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HISTORY AND PRESENT STATE OF INVESTIGATIONS ON LANDSLIDES CAUSED BY RESERVOIR FILLING: A REVIEW*

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SUMMARY

The internationally most famous landslide caused by reservoir landslide is the landslide at the Vajont Dam in Italy in 1963. Before the occurrence of the landslide at the Vajont Dam, reservoir landslides occurred at many Japanese dams such as the Ishibuchi Dam, Shichikawa Dam, Naruko Dam, Kanogawa Dam and Futase Dam. Since the occurrence of the landslide at the Vajont Dam, reservoir landslides occurred at the Shimokubo Dam, Shingu Dam, Yanase Dam, Odo Dam, Hachisu Dam and Takizawa Dam. In 1995, a manual titled “Investigations and countermeasures for landslides around reservoirs” was published by the Japan Institute of Construction Engineering. This manual was revised in July 2009 as the guideline titled “Technical Guideline for investigations and countermeasures of a landslide around a reservoir” by the Ministry of Land, Infrastructure and Transportation. Uniform and systematic investigations and stability analyses can be performed based on the manual and the guideline. Not one disaster has ever been caused by a reservoir landslide in Japan, because suitable countermeasures are taken based on the results of many kinds investigations of reservoir landslides.

Keywords: Geological investigation, Landslide, Reservoir slope, Ishibuchi Dam, Shichikawa Dam, Naruko Dam, Kanogawa Dam and Futase Dam, Shimokubo Dam, Shingu Dam, Yanase Dam, Odo Dam, Hachisu Dam and Takizawa Dam, Koya Dam, Sagae Dam.

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* *Synthèse de l’historique et de la situation actuelle des enquêtes sur les glissements de terrain causés par le remplissage des réservoirs*

RÉSUMÉ

Le glissement de terrain le plus célèbre à l'échelle internationale est celui qui s'est produit dans le réservoir du barrage de Vajont en 1963. Avant ce glissement de terrain, d'autres ont eu lieu dans de nombreux barrages japonais tels que le barrage d'Ishibuchi, le barrage de Shichikawa, le barrage de Naruko, le barrage de Kanogawa et le barrage de Futase. Depuis l'occurrence du glissement au barrage de Vajont, des glissements de terrain dans des réservoirs ont eu lieu au barrage de Shimokubo, au barrage de Shingu, au barrage de Yanase, au barrage d'Odo, au barrage de Hachisu et au barrage de Takizawa. En 1995, un manuel intitulé « Enquêtes et contre-mesures pour les glissements de terrain autour des réservoirs » a été publié par l'Institut japonais d'ingénierie de la construction. Ce manuel a été révisé en juillet 2009 avec la ligne directrice intitulée « Directives techniques pour les enquêtes et les contre-mesures des glissements de terrain autour des réservoirs » par le ministère des Terres, de l'Infrastructure et des Transports. Des analyses de stabilité ainsi que des enquêtes uniformes et systématiques peuvent être effectuées en fonction du manuel et de la ligne directrice. Au Japon, aucune catastrophe causée par des glissements de terrain dans des réservoirs ne s'est produite, ceci grâce à des contre-mesures appropriées prises en fonction des résultats de nombreux types d'enquêtes sur les glissements de terrain dans les réservoirs.

1. INTRODUCTION

The internationally most famous landslide caused by reservoir filling (below "reservoir landslide") is the landslide at the Vajont Dam in Italy in 1963. Reservoir landslides were known in Japan before the landslide at the Vajont Dam. However, reservoir landslides have not caused a large disaster in Japan, because many kinds of investigations of reservoir landslides have been performed since the 1960's. This paper describes the history and present state of investigations on reservoir landslides in Japan.

2. RESERVOIR LANDSLIDES BEFORE 1962

Reservoir landslides were recognized at the Ishibuchi Dam, Shichikawa Dam, Naruko Dam, Kanogawa Dam and Futase Dam (Table 1) earlier than the landslides at the Vajont Dam in 1963.

Table 1
A list of reservoir landslides in Japan.

Date	Dam	Location(s) of a reservoir landslide
1953?	Ishibuchi	Unknown
July 1957	Shichikawa	Unknown
Apr. 1957	Naruko	Hantawarayama, Mitenohara, Mizunasi, Motoyama and Denryokushusuiko
Dec. 1959	Kanogawa	Daichi, Kurinoki and Sakaishi
July 1961	Futase	Aso and Kaminakao.
Oct. 1963	Naruko	Minenohara
Jun. 1969	Shimokubo	Kobe, Mumanokubo and Ogiya
1972	Shimokubo	Mukozawa
May 1976	Shimgu	Tsudurehata
before 1980?	Yanase	Miyamae
Apr. 1982	Odo	Tosaki, Washinosu
Mar. 1991	Hachisu	L' -landslide
Nov. 2005	Takizawa	Unknown
May 2007	Takizawa	Unknown

The Ishibuchi Dam was completed in 1953. Its geology is Neogene pyroclastic rocks. A landslide occurred after the reservoir was filled, and the size of the landslide was 400 m by 150 m [1].

The Shichikawa Dam was completed in 1956. A landslide covering about 2 ha occurred on July 12 1957 [1].

According to SASAKI [2], the states of the reservoir landslides at the Naruko Dam which was completed in October 1957 are as follows. A reservoir landslide struck at Hantawarayama during first reservoir filling in April 1957 (Fig. 1). The first sign of the landslide appeared as a small slope failure and cracks in road surfaces and in stonemasonry when the reservoir water level reached 231.0 m above sea level on April 11 (Fig. 2). Cracks developed and the road surface collapsed for 30 m when the reservoir water level reached 240.0 m above sea level on April 22. The road surface collapsed for 42 m, and then the first landslide occurred on April 26. Finally, a large landslide called the Hantawarayama landslide occurred on April 26. The landslide was 250 m by 200 m with volume of 800,000 m3. Its vertical and horizontal displacements were 30 m and 10 m respectively. Basement rock at Hantawarayama is andesite covered by talus deposits. The landslide occurred in the talus deposits. Road surfaces were displaced in the Mitenohara, Mizunasi, Motoyama and Denryokushusuiko areas at the same time as the occurrence of the Hantawarayma landslide. Causes of these landslides were considered to be a rise of the water level in landslide bodies caused by reservoir filling and removal of the load at toes of the landslides. The following countermeasures were taken. Complete repair was done at the Hantawarayama landslide. Steel pipe piles and a buttress were constructed in the Mitenohara Landslide. Drainage boring, channel works and drainage wells were constructed in the Mizunashi landslide. Channel works were executed in the

Motoyama landslide. Channel works and drainage wells were constructed in the Denryokushusuiko landslide. The reservoir water level was lowered to repair the retaining wall of the intake of the spillway and cracks in the tunnel of the power station in October 1963. A landslide occurred at this time in Mitenohara. Cracks appeared in road surfaces when the reservoir water level reached 226.6 m above sea level on October 24. It rained on the 29th recording 30.4 mm of precipitation. Many cracks also occurred on the reservoir slope on the 30th. The reservoir water level reached its lowest level of 223. 63 m on the 29th, and then rose from the 30th. Vertical and horizontal displacements of 210 mm and 218 mm respectively were measured for 30 m on the road. The cause of the landslide was considered to be residual ground water. Steel pipe piles were constructed as a countermeasure. These countermeasures reduced the movement of these landslides caused by rising and falling of the reservoir water level at the Naruko Dam.

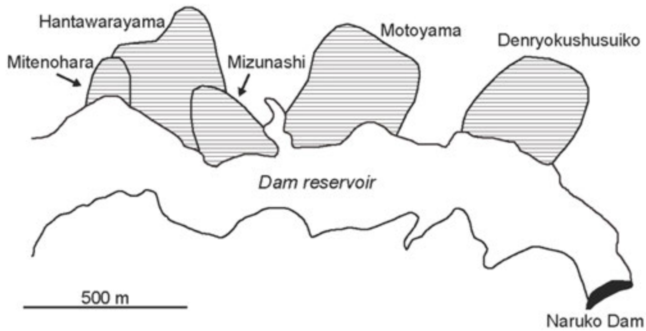

Fig. 1
Distribution of reservoir landslides at the Naruko Dam. Based on Sasaki [2].
Répartition des glissements de terrain dans le réservoir du barrage de Naruko. Basé sur Sasaki [2].

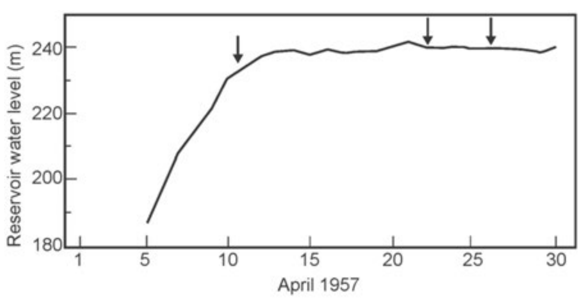

Fig. 2
Change of reservoir water level and occurrences of deformation and a landslide at the Naruko Dam. Arrows indicate occurrences. Simplified from Sasaki [2].
Changement du niveau d'eau du réservoir et des occurrences de déformation et d'un glissement de terrain au barrage de Naruko. Les flèches indiquent les occurrences. Simplifié depuis Sasaki [2].

The Kanogawa Dam was completed in January 1960. The area's geology is Chichibu accretionary complex mainly composed of slate, mixed rocks of slate and sandstone. According to TANIGUCHI [1], the states of the landslides are as follows. The main landslides are distributed in Daichi, Kurinoki and Sakaishi (Fig. 3). The first reservoir filling started in November 1959. Reservoir landslides occurred in December. Small failure of the road and cracks appeared on slopes, and then the abutment of the bridge moved in Daichi. Two months later, horizontal displacement of the abutment reached 32 cm. Movement of the landslide was stopped by the construction of a drainage tunnel and borings. However, the abutment moved again beginning June 1962. Horizontal and vertical displacements of 1.18 m and 1.07 m respectively appeared after the first movement. A part of the road 70 m long on a 50 m wide slope slid into the reservoir in June 1963. The groundwater level was observed at two wells. The surface of the road cracked and the retaining wall cracked and collapsed in a cultivated area in Kurinoki. Movement of the landslide was stopped by drainage and drainage borings. However, a 100 m by 80 m slope slid during heavy rainfall in June 1962. Slope failure and road surface cracking occurred in Sakaishi. Movement of the landslide was stopped by drainage boring and cutting the slope. The cause of these reservoir landslides was considered to be a rise of the reservoir water level.

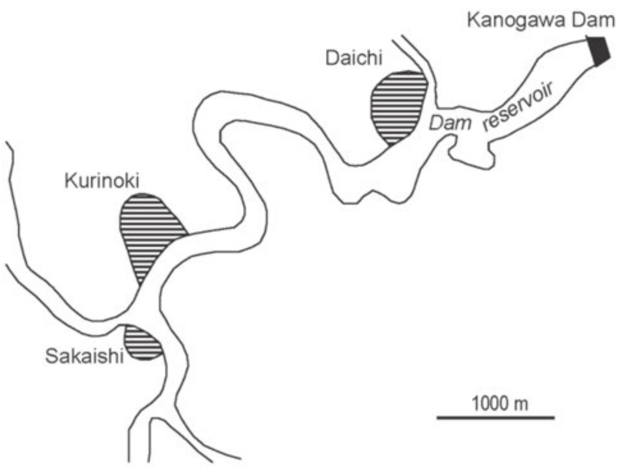

Fig. 3
Distribution of reservoir landslides at the Kanogawa Dam. Based on Taniguchi [1].
Répartition des glissements de terrain dans le réservoir du barrage de Kanogawa. Basé sur Taniguchi [1].

The Futase Dam was completed in December 1961. The geology of the Futase Dam area is also Chichibu accretionary complex. Reservoir landslides occurred in Aso and Kaminakao (Fig. 4). Cracks on the surface of the road were discovered on July 7, 1961. After July 7, the reservoir water level was started to fall, and its vertical displacement reached 1.52 m on July 25. Additional displacement of 65 cm was caused by falling of the reservoir water level starting on

February 1, 1962. The landslide displaced another 1.40 m by continued fall of the reservoir water level starting on July 1, 1962. Movement of the landslide was stopped by constructing steel pipe piles. Remarkable cracks appeared on the slope at Kaminakao. However, the landslide moved very slowly [1].

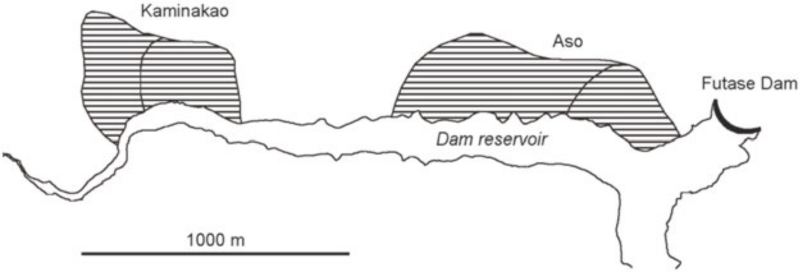

Fig. 4
Distribution of reservoir landslides at the Futase Dam.
Répartition des glissements de terrain dans le réservoir du barrage de Futase.
Basé sur Taniguchi [1].

3. RESERVOIR LANDSLIDES FROM 1963 TO PRESENT

The Shimokubo Dam was completed in 1968. According to TAMADA [3], the state of the reservoir landslides were as follows. First reservoir filling began on November 24, 1967, and 13 landslides were investigated before the first reservoir filling from 1959 to 1968. The investigations consisted of seismic exploration, electrical exploration, well logging, drilling, permeability testing, ground water logging and soil tests. Based on results of these investigations, countermeasures were made in four landslides which were assumed to affect houses and roads. The reservoir water level reached 292.4 m above sea level in early April 1969, but no landslide moved until this time. Then the reservoir water level was fallen until it reached 250.12 m above sea level in the middle of June. Cracks and collapses occurred in the Kobe, Mumanokubo and Ogiya landslides from late May to late June (Fig. 5 and 6). Drilling, ground water logging and movement observations were performed at these landslides. It was assumed that these landslides were caused by residual pore pressure, then drainage wells and borings and steel pipe piles were constructed. The reservoir water level was kept above 290 m above sea level from October 1971 to June 1972. When the water level was only risen in 1972, a landslide occurred in Mukozawa. Eight drilling and movement observations were done. Drainage borings and steel pipe piles were constructed as countermeasures. Surface intake facilities were constructed in the Shimokubo Dam from 1975 to 1978. The reservoir water level had to be lowered 80 m during this period to execute the construction; the water level was reduced by 60 m from April to September 1976 in particular. The water level was fallen at a rate of 1 m/day. At each landslide, 23 extensometers, 42 inclinometers, borehole water level recorders and strain gages were installed to observe landslide movement. Based on the movement observations, it is assumed that Inume and Maeno landslides were induced. Five drillings and nine drillings were done in Inume and Maeno landslides respectively. Steel pipe piles were constructed in both landslides.

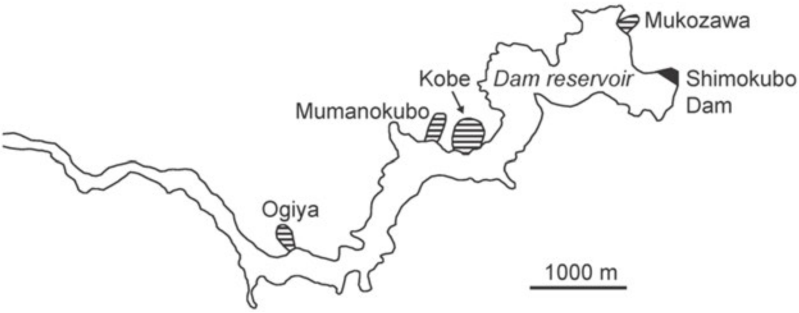

Fig. 5
Distribution of reservoir landslides at the Shimokubo Dam. Based on TAMADA [3].
Répartition des glissements de terrain dans le réservoir du barrage de Shimokubo. Basé sur TAMADA [3].

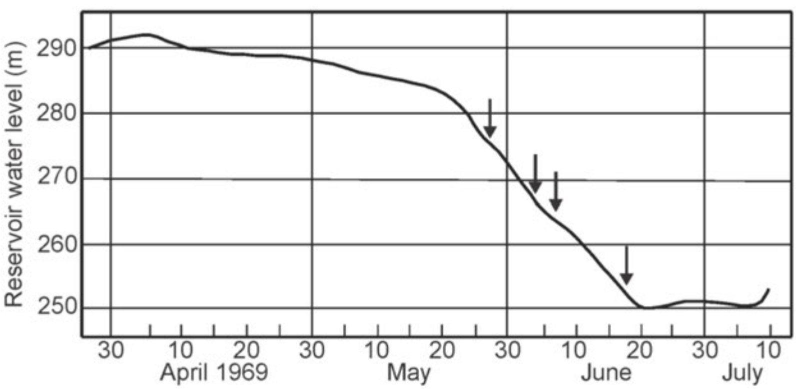

Fig. 6
Change of reservoir water level and occurrences of deformation and a landslide at the Shimokubo Dam. Arrows indicate occurrences. Simplified from TAMADA [3].
Changement du niveau d'eau du réservoir et des occurrences de déformation et d'un glissement de terrain au barrage de Shimokubo. Les flèches indiquent les occurrences. Simplifié depuis TAMADA [3].

The Shingu Dam was completed in 1974. Its geology is Sambagawa metamorphic rocks consisting mainly of psammitic schist with thin layers of basic and pelitic schists. The road surface cracked in May 1976 in Tsudurehata (Fig. 7).

Fig. 7
Distribution of reservoir landslides at the Shingu Dam. MORIKAWA [4].
Répartition des glissements de terrain dans le réservoir du barrage de Singu. Basé sur MORIKAWA [4].

Cause of the deformation was considered to be the rise of the ground water level due to reservoir filling. Steel pipe piles, drainage and retaining wall were executed as countermeasures [4].

The Yanase Dam was completed in 1953. Its geology is Sambagawa metamorphic rocks consisting mainly of basic schist. The Miyamae landslide was discovered in 1980 by a landslide investigation. Detailed investigations were performed from 1986. Active movement of the Miyamae landslide was observed from 1987 to 1988 [5]. Up till now, drilling has often been done and movement has been measured.

The Odo Dam was completed in 1987. Its geology is Chichibu accretionary complex. Landslides in Moriyama, Sawado, Oo and Takase (Fig.8) were investigated from 1963 to 1981. The investigations included field geological surveys, drillings, seismic exploration, electric exploration and excavation of adits. The first reservoir water filling was started on February 13, 1980, and the third reservoir water filling was started on April 1, 1982. A landslide occurred in Tosaki on April 19, followed by a landslide in Washinosu on April 20, when the reservoir water level was 204.00 m above sea level. The reservoir water filling was stopped; then the water level was lowered to 155.10 m above sea level at a rate of 0.5 m/day in order to investigate the landslides and take countermeasures. Investigations of landslides distributed in all reservoir slopes were repeated and required countermeasures were done. All countermeasures were completed in September 1985; reservoir filling was restarted on October 22, 1985 [6].

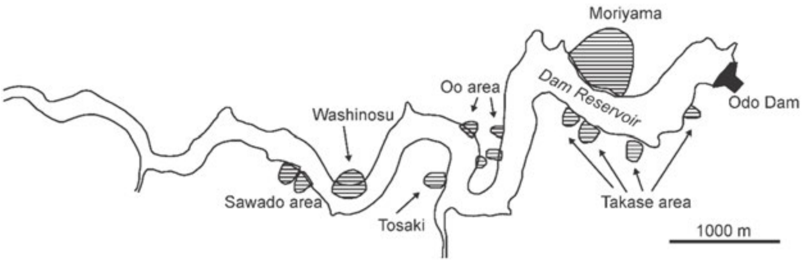

Fig. 8
Distribution of reservoir landslides at the Odo Dam. COMMITTEE ON CONSTRUCTION RECORD OF ODO DAM [6].
Répartition des glissements de terrain dans le réservoir du barrage de Odo. Basé sur COMMITTEE ON CONSTRUCTION RECORD OF ODO DAM [6].

The Hachisu Dam was completed in 1991. Its geology is Sambagawa metamorphic rocks composed of pelitic, psammitic and basic schists. OTAKA and MORI [7] reported that 20 landslides were found by interpreting aerial photographs and by geological surveys (Fig.9). These landslides were classified into five grades based on evaluations of natural slope, artificial slope and reservoir slope. The five grades consist of AAA, AA, A, B and C, with AAA defined as is the most unstable and most important. There were 17 landslides classified as grade A or higher. Among the 17 landslides, countermeasures were constructed at 12. A landslide occurred in an area where no landslide has been predicted on March 9, 1991. This was during the first reservoir filling which was started in March 1989. Just after this landslide, the reservoir water level was unchanged, however a crack in the crown part of the landslide was enlarged. Therefore, the reservoir water level was slowly lowered to 310 m above sea level at rates of 10 cm/day and 20 cm/day. Next, the water level was lowered by 1 m/day to the level of the toe of the landslide at 290 m above sea level. Shaft works were selected as the countermeasure [7].

The Takizawa Dam was completed in 2007. Its geology is Chichibu accretionary complex composed of chert, slate, sandstone and altered basaltic rocks. According to MATSUEDA et al. [8], the states of the reservoir landslides were as follows. First reservoir filling was done from October 1 2005 to July 2009. Three landslides occurred during the first reservoir filling. The first landslide appeared as slope deformation on November 2, 2005 (Fig. 10). Just after this deformation, the reservoir water level was kept at 502.82 m above sea level; and then the water level was lowered to 485.0 m at a rate of 0.3 m/day. Counter-weight fill was constructed. The second landslide occurred on May 1, 2007. The reservoir water level was kept at 549.06 m above sea level. Measurement of its movement detected some deformation from May 10, so the water level was lowered to 546.06 m at a rate of 0.3 m/day. A countermeasure was taken. After construction of the countermeasure, the maximum reservoir level 565.0 m was reached on March 30, 2008. The water level then was fell starting April 1, 2008.

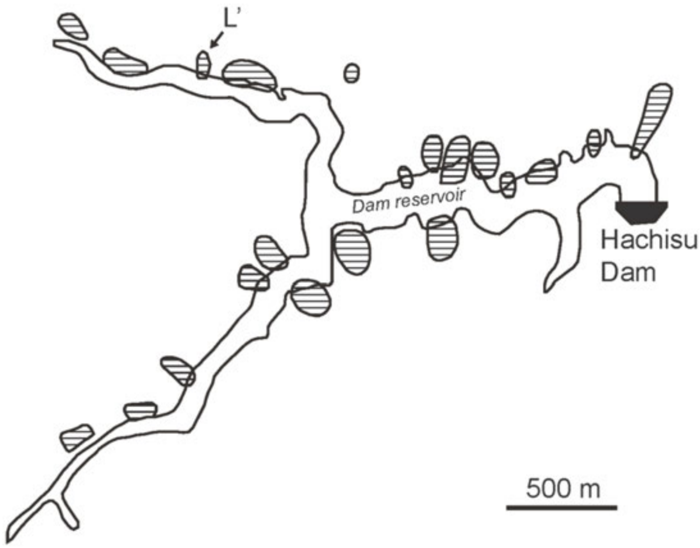

Fig. 9
Distribution of reservoir landslides at the Hachisu Dam. MORI [7].
Répartition des glissements de terrain dans le réservoir du barrage de Hachisu. Basé sur MORI [7].

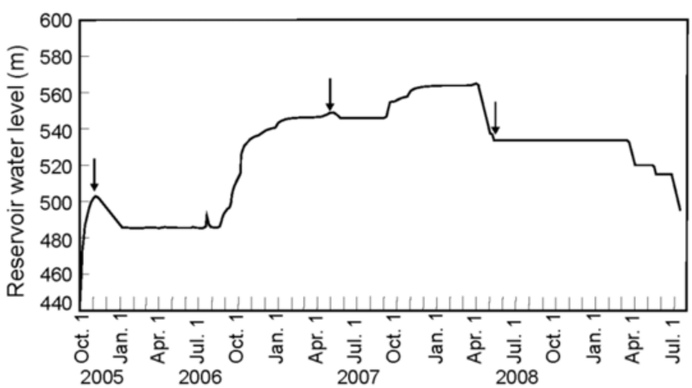

Fig. 10
Change of reservoir water level and occurrences of deformation and a landslide at the Takizawa Dam. Arrows indicate occurrences. Simplified from MATSUEDA et al. [8].
Changement du niveau d'eau du réservoir et des occurrences de déformation et d'un glissement de terrain au barrage de Takizawa. Les flèches indiquent les occurrences. Simplifié depuis MATSUEDA et al. [8].

The third landslide occurred on May 11 when the water level was 534 m. The water level was kept at 533.6 m. A Countermeasure was taken. The first reservoir filling was finished on July 14, 2009.

The Koya Dam was completed in 1982. Its geology belongs to Sanchu graben; basement rock is composed of shale. TOKUNAGA [9] reported on the state of the landslide. A reservoir landslide did not occur. The landform on the left bank upstream from the dam site suggested the presence of a landslide. Drillings, excavation of adits and seismic exploration had been performed since 1971. Slip surface of the landslide was determined by these investigations. The counter-weight fill method was selected as the countermeasure. After construction of the countermeasure, two borehole strain gages and a borehole ground water level recorder were installed; no displacement was measured, and the ground water level has correlated with the reservoir water level.

The Sagae Dam was completed in 1990. Its geology consists of Neogene andesite, sandstone, shale and basaltic dyke. No reservoir landslide had occurred. NAKAMURA [10] reported investigations and monitoring for landslides. In this dam, systematic investigation and classification of landslide grades were performed. The systematic investigation included topographical surveys such as the interpretation of aerial photographs, making a landslide information map, geological surveys, making a landslide block map and making charts of each landslide. Classification of landslide grades is made by charts of each landslide, grade classification of stability under present condition, influence of reservoir water filling, grade classification of stability after reservoir water filling, importance of objects for preservation and comprehensive classification of landslide grades. Landslide grades were divided into three categories, A, B and C.

4. STUDIES OF RESERVOIR LANDSLIDES

4.1. CAUSES OF RESERVOIR LANDSLIDES

Reservoir landslides are phenomena different from other natural landslides. Therefore, their causes are different from those of natural landslides. TANIGUCHI [1] classified reservoir landslides into two cases based on the occurrence timing of the landslides. One is the case in which a landslide occurred while the reservoir water level was rising (case 1), the other is the case in which a landslide occurred while the reservoir water level was falling (case 2). He considered causes of the reservoir landslides to be as follows. Slope collapse occurs in the immersed slope, then the balance of the slope is broken, including a landslide in case 1. When the reservoir water level suddenly falls, ground water level is not followed by the reservoir water level, then upward hydrostatic pressure and weight of water equal to the volume of an immersed slope remained in case 2. Due to the pressure and weight, the driving force of the landslide increases, destabilizing the slope. The upward hydrostatic pressure is considered to be residual pore water pressure. After TANIGUCHI [1], many researchers proposed the causes of the reservoir landslides as shown in Table 1.

Table 2
Causes of reservoir landslides

Causes of a reservoir landslide	Taniguchi(1964)	Watari(1971)	Fujita(1977)	Yoshimatsu(1979)	Yoshimatsu(1981)	Fujita ·Yoshimatsu ·Sakamoto(1983)	Yoshimatsu(1984)	Fujita(1985)	Nakamura ·Sakamoto(1987)	Nakamura(1988)
Collapse of the immersed slope	○	○		○	○	○	○	○		
Occurrence of residual pore water pressure	○	○	○	○	○	○	○	○	○	○
Decrease of shear strength in the immersed part			○	○	○	○	○		○	○
Change of ground water condition, rising ground water level			○		○	○	○	○		
Occurrence of flow pressure						○	○			
Displacement or strain of ground due to load by the reservoir water					○	○	○	○	○	○
Occurrence of buoyancy									○	○

“Collapse of the immersed slope” is the same as TANIGUCHI [1].

“Occurrence of residual pore water pressure” causes only rapid drawdown of the reservoir water level. When the water in a reservoir has been kept near the high level for certain period, the ground water level in the slope has also remained at a high elevation conforming to the level of reservoir water. Before the typhoon season, the water level in reservoirs must be dropped rapidly. The ground water level in the slopes does not drop so fast. This difference causes residual pore water pressure in the slopes [11]. The possibility of residual pore water pressure is high in a slope in which permeability is 10^{-3} to 10^{-4} cm/s [12].

“Decrease of shear strength in the immersed part” is driven by water filling in between soil particles, and when inter soil particles are filled by water, the water contents of soil increases, so shear strength is weakened [13]. Cohesion of materials which compose a slope decrease when the slope is immersed below the reservoir water level [12].

“Change of ground water condition, rising ground water level” means as follows; Immersion of the toe of a landslide indicates rising ground water level downstream. Therefore, ground water level in the slope will become remarkably high, then the pore water pressure in the slope increases, destabilizing the slope [14].

“Occurrence of flow pressure” means that a landslide composed of sandy material is induced by many small slope failures caused by the removal of ground water to the reservoir during a rapid drawdown of the reservoir water level [14].

“Displacement or strain of ground due to load by the reservoir water” means the displacement, strain and distortion of a slope due to load imposed by reservoir water weight. Internal stress in the slope is changed by sudden load by the reservoir water weight [14].

“Occurrence of buoyancy” was proposed by NAKAMURA and SAKAMOTO [12]. Shear resistance decreased due to declining effective stress in the slip surface caused by the occurrence of buoyancy or uplift pressure when a landslide is immersed.

KOMATA et al. [15] carried out centrifugal experiments to investigate stability of slopes and change of water level in model slopes. The water level was raised and lowered as part of the experiments. The results show that the model slopes were not destroyed only by buoyancy; decreasing saturation in the slopes and weakening shear strength were also required to destroy the slopes. According to the centrifugal experiments and unsaturated seepage flow analyses, ground water is easy to retain when the following conditions are completed; slow falling rate of reservoir water level, a gentle slope, a thick landslide body.

4.2. Occurrence time of reservoir landslides

YOSHIMATSU [16] divided occurrence time of reservoir landslides into three periods as follows;“landslides due to the first storage of reservoir water”,“landslides due to the rapid drawdown of reservoir water level” and “landslide due to the fluctuation of reservoir water level”. He also reported the occurrence percentages of these reservoir landslides as follows; landslides due to the rapid drawdown: 60%, landslides due to the rise of reservoir water: 8%, landslides due to the water fluctuation: 8%, landslides due to the first storage: 8% and indistinct cause: 16%.

KOMATA et al. [15] divided occurrence times of reservoir landslides into rising reservoir water level at first reservoir water filling (20 examples), falling reservoir water level at first reservoir water filling (11 examples), falling reservoir water level during operation of reservoir (8 examples) and rising reservoir water level during operation of reservoir (1 example).

4.3. Investigation methods

Depth of a slip surface can be estimated based on the distribution of loosened rocks as shown by a few drilled cores. Rocks which from a landslide body are weathered, so the color of drilled cores plays an important role in identifying a landslide body [17].

An in situ geological survey is performed after the distribution of landslides is estimated based on geology and topography. Following are excluded from a landslide; places where a landslide landform is not observed along a reservoir slope, fresh basement rocks are distributed in a riverbank, a reservoir slope forms a steep cliff although an upper part of a slope is not landslide landform, and weakly weathered rocks exposed. Four to five drillings in a slope and one drilling in an upper slope are done along one or two measuring lines in a concave slope. Parallel use of seismic exploration is suitable in the case of a large landslide. Potential movement is observed by more than two inclinometers in a slope surface [18].

FUJITA [11] divided the investigation of a reservoir landslide into investigations of landslides' distribution by geological and topographical investigations, detailed landside investigation, and analysis of slope stability influenced by water level fluctuation.

FUJITA [19] reported states of investigations for reservoir landslides. Contents and percentage of each of the investigations are as follows; before first reservoir filling; field geological survey: 91%, drilling: 68%, measurements of movement: 32%, investigation of ground water: 39%, strain gages in borehole: 39%, inclinometer: 36%, seismic exploration: 16%, electric exploration: 34%, seismograph: 23%, after first reservoir filling; field geological survey: 83%, drilling: 78%, measurements of movement 65%: investigation of ground water: 61%, strain gages in borehole: 57%, inclinometer: 61%, seismic exploration: 13%, electric exploration: 0%, seismograph: 26%.

TAGUCHI et al. [20] described essential points in the investigation of a reservoir landslide.

1) Identification of the landslide is accurately performed at the crown, a flat or gentle part of the crown and in small valleys both sides of a landslide.
2) 1/10,000 to 1/8,000 scale aerial photographs are suitable to identify average landform of a landslide, whereas a 1/40,000 aerial photograph is suitable to interpret a large landslide.
3) The inclination of the crown is less than 45 degrees and the difference of inclination of that crown and that of the natural slope is 10 to 20 degrees, inclination of a flat to gentle part of the upper slope is 10 to 20 degrees.
4) Comprehensive investigations including systematic drillings and mineral composition are required to identify a slip surface.
5) Systematic drillings are composed of more than three drillings along a main measuring line, and if necessary, one or two drillings along both sides line of the main line.
6) Suitable investigations and necessity for countermeasures are determined to do efficient investigations by evaluating natural conditions and stability of the landside after reservoir filling.

FUJIWARA [21] proposed the classification of drilled cores around a landslide body. The classification is mainly based on states of weathering. The classifications are Rf: fresh rock, W_1: heavily weathered rock, W_2: middle weathered rock and W_3: weakly weathered rock.

WAKIZAKA et al. [22] and WAKIZAKA [23] described the difference between crushed rocks of landslide origin and those of tectonic fault origin. Crushed rocks of landslide origin show random fabric, whereas those of tectonic fault origin have some fabric such as a shear plane. They proposed a classification of rocks based on degree of crushing to determine a landslide body.

4.4. Simulations of ground water

YOSHIMATSU [13] easily estimated fluctuation of ground water level in a natural slope caused by fall of the reservoir water level based on a continuity equation. FUJITA et al. [24] considered finite difference approximation to be a good way to simulate ground water level in a landslide body. NAKAMURA [25] dealt with unsteady seepage flow in two dimensions. He analyzed ground water level by difference approximation because the approximation was favorable in rum time, and it is simple and easy to input initial data. YOSHIMATSU [16] proposed an approximate estimation method of residual pore water pressure due to rapid drawdown of reservoir water level.

4.5. Stability analysis

WATARI [17], NAKAMURA and SAKAMOTO [12] and NAKAMURA [25] used the Swedish sliced method to analyze the stability of a reservoir landslide. WATARI [17] described conditions for stability analysis as follows;

1) Increase of unit weight of a landslide body is not considered.
2) Pressure in the direction opposite to water weight and sliding directions in an immersed slope is considered.
3) Cohesion of a slip surface is not changed after immersion by reservoir water.
4) Buoyancy is not considered.
5) Collapse in an immersed slope is determined by the form of an impervious layer.
6) Decrease of pore water pressure is not considered during rapid water level falling from HWL to LWL.

FUJITA et al. [24] and FUJITA [19] used the Swedish sliced method and Morgenstern and Price method for stability analyses. Compared Swedish sliced method with the Morgenstern and Price method showed that the safety factor obtained by the Morgenstern and Price method was higher than that obtained by the Swedish sliced method.

5. A MANUAL AND A GUIDELINE FOR RESERVOIR LANDSLIDES

5.1. A MANUAL

As mentioned above, many reservoir landslides have occurred in Japan, however not one of these reservoir landslides has caused a large disaster, because suitable investigations and countermeasures were performed for these landslides based on the results of studies. However, uniform and systematic investigations and stability analyses have not been done, so a manual for reservoir landslides was required. The Ministry of Construction organized a committee to prepare a manual for reservoir landslides in 1983. As the results of a discussion and examination by the committee, a manual titled "Investigations and countermeasures for landslides around reservoirs" [26] was edited by the Japan Institute of Construction Engineering in 1995.

The contents of the manual are as follows.

1) Outline
2) Characteristics of reservoir landslides
3) A process of investigations
4) Rough investigations
5) Evaluation of importance of landslides based on the results of rough investigations
6) Detailed investigations
7) Conclusions from the results of investigations
8) Planning, designing and construction of countermeasures
9) Management of slopes during reservoir filling

Causes of reservoir landslides described in "Characteristics of reservoir landslides" are as follows;

1) Occurrence of buoyancy due to immersion of the landslide body,
2) Occurrence of residual pore water pressure due to rapid drawdown of reservoir water level,
3) Rising ground water level due to immersion of the landslide body,
4) Decreasing load due to collapse of an immersed slope.

A preliminary distribution map of landslides is made based on topographical interpretation, and then a distribution map of landslides is made based on field geological survey during the rough investigation process.

Importance of landslides is evaluated based on degree of sliding due to reservoir water filling, size of a landslide and type of conservation. The degree of sliding is determined by topographical development, history of activity, and by the type and form of sliding surface of a landslide. The size of a landslide is divided into small (volume: less than 30,000 m^3), middle (30,000 to 400,000 m^3) and large (more than 400,000 m^3). Type of conservation is divided into slopes where they are related to dam facilities and facilities around reservoir slopes and other reservoir slopes. Importance of landslides is ranked as A, B, C and D; among these ranks, A is the most important.

Detailed investigations must be done on ranks A and B, and if necessary detailed investigations are performed on rank C. Detailed investigations include making a topographical map, division of blocks of a landslide, setting measuring lines, geological investigations, investigation of a slip surface, investigation of ground water, measurement of movement and investigation of soil. The geological investigations consist of field survey and drillings.

Analyses of landslide mechanism, making a plan and section, and stability analysis are included in a conclusion of the results of the investigations. Stability analysis is performed by the Swedish sliced method. A landslide dose not move before reservoir water filling; the safety factor is set to 1.00. Cohesion of a slip surface is determined by thickness of the landslide body, and internal friction angle is obtained by calculating backward using the safety factor 1.00 and cohesion. Residual pore water pressure is set as 50%. When as the result of stability analysis of a landslide, the minimum safety factor during rising or falling reservoir water level is less than 0.95; the landslide will move due to rising or falling of reservoir water level. Countermeasures are required for landslide.

5.2. A GUIDELINE

The manual was revised in July 2009. The revised manual was published as a guideline titled "Technical Guideline for investigations and countermeasures of a landslide around reservoirs and its explanation" [27] by the Ministry of Land, Infrastructure and Transportation.

Contents of the guideline are as follows.

1) General remarks
2) Rough investigations
3) Detailed investigations
4) Analyses
5) Planning countermeasures
6) Management of slopes during reservoir filling

The main differences between the manual and the guideline are as follows;

1) A landslide does not move before reservoir water filling; the safety factor is set as 1.05. So, the minimum safety factor during rising or falling reservoir

water level is less than 1.00; the landslide will move due to rising or falling of reservoir water level.

2) Residual pore water pressure can be set at 30% when a landslide has high permeability, slope inclination is more than 30 degrees and the landslide body is less than 30 m thick.

6. CONCLUSION

Many reservoir landslides have occurred in Japan before and after the disaster caused by the reservoir landslide at the Vajont Dam. However, not one reservoir landslide has caused a large disaster, because suitable investigations and countermeasures of the reservoir landslides were carried out. Since the publication of the manual titled "Investigations and countermeasures for landslides around reservoirs", uniform and systematic investigations and stability analyses can be performed.

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