landslides, occurred due to the rainfall of the disaster, finite difference analysis was conducted using airborne laser scanning data before and after the disaster (**Fig. 6.3**). Based on the outcomes from this study, methods for obtaining data, as well as methods for finite difference analysis, have been examined as tools for monitoring slopes.

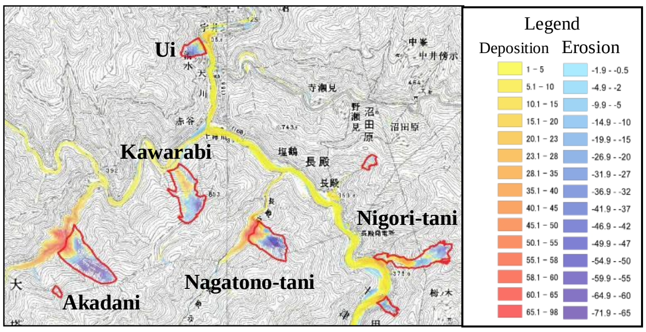

Fig. 6.3 Finite difference in aerial laser measurement data after the disaster (Area with many deep-seated landslides)

7. ESTABLISHMENT AND USE OF THE LARGE-SCALE SEDIMENT DISASTERS ARCHIVE

For the goal of handing down the records and knowledge of the disaster and the Great Flood in Totsukawa Village in the Meiji Period (1889) to the next generation, the large-scale sediment disasters archive has been built on an ongoing basis.

Specifically, the basic data of topography, geology and hydrology obtained by “Research and study to unravel the mechanism of deep-seated landslides” as well as information of evacuation at the time of emergency and damage were collected as digital data. In addition, assuming the archive will be used for the establishment of an integrated disaster prevention system which improves the community disaster prevention force; data and information obtained are organized to provide “notice” and “opportunity” to the communities through disaster prevention education, emergency drills and disaster history teaching. It has been an effort to make this data easy to access for the next generation.

8. FURTHER WORK

To improve safety of the communities, post-disaster recovery and reconstruction in Nara Prefecture continues till FY2014, which marks three years since the disaster. The approaches currently taken will be reviewed in the coming autumn.

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