Analysis on the damage causes of sabo dam with one open cross section at upstream of Fuxing bridge in Lacus Creek

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Abstract. Lacus Creek is one of the important tributaries of the Laonong River upstream of the Gaoping River, which is an important river in southern Taiwan. After Typhoon Morakot in 2009, severe sediment disasters occurred, which affected the security of local revitalization, and the government has since invested in numerous projects to reduce the impact of sediment and flood disasters. In 2017, the Kaohsiung City government built a sabo type dam upstream of Fuxing Bridge in Lacus Creek; however, it was severely damaged by a heavy rain less than a year later. To investigate the cause of the damage, site investigations, concrete sampling tests, hydrology analysis, and reviews of the planning and design methods, construction process, etc. have been conducted, in order to understand the cause of the problem, avoid repeating mistakes, and clarify the responsibility of the administrative agency. The investigation and research found that many recent cases of torrent management have considered the transverse structures as isolated wildlife corridors, reduce the height of the transverse structures, create gentle slopes of the downstream surfaces, add fish passages, cut (openings) export slits, etc.; however, after setting up these environmentally friendly facilities, their effect and impact have not been explored in depth. This research survey found that, although the frequency of heavy rain events is not high in recent years, the current iterative impact of continuous rainfall may exceed the original design requirements. If the overflow mode with a single export opening is added, the scouring energy will be concentrated, and this additive effect is likely to cause the foundation of the sabo dam to lose bare space, and finally, the dam will be damaged. Therefore, it is recommended that when designing these torrent transverse structures, try to avoid using the method of a single narrow opening: it is better to increase the number of export openings (like a slit dam), expand the size of a single export opening, or adopt a fully enclosed dam design.

1. Introduction
After being collected by all tributaries from the upstream catchment, the rainfall runoff (flood) carrying scoured sediment finally flows to the downstream area. During the process, due to the effects of terrain and fluvial facies, the changes in erosion and deposition occur naturally. According to the review of sediment control projects, various river structures are built to control flows and bed deformation, in order to prevent upstream, downstream, and surroundings areas from being harmed by excessive erosion or deposition[1-4]. While river structures can control temporary and local changes,
the changing trend of the regional river dynamic balance may be known through a series of reviews[5-9]. At the end of 2015, the Water Resources Bureau of Kaohsiung City Government built a sabo dam at the upper reaches of Lacus Creek in Fuhsing Village (Taoyuan District, Kaohsiung City) to control the flood and sediment of this creek. The project built a large sabo dam 160m in length and 8m in height according to the design standards of a 50-year recurrence period, which especially have one open cross section for ecological reasons. This construction method is to build a permanent structure with in-situ block filler and a reinforced concrete section shell, in order to reinforce the overflow part with high-strength concrete. The purpose is to stabilize the bed of Lacus Creek, block 200,000 m$^3$ of sediment from the upstream slope, and prevent the abnormal increase of the downstream bed from causing overflows, in order to maintain the safety of the downstream Fuxing Village. The stream bed when the dam was built is shown in Figure 1.

This sabo dam had never encountered typhoons or heavy rains until June 1 to June 4, 2017. After the first plum rain front, and under the accompanied effect of a southwesterly flow, the accumulated rainfalls in the upstream area of the catchment were up to thousands of millimeters, and the sabo dam, which was the second stage of the upstream earthwork project of Fuxing Bridge in Lacus Creek, was damaged. The damaged length of the dam was nearly 60m, the sediment in the rear was scoured with the dam failure, and the condition before the dam was built was restored, as shown in Figure 2.

In recent years, for the good of the environment, many stream renovations have considered the passage of transverse structures as wildlife corridors, reduced the height of the transverse structures or the gentle slope of the downstream surface, added fish passages, cut (openings) export slits, etc.. However, after setting up these environmentally friendly facilities, the effect and impact have not been explored in depth. Affected by global climate change, hydrological extremes occur frequently, and rainfall intensity and accumulation are more severe than in the past[10-21]. However, whether the failure of the sabo dam was caused by natural factors, improper design, or construction problems, this case deserves in-depth study. Hence, this paper analyzes and explores the dam failure, in order to understand the failure causes and factors in-situ, and provide reference for future engineering facilities.
2. Materials and Method

2.1. Description of the research site

Lacus Creek is one of the important tributaries of the Laonong River upstream of the Gaoping River, which is an important river in southern Taiwan (as shown in Figure 3). In 2009, Typhoon Morakot caused severe sediment disasters, which affected the security of the local Fuxing Village, and a national claim was made. The government has since invested in a lot of projects in the area to reduce the impact of sediment and flood disasters. As reported by the Liberty Times on March 16, 2016, Fuhxing Village was a severely afflicted area of Typhoon Morakot in the past. Kaohsiung City Government Water Resources Bureau carried out the upstream sediment prevention project of Fuxing Bridge in Lacus Creek and built the huge sabo dam to maintain the safety of Fuxing Village.

Fuhxing Village has 113 households and a population of about 365. In the past, it was a severely afflicted area of Typhoon Morakot, where a large amount of soil and rocks destroyed roads and bridges. The heavy rain in 2012 damaged 10 houses. Fortunately, no one was injured.

Lacus Creek became a 160 m wide river from a little stream due to Typhoon Morakot, and it is 7 km from Fuxing Bridge in Taoyuan District to the forest compartment of the Forestry Bureau, thus, it was announced that the creek had the potential for debris flows.

In order to regulate Lacus Creek, the Kaohsiung City Water Resources Bureau cooperated with the central government, while the Forestry Bureau added sand control facilities in the upstream forest compartment. Additionally, a grant of 30 million to the Soil and Water Conservation Bureau of the agricultural commission will strive to carry out the upstream sediment prevention project of Fuxing Bridge on Lacus Creek (as shown in Figure 4 and Figure 5).

The Water Resources Bureau explained that the proposed large sabo dam is 160m long and 8m high, and the construction method will use in-situ blocks and reinforced concrete sections to stabilize the bed of Lacus Creek and to block the 200,000 m³ of sediment on the upstream slope. At present, the construction progress is ahead of schedule, and the project will be completed before the flood season. The Water Resources Bureau also points out that, the completion of this prevention project can effectively and instantly stop a large number of sediments from moving downward, which will prevent
the lifting of the riverbed from causing overflows, and thus, reduce the risk of causing disasters to Fuxing Village (as shown in Figure 6).

2.2. Methods of disaster investigation and analysis
Since the project was tested by abnormal rainfall at the level of heavy rain and damaged in less than 1 year after completion, all sides hope to know the exact causes of the disaster, which can also be used as a reference for subsequent reconstruction. In general, project damages are often caused by weather, planning and design, construction, or a combination of the above factors, as it is difficult to investigate, research, and determine the problems, thus, the responsibilities are heavy.

Figure 3. The location of Lacus Creek.

Figure 4. The construction situation of the giant sabo dam at upstream of Fuxin bridge in Lucas Creek by Water Resources Bureau of Kaohsiung City Government.
Figure 5. The aerial photography of the giant sabo dam at upstream of Fuxin bridge in Lucas Creek by Water Resources Bureau of Kaohsiung City Government.

Figure 6. The completion of the construction of the giant sabo dam at upstream of Fuxin bridge in Lucas Creek by Water Resources Bureau of Kaohsiung City Government.

Hence, in terms of weather, the hydrology and hydrophysical analysis of continuous heavy rains are focused. According to the planning data adopted in project construction, the flow estimates at the design stage are based on the empirical formula of the United States Soil Conservation Service, which is combined with the rainfall patterns calculated by Horner’s formula, and the method is described, as follows:

The triangle unit hydrograph method assumes that the flow hydrograph, as produced by rainfalls per unit time, is triangular, and its shape (as shown in Figure 7) is deduced based on empirical formulas. According to the empirical formula of the United States Soil Conservation Service:

\[ Q_p = 0.208 \times A \times \text{Re/Tp} \]
\[ T_p = D/2 + 0.6 \times T_c \]
\[ T_r = 1.67 \times T_p \]
where:

- **Qp**: Peak flow (cms)
- **A**: Catchment area (km²)
- **Re**: Precipitation (mm)
- **Tp**: Time from rise to peak (hour)
- **Tc**: Time of concentration (hour)
- **D**: Unit rainfall duration (hour)
- **Tr**: Time from peak flow to the end of hydrograph (hour)

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**Figure 7. U.S. Bureau of Soil and Water Conservation triangular unit calendar empirical formula of unit flow calendar**

The above rainfall duration (D) is determined based on the time of concentration (Tc). For rainfall pattern analyzed based on many rainstorms, D ≦ 1/5Tc is taken; for the rainfall pattern analyzed based on the rainfall strength formula, (1) Tc >6 hour, D = 1 hour, (2) 3 hour < Tc ≤ 6 hour, D = 0.8 hour, (3) 1 hour < Tc ≤ 3 hour, D = 0.4 hour, and (4) Tc ≤ 1 hour, D = 0.15 hour are taken. Regarding the rainfall pattern analyzed based on many rainstorms, because the unit scale of the rainfall pattern is one hour, the unit hydrograph of the effective rainfall duration D must be converted by S-curve to that of the effective rainfall duration of one hour to calculate the flood hydrograph; for the rainfall pattern analyzed based on the rainfall strength formula, the unit scale of rainfall pattern is consistent with the effective rainfall duration D, thus, the unit hydrograph does not need to be converted. Horner’s formula is used to calculate rainfalls in this project, where both the value of D and the value of △D, as calculated by Horner, are 0.15hr or 0.4hr, thus, the unit hydrograph does not need to be converted.

The steps to estimate the Peak flow are, as follows:

1. Multiply the storm rainfall of this typhoon by the percentage of rainfall per unit time in the rainfall pattern to obtain the precipitation per unit time (or unit rainfall duration) in the selected rainfall duration (24 hours).
2. Obtain the triangle unit hydrograph created by the excess rainfall of the unit rainfall duration based on the above empirical formulas, such as Qp, Tp, Tr.
3. Finally, insert the precipitation per unit time in the rainfall duration (24 hours) into the triangle unit hydrograph, and stagger it by a unit time for superposition, in order to obtain the flood hydrographs and Peak flow of all control points.
4. Calculate the time of concentration Tc used in the above formulas with the commonly used formula, as put forward by the Highway Administration Bureau of California, and the formula is:

   \[ Tc = (0.87L^3 / H)^{0.385} \]
where $L$ is the longest runoff path (km) in the catchment; $H$ is the maximum elevation difference (m) between the catchment boundary and the outlet.

In planning and design, both in-situ exploration and aerial shots are adopted to understand whether the facilities, sites, material selection, and dam selection are appropriate, and whether there are problems, such as, upstream and downstream topography, the water-flow effect, etc., which are taken as reference for analysis and discussion.

During construction, construction supervision, sectional inspections, and completion acceptance of this case have been carried out, and there are certain short control procedures. Therefore, if there are no major defects, the residue shapes and parts of the junction points shall be inspected on site, while the concrete strength can only be discussed for poor construction.

3. Results and Discussion

3.1. Hydrology and hydrophysical analysis

On-site investigation results of Kaohsiung City-Taoyuan District-D346 can be roughly divided into 2 zones, which run through the whole slope from the center and are bounded by erosion gullies, with the main event block in the north and a collapsed slope due to lateral erosion of the bank of the Baolai River in the south. The slope in the south zone is exposed due to the hard laccolith, the only remaining colluvial soil is on the abdomen of the slope, and the lower slope has severe lateral erosion of the bank of Baolai River. Due to continuous development and collapse of lateral erosion, the upper slope tends to be stable, while the lower slope continues to collapse and go upstream. The northern border of the sliding block is the northern erosion gully, which is the lateral collapse of the sliding block travelling slightly parallel with the sliding direction. Moreover, due to the tension and fracture development of the slide (Figure 3), this point location is the area with the most significant surface activities. In a sliding block, rock cracks and strain breaks on the upper half of the slope are often under tension due to collapse (Figure 4), and such pushing and fracturing on the lower half of the slope are often caused by collapse and slides.

1. Hydrological analysis

According to the above analysis formula of the triangle unit hydrograph, the characteristics of the stream catchments in the research area (as shown in Figure 8) are analyzed, and all parameters related to all catchments and triangle unit hydrograph are estimated, as shown in Table 1. Moreover, the flows during all time sequences of the triangle unit hydrograph in the catchments of Lacus Creek can be estimated, as shown in Table 2, and on this basis, estimates of Peak flows during all periods can be conducted by using the iterative proportional weights, in order to understand the relationship between Peak flow and design flow.
Figure 8. The situation of the main stream catchment area within the Lacus Creek scope.

Table 1. List of related parameters of unit calendar of water catchment area.

| Catchment Number | Difference of Elevation (m) | River Length (km) | Area (km²) | Unit duration (D(hr)) | TC(hr) | TR(hr) | TB(hr) | TP(hr) | Qp(cms) | Remarks |
|------------------|----------------------------|-------------------|------------|-----------------------|--------|--------|--------|--------|---------|---------|
| 1                | 2265                       | 18.00             | 61.65      | 0.40                  | 1.36   | 1.70   | 2.72   | 1.02   | 12.59   | Lacus Creek |

Table 2. Estimation Table of Time Series Discharge of Triangle Unit Hydrograph of Water Catchment of Lacus Creek.

| T(hr) | Q(cms) | T(hr) | Q(cms) | T(hr) | Q(cms) |
|-------|--------|-------|--------|-------|--------|
| 0.00  | 0.00   | 0.95  | 11.96  | 1.90  | 5.92   |
| 0.05  | 0.63   | 1.00  | 12.59  | 1.95  | 5.55   |
| 0.10  | 1.26   | 1.05  | 12.22  | 2.00  | 5.18   |
| 0.15  | 1.89   | 1.10  | 11.85  | 2.05  | 4.81   |
| 0.20  | 2.52   | 1.15  | 11.48  | 2.10  | 4.44   |
| 0.25  | 3.15   | 1.20  | 11.11  | 2.15  | 4.07   |
| 0.30  | 3.78   | 1.25  | 10.74  | 2.20  | 3.70   |
| 0.35  | 4.41   | 1.30  | 10.37  | 2.25  | 3.33   |
| 0.40  | 5.04   | 1.35  | 10.00  | 2.30  | 2.96   |
| 0.45  | 5.67   | 1.40  | 9.63   | 2.35  | 2.59   |
| 0.50  | 6.30   | 1.45  | 9.26   | 2.40  | 2.22   |
| 0.55  | 6.92   | 1.50  | 8.89   | 2.45  | 1.85   |

Catchment area=6,165 ha
Overland flow length=0.1km
Creek length=18.1km
Difference of elevation=2.265km
The flow is based on the analysis results of the above rainfall hyetograph and the unit hydrograph, and the flow hydrograph with a 50-year recurrence period at the catchment outlet can be drawn, as shown in Figure 9 and Table 3.

Table 3. The flow hydrograph with a 50-year recurrence period from catchment outlet to peak flow

| Catchment Number | Catchment Area A(km²) | Concentration time Tc(hr) | Flow hydrograph with 50-year recurrence period (cms) | Reference rainfall station |
|------------------|------------------------|---------------------------|---------------------------------------------------|---------------------------|
| 1                | 61.65                  | 1.36                      | 1387.9                                            | Meishan (2)               |

2. Hydrophysical analysis

The main purpose of hydrophysical analysis is to examine the water passing capacities of channels, as well as their river-crossing facilities, and to provide reference for reviewing flood causes, design improvements, and analyzing flood losses. The general mountain floods, debris flows, and bridge sections are calculated, respectively, and the flood discharging capacities are reviewed. Limited by the abutments on both sides, bridge sections usually have less width and clearance height than other river sections, and thus, become bottleneck sections for rivers to discharge floods and convey sand. Insufficient bridge sections will affect the normal discharge of mountain floods and debris flows,
which cause dangerous situations, such as silting and flooding, thus, it is necessary to calculate the flood discharging capacities of bridge sections on rivers.

The hydrophysical parameters of general streams are calculated based on the results of the general Peak flow, thus, in consideration of the sand-bearing flow, the existing bottleneck sections shall be calculated based on the Manning Formula to review their flood discharging capacities.

The Manning Formula is widely used to determine drainage slopes for water, soil conservation, and river regulation works, as follows:

\[ Q = A \times V \]

\[ V = \frac{R^{2/3} \times S^{1/2}}{n} \]

where:

- \( Q \): Flood drainage quantity
- \( A \): Flood drainage section
- \( V \): Velocity
- \( n \): Roughness coefficient
- \( R \): Wetted perimeter (\( R = A/P \), \( P \): perimeter)
- \( S \): Slope (%)

As shown in the design of the sabo dam for the second stage of the upstream earthwork project of Fuxing Bridge on Lacus Creek and the stress calculation table, the calculation is recorded, as follows: the catchment area is 6165 ha., runoff coefficient is 0.75, time of concentration is 56.20 min, rainfall intensity of the 50-year recurrence period is 112.32 mm/hr, flood discharge is 1442.67 cms, and overflow water depth is 3.55 m. In other words, the above data are based on the results of the hydrological analysis presented in the budget. However, from June 1 to June 4, 2017, it rained for four consecutive days, and the rainfall data of the nearby Meishan rainfall station are shown in Table 4; while the accumulated precipitation on June 2 and June 3 was quite heavy, the instantaneous rainfall did not reach the hourly precipitation of hundreds of millimeters as planned and designed.

| Time(hr) | Date       | 6/1 | 6/2 | 6/3 | 6/4 |
|----------|------------|-----|-----|-----|-----|
| 1        | 7          | 28.5| 6   |
| 2        | 10         | 39.5| 2.5 |
| 3        | 9          | 28  | 14.5|
| 4        | 11.5       | 16  | 17.5|
| 5        | 39.5       | 17.5| 19  |
| 6        | 13.5       | 9.5 | 28.5|
| 7        | 8.5        | 19  | 28  |
| 8        | 12.5       | 14.5| 3   |
| 9        | 0.5        | 12  | 20.5| 5   |
| 10       | 1          | 21.5| 26.5| 0.5 |
| 11       | 4.5        | 23.5| 6   | 5.5 |
| 12       | 3.5        | 44.5| 12.5| 5   |
| 13       | 0.5        | 25  | 29  | 2.5 |
| 14       | 32.5       | 39.5| 3   |
| 15       | 10         | 39.5| 58.5|
| 16       | 6          | 80.5| 52.5| 0.5 |
| 17       | 15         | 42.5| 13.5| 2   |
| 18       | 7.5        | 30.5| 25.5| 1   |
| 19       | 8          | 18.5| 16.5| 0.5 |
| 20       | 22.5       | 10.5| 20.5|
| 21       | 18.5       | 18.5| 15.5|
The maximum hourly rainfall was 80.5 mm/hr, which is not larger than 12.32 mm/hr of the 50-year recurrence period as originally designed, thus, single rainfall analysis was adopted. For any situation similar to the consecutive-multi-day rainfall analysis of this time, the data of the non-dimensional rainfall formula in planning and design are compared with those of the Meishan rainfall station, and the results are shown in Table 5. Among them, 1hr equals to 60 min, 24hr equals to 1440 min, 48 hr equals to 2880 min, and 72hr equals to 4320 min, and the analysis results show that this plum rain frontal rainfall continued for more than 72 hours in terms of rainfall duration or time of concentration (it is more reasonable to adopt this method for analysis and review). Statistically, the accumulated precipitation of a 100-year recurrence period is 1051 mm, and the precipitation amount greatly exceeds this standard for the above first 3 days or last 3 days. The accumulated precipitation of a 500-year recurrence period is 1244 mm, and the precipitation amount often exceeds this standard for the above first 3 days or last 3 days. In hydrological statistical analysis, higher values are not used to make more explorations after the standards of 100 years’ recurrence period are calculated; therefore, based on the analysis results in this research, the precipitations in 24hr (1 day), 48hr (2 days), or 72hr (3 days) exceed the standards of the 100-year recurrence period.

Table 5. Hydrological statistical analysis of the rain at the plum rain front from Meishan Station from June 1 to June 4, 2017.

| P     | 2837 | Meishan Station | Rainfall duration or time of concentration |
|-------|------|-----------------|------------------------------------------|
| A     | 16.92924278 | 1hr | 24hr | 48hr | 72hr |
| B     | 55   | 25              | x 6/2and6/3                               |
| C     | 0.577895571 | 50  | x 6/3 | 6/2-3and6/3-4 | 6/1-3and6/2-4 |
| G     | 0.552686909 | 100 | x 6/3 |
| H     | 0.304240995 | 200 | x 6/3 |
| I     | 94.41655751  | 6/1-3and6/2-4 |

Remark: x means not reach

The block font represent that actual rainfall exceeds the calculated value
The red font represent that actual rainfall close the calculated value

| I50/1440 | 22.8777013 | 549.064831 |
| I50/2880 | 15.49202196 | 743.617054 |
| I50/4320 | 12.3003757 | 855.627051 |
| I50/60   | 11.01620798 | 715.629426 |
| I50/56.2 | 112.3221447 | mm/hr |
| I100/56.2 | 121.9400015 | mm/hr |
| I100/60  | 119.549758  | 1566.16689 |
| I100/1440| 27.16251665 | 1689.69624 |
| I100/2880 | 18.39355707 | 882.890739 |
| I100/4320| 19.2211482 | 952.527582 |
| I100/60  | 19.84432462 | 1022.16442 |
| I100/1440| 30.58515248 | 733.395659 |
| I100/2880 | 20.69296924 | 993.265254 |
| I100/4320| 16.4293057 | 1182.9478 |
| I130/60  | 129.027872  | 134.545762 |
| I130/1440| 31.447332   | 754.735968 |
| I130/2880 | 21.29509218 | 1022.16442 |
| I130/4320| 16.90790492 | 1217.36915 |
3. Flow analysis

As the planning and design are carried out according to the technical specifications of soil and water conservation, the Peak flow is only evaluated based on rainfalls with the concentration time of the 50-year recurrence period, while less estimations and evaluations are made on flow hydrograph for frontal rainfalls with long duration. Hence, in this research, the model is particularly established based on the triangle hydrograph of the hourly precipitation unit by combining the 4-minute difference between the time of concentration and the hourly precipitation unit, as shown in Figure 10. Furthermore, the rainfall of Meishan Station is used for analysis, which is then compared with the data, such as the Peak flow of 1443cms of the 50-year recurrence period, the Peak flow of 1566cms of the 100-year recurrence period, and with the time of concentration of 56.2 minutes.

In this research, the calculated unit flows are arranged and superimposed to become a hydrograph, as drawn in Figure 11. The superimposed flow hydrograph clearly shows that the flow is greater than 1400cms at about 2000 minutes after the beginning of the rain and the highest hourly precipitation. By comparing the hourly precipitation and hydrograph data, the precipitation at 16:00 on June 2, 2017 was the highest of the plum rain front, with the maximum Peak flow of about 1680cms. Based on the results of the Peak flow calculation minutes between 1933 and 2020, there are 88 minutes (about 1.5 hours) of flood in the period, which is more than the 50-year recurrence volume. Additionally, based on the results of the Peak flow calculation minutes between 1944 and 1974, there are 31 minutes (about half an hour) of flood in the period, which is more than the 100-year recurrence volume.

The above analysis shows that the runoff coefficient of Lacus Creek cannot maintain 0.75 in the case of prolonged rainfalls, and so much precipitation and Peak flow are enough to move a large amount of sediments. However, according to the general conservative estimation, this research shows that the Peak flow generated under the influence of the plum rain front in this area has exceeded the design standards previously stipulated by the technical specifications of soil and water conservation, and the precipitation and Peak flow has reached the situations of the 100-year or even the 200-year recurrence period. The abovementioned is the problem in the current law, theory, and practice, and the destruction scene shows that this analysis result is possible.
3.2. Exploration of terrain and water impact
In this research, the correlation between the site terrain and the upstream and downstream areas is additionally investigated by aerial shots. As shown in Figure 12 and Figure 13, the sabo dam is located at the straight line between the two curve sections, and functions as sediment blocking and centerline adjustment. Overall, the construction location meets the principle of the technical specifications of soil and water conservation (built on the straight line as stipulated by the specifications). This plum rain front was under the accompanied effect of southwesterly flow with large precipitation and prolonged duration, and this peak also brought a lot of sediments to hit the sabo dam. After the event, the bed showed that there was an s-shaped stratum appeared upstream, which diverted the water to the right bank (the left side of the sabo dam) and reduced the water passing section before hitting the dam (its destructive power doubles). Such impacts also caused many consolidation works in the upstream area to be scoured, damaged and destroyed, and the slit dam worn. While the works of the sabo dam were low-rise structures, they still could not withstand the impact of severe floods, and thus, were damaged. Therefore, based on the above data, it is concluded that the sabo dam on the first slope was seriously damaged by the peak of more than the 100-year recurrence period on June 2 (it should not be lost completely; otherwise, the dam will be completely lost). Affected by the subsequent and continuous floods, the damage scale was continuously increased and created the remaining state.
Figure 12. Damage the upstream of Sabo Dam to produce S-shaped flood front current and compress the water flow section.

Figure 13. The siltation situation of the upstream Comb Dam was judged during this period, and the two wings may be completely submerged and gradually exposed afterwards.

Furthermore, the failure of the right bank ruined the upstream area of the sabo dam, which was also one of the causes for the channel compression and centerline deviation, parts of the sabo dam were impacted by sediments and floods, and the impacts on the right wing at that time can be inferred from the water flow, as shown in Figure 12. Additionally, Figure 13 shows that a large amount of sediments (debris flow) moved down to the cut (opening) in the middle of the sabo dam, thus, it was possible for
the rear of the dam, which was originally empty (the rear of the silt dam was not fully filled), to be
impacted by the instantaneous deviation and downward movement of a large amount of sediments.

In addition, it was learned from the project sponsor and the planning and design unit that the sabo
dam in this area was not excavated to the laccolith for establishment (there is laccolith on the two
wings, but with thick accumulative formation). The purpose of this research is to explore whether it is
possible that the stable foundation was impacted by the flow caused by the centerline deviation.
Unfortunately, the subsequent water expanded the disaster, and left limited evidence of the damages;
however, it can be observed from the aerial shot, as shown in Figure 12, that the cut (opening) in the
middle was scoured the deepest. After the disaster, the water flowed out vertically from the right wing
to the middle, and the downstream surface was seriously scoured, which may have been unexpected
during planning and design due to the original consideration of the good environment and ecological
path (as shown in Figure 14). In recent years, there have been a lot of controversial designs produced
regarding the downstream surface, which was seriously scoured due to the transverse structures with
single cuts (openings).

3.3. Core-drilling test of concrete
Concrete core sampling was conducted on site, and two samples were selected from the left of the
sabo dam and sent to Dazhong Inspection Technology Co., Ltd. for certified testing by TAF. The
sampling test photos, the test results extracted from the compression test reports, and the concrete
strength of the dam are shown, as follows. Referring to the requirements of design strength in the
completion drawing: “350kg/cm² concrete shall used for 1m below the spillway and 210kg/cm²
concrete for the remaining”, thus, the dam meets the existing requirements of research and
construction in this test.

| Specimen NO | Specimen Size (cm) | Diamet er (cm) | Maximum load(kgf) | Compressi on area (cm²) | Length to diameter ratio | Coefficient of correction | Strength Kgf/cm² | Fractur e morphology |
|-------------|-------------------|--------------|------------------|------------------------|------------------------|-------------------------|-----------------|------------------|
| 1-1         | 28.15             | 15.11        | 15.07            | 10.00                  | 23846                  | 78.54                   | 1.51            | 0.96             | 291              | 28.5             | A               |
| 1-2         | 27.65             | 14.82        | 15.09            | 9.98                   | 25051                  | 78.23                   | 1.51            | 0.96             | 307              | 30.1             | A               |
| 1-3         | 26.70             | 15.14        | 15.36            | 9.99                   | 25727                  | 78.38                   | 1.54            | 0.96             | 315              | 30.9             | A               |
| 2-1         | 26.75             | 14.98        | 15.28            | 9.99                   | 20452                  | 78.38                   | 1.53            | 0.96             | 250              | 24.5             | A               |
| 2-2         | 25.80             | 15.03        | 15.03            | 10.00                  | 18685                  | 78.54                   | 1.50            | 0.96             | 228              | 22.4             | A               |
| 2-3         | 27.15             | 15.41        | 15.26            | 10.01                  | 20314                  | 78.70                   | 1.52            | 0.96             | 248              | 24.3             | A               |
3.4. Review and research

The sabo dam in the upstream area of the Fuxing Bridge in Lacus Creek is a dam with a single cut (opening) for “the second stage of the upstream earthwork project of Fuxing Bridge in Lacus Creek”. After supervision, sectional inspection, and completion acceptance, no major defects were found to be improved in the sabo dam, thus, there is no problem in construction. Moreover, according to testing, the design strength of the drilled cores meet the requirements that “350kg/cm² concrete shall used for 1m below the spillway and 210kg/cm² concrete for the remaining”, thus, the dam meets the existing requirements of research and construction in this test. The dam body with in-situ sandstone material backfill in the middle was not the main cause of the damage; however, when the gap appeared, the backfill materials, as affected by the subsequent water, expanded the disaster, showing a failure up to 60 meters.

The sabo dam is located at the straight line between the two curve sections, which functions as sediment blocking and centerline adjustment. Overall, the construction location meets the principle of the technical specifications of soil and water conservation. However, after the event, there was an s-shaped stratum appeared upstream, which diverted the water to the right bank (the left side of the sabo dam) and reduced the water passing section before hitting the dam, thus, the doubled destructive force was probably one of the causes of the initial damage.

This plum rain front had large precipitation and prolonged duration, thus, a large amount of mud and sand was produced in the catchment, which also brought a lot of sediments to hit the sabo dam. According to the hydrology and hydrograph, it is estimated that both the precipitation and flood reached above the 100-year recurrence period, which was unexpected during the design stage, as it used the single rainfall method.

Such impacts also caused many consolidation works of the construction units in the upstream area to be scoured, damaged and destroyed, and the slit dam worn. While the works of this sabo dam are
low-rise structures, they still could not withstand the impact of severe floods, and were damaged.

4. Conclusion

Through the above comprehensive analysis and evaluation, it can be seen that the sabo dam of the second stage of the upstream earthwork project of Fuxing Bridge in Lacus Creek was damaged by natural disasters. In particular, the floods of a 100-year recurrence period, debris flows, and impacts of terrain compression and deviation were unexpected in the design, which used the single rainfall method.

If the overflow mode with a single opening export is added, the scouring energy will be concentrated, and the additive effect is more likely to cause the foundation of the sabo dam to lose bare space, which will eventually damage the sabo dam. Therefore, it is recommended that when designing these torrent transverse structures in the future, try to avoid using the single narrow opening method. It is better to increase the number of opening exports (like a slit dam), expand the size of a single opening export, or adopt a fully enclosed dam design.

In this paper, no review and analysis was conducted on the impacts of debris flows on the flanks of the sabo dam, which was mainly because the failure in the initial stage cannot be effectively controlled with only a small amount of available evidence on site. It is recommended that this shall be discussed further in the future.

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