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LANDSLIDE DAMS INDUCED BY TYPHOON MORAKOT AND RISK ASSESSMENT

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ABSTRACT

As with other compound disasters caused by climate change, the occurrence probabilities of landslide dams and their secondary disasters have increased and became a serious issue after the 2009 Morakot typhoon in Taiwan. This paper describes the mechanism of the landslide dam formation. Different types of landslide dams are classified by their danger level. This study also describes the inducements behind earthquake-landslide-triggered and typhoon-triggered landslide dams and compared their differences. Finally, both engineering and non-engineering aspects of the disaster management strategies are outlined. This study concluded that better disaster management strategies for landslide dams should focus on the long-term mitigation which includes a warning and monitoring system, engineering facilities, and a response process.

Key words: *landslide dam, Typhoon Morakot, failure, disaster prevention, response, mitigation strategy*

INTRODUCTION

Taiwan is sensitive to sediment disasters because of fragile geologic conditions and a steep topographic environment. More than 70% of the landscape is hillslope; the typhoon season brings concentrated and heavy rainfall, thus sediment disasters occur frequently during that time. Recently, disasters triggered by landslide dams have become a significant issue in Taiwan, especially those triggered by the 1999 Chi-chi earthquake and by the 2009 typhoon Morakot (Chen & Hsu, 2009; Liao *et alii*, 2003). More than 500 people died, and countless property losses occurred in those events. The two disasters showed the need to improve Taiwan's insufficient emergency response to landslide dam disasters. A landslide dam is caused by other serious sediment hazards, especially during typhoon events in the summer.

The formation of a landslide dam involves a series of complicated sediment movements. Analyzing this complicated natural phenomenon, involves several scientific disciplines, including hydrology, geography, landscape, and soil physics. Schuster & Costa (1988) attributed the formation of roughly 90% of landslide dams to precipitation, earthquakes, and volcano avalanches, among these factors, precipitation and earthquakes are the principle ones accounting for approximately 84% of landslide dams. Chen (1999) confirmed that the landslide dams formed after the 1999 Chi-chi earthquake. Some of these dams still exist, however they are not a source of immediate danger. Furthermore, some landslides dams were also formed after typhoon Morakot. However, until now no detailed studies investigate the differences of the dams produced in 1999 and those produced in 2009, as well as the response strategies.

Firstly, this study describes the inducements, types, and failure processes of the landslide dams to show the two types of landslide dams induced by different hazards. Then the four landslide dams with the highest danger levels are focused and the difference among the two types of landslide dams is represented. Furthermore, this study investigated the potentially efficient mitigation measures to reduce risks that include engineering and non-engineering strategies by the processes that lead to landslide dam failure. An emergency response process to improve the existing response mechanism is offered by the experiences on dealing with slopeland disasters, which is divided into initial, short-term and long-term stages. Finally, some conclusions are summarized according to the significance in every section.

THE MECHANISM AND TYPE OF LANDSLIDEDAM FAILURE

Landslide dams are made when a stream is blocked by the mass from a landslide, debris flow, volcano mudflow, glacial ice, or other process. As debris blocks the stream, the upstream water level increases. Since the dam body is composed of debris material, its structure is not solid and lacks of soil cement. Erosion of the dam body, generates flow rush, melting, sliding of the geologic material, and overtopping flow (Yan & Cao, 2009). Finally the dam suddenly fails, leading to aggradations downstream and causing severe losses. Thus, identifying and classifying different levels of risk is necessary for providing early warning of landslide dam failure.

We defined three landslide-dam formations by their danger level potentials; high danger dam, stable dam, and crushed dam. A high danger dam poses great risk with a high probability of the dam failing immediately. Sediment material blocks the main flow path completely, resulting in blocked deposits and no outflow. Generally, this type of dam fails in a few hours or days because either the river water increases or the dam's length-to-depth ratio is between 10 and 20. Serious losses are caused by floods and energy released when the dam fails.

A stable dam forms when the landslide dam experiences conditions of overtopping and unblocked outflow. The water either flows out at the same outlet of the main river or follows a different flow path. The water attains a balance between inflow and outflow. Additionally, this type of dam is more stable than a highly dangerous dam because length-to-depth ratio of the stable dam exceeds 20. Engineering measures can extend the life of this type of dam. For most of the energy associated with the deposits and the flow is low. Accordingly, this kind of dam has a low probability of causing serious disasters.

A crushed dam is a short-term dam that can fail suddenly. Often, a crushed dam results from a highly dangerous dam. The length-to-depth ratio of a crushed dam is lower than 10. The deposits silt up after crushing and are displaced downstream. Many landslide dams formed after typhoon Morakot are crushed dams (Korup, 2005).

THE FAILURE CHARACTERISTICS OF LANDSLIDE DAMS

Schuster & Costa (1986) reviewed 63 landslide dam cases and stated that 22% of the landslide dams failed within one day, 50 % failed within 10 days, 83% failed within six months, and 91% survived for a year. Most landslide dam failures result from various factors and produce dangerous flooding downstream. In the following section, the stability assessment utilized to identify the danger levels of a landslide dam is described.

Normally the stability of a landslide dam should be classified in terms of numerical simulations or an experimental model. When accurate numerous parameters and materials are prepared, a numerical simulation method identifies the phenomenon of landslide dam failure more precisely than an experimental model. However, an experimental model is more appropriate for application in an emergency, when information is urgently needed. Outburst flooding data also relies on numerous empirical data (Korup, 2005). Therefore, when an immediate need arises for information about the danger level, an experimental result is preferable.

The dimensionless Blockage Index (DBI) formula is an effective index for assessing the stability of a landslide dams based on the dam's area, height, and volume (Ermini & Casagli, 2003). The DBI formula is defined as follows:

$$\mathrm{DBI} = \log(A_b \times H_d / V_d) \quad (1)$$

where A_b is the area of the landslide dam, H_d is the accumulated sediment height of a dam, and V_d is the accumulated sediment volume of a dam.

Ermini & Casagli (2003) also discovered the characteristics of DBI values by reviewing 84 landslide dam cases. A landslide dam is more stable when its DBI is less than 2.75, and unstable when its DBI is more than 3.08. A DBI value between 2.75 and 3.08 is transitional.

THE TYPES OF LANDSLIDE DAMS AFTER CRUSHING

Many studies demonstrate the main mechanism of dam failure (Takahashi, 1988; Yan & Cao, 2009; Nicoletti & Parise, 2002). This study focused on three principle mechanisms in describing the differences in how dams fail: overtopping, piping, and slope failure. Schuster & Costa (1986) and Evans (2006) surveyed 202 landslide dam cases in that occurred in 1985; they discovered that more than half of those cases were largely caused by overtopping. Specifically, 197 cases were caused by overtopping, four were caused by piping, and 3 only one was triggered by slope failure. The characteristics of landslide dam body material, dam strength, infiltration coefficient, and hydrologic conditions upstream are principle factors involved in landslide dam failure. The above factors define the three types of landslide dams.

First, the factors leading to overtopping are high strength of the dam body and the dam's low permeability. These factors cause the speed of water level rise to be greater than the seepage velocity. Since the dam is naturally formed and lacks mitigation engineering to deal with overtopping, the dam's body is destroyed soon after erosion from overtopping occurs (Tabata *et alii*, 2002). Second, instantaneous slip failure occurs when the permeability coefficient is large, and the strength of dam body is low. Sediment accumulates at the slope toe and is easily carried downstream by the river.

Finally, a comparison of the progressive failure type with the other two types of dam shows that, in the former, the permeability coefficient is the largest and the strength of the dam body is the lowest. The dam erodes even though the water depth is low. This process triggers some small-scale landslides, and the dam eventually fails (Awan *et alii*, 2007).

LANDSLIDE DAMS INDUCED BY TYPHOON MORAKOT AND THE DIFFERENCE WITH EARTHQUAKE-INDUCED CASE

Typhoon Morakot was a mid-level typhoon that passed by Taiwan in a slow path. The rainfall during this typhoon was intense and reached an cumulative rainfall of 2,000 mm across the island, causing landslides and debris flows and producing 17 landslide dams. Most of these dams were located in Chenyoulen-xi catchment in central Taiwan and Chisan-xi and Lounoun-xi catchments in southwestern Taiwan (Fig.1). Most of these dams are failure because of heavy rainfall and the risk of some dams decreased due to overtopping soon after their formation. However, the complex physical conditions of these dams mean that uncertainties remain. Accordingly, the mitigation work for these dams is still important.

In Taiwan, mitigation projects related to hillslope disasters are managed by different institutions, including the Water Resources Agency, Soil and Water Conservation Bureau (SWCB), and Forestry Bureau. The 17 landslide dams have been monitored and were classified into three levels according to their danger potential (Tab. 1). The first level (Level A) lists three dams considered highly dangerous. Therefore, these dams are carefully monitored, and evacuation announcements and emergency respondent activities are prepared for emergencies. The second level (Level B) contains six dams identified as not immediately dangerous. The strategies for dealing with this type of dam are monitoring and when needed engineering strategies. The third level (Level C) contains ten dams that were already crushed. In the following sections, this study details interpretations of the three important landslide dams in Level A, examine the special case of Shou-lin village (Liao *et alii*, 2003), and show their features in Tab. 2.

SHIBUN-XI LANDSLIDE DAM

This dam was made by a catastrophic landslide, which occurred upstream of the Shibun-xi stream, Pingdong County, southern Taiwan. The dam's distance from the nearest downstream village is 11 km. The water storage volume in the landslide dam is approximately 500,000 m^3; the maximum water depth is about 23 m and the watershed area is about 4 ha. Debris distributed on the flow bed after the first failure triggered the progressive wash continuously. Due to unstable geologic conditions and many landslide spots in the downstream areas, a prediction was made that either a series of landslide dams would form or a second disaster would occur.

Fig. 1 - Locations of landslide dams Taiwan relative to isohyets of rainfall totals (mm) in Typhoon Morakot

No.	Blocked River/Stream	Location	Level	Note
1	Sarisen-xi Stream	Nantou County	C	1. Failed, with no danger 2. Authority is Taiwan university
2	Heshe-xi Stream	Nantou County	C	1. Failed, with no danger 2. Authority is SWCB
3	Heshe-xi Stream	Nantou County	C	1. Failed, with a elementary school destroyed 2. Authority is Forestry Bureau
4	Laonong-xi River	Kaohsiung County	C	1. Failed, with no danger 2. Authority is Forestry Bureau
5	Laonong-xi River	Kaohsiung County	C	1. Failed, with no danger 2. Authority is SWCB
6	Laonong-xi River	Kaohsiung County	C	1. Failed, with no danger 2. Authority is Water Resource Agency
7	Chisan-xi River	Kaohsiung County	C	1. Failed, with no danger 2. Authority is Water Resource Agency
8	Laonong-xi River	Pingdong County	C	1. Failed, with no danger 2. Authority is SWCB
9	Koushe-xi Stream	Pingdong County	C	1. Failed, with no danger 2. Authority is SWCB
10	Tzengwen-xi River	Tainan County	C	1. Overtopped, with no danger 2. Authority is Forestry Bureau
11	Chenyoulan-xi Stream	Nantou County	B	1. Failed, with steady overtopping flow 2. Authority is Taiwan University
12	Laonong-xi River	Kaohsiung County	B	1. Failed, with steady overtopping flow 2. Authority is Forestry Bureau
13	Laonong-xi River	Kaohsiung County	B	1. No danger, with steady overtopping flow, storage area is 1 ha 2. Authority is Forestry Bureau
14	Laonong-xi River	Kaohsiung County	B	1. Failed, with steady overtopping flow, storage area is 2 ha 2. Authority is Forestry Bureau
15	Shibun-xi Stream	Pingdong County	A	1. Failed, with steady overtopping flow, storage area is 4 ha 2. Authority is Forestry Bureau
16	Chisan-xi River	Kaohsiung County	A	1. Failed, with steady overtopping flow, storage area is 23 ha 2. Authority is Forestry Bureau
17	Taimari-xi Stream	Taidong County	A	1. Failed, with steady overtopping flow, storage area is 70 ha 2. Authority is Forestry Bureau

Tab. 1 - Details of the 17 landslide dam cases

CHISAN-XI LANDSLIDE DAM

This dam is located upstream of the Chisan-xi stream, Kaohsiung County. The dam's distance to the nearest village is 7 km because the dam was found when the avalanche caused debris to slide down from the right bank and deposited debris in the left bank. The approximate volume of the landslide dam is about 1.85 million m^3; the maximum water depth is 10 m and the watershed area is 23 ha. The dam material moisture is high, and the material is fragile. For these reasons, overtopping could easily trigger a secondary failure.

TAIMARI-XI LANDSLIDE DAM

This dam is located upstream from the Taimari-xi stream in southeast Taiwan. This dam was produced when the avalanche blocked the stream flow. The dam's volume is approximately 5.33 million m^3; the maximum water depth is 10 m and the watershed area is 70 ha. With the geomorphic survey result showing that the dam has already failed three times. The debris material was scattered and displaced on the river bed and in the downstream area.

Most part of the silted dam is not eroded except of the outlet part. The width of the outlet is about 20 m and the depth of the outlet is about 5 m. This dam is typical in the case of progressive failure, thus erosion will continuously occur on the dam. The landslide amount is considerable, so the blockage will likely continue in the next rainfall season.

SHOU-LIN VILLAGE LANDSLIDE DAM

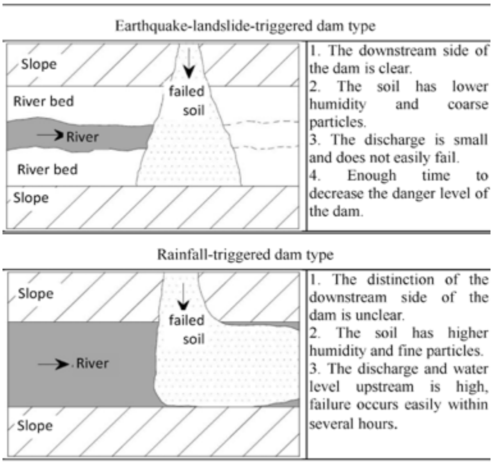
The landslide in Shou-lin village caused the most severe losses during typhoon Morakot. More than four hundred people were dead during the landslide dam crushing. A landslide involving a total volume of about 20 million m^3 first occurred north of the village. The debris with high water capacity blocked the stream, producing the landslide dam. The landslide dam crushed quickly because of the dam's thickness and the high water level of the stream. Flood water and debris from the dam destroyed most of the houses in the village.

DIFFERENCES BETWEEN EARTHQUAKE-LANDSLIDETRIGGERED AND RAINFALL-TRIGGERED LANDSLIDE DAMS

Approximately 20 landslide dams were generated after the 1999 Chi-chi earthquake and the 2009 typhoon Morakot, respectively. Only one dam formed after the Chi-chi earthquake still exists; none of the dams formed after typhoon Morakot still exist. This study compared these dams according to their primary inducing factors, earthquakes and heavy rainfall (Tab. 2). The main difference between these two types of dams stems from their various basic mechanisms and soil humidity. Generally, the rainfall-triggered dams are less stable and fail more easily. However, if a landslide dam is triggered during a heavy rainfall event, its stability could worsen and a failure could cause a more serious disaster.

Name	Shibun-xi	Chisan-xi	Taimari-xi	Shou-lin
Backwater length (m)	700	1700	2000	2000
The length of river block (km)	> 1.0	> 1.0	> 1.0	0.6
Type of lake basin	Tributary valley	Main valley	Main valley	Main valley
Landslide dam area (ha)	6.5	25.0	75.0	92.3
The upstream catchment area (ha)	3,300	21,200	6,500	200,000
Type of dam after failure	Progressive type	Overtopping type	Progressive type	Overtopping type

Tab. 2 - Main features of the landslide dams after typhoon Morakot



Tab. 3 - The differences between landslide-triggered and rainfall-triggered dams

THE MITIGATION STRATEGIES FOR PREVENTION AND RESPONSE

THE ENGINEERING STRATEGIES FOR LANDSLIDE DAM MITIGATION

The danger of a landslide dam is caused by continuously increasing river water levels that negatively affect the dam body. The water pressure increases with water depth by an order of two; the raising water level increases the infiltration phenomenon and also the failure probability. Rising water levels and overtopping also cause damage such as gullies and debris flow to the dam surface. These phenomenon may finally trigger the crush of landslide dam. Therefore, some engineering measures are needed and offered to reduce the danger of the landslide dams corresponding to three different types of dam failure mentioned earlier.

Lowering the water level

As part of a stability dam check, a fixed critical water level is important to consider. Any river water that rises above this critical level should be removed or be led downstream by the spillway. To avoid overtopping, the fixed water level should be higher than the storage water level of the dam. This measure is available to the overtopping type landslide dam to reduce its increasing water level. The culvert or the pump is also determined under the small catchment in the upstream and with less inflow.

The conveyance structure

A spillway is the one of the most appropriate conveyance structure for landslide dams. The structure should be considered along the river path. This measure could be utilized to the overtopping failure type of landslide dams for controlling the water. Such construction is built through the compression soil to decrease the infiltration rate, raise the soil's resistant to erosion, and reduce flow velocity. This measure is also utilizing at some existing landslide dams currently.

Reinforcement engineering facility

Reinforcement engineering includes compressing the dam, constructing a check dam, or other stable engineering. The compression is normally determined based on conditions, such as length, height, dam material, water pressure, or erosion. This measure is usually utilized when the landslide dam is stable and with the dam probably is failure by progressive or instantaneous type.

Stability engineering of the hillslope

The secondary failure of a landslide dam or a landslide is likely to occur because the fragile slope land and the debris flow torrent are potentially dangerous and close to the initial hazard spots. However, engineers struggle to stabilize a landslide area with an extended magnitude in a short period of time. To solve this problem, a monitoring system is necessary, along with reinforcement engineering to strengthen the hillslope toe. This measure is utilized when the landslide dam is crushed or stable and may be failure by instantaneous slip way.

The risk assessment level procedure for landslide dams

In addition to engineering measures, non-engineering measures, such as announcement systems and disaster education are significant to decrease risks associated with landslide dams. Generally, after a landslide dam forms, a urgent series of mitigation efforts are preformed. These efforts include monitoring, announcement, and risk assessment.

In reality, a comprehensive monitoring system is difficult to put in place, because of limited time and sediment hazards occur in the hillslope areas. For these two reasons, around-the-clock manual observations are typical. However, the announcements and risk assessments are always carried out after detailed professional investigations are represented, which is not responsive to the emergency demands. Therefore, how to utilize existing information to evaluate the potential dangers of a landslide dam and to propose early warning and mitigation strategies is important.

Few studies examine immediate damage assessment of a landslide dam. Instead many studies analyze landslide dams in relation to long-term safety monitoring. However, such information cannot be employed to determine the rainfall-threshold criterion in relation to early warnings and downstream disaster evaluation. This study classified the different danger levels for 17 landslide dams by applying the method mentioned earlier (Tab. 2). Nonetheless, a more detailed assessment process is required for future studies.

THE PROCESS OF LANDSLIDE DAM RESPONSE

As described in the Disaster Prevention and Response Law, different governmental departments in Taiwan have authority over different hazards. The Soil and Water Conservation Bureau (SWCB) is in charge of debris flow and the Water Resource Agency is in charge of flooding. However, landslide dam disasters possess the inducements and characteristics of both flood and sediment hazards, for this reason, a landslide dam disaster is defined as a compound disaster. This is why a special response process for landslide dam disasters is necessary. After typhoon Morakot, the Forestry Bureau (2009) wrote a document draft focusing on landslide dams. The initial cooperation and the responsibility of each government department were clarified by discussions, and a basic consensus was achieved. The National Science Committee and National Security Affairs provides satellite imagery employed in risk level classification; the Water Resource Bureau is in charge of the landslide dam management in the primary level rivers; SWCB and Forestry Agency are responsible for torrents in mountainous areas and national forests, respectively; and local governments are in charge of landslide dam management for the secondary-level rivers and the resident evacuation. Each department's primary authority has been clarified, however details regarding such operations are lacking and should be legislated.

This study also consulted Japanese regulations and laws regarding emergency response and disaster management. In the primary Japanese sediment-hazard laws, the main concerns are rock avalanches, debris flows, and landslides. Until now no studies have discussed response strategies for landslide dams. This is because landslide dams are a type of complex disaster, that have only recently grown more important, and also because many uncertainties regarding the inducement and formation of such dams exist. Additionally, the affected range regards of such a dam is related to changes in its size and the downstream elevation. For these reasons, any warning, monitoring, and evacuation systems should be determined and established according to actual situations. This study referred to an initial framework for landslide dams based on the technological reports on evacuation and disaster management produced by the Forestry Bureau and Japan (Ministry of Land, Infrastructure, Transport and Tourism of Japan, 2009) (Fig.2).

In the first stage, when an un-defined landslide dam is found, an emergency investigation and announcement are necessary. The purpose of the responding process is to access the danger related to the landslide dam and to identify the probability and types of the dam's failure. The announcement can be released after the safety of the landslide dam is assessed. The second stage involves verifying the detailed information of a landslide dam and setting up a monitoring system. Simultaneously, other strategies are arranged and modified according to a drill or prior disaster experiences. When the landslide dam is identified as extremely dangerous, then the emergency management processes are implemented. The emergency management processes includes field investigation, monitoring, evacuation of local residents, and a risk assessment related to the application of engineering strategies mentioned earlier. In some cases, the engineering methods utilized in the second stage in attempt to stabilize the landslide dam can lead to the dam's crush. In such a situation, the rescue and evacuation system is still maintained until the dam is verified not to be dangerous. In the third stage, long-

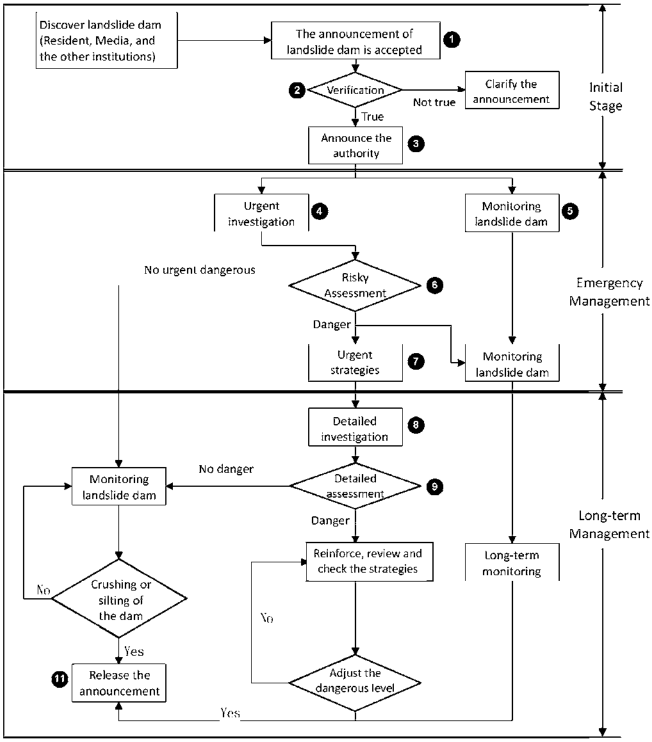


Fig. 2 - The processes for responding to landslide dam disasters

term disaster management should be considered. The landslide dams in this stage are mostly stable or crushed ones. As part of a detailed investigation, long-term monitoring is carried out to assure the security of both property and residents. Simultaneously, the engineering strategies, such as reducing the storage water, reinforcing the dam body and constructing protection facilities, are performed by different failure types of landslide dam to reduce the future risk. All of these strategies should be preserved until the announcement is released.

The two serious natural hazards in Taiwan generated many landslide dams, most of which failed quickly. One of the landslide dams triggered by the Chi-chi earthquake still exists in central Taiwan. The equipment for monitoring and recording the dam are still employed and an evacuation system is in place for potentially dangerous situations. This case could be a good model for developing a program of disaster management to avoid landslide dam disasters.

CONCLUSIONS

Disasters triggered by landslide dams have become an important issue because of their complex mechanism of formation and the uncertainties accompanying them. Such disasters necessitate both emergency responses and the long-term recovery projects. The high intensity and concentrated heavy rainfall brought by typhoon Morakot caused not just landslides and debris flow disasters for residents, but also many landslide dams that submerged downstream areas. This study clarified the formation and types of landslide dams and addressed how such dams fail. The cases triggered by landslide and precipitation showed different inducements of landslide dams in their characteristics and results. Most typhoon-triggered dams fail quickly and cause great losses. Conversely, earthquake-landslide-trigger dams last longer and cause fewer losses. This study listed the most dangerous cases of landslide dams produced during typhoon Morakot to compare the differences in their characteristics. We identified three development types based on their mechanisms of failure: overtopping erosion, instantaneous slip failure, and progressive failure. Most cases involve progressive failure, in which a stable flow is achieved and the dam poses no urgent threat.

In the second part of this study, some engineering and non-engineering strategies for landslide dam mitigation are explained. The engineering strategies emphasized decreasing water levels to reduce both the water head pressure and erosion on the dam body. The non-engineering strategies focused on issues of authority and the response process. Regarding the issue of authority, departments related to landslide dams in Taiwan are cooperating in disaster management, however the regulations are still insufficiently detailed. Regarding the response process, this study discussed the need for both a well-organized emergency strategy and long-term mitigation that includes announcement, monitoring, risk assessment, and engineering strategies.

Landslide dam mitigation is a significant issue that influences the development of downstream areas, land-use and residential safety. The mitigation strategies offered in this study demonstrate the significance on the long-term strategies that authorities can plan to prevent the landslide dam disasters.

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