Study on Characteristics and Prediction of Bank Collapse Caused by Water Conservancy Projects in Shanxi Province

Shuxing Li*, Fei Song and Gengshuo Tian
School of Geological Engineering and Surveying, Chang'an University, Xi'an, China

*Corresponding author e-mail: 2018126094@chd.edu.cn

Abstract. Bank collapse is a common engineering geological problem during the operation of water conservancy and hydropower projects. Due to different regional geological environment conditions, types and characteristics of bank collapses are various. Based on the field investigation of water conservancy projects in Shanxi Province, according to the different regional and geological environment conditions, the bank collapse caused by the water conservancy project in Shaanxi Province is divided into abrasion-induced bank collapse, erosion-induced slipping bank collapse, erosion-induced falling bank collapse and storage-induced slipping bank collapse. This paper described basic characteristics of four typical bank collapses separately, and summarized regional distribution characteristics of the four typical bank collapses; Through field investigation, we obtained the water stable slope angle, underwater stable slope angle and wave strike belt slope angle of various types of reservoir collapse banks, and used the graphical method to predict the width and development trend of different types of bank collapse and analyzed the impact of bank collapse scope and degree of influence.

Keywords: Shanxi Province; Hydraulic Engineering; Typical Bank Collapse; Type; Characteristic; Prediction

1. Introduction
Water conservancy and hydropower construction projects are mostly located in the complex geological environment and have long-term hydrophilic characteristics. After the reservoir impoundment, the change of hydrogeological conditions in the reservoir area will inevitably cause some engineering geological problems. Among these engineering geological problems, reservoir bank collapse is the most obvious one [1]. The bank collapse of the reservoir to a certain extent will bring great harm to the social and economic development of the reservoir area and the safety of people's lives and property. First of all, the most direct harm is that a large number of soil collapse and storage will result in siltation, reducing the effective storage capacity of the reservoir. As the sanmenxia reservoir, field measurements, the length of the bank collapse occurred east of tongguan accounted for 41% of the reservoir shoreline length, the width of each fall generally 3 to 5 m, so much can reach 60 m, stage, the accumulative width of bank collapse are generally 50-100 - m, KuanZhe amounted to hundreds of meters, spi somewhere, the total width of bank collapse more than 1500 m from...
September 1960 to December 1961, bank collapse of the earthwork volume of 177 million m$^3$ after, 250 million tons, accounting for the same period the reservoir sediment deposition (1.53 billion tons) of 16.3%, occupy 1.8% of the usable capacity [2]. Secondly, the normal operation of important engineering facilities and hydraulic buildings within the reservoir area will also be affected, such as silting and plugging the intake of diversion works. Thirdly, due to the bank collapse of the reservoir, the bank line is constantly receding, resulting in casualties on both sides of the bank, farmland destroyed, traffic facilities damaged, and other major hazards to the lives of residents in surrounding towns and cities [3]. In addition to the above hazards, other geological disasters caused by reservoir bank collapse can be found everywhere at home and abroad.

Shaanxi province spans the Two major basins of the Yellow River and the Yangtze River, with great difference in geographical features between the north and the south. In recent years, with the increase of the national western development strategy and water conservancy investment, Shaanxi province is now at the peak of water conservancy and hydropower construction. After the completion of water conservancy and hydropower projects, the geological environment in the reservoir area will be disturbed in the late operation process, resulting in different degrees of bank collapse. In shaanxi province water conservancy engineering characteristics of bank collapse and prediction research, can be under the threat of water conservancy engineering geology disaster areas formulate emergency measures, and in order to ensure the security of lives and property to provide important technical support, at the same time can also to evaluate the possibility of secondary disasters of water conservancy projects and provide basis for loss, has a certain theoretical guidance and reference value.

2. Types and characteristic of bank collapse in Water conservancy projects in Shaanxi Province

On the basis of a lot of field geological survey and exploration, according to the form of bank collapse and the causes of bank collapse, the bank collapse of water conservancy projects in Shaanxi province can be divided into four types: abrasion-induced bank collapse, erosion-induced slipping bank collapse, erosion-induced falling bank collapse and storage-induced slipping bank collapse.

2.1. Abrasion-induced bank collapse characteristics

The abrasion-induced bank collapse is mainly manifested as the gradual erosion and erosion of loose deposits on the bank slope of the bank under the long-term action of reservoir water, surface water, wind and wind scouring and other external forces. Part of the bank collapse material is carried away by shore flow and the other part is accumulated under water, thus making the bank slope slowly receding. This kind of bank collapse is mainly distributed in Jingbian block in Yulin of Northern Shaanxi, and the Wanggedu Blocking reservoir and Jinjisha reservoir in northern Shaanxi are more typical.

Wanggedu Blocking Reservoir project is located in the middle reaches of Wuding River, a first tributary on the right bank of the Yellow River. The backwater of the reservoir is about 13km long and the surrounding bank of the reservoir is about 50km long. In the reservoir area, the Wuding River reaches the east-west direction, with the valley cutting depth of 70~80m and width of 400~1000m. The mountains on both sides of the reservoir are thick and the topographic height difference is about 50~100m. The reservoir bank is mainly sandy slope, the natural slope of the right bank is about 26~50°, and the left bank is about 30~37°. The right bank gully is developed, the bank slope is cut and broken, and the first and second echelons are developed sporadic. The step surface is relatively narrow and slightly inclined to the downstream and the river, with a width of about 100~500m. The left bank slope is relatively intact.

The field investigation shows that the Banks of Wanggedu Reservoir are mostly alluvial Banks, mainly distributed on the left bank of Wuding River. The natural slope is 30°~37° and the slope height is generally 50~70m. The upper part is covered with quaternary Holocene slope deposit (Q$^{4th}$) or quaternary Holocene aeolian fine sand with loose structure and thickness of 0.5~2.0m. The lower part is alluvial (Q$^{3al+1}$) fine sand loam with medium densification and large distribution thickness, which is
the main formation forming the bank collapse of reservoir. A typical cross-section is shown in Figure 1.

![Figure 1](image-url)  
**Figure 1.** Typical section of collapsed bank on the right bank of the Wanggedu Reservoir

### 2.2 Characteristics of erosion-induced slipping bank collapse

The main manifestation of the erosion-induced slipping bank collapse type is that the rock mass of the slope is not conducive to the development of stable joint fractures. Under the action of external forces such as wind wave scouring and reservoir water, wave erosion holes are formed at the foot of the slope, and the soil mass loses its balance and collapses along the joint fracture surface. Such bank collapses are mainly distributed in the Weibei and Weinan plateau and the steep slopes of Weihe Plain in the Guanzhong Basin, with Fengjiashan reservoir and Sanyuan Xijiao Reservoir as typical examples.

Wang Yao reservoir is located in yan'an (apricot river within the territory of the middle section, reservoir area belongs to typical loess Liang Mao terrain landform, the loess ravine geomorphologic, reservoir area (apricot) river valley is asymmetrical type "U" valley, cross-strait development dendritic symmetric distribution of the larger branch lander, the reservoir bank slope due to the collapse of 45~60°, more steep terrain, and slower in the left bank, on the right bank are relatively steep, water storage for many years, on both sides of bank collapse is relatively serious, local area boundary markers have been collapsed into the Treasury.

According to the field investigation, the bank collapse is still occurring. The typical bank collapse surface is relatively steep, and the upper part falls directly along the loess crack or the steep slope at the back edge. Generally, the back edge of the stable bank slope is a scarp belt, which is generally 3 ~ 5m high and the Angle of the scarp is generally 80~85°. A typical cross-section is shown in Figure 2.
2.3. Characteristics of erosion-induced falling bank collapse

The main manifestation of the erosion-induced falling bank collapse type is that the rock mass of the slope is not conducive to the development of stable joint fractures. Under the action of external forces such as wind wave scouring and reservoir water, wave erosion holes are formed at the foot of the slope, and the soil mass loses its balance and collapses along the joint fracture surface. Such bank collapses are mainly distributed in the Weibei and Weinan plateau and the steep slopes of Weihe Plain in the Guanzhong Basin, with Fengjiashan reservoir and Sanyuan Xijiao Reservoir as typical examples.

Fengjiashan Reservoir area flows through Qianyang County, Fengxiang County and Chencang District, and the backwater length of the reservoir area is about 10km. Close to the dam section, the bedrock is exposed, the amount of bank collapse is relatively small, mainly in the middle jiankou River ~ Baishi River section. Water storage for many years, the bank collapse is more serious, local reservoir area boundary piles have collapsed storage.

According to the field investigation, the typical bank collapse surface is relatively steep, and the part is nearly steep. The wave erosion slope Angle at the lower reservoir water level change is 15~20°. The upper part of the bank directly collapses along the loess cracks or the steep slope at the back edge, and the current bank slope is erosion - accumulation bank slope. A typical cross-section is shown in Figure 3.
2.4. Characteristic of storage-induced slipping bank collapse

Under the influence of reservoir water level rise, rainfall and other factors, the loose deposits along the reservoir bank slide along the soft structural surface or the contact between soil and rock. This kind of bank collapse is mainly distributed in the steep loose accumulation areas in the mountains of southern Shaanxi and the south bank of Weihe River. The bank collapse of Heihuya reservoir and Heihe reservoir are typical examples.

The geomorphic unit in the area affected by the bank collapse of Heihuya in Sanhekou river is soil slope with natural slope Angle of 32 ~ 36°. The surface layer is the mountain excavated and abandoned slag from the Western Han Dynasty expressway, and the quaternary Holocene artificially accumulated crushed stone soil, with a general thickness of 5 ~ 12m. In the middle part, the quaternary Holocene colluvial silty clay with block stone is 2-9.5m thick. The lower part is bedrock and the bed is stable. Among them, the bank slope is relatively slow in the middle part, which is the accumulation platform. The natural slope Angle is 5 ~ 14°, the distribution elevation is 634 ~ 640m, the height difference is 6m, and the outcrop width is 25 ~ 35m.

Under the influence of long-term rainfall, several local collapses have occurred in the periphery of the observation deck, generally on a small scale. At the same time, a tensile crack with a length of more than 30 meters, width of 1 ~ 3cm and depth of 2 ~ 5m has been generated in the middle of the observation deck. From the current situation, the front slope of this section is the abandoned slag (fill) excavated from the Western Han Highway. The lithology is gravel soil with a thickness of 2 ~ 9.5m and a loose structure. When rain water infiltrates into the upper part of the gravel soil, uneven settlement, resulting in upper tensile cracks. Under the scouring action of reservoir water after impoundment, the lower slope foot was damaged, and the upper slope was further collapsed. A typical cross-section is shown in Figure 4.
3. Graphical bank collapse prediction

On the basis of field investigation, the graphical method is used to predict the typical bank collapse width. For reservoir bank collapse, the role of the wave is the main, bank collapse after the bank slope can be divided into shallow edge slope (I), piling shallow shoals (II), erosion (III), climbing belt (IV) and water bank slope belt (V), and other five sections, as shown in figure 5.

![Graphical prediction section](image)

The specific prediction steps are as follows:
1. To draw the terrain and geological section of the predicted site;
2. Mark the highest and lowest water levels of the reservoir under normal conditions;
3. Mark the wave climbing height line from the highest water level upwards, and the climbing height \(h_b\) is taken as a wave height;
4. From the lowest water level down, mark the wave influence depth line, the influence depth \(h_p\) is \(1/3\text{–}1/4\) wave wavelength, cohesive soil should be larger, sandy soil is smaller;
5) Wave influence depth line selection point a, which is located in the stack up, shallow belt (Ⅱ) and shallow edge of the steep slope zone (Ⅰ) turning point, the selection of which should make Ka accumulation coefficient to the expected value;

6) From point a downward, draw the outer edge steep slope line according to the lithology of the shoal deposits to make it intersect with the original slope line, and its stable slope is $\beta_1$. Methods of $\beta_1$ value: $\beta_1$ is less than 8°~12° when the shoal deposits are fine sandy soil and cohesive soil, and less than 18°~20° if the shoal deposits are pebble soil and coarse sandy soil. Draw the slope line of the heaped shallows upward from point a, and The original slope line intersects at Point b; Its stable slope is $\beta_2$. Methods of $\beta_2$ value: The accumulation is 1°~1.5° of fine sand and 3°~5° of coarse sand and gravel.

7) Make the slope line of erosion shoal from Point b, and intersect with the normal highest water level at Point c; Its stable slope $\beta_3$ is determined by the lithology of the bank;

8) The slope line of wave climbing zone is made at point c and intersects with the water level of wave climbing height at point d. Its stable slope Angle $\beta_4$ is determined by lithology and wave climbing height;

9) Draw the surface line de of water ashore slope, $\beta_5$ determined according to the natural slope Angle;

10) Check whether the accumulation coefficient Ka is consistent with the predetermined value. If not, move point a to the right or left and redraw the diagram according to the above steps until it is suitable.

For the rock slope that is easy to be scoured and softened, or the section where all the loose accumulation materials are washed away by waves or onshore flow, the shoal has only abrasion part, and the accumulation rate should be set as zero. In this case, point a should be located on the initial bank slope line.

3.1. Prediction of abrasion-induced bank collapse

**Table 1.** Slope angle survey table for various types of shore slope above water, underwater and wave strike zone

| reservoir name       | rock character | project | uphill angle of water(°) | downhill angle of water(°) | Slope angle of wave strike zone(°) |
|----------------------|----------------|---------|--------------------------|-----------------------------|-----------------------------------|
| Zhongyinpan Reservoir| fine sand      | range value | 30~31                   | 6.5~10                     |
|                      |                | average value | 30                      | 7.5                         |
| Hekou Reservoir      | fine sand      | range value | 31~33                   | 4.3~10.5                    |
|                      |                | average value | 32                      | 8.6                         |
| Hongshixia Reservoir | fine sand      | range value | 31~33                   | 2~5.4                       |
|                      |                | average value | 32.                     | 3.3                         |
| Batuwan Reservoir    | fine sand      | range value | 33                      | 3.5~12                      |
|                      |                | average value | 33                      | 7.4                         |
| Xinqiao Reservoir    | loess          | range value | 40~50                   | 2.8~11.1                    |
|                      |                | average value | 45                      | 5.6                         |
| Zhangjiamao Reservoir| loess          | range value | 40~50                   | 10.5~18.3                   |
|                      |                | average value | 45                      | 16.2                        |
| Zhutoushan Reservoir | loess          | range value | 40~50                   |                              |
|                      |                | average value | 45                      |                              |
According to the investigation results (Table 1) of the current stable slope angles of the same type of bank slope of several reservoirs around Wangge Block reservoir area (Batuwan Reservoir, Xinqiao Reservoir, Zhongyinpan Reservoir, Hongshixia Reservoir, And Zhutou Mountain reservoir), the calculation parameters of bank collapse were determined. The diagrammatic method is used to predict the bank collapse of various types of bank slope: Loess bank slope, stable slope Angle below normal water level is taken as 10°, stable slope Angle above normal water level is taken as 45°, and the predicted width of bank collapse is about 35 ~ 70m; (2) Alluvial bank slope, the stable slope Angle of reservoir bank below dead water level is taken as 16°, and the stable slope Angle of bank slope between dynamic water level and 4° ~ 9° is taken as 5°. The stable slope Angle above the normal water level is 30°, and the width of bank collapse is about 59 ~ 200m. (3) Alluvial bank slope, stable slope Angle below dead water level is taken as 16°, stable slope Angle below dynamic water level is taken as 5°, stable slope Angle above normal water level is taken as 30°, and predicted width of bank collapse is about 58 ~ 130m.

According to the topographical and geological conditions of the bank slope in the reservoir area, bank collapse will be mainly caused by asymptotic failure, and generally there will be no large volume speed sliding, no large surge, and no great impact on the safety of the dam. The Leihui Canal embankment body on the right bank of Wangge Blocking Reservoir area is mainly located within the wave strike zone of the reservoir, and the embankment surface is not built and protected. Under the action of wave strike during the operation of the reservoir, the gully soil embankment may cause bank collapse.

3.2. Prediction of erosion-induced slipping bank collapse
Field investigation was carried out on various slope angles of the stable bank slope within 4km in front of the lower dam of the current storage level of Wangyao Reservoir. The values of various characteristic angles of the bank slope collapse were shown in Table 2. The predicted width of bank collapse after reservoir impoundment is 30 ~ 100m by graphical method, and the widest part is 110.7m.

The width of bank collapse is generally small at the end of the reservoir and large in front of the dam. Some houses in puwanzi, Yangchuan, Yangjiayao, Yangyagen and Lujiachuan sections of Niugou Village on the upper reaches of the main channel xingzi River were affected. Some houses in Chuanwangtai Village, Caotsui Village and Kangmiao Village of tributaries were affected, with a small amount of farmland and orchards affected, and the rest were mostly barren hills. It is suggested that housing, farmland, orchards and other sections of immigration, compensation processing.

### Table 2. Actual measured angle values of bank collapse of Wangyao Reservoir

| Stratigraphic genetic age | rock character | Underwater stable slope angle(°) | shoal abrasion angle(°) | Stable slope angle on water(°) | Steep angle(°) |
|--------------------------|----------------|---------------------------------|------------------------|-------------------------------|---------------|
|                          |                | range value | average value | range value | average value | range value | average value | range value | average value | range value | average value |                      |
| Q₄₉al                    | loam           | 5~15        | 8             | 6~16         | 8             | 50~60       | 57           |                |
| Q₄₉al                    | sand gravel    | 10~20       | 15            | 6~16         | 12            | 60~75       | 65           |                |
| Q₃sol                    | loess          | 5~18        | 12            | 4~16         | 6             | 60~70       | 65           | 80~85         |
| Q₃sol                    | loess          | 6~15        | 12            | 4~16         | 6             | 65~75       | 70           |                |

3.3. Prediction of erosion-induced falling bank collapse
According to the investigation and analogy of reservoir bank collapse in loess Plateau region, the prediction parameters of fengjiashan reservoir bank collapse are shown in Table 3. The bank collapse occurs mainly in the near dam section. According to the prediction, the maximum width of the bank collapse is about 38m, generally 20 ~ 30m.
Table 3. Values of prediction parameters of Fengjiashan Reservoir bank collapse

| formation lithology      | Underwater stability angle(°) | Shoal slope angle(°) | Stable slope angle on water(°) |
|--------------------------|-------------------------------|----------------------|--------------------------------|
| Shape of loess soil      | 24                            | 22                   | 60                             |
| silty clay               | 27                            | 24                   | 55                             |
| silty-fine sand          | 22                            | 18                   | 50                             |

The bank collapse of Fengjiashan reservoir directly affects the surrounding rural land and the highway safety of Jiankou River ~ Baishi River section. The bank collapse of the reservoir in the western suburb has a large amount, which has a great impact on the existing village roads, coastal cemetery, workshops, cultivated land (mainly vegetable fields) and so on. Below the double estuaries on the right bank, the amount of bank collapse is large, which has a great impact on the existing village roads, coastal farmland (vegetable fields and orchards).

3.4. Prediction of storage-induced slipping bank collapse

The suggested values of bank collapse prediction parameters in southern Shaanxi are shown in Table 4. The actual bank collapse of Stone River reservoir and Jin-Pan Reservoir was investigated. The slope Angle of each soil layer was 25° ~ 30° loess, 30° ~ 35° gravel soil and 35° ~ 38° block rock soil, all of which were larger than the conventional understanding. According to the analysis by drawing method, the width of bank collapse was predicted to be different from 20 ~ 50m.

It is predicted that the bank collapse width of Heihuya bank of Sanhekou Reservoir is 49m. The bank collapse of Heihuya has great influence on the viewing platform of the upper Xihan expressway. The bank collapse in Heihe reservoir area may cause the zhoucheng highway above it to be greatly affected.

Table 4. Recommended values of bank collapse prediction parameters in southern Shanxi

| Stratigraphic genetic age | rock character          | near future | permanent |
|--------------------------|-------------------------|-------------|-----------|
|                          | Underwater stable slope angle(°) | Stable slope angle on water(°) | Underwater stable slope angle(°) | Stable slope angle on water(°) |
| Q₄col+dl                 | Silty clay with crushed stone | 20          | 50        | 20        | 40        |
| Q₄s                      | Fragment stone          | 20          | 40        |

4. Conclusion

(1) Based on the field investigation of water conservancy projects in Shaanxi Province, bank collapse caused by water conservancy projects in Shaanxi province is divided into abrasion-induced bank collapse, erosion-induced slipping bank collapse, erosion-induced falling bank collapse and storage-induced slipping bank collapse.

(2) The abrasion-induced bank collapse is mainly distributed in Jingbian block area of Yulin in northern Shaanxi. The erosion-induced slipping bank collapse is mainly distributed in Huangling-Yan’an block. The erosion-induced falling bank collapse is mainly distributed in the Weihe, Weinan tableland and the steep slope area of Weihe Plain in The Guanzhong Basin. The storage-induced slipping bank collapse is mainly distributed in the loose accumulation areas of steep slopes in the mountains of southern Shaanxi and southern Weihe river.

(3) Through on-site field investigation, for each type of the reservoir bank collapse of water stable slope Angle, slope underwater stable slope Angle and breaking Angle, using graphic method and the development trend of various types of reservoir bank collapse in shaanxi province bank collapse width
has made the forecast and prediction results as follows: in the abrasion-induced bank collapse type, the loess slope width of bank collapse is 35~70 m, width of the fluvial bank bank collapse is 59~200 m, width of alluvial bank bank collapse is 58~130 meters; The width of the erosion-induced slipping bank collapse is 30~100 meters. The width of erosion-induced falling bank collapse is 20~30 meters. The width of storage-induced slipping bank collapse is 20~50 meters.

Acknowledgments
This work was financially supported by Shanxi Water Conservancy Science and Technology Project fund.

References:
[1] Zhu H Y, Hu X W. 2007. Research status and evaluation of bank collapse prediction method in mountainous area[J]. Subgrade Engineering, (01): 85~86.
[2] Gao D S, Xi Z P, Wang X C, et al. 1997. Calculation and analysis of bank collapse of Sanmenxia Reservoir[J]. Yellow River, (03): 13~15.
[3] Tang M G.2007. Research of forecast,evaluation and protective measures of bank failure in mountain reservoir——A case of Three Gorges Reservoir[D].Chengdu: Chengdu University of Technology.
[4] Dai Z W, Wei Y J, Hou S P. 2016. Deformation and failure mechanism of Yangjia Well landslide in Three Gorges Reservoir Area[J]. Journal of Engineering Geology, 24(04): 527~534.
[5] Deng H Y.2011. Research on the mechanism of reservoir landslides and the effect of water in the imporment hydropower engineering regions.Chengdu: Southwest Jiaotong University.
[6] Du F, Xu M, Xiao X X, et al. 2018. Physical simulation modeling for stability analysis of reservoir landslide in gently underdip slopes: A case study of Xiangjiaping landslide[J]. Journal of Engineering Geology, 26(3): 694~702.
[7] He L D, Zhu X J. 2007. Retrospection and evaluation of prediction method for reservoir bank ruin[J]. Journal of North China University of Water Resources and Electric Power, 28(02): 69~72.
[8] Jiang Z W, Wang Q Y, Zhang Y. 2008. The bank collapse model of Wangedu Reservoir and its long-term bank collapse prediction[J]. Yellow River, 30(3): 78~79.
[9] Liao Y. 2016. Slope mountain reservoir bank collapse prediction of soil——A case of Longkaikou Reservoir in YunNan[D]. Chongqing: Chongqing Jiaotong University.
[10] Lu G C. 2019.Prediction of bank collapse of loess reservoir in northern Shanxi[J]. Resources Environment & Engineering, 33(03): 392~395+415.
[11] Su Y D,Liu Y. 2014.Review on prediction of reservoir bank collapse[J]. Science & Technology Information, (07): 46~47.
[12] Xu F, Miao D, Luo Y T, et al. 2019.Prediction of Liushutan’s soil bank collapse of the Xiaolangdi reservoir on Yellow River[J]. Journal of Hebei GEO University, 26(03): 694~702.
[13] Zhang X A, LI P. 2018. Preliminary Study on Environment Geological Hazard Due to Water Conservancy Project of Sanyuan Western reservoir[J]. Journal of Catastrophology, 33(3): 123~125.