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Study on the influencing factors and evolution of loess bank collapse with physical modelling

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Abstract

Background Reservoir bank collapse in loess areas may lead to the siltation of reservoir and bank retreat. Therefore, the study of reservoir bank collapse has practical significance. Almost of the bank collapse width prediction method were based on the classical graphical method which do not consider the process of bank collapse. But practice shows that this method can overestimate the width of bank collapse. Meanwhile, there are few studies specifically focused on the collapse of loess bank slopes.

Methods To improve the prediction method of loss bank collapse width, the influence of water depth, dry density and bank slope angle on loess bank collapse was studied by physical modelling. The bank collapse width and the morphology of the bank slope were recorded during the experiment.

Results The bank collapse width increases with the increase of water depth, increases with the increase of slope angle, and decreases with the increase of dry density. The modeling process shows that the loess bank collapse occurs firstly underwater, the erosion niche will be formed underwater, and then the above water slope is damaged. This process is repeated until the underwater accumulation slope reaches the stable state, and then bank collapse stops. After the bank collapse, the above water slope is polyline, while the underwater slope is curved. When the slope angle is less than 27°, the bank collapse will not occur, and when the slope angle is between 27° and 40°, the bank collapse type is abrasion type. When the slope angle is greater than 40°, the bank collapse type is dumping type or shear type. Based on this, the improved balanced alluvial accumulation approach was proposed, which considers the mechanical equilibrium of above water bank slope and the morphology of underwater slope. The new method can reflect the stage characteristics of loess bank collapse, which is more reasonable than the empirical graphical method.

Conclusions The experimental results indicate that when predicting the width of loess bank collapse, it is necessary to combine the bank collapse width and process of bank collapse. The relevant conclusions have a certain role in exploring the mechanism of loess bank collapse and bank collapse prediction methods.

Keywords Loess reservoir, Bank collapse, Physical modelling, Collapse process, Influence factors

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Introduction

After the impoundment of loess reservoir, the hydrodynamic conditions of bank slope will change. The bank collapse not only leads to the retreat of the bank slope, but also causes the siltation in the reservoir. Therefore, the study of reservoir bank collapse has practical significance. Savarenski (1935) first proposed the problem of reservoir bank collapse in 1935, and then many scholars focused on the study of reservoir bank collapse. Kachugin (1949) proposed the first empirical graphical method for bank collapse prediction in 1949, and it has been used ever since. This method selects the stability angle obtained from the field investigation to fit the bank slope profile shape after the bank collapse, and then predicts the bank collapse width. Rochovsky et al. (1954) considered the influence of wave and added a correction coefficient on the basis of the Kachugin method, clarifying the meaning of the stacking coefficient N in the Kachugin method. Zolotalev (1950) divided the reservoir into upstream and downstream parts based on hydrodynamic characteristic, and used the percentage of loss coarse-grained materials as the stacking coefficient. Subsequently, Wang et al. (2000) revised the starting point of bank collapse for the Kachugin method to the historical flood level of the river, and established the two-stage method. Xu et al. (2007) proposed the bank slope structure method considering the geological structure characteristics of the Three Gorges Reservoir area bank slope in south China. Peng (2014) believed that the starting point of bank collapse is not fixed, and the accumulation characteristics after bank collapse should be considered. Based on this concept, the balanced alluvial accumulation approach was proposed. However, all the above methods have their own scope of application, which is mainly due to the applicable conditions and defects of methods (Fan et al. 2002; Peng & Chen 2014; Sun 2013; Tang, Xu, and Huang, 2006; Wang et al. 2000; Zhang et al. 2010). To predict the bank collapse width more accurately, many scholars have studied the bank collapse process and fluid dynamics (Shu et al. 2012; Yao et al. 2011; Yu et al. 2015). But there is little research on the prediction of bank collapse width.

In previous investigations, model experiments were mostly used to simulate specific reservoir bank collapse, and some were also used for sensitivity analysis. Tang and Xu et al. (2008, 2006, 2006, 2007) summarized typical bank collapse modes in the Three Gorges Reservoir, and founded that the prediction parameters of bank collapse are mainly influenced by the soil strength of the bank slope, the content of coarse aggregate, and the hydrodynamic effect of the reservoir. They also provided the importance ranking of different factors through the AHP method. Deng et al. (2017) studied the impact of water level fluctuations on the stability of bank slopes through model experiments, and pointed out that the degradation of bank slope soil caused by water level fluctuations is the mainly reason for the failure of reservoir water level fluctuation zones. Bai (2007) studied the influence of slope gradient, water level and rainfall intensity on bank collapse in the Three Gorges Reservoir by model test. The results show that the sensitivity of bank collapse width to each factor is quite different, and there is a critical point effect. Based on this, a multiple regression method suitable for the prediction of bank collapse in the Three Gorges Reservoir area is established. Based on the model test, Zhang (2010) revised the calculation formula of the saturation line of the bank slope and improved the bank collapse prediction method. Wang et al. (2011) studied the characteristics of bank collapse during initial impoundment and found that the increase of coarse-grained material is beneficial to enhance slope stability, they also founded that bank morphology also has an effect on the bank collapse width. Liu et al. (2016) indicated that the material composition of bank slope had the greatest influence on bank collapse, followed by slope angle, wave height and water level. Wu and Yu (2014) founded that the near-shore flow velocity is positively correlated with bank collapse width and negatively correlated with siltation through bend flume experiments, and indicated that river bank collapse is a recurrent action process of erosion, slip and siltation. Patsinghasanee et al. (2015) simulated the bank collapse process of river cohesive soil bank with the help of numerical simulation technique and compared with the model test, pointing out that the underwater accumulation after the bank collapse is not negligible. Ji et al. (2018) pointed out that slope angle has the greatest effect on bank collapse, followed by soil density, clay content, wave height and water level, and established an empirical multiple regression formula for bank collapse prediction.

In conclusion, whether it is the classical graphical method or model test, most of the studies on bank collapse are on gravelly soil, and mainly focus on prediction of bank collapse with and influence factors of bank collapse. There are relatively few studies on bank collapse of reservoirs converging in loess areas, especially those on the prediction of bank collapse width in combination with the collapse process are basically blank. Based on this, the influence of water depth, slope angle and soil density on bank collapse was investigated by model tests, and the evolution process and stabilization termination conditions of the bank collapse were analyzed. Finally, an improved balanced alluvial accumulation approach was established.

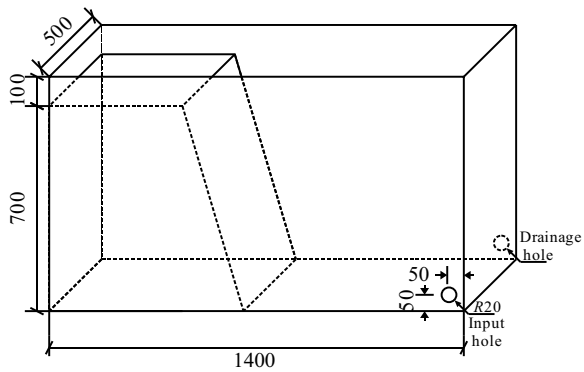

Fig. 1 Three dimensional view of simulation

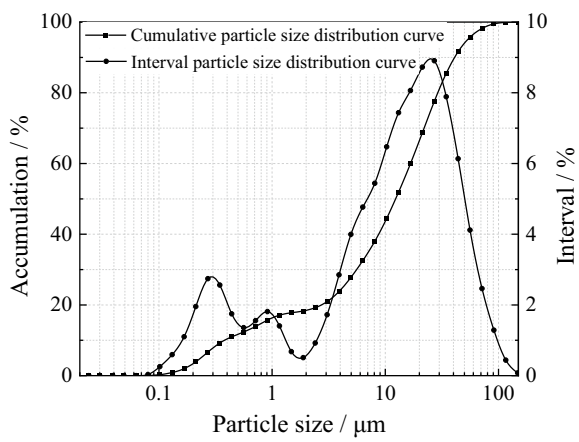

Fig. 2 Grain size distribution curves of the loess

Method and materials

Materials

The reservoir water storage model included a testing flume with a length of 1.4m, width of 0.5m, and height of 0.8m. and two 2.0 cm diameter holes were set symmetrically on both side of the flume for water injection and drainage (Fig. 1). The soil in experiment was taken from the Dabeigou Reservoir in the Weibei Loess Plateau, which the natural density is 1.53g/cm^3, the maximum dry density is 1.70g/cm^3, and optimal moisture content is 16.2%. The particle size distribution is shown in Fig. 2.

Experiment plan

To study the influence of water depth, slope angle and dry density on loess bank collapse, a three-factor, five-level experiment scheme was designed as shown in Table 1.

As shown in Fig. 3, the model test process was divided into sample preparation, model filling and test observation. Among them, the loess for experiment was mixed with water until the moisture content is 16%, and it was sealed and stored for 48h. Then, the loess was compacted layer by layer with layer thickness of 5 cm. Finally, water was injected into the flume to the predetermined height according to the plan. The measurement was performed during the experiment, and the phenomena of bank collapse was described.

Result

The relationship between water depth and bank collapse width

In order to avoid the influence of slope angle on the bank collapse starting point under different water depth (Ji et al. 2018), this condition was tested only for upright

Table 1 Experiment scheme

No	Slope Height *H*/cm	Slope Angle *α*/°	Dry Density ρ_d/g·cm^{-3}	Water Depth *L*/cm	Purpose
A_1	70	90	1.36	15	The relationship between water depth and bank collapse
A_2	70	90	1.36	25	
A_3	70	90	1.36	40	
A_4	70	90	1.36	55	
A_5	70	90	1.36	65	
B_1	70	60	1.28	40	The relationship between dry density and bank collapse
B_2	70	60	1.32	40	
B_3	70	60	1.36	40	
B_4	70	60	1.40	40	
B_5	70	60	1.45	40	
C_1	70	90	1.36	40	The relationship between slope angle and bank collapse
C_2	70	75	1.36	40	
C_3	70	60	1.36	40	
C_4	70	45	1.36	40	
C_5	70	30	1.36	40	

Fig. 3 The process of model test

Table 2 Slope angle under different water level

Water depth / cm	Underwater slope angle /°	Above water slope angle /°	Width of Bank Collapse (BCW) / cm
15	19	67	15
25	16	80	23
40	16	90	35
55	19	90	44
65	19	90	50

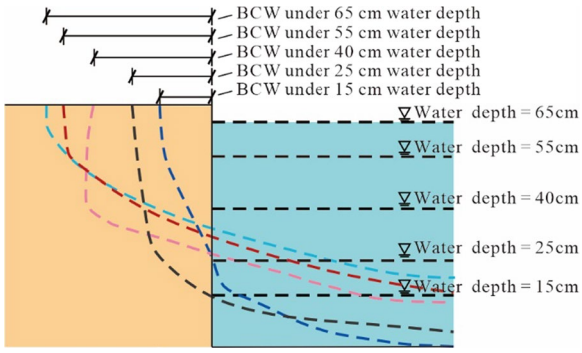

Fig. 4 Final shape of bank collapse under different water depth

bank slopes, and the dry density of the model was controlled at 1.36g/cm^3 in all cases.

The key parameters of bank collapse prediction and bank collapse width under different water depths were shown in Table 2; The bank morphology after bank collapse was shown in Fig. 4; and the relationship between water depth and bank collapse width was shown in Fig. 5.

It can be seen that after bank collapse, the above water slope is folded and the underwater slope is curved (Sun 1958). With the increase of water depth, the above water slope angle increases, while the underwater slope angle fluctuates. Meanwhile, the bank collapse width increases with the increase of water depth, and it is linearly related to the water depth. This result is consistent with the trend of empirical graphical methods (Kachugin 1949; Zolotalev 1950). Due to the influence of water, the collapsed loess will disintegrate and then re-accumulate, so the underwater slope angle is basically the same. The volume of underwater accumulation soil will increase with the increase of water depth, and as the source of underwater accumulation soil, the width of collapsed bank slope above water will also increase accordingly. It

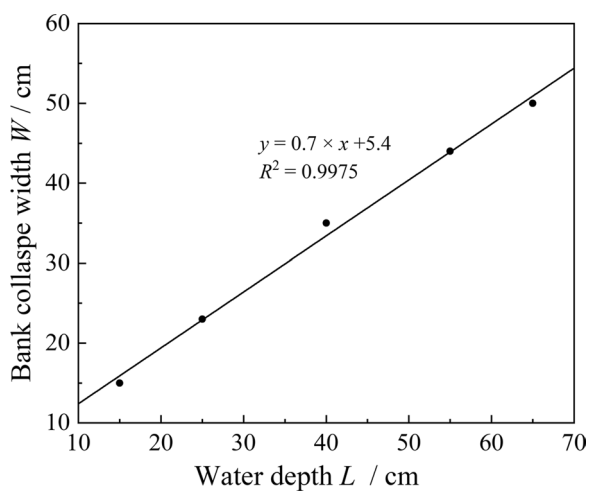

Fig. 5 Relationship between bank collapse width *W* and water depth *L*

Table 3 Slope angle under different dry density

Dry density / (g/cm^3)	Underwater slope angle /°	Above water slope angle /°	Width of Bank Collapse (BCW) / cm
1.28	16	58	40
1.32	16	59	38
1.36	16	67	30
1.40	20	66	29
1.45	21	76	25

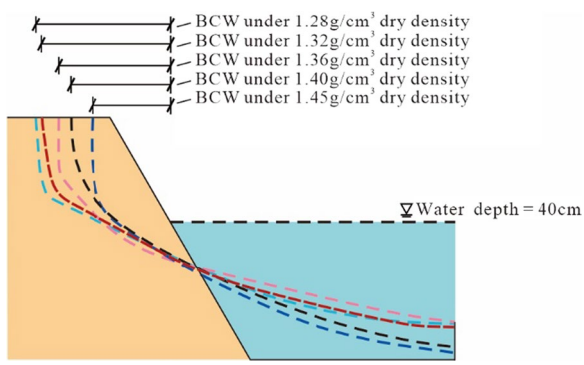

Fig. 6 Final shape of bank collapse under different dry density

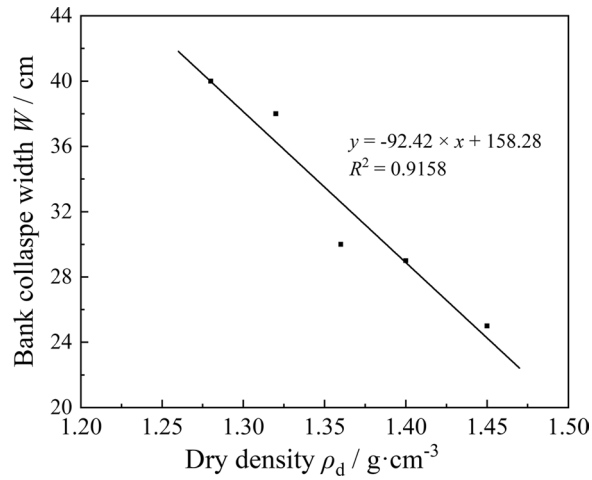

Fig. 7 Relationship between bank collapse width *W* and dry density ρ_d

Table 4 Slope angle under different water level

Slope angle/°	Underwater slope angle /°	Above water slope angle /°	Width of Bank Collapse (BCW) / cm
90	16	90	35
75	16	83	33
60	16	67	30
45	20	57	22
30	26	30	5

is worth pointing out that the starting point of bank slope above water after bank collapse when the water depth is small will move toward the reservoir water side, which indicates the influence of the accumulation part on the bank slope morphology must be considered in the bank collapse prediction, but this is not reflected in the empirical graphical method.

The relationship between dry density of bank soil and bank collapse width

Considering the vertical bank slope is difficult to self-stabilization when the dry density is small, the slope angle of this condition is 60° and the water depth is controlled at 40 cm.

The key parameters of bank collapse prediction and bank collapse width under different dry density were shown in Table 3; The bank morphology after bank collapse was shown in Fig. 6; and the relationship between dry density and bank collapse width was shown in Fig. 7. It can be seen that with the increase of dry density, the above water slope angle and the underwater slope angle increase, while the bank collapse width decrease and it is linearly related to the dry density. In addition, when the dry density of the soil is small, the morphology of the bank slope above water is transformed from linear to polyline. This is due to the fact that strength of soil will decrease with the decrease of dry density, the bank collapse is transformed from toppling failure to slipping failure.

The relationship between slope angle and bank collapse width

The dry density of this condition is controlled at 1.36g/cm^3, and the water depth is controlled at 40cm for experiment.

The key parameters of bank collapse prediction and bank collapse width under different slope angle were shown in Table 4; The bank morphology after bank collapse was shown in Fig. 8; and the relationship between slope angle and bank collapse width was shown in Fig. 9.

$$W = 36.18 - 152.3e^{-0.05286\alpha} \quad (1)$$

With the increase of slope angle, the underwater slope angle decreases and tends to stabilize, and the underwater slope is curved, which can be fitted with an exponential curve, as shown in Eq. (1). And the above water slope angle has no change from before the bank collapse. Since the stability angle of loess is greater than

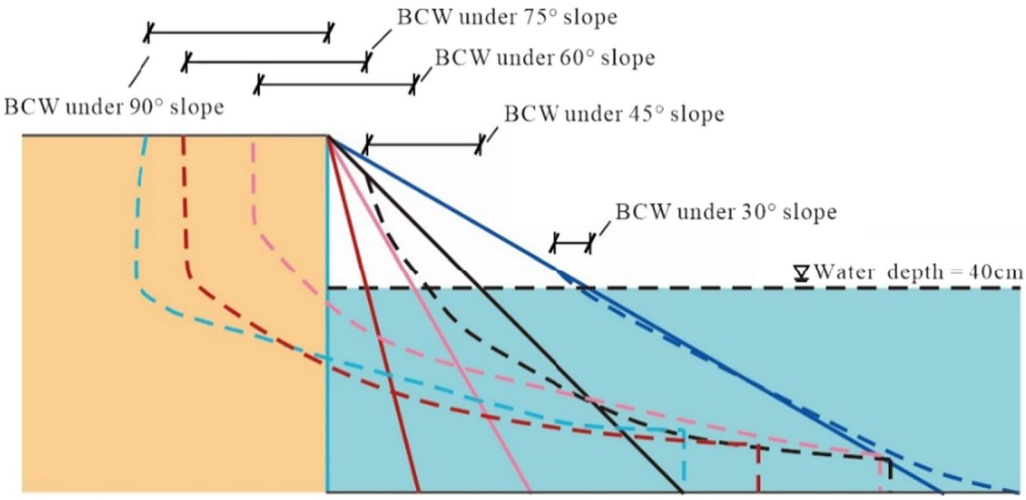

Fig. 8 Final shape of bank collapse under different slope angle

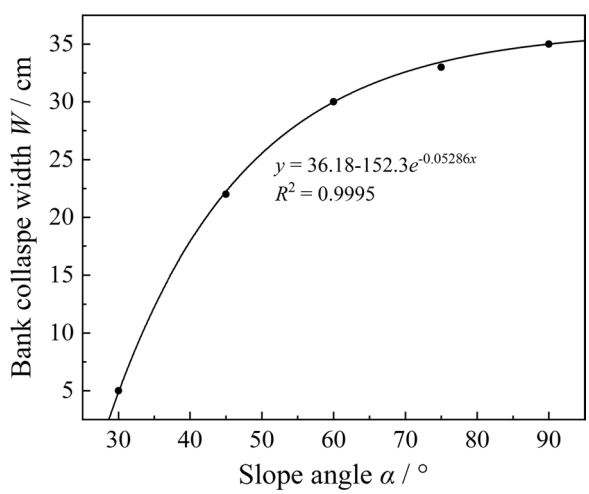

Fig. 9 Relationship between bank collapse width *W* and slope angle *α*

under water deposits, when the slope angle is small, there is no obvious change in the underwater slope and above water slope, which indicates that the reservoir bank collapse is caused by the instability of the underwater bank slope. Meanwhile, with the increase of slope angle, the bank collapse width will increase and is exponentially related to the slope angle, indicating that the damage pattern of loess bank slope changes with the change of bank slope angle (Bai 2007; Ji et al. 2018, 2017).

The trend of the exponential curve will change significantly when the derivative is 1. Therefore, it can be considered that the derivative of 1 is the inflection point of the bank damage model transformation. When the derivative is 1, the bank slope angle is 40°.That is, when the slope angle is greater than 40°, the loess bank collapse pattern is collapsed or slip type, otherwise it is abrasion type.

At the same time, it can be concluded that the self-stabilization angle of underwater loess bank is 27°. When the slope is less than 27° the underwater bank slope is stable, and the water bank slope will not collapse. And the damage mode of 30° bank slope is abrasion type, and its underwater slope angle is 26°, which is very close to the self-stabilization angle of underwater loess bank, which indirectly confirms the correctness of the above conclusion.

It is worth pointing out that the above stability angle is derived on the basis of dry density 1.36g/cm^3, the applicability to other dry density-controlled loess bank slopes still need more investigation.

Evolution of loess bank collapse

From the view of the bank collapse processes, the greater the water depth or the greater the slope angle or the smaller the dry density, the shorter the interval time between the bank collapse and the longer the time required for bank stabilization. Meanwhile, the development of loess bank collapse has a phased characteristic, the bank collapse develops quickly at the beginning, and then slows down and finally stabilizes. The typical process of bank collapse in model tests is shown in Fig. 10.

The process of loess bank collapse can be divided into three parts (Fig. 11):

(1) The surface erosion stage.

In this stage, the soil on the surface of underwater slope is rapidly eroded by the water, and accumulates at the foot of the slope. Due to the collapse of soil, the

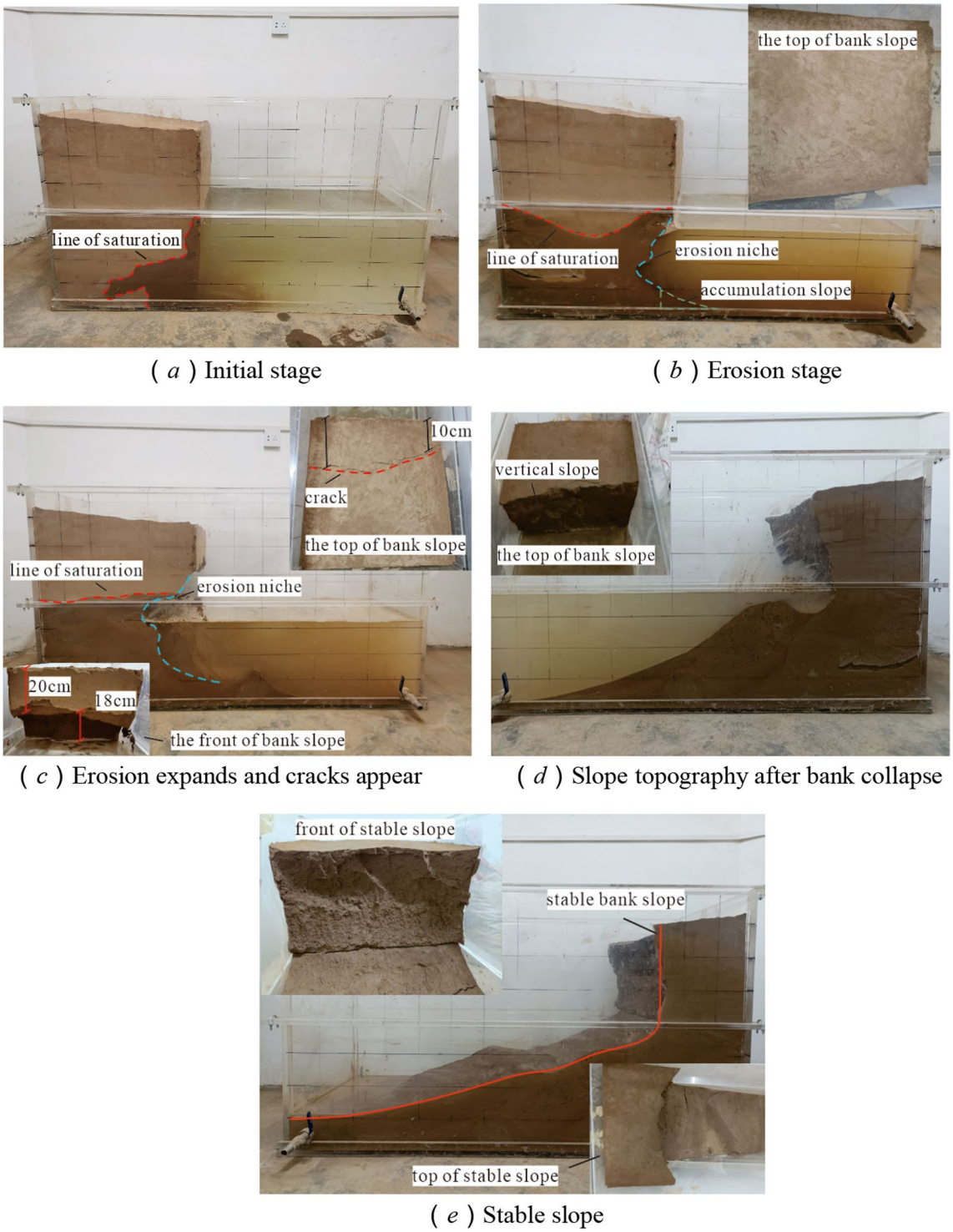

Fig.10 Typical bank collapse process and damage pattern of the bank slope

angle underwater accumulation slope is relatively gentle (Fig. 10a).

(2) The deep excavation stage.

In this stage, the underwater slope is influenced by the water, but due to the strength of soil, the erosion stage of underwater slope become slower than first stage. The disintegration of loess will produce a large number of air

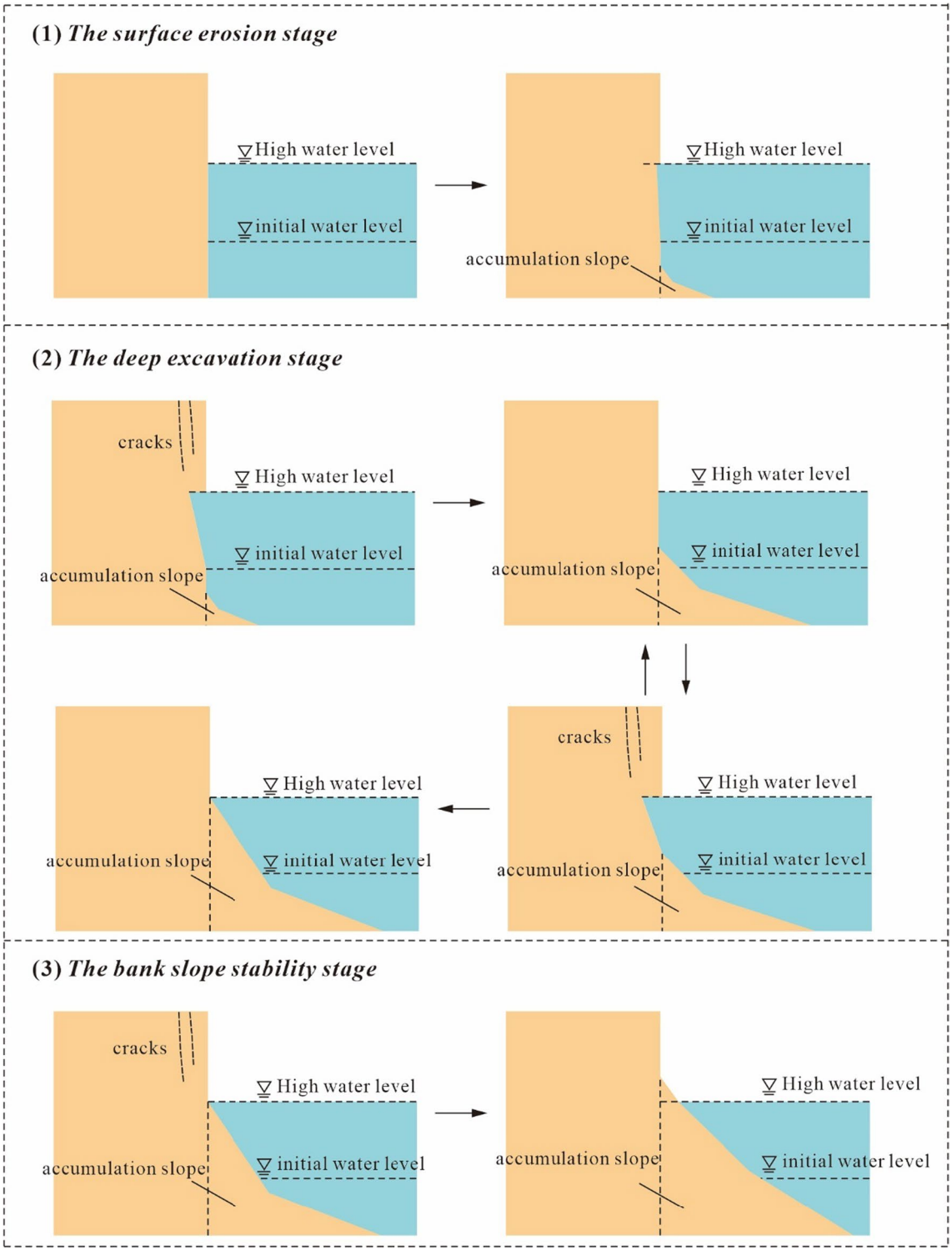

Fig. 11 The failure stages of loess bank collapse

bubbles, which rise along the soil–water interface with a zigzag trajectory and eventually rupture at the air–water interface, thus forming an erosion niche (Fig. 10c). It is worth pointing out that the phenomenon at this stage is recurrent, manifesting as a cycle of erosion, bank collapse and accumulation.

(3) The bank slope stability stage.

In this stage, the underwater bank slope is basically stable, and the bank collapse stops. The slope gradually tends to stabilize without the influence of other factors. At the end of this stage, the underwater accumulation slope is higher than water surface (Fig. 10e).

Prediction model for loess bank collapse

Analysis of critical state stress of above water slope

As previously mentioned, the erosion niche will occur underwater, which may lead to the above water slope to be hollow and collapse. Many scholars have analyzed this bank collapse mode and proposed four modes such as shear failure, cantilever beam failure, dumping failure and tensile failure (Abam 1997; Hu et al. 1996; Patsinghasanee et al. 2015; Wang et al. 2021; Yu et al. 2015) (Fig. 12). Combined with the bank collapse process shown in Figs. 10, 11, it can be seen that the loess bank collapse is dominated by shear failure or dumping failure, as shown in Fig. 12a, d

According to the filed investigation and laboratory test, we can get the slope height H, the cohesion of bank slope soil c, and the tensile strength σ_c. Then, the single bank collaspe withd corresponding to dumping failure or shear failure can be calculated according to Eqs. (2) and (3).

$$\gamma \cdot A_b \cdot l = \sigma_c \cdot \frac{H^2}{2} \tag{2}$$

$$\gamma \cdot A_b = c \cdot H \tag{3}$$

where, γ is the weight of the bank slope loess, kN/m^3; A_b is the area of the pro-void block, m^3; c is the cohesive of the bank slope loess, kPa; σ_c is the tensile strength of the bank slope loess, kPa; H is the length of the height of the above water bank slope, m; l is the force arm of the pro-void block, m.

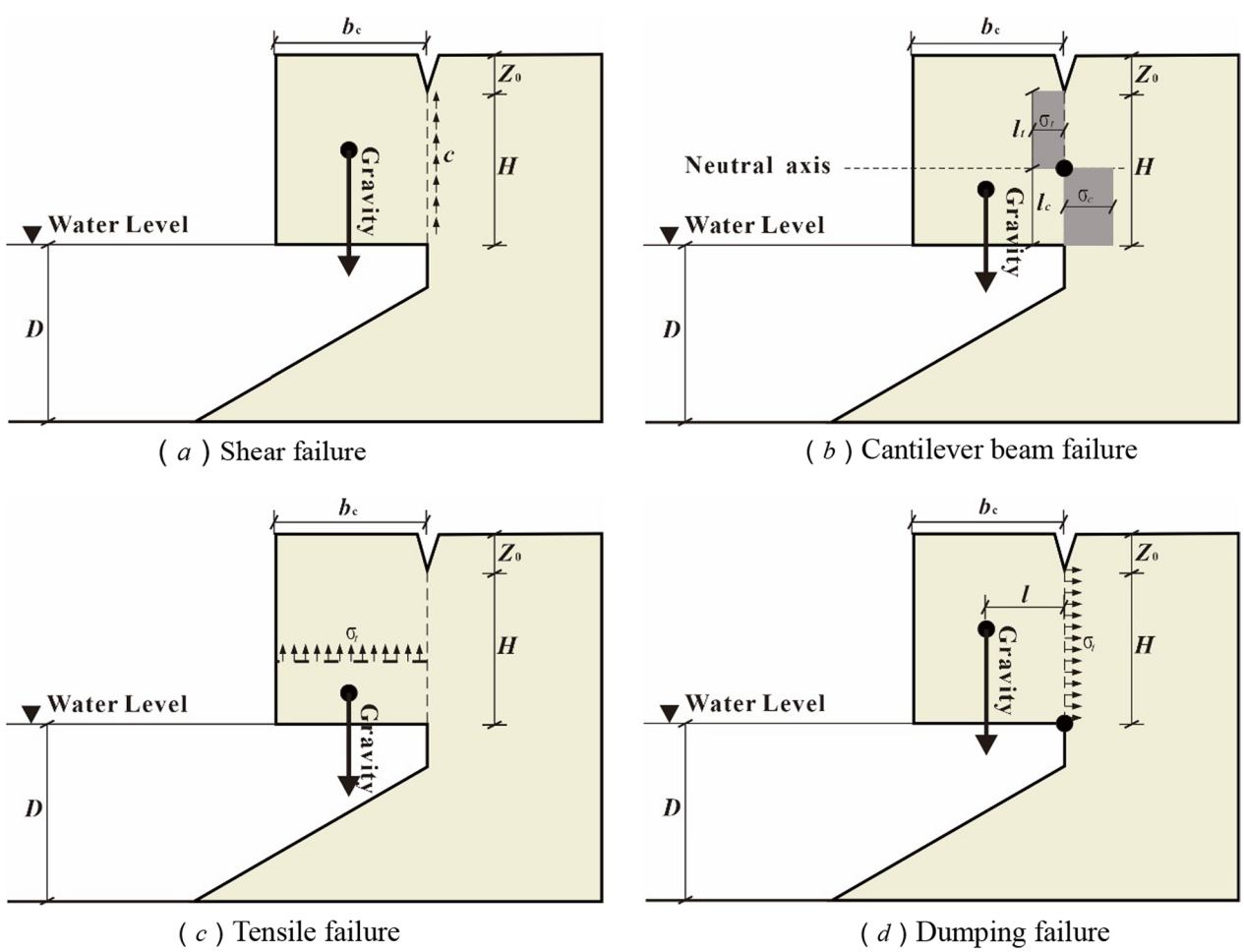

Fig. 12 The failure model of loess bank collaspe

Under water accumulation slope from

The stability of underwater slope is a prerequisite for bank collapse termination, so the study of underwater slope morphology is important for bank collapse prediction. According to the process of bank collapse, the underwater slope is composed of deposits. Therefore, the stable form if underwater bank slope after bank collapse is essentially the form of deposits.(Zhang 2010).

Taking the intersection of the vertical extension line of the lowest point *A* of above water slope and the horizontal extension line of the lowest point *B* of underwater slope as the origin *O*, with the L-axis orthogonal to the horizontal pointing out of the slope and the vertical upward as the Z-axis orthogonal, a coordinate system is established to try to establish a prediction model of the morphology of the underwater accumulation slope (Fig. 13).

As mentioned earlier, the underwater bank slope has a curved shape, so an exponential curve as shown in Eq. (4) is attempted:

$$Z = a \cdot e^{-bL} + c \cdot L \tag{4}$$

The fitting results of underwater bank slope terrain feature points in different model experiments were shown in Fig. 14. It can be seen that the underwater bank slope terrain can be well fitted by Eq. (4).

It can be seen from Table 5 that the parameter a is equal to the water depth after bank collapse. This phenomenon is determined by the characteristics of the curve function. Therefore, only the *b* and *c* need to be analyzed. The prediction parameters in Table 5 were plotted against the potential influencing factors in Fig. 15. it can be seen that *b* tends to decrease and then increase as *D/H* increases, decreases with the increase of ρ_d, and fluctuates as α increases. This indicates that the shape of underwater bank slope is related to *D/H* and ρ_d, but the correlation between *b* and α is poor. This is due to the the water pressure on the underwater slope with the change of water depth during the

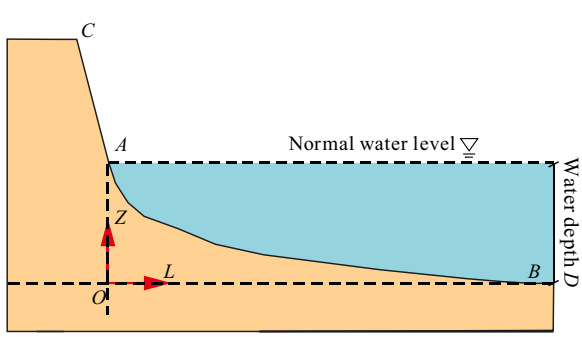

Fig. 13 Coordiante system of underwater bank slope

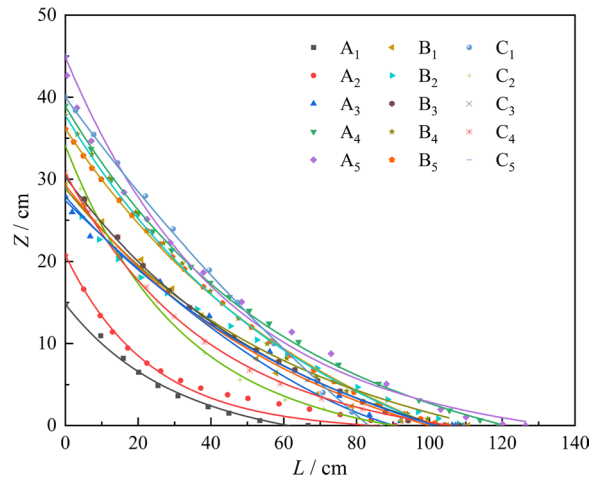

Fig. 14 Fitting results of underwater accumulation bank morphology

model test is different, and the influence of collapse impact on the underwater slope is also different, which leads to the change of the underwater bank slope form. With the increase of ρ_d, the disintegration rate of loess decreases, and the collapsed soil will form a hard core after being soaked by water, which will lead the increase of slope angle, and then lead to the change of underwater morphology, but this phenomenon will continue to weaken with time(Gu et al. 2017; Li et al. 2009; Yuan et al. 2017). However, it is difficult to use formulas to describe the relationship between them.

As mentioned before, existing loess bank collapse prediction methods only consider the impact of hydrodynamic and soil density change on the accumulation volume, and use linear underwater slope to predict the bank collapse width, which will overestimate the amount of underwater accumulation and thus lead to large prediction results of bank collapse. Therefore, it is necessary to study the correction of the accumulation volume. It can be seen from Fig. 15 that the key parameters of the underwater slope form are related to the water depth and slope height, but it is difficult to determine the key parameters by slope height and water depth. Table 6 shows the volume error of underwater accumulation bank slope was calculated based on the model test.

It can be seen from Table 6 that the accumulation volume error due to the bank slope pattern ranged from 12.04 to 47.32%, with a mean value of 31.03%. When the bank slope angle is 30°, the accumulation volume error is 12.04%, which is obviously deviated from the mean value. This is due to the fact that the bank collapse pattern is of abrasion type, the changes of underwater bank slope is small. Considering that the loess bank slope is mostly large inclined angle, the collapse pattern

Table 5 Parametric statistics of Underwater Accumulation Bank Slope

No	Slope height *H*/cm	Slope angle *α*/°	Dry density ρ_d/g·cm^{-3}	Water depth *D*/ cm	Water depth after bank collapse /cm	*a*	*b*	*-c*
A_1	70	90	1.36	15	14.8	14.8	0.03664	0.02573
A_2	70	90	1.36	25	20.8	20.8	0.04387	-0.00614
A_3	70	90	1.36	40	27.4	27.4	-0.00895	0.68100
A_4	70	90	1.36	55	38.9	38.9	0.01834	0.03512
A_5	70	90	1.36	65	44.9	44.9	0.02340	0.01465
B_1	70	60	1.28	40	29.3	29.3	0.01827	0.04741
B_2	70	60	1.32	40	28.9	28.9	0.01784	0.03304
B_3	70	60	1.36	40	30.3	30.3	0.01863	0.04340
B_4	70	60	1.40	40	37.8	37.8	0.01793	0.06103
B_5	70	60	1.45	40	36.5	36.5	0.01657	0.06670
C_1	70	90	1.36	40	27.9	27.9	0.01651	0.05173
C_2	70	75	1.36	40	30.8	30.8	0.02674	0.01742
C_3	70	60	1.36	40	30.3	30.3	0.01863	0.04340
C_4	70	45	1.36	40	34.1	34.1	0.03272	0.01962
C_5	70	30	1.36	40	40.0	40.0	0.01028	0.20390

is mostly collapsed or slip type. And the volume error distribution conforms to normal distribution (Fig. 16). So, the volume error is suggested to be 0.6 ~ 0.8.

Loess bank collaspe prediction method

As shown in Fig. 16, the balanced alluvial accumulation approach method considers the siltation of bank collaspe. The method first determines the stable form *ABCF* of the underwater slope and the stable form *FE* of the above water slope. Then, by translating *ABCFE* until $V_1 + V_2 n = V_3$, the bank collapse width is the horizontal distance between *D* and *E*. the *n* in formula is the stockpile coefficient, is used to correct the volume change due to the current scour and the density change before and after bank collapse. However, the balanced alluvial accumulation approach method only considers the bank morphology after bank collaspe, but ignores the process of bank collaspe and the volume error of underwater slope. Therefore, it is necessary to improve it.

Therefore, the balanced alluvial accumulation approach is improved based on the shear failure and dumping failure. In the improved balanced alluvial accumulation approach, the total bank collapse width is the sum of single collapse width, and the Eqs. (2) and (3) are used to calculate the single bank collapse width b_c according to the slope height and strength of the slope soil. Continuously calculate b_c and update the total bank collapse width until $(V_1 + V_2) \cdot n \cdot \eta > V_3$,where *n* is the stockpile coefficient and the η is volume correction coefficient.

The improved balanced alluvial accumulation approach has better applicability as it accurately describes both the process and the final stabilization pattern of loess bank collapse.

Example verification

(1) Small scale model test.

Patsinghasanee et al. (2015) investigated the dumping failure of riverbank slope, the parameters of the model test are shown in Table 7. The model soil will be completely saturated during the test due to the influence of capillary water, so the soil weight is taken as saturated weight.

The predicted single bank collapse width obtained by the improved balanced alluvial accumulation approach is 0.108m, and the total bank collapse width is 0.108m, the collapse type is dumping type. The actual collapse width is 0.095m. The predicted bank collapse width is closed to measured width, which indicates that the improved balanced alluvial accumulation approach is more accurate in the bank collapse.

(2) Actual measurement verification.

Hu et al. (1996) investigated a potential bank collapse point in the loess area, they found the fracture on the top of slope, while will lead the bank collapse, the parameters of the loess is shown in Table 8.

The predicted single bank collapse width obtained by the improved balanced alluvial accumulation approach is1.61m, which is the same as the distance between the fractures, and the collapse type is shear type. This indicates that the improved balanced alluvial accumulation approach can accurately predict the width of a single bank collapse.

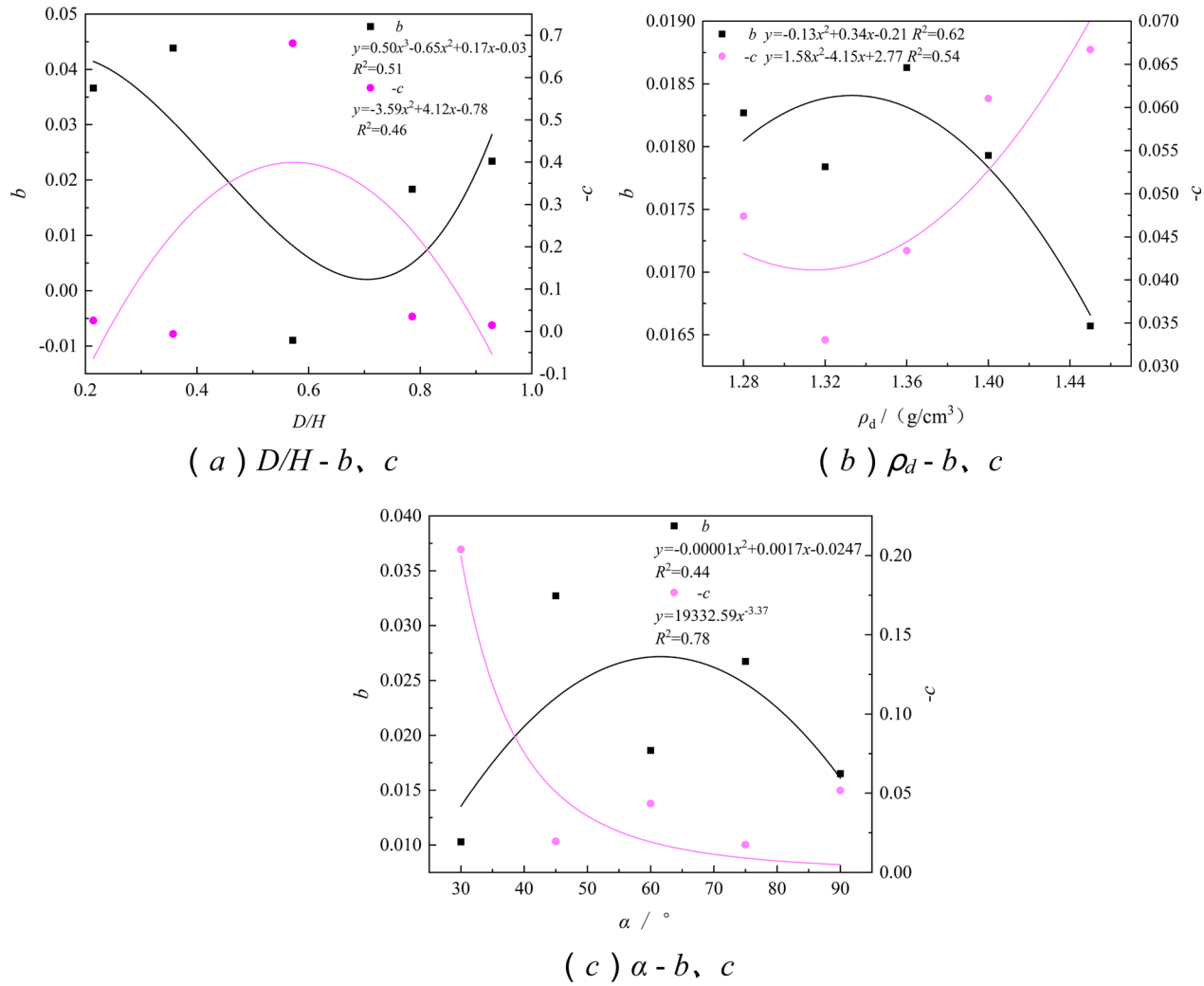

Fig. 15 The relationship between predicted parameters with influencing factors

The empirical graphical method does not consider the minimum width of the failure of above water slope, and the underwater accumulation slope is not accurately described. As a result, the error in bank collapse prediction is large. the improved balanced alluvial accumulation approach considers the accumulation form of underwater slope and corrects it, and then calculates the minimum bank collapse width of above water slope based on the mechanical equilibrium, and finally uses the principle of empirical graphical method to predict the bank collapse. The prediction process is consistent with the actual bank collapse process, and the slope form is similar to the measured results, so the prediction bank collapse width is more accurate. However, the physical and mechanical properties of loess are somewhat discrete, and further research is needed on how to reasonably select the calculation parameters (Fig. 17).

Discussion

In this study, the model tests were used to study the influencing factors and evolution of loess bank collapse and proposed a new prediction method for loess bank collapse.

Consistent with previous studies(Ji et al. 2018, 2017), we found that water depth, bank slope angle, and dry density of bank soil all affect the bank collapse width. However, we also found that the reservoir bank collapse is phased, and existing methods for predicting bank collapse width cannot reflect this characteristic(Kachugin 1949; Peng 2014; Peng and Chen 2014; Wang et al. 2000). Therefore, we proposed a new method which considered the process of bank collapse and the physical and mechanical indicators of bank soil. Moreover, the morphological characteristics of underwater bank slope was also considered in new method.

Table 6 The volume error of underwater accumulation slope

No	Slope height *H*/cm	Slope angle *α*/°	Dry density ρ_d/g·cm^{-3}	Water depth *D*/cm	Volume error /%
A_1	70	90	1.36	15	39.80
A_2	70	90	1.36	25	29.31
A_3	70	90	1.36	40	27.93
A_4	70	90	1.36	55	47.32
A_5	70	90	1.36	65	35.83
B_1	70	60	1.28	40	31.75
B_2	70	60	1.32	40	24.62
B_3	70	60	1.36	40	29.34
B_4	70	60	1.40	40	27.10
B_5	70	60	1.45	40	24.26
C_1	70	90	1.36	40	27.93
C_2	70	75	1.36	40	41.58
C_3	70	60	1.36	40	29.34
C_4	70	45	1.36	40	41.40
C_5	70	30	1.36	40	12.04

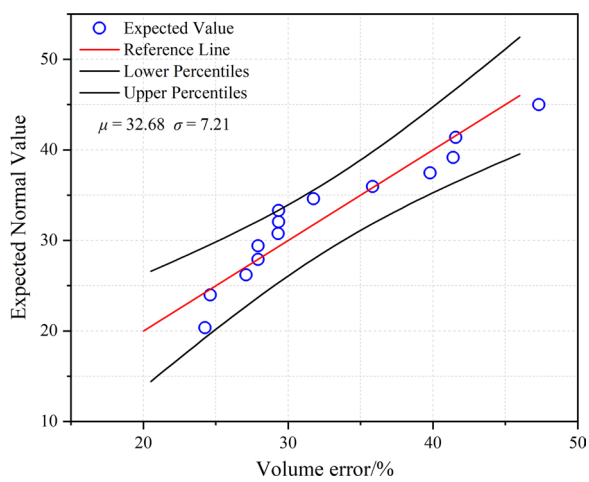

Fig. 16 The normal *Q-Q* plot of the volume error

Table 7 The parameters of above water slope soil

Cohesion c/kPa	Compressing strength σ_t/kPa	Tensile strength σ_c/kPa	Above water slope height H/m	Depth of fractureZ_0/m	Weight *γ*/kN·m^{-3}
6.41	23.88	2.50	0.09	0.05	19.14

However, the action of hydrodynamic was not considered in new method, although the water flow in loess reservoirs is slow, it still has a certain impact on the shape of underwater bank slopes. Meanwhile, although the new method can reflect the phased nature of bank collapse, it is not very helpful in determining the interval time of bank collapses.

Table 8 The parameters of above water loess slope

Cohesion c/kPa	Compressing strengthσ_t/kPa	Tensile strength σ_c/kPa	Above water slope height H/m	Depth of fracture Z_0/m	Weight *γ*/kN·m^{-3}
40.0	75.0	6.75	11.91	8.29	14.6

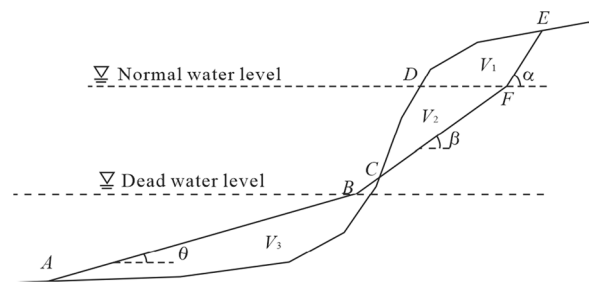

Fig. 17 The balanced alluvial accumulation approach

Therefore, in future research, the time effect of bank collapse should be studied, and an attempt should be made to establish a prediction model for the width of bank collapse that can reflect the physical and mechanical properties of rock and soil on the bank slope, consider hydrodynamic conditions, and predict the time of bank collapse.

Conclusion

In this paper, the influential factor of loess bank slope was studied by model tests, and the process of bank collapse was analyzed. The main conclusion are as follows:

(1) The physical model test indicate that the bank collapse width increases with the increase of water depth, increases with the increase of slope angle, and decreases with the increase of dry density.

(2) The bank collapse width is linearly related to the water depth and the dry density of loess, but exponentially related to the bank slope angle. When the slope angle is less than 27°, the bank collapse will not occur, and when the slope angle is between 27° and 40°, the bank collapse type is abrasion type. When the slope angle is greater than 40°, the bank collapse type is dumping type or shear type. At the same time, the above water slope angle remains basically unchanged after the bank collapse.

(3) The modeling process shows that the loess bank collapse occurs firstly underwater, the erosion niche will be formed underwater, and then the above

water slope is damaged. This process is repeated until the underwater accumulation slope reaches the stable state, and then bank collapse stops.

(4) Based on the model test, an improved balanced alluvial accumulation approach was proposed. The new method not only considers the mechanical equilibrium of the above water slope, but also the pattern of the underwater accumulation slope. Moreover, the new method can reflect the stage characteristics of loess bank collapse, which is more reasonable than the empirical graphical method.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Data availability

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Declarations

Competing interests

The authors declare no competing interests.

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