Experimental investigation of the erosion-reducing effect of willow piles in the evolution of gully

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Abstract. The Yellow River Basin is ecologically fragile. The sand production in the Loess Plateau gully erosion accounts for more than 50% of the total sand production in the basin. Plant foliage can reduce the raindrop-scouring force. The root system can reduce the erosion of the soil. In contrast, the willow pile arrangement and combination of the impact of the water flow in the gully energy dissipation and erosion reduction should be studied more. To investigate the effect of different combinations of willow piles on the erosion reduction of the gully. The optimal combination of hexagonal (corner facing upstream A, side facing upstream B) and triangular (C) arrangements for energy dissipation and erosion reduction of willow piles at scouring intensities of 1.8 $L\cdot min^{-1}$, 2.4 $L\cdot min^{-1}$, and 3.0 $L\cdot min^{-1}$ was quantitatively analyzed. The results indicate that the willow pile group has an inhibiting effect on the erosion of the gully. After 20 min scouring of the slope, the gully scour erosion of class A arrangement is the smallest. This arrangement has the most considerable inhibiting effect on the erosion of the gully. The cumulative erosion-reducing effects of the willow pile group of class A, class B, and class C on the average sediment of the gully are 54.2%, 50.0%, and 38.8%. Respectively, erosion reduction benefits: class A> class B> class C. In conclusion, the erosion reduction effect of the Class A arrangement is better than that of other arrangements in this research. This research provides new ideas for the management of gully on the Loess Plateau. To provide technical references for the Yellow River Basin ecological protection and high-content development.

Keywords: loess gully, pile group combination, energy dissipation and erosion reduction, ecological protection.

1 Introduction

The quaternary loess in the Yellow River Basin is widely distributed with the development of incised gullies and the rapid and unpredictable development of hydraulic erosion, which is an important sediment source in the lower reaches of the Yellow River. It seriously affects the ecological protection and high-quality development Yellow River basin's ecological protection and high-quality development of the Yellow River Basin [1]. Sand production up to 84% or more in some arid and semi-arid areas [2]. The

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prevention and control of gully erosion have become one of the most essential elements of soil erosion control in the Loess Plateau.

After 20 years of returning farmland to forests, 40 years of demographic adjustment in agriculture and animal husbandry, and more than 60 years of soil and water erosion control in the Yellow River Basin, the vegetation cover of the Loess Plateau has been substantially improved since 2000 [3,4]. Vegetation, as an essential soil and water conservation measure, significantly impacts watershed runoff, sand production, and the erosion and development process of the Loess Plateau, which incised the gully[2,5]. The influence of vegetation on soil erosion can be summarized in two aspects [6]: one is that vegetation stems, and leaves reduce the kinetic energy of rainfall, increase rainfall infiltration, and thus reduce the surface runoff volume and flow rate. The other is to improve the soil erosion resistance through solidifying the vegetation root system. Many scholars focus on the research of vegetation erosion resistance on slope flow [7,8]. Such as Wang Diyuan et al. [9], through indoor flume experiments, the study shows that the slope flow rate increases with the increase of flow rate. Zhao Bingqing et al. [10] through the fixed-bed scouring experiments. The results show that the flow pattern of slope water flow is affected by the combination of grass cover and slope, mainly in the laminar and transition flow areas. Through the flume test, Xie Yan et al. [11] found that the resistance coefficient of the flexible and rigid vegetated slopes is lower than that of the vegetation. Verschoren et al. [12] experimentally demonstrated that the average velocity of water flow slows down in the portion passing through vegetation and increases around it. The study on the effect of rigid and flexible vegetation on hydrodynamic characteristics found that rigid vegetation's flow velocity mitigation effect was better than that of flexible vegetation [13]. Yang Jie et al. [13] concluded that the same of vegetation type in ecological engineering construction should be selected as vegetation with greater stiffness.

The effects of rigid and flexible vegetation on the energy dissipation of water flow differ significantly [13,14]. There are few studies on the hydraulic energy dissipation and corrosion reduction effect of rigid vegetation arrangement in the gully. The literature [15] proposes a new idea of slope gully scour prevention system and construction method. Sediment retention shrubs are placed behind the opening of catchment areas on slopes. Polygonally arranged dry willow stakes are inserted into the soil in the catchment area. The viable willow piles were selected as the research object in this investigation. Three kinds of willow pile arrangements were set up. Through the indoor scouring test method, the energy dissipation and erosion reduction effects of different combinations of willow piles on the water flow of the incised gully were researched. Moreover, it is optimized to determine the best combinations of willow piles. To provide a new idea for the evolution of managing the incised gully in the Yellow River Basin.

2 Research Methodology

2.1 Test setup

LSW-TK1 trough soil scouring resistance instrument was used in the test, as shown in Fig. 1. It was composed of a stainless-steel variable slope test bench, needle scouring device, needle, water pressure gauge, pressure relief valve, voltmeter, impact resistance instrument control box. The scour groove specifications were 300 mm×100 mm×200 mm. The slope of the scour groove could be adjusted within the range of 0° ~ 45°. The needle scouring platform's needle hole is 5cm away from the soil layer. Furthermore, the needle diameter is 0.8mm. A water pump, reservoir, and battery charging controller are installed in the control box of the anti-impact instrument.

Fig. 1. Schematic diagram of experimental apparatus and filling soil

2.2 Hydraulic similarity determination

This test similarity scale $\lambda_l = 20$. The age of the tree is 3 years to 5 years for the bottom end of the chipped columnar structure of living willow stakes. The diameter of the willow stakes is 10 cm. This test willow stakes diameter according to the geometric similarity scale, using disposable chopsticks with a diameter of 0.5cm to simulate the dry willow wood stakes.

2.3 Experimental design

The slope gradient of the loess hilly area is roughly around 20°. The slope of the scouring table is adopted as 20°. The test scouring intensity was obtained by converting the single-width flow rate generated on the standard runoff plots in the field to the test soil trench flow rate according to the frequency of heavy rainfall in the Loess Plateau region[16]. Three scouring intensities of 1.8 $L\cdot min^{-1}$, 2.4 $L\cdot min^{-1}$, and 3.0 $L\cdot min^{-1}$ were selected for this test. According to the study of Zhou Bo et al. [15], this test was designed with three types of willow pile arrangement (space is limited optimal, and only these three types of methods are discussed). The bare slope was used as the control group, as Fig. 2.

(1) Hexagonal arrangement with sides facing upstream (class A arrangement).
(2) Hexagonal arrangement with corners facing upstream (class B arrangement).
(3) Triangular arrangement with corners facing upstream (class C arrangement).
(4) The control group was on a bare slope with no treatment measures installed.

Fig. 2. Diagram of the way willow stakes are arranged

2.4 Test methods

The test was conducted in a 30 cm long and 10 cm wide scouring trough. Before filling the test soil, the inside of the scouring trough was filled with 10 cm of natural sediment to keep the permeability of the test soil close to the natural slope. The soil samples collected in the field were then configured to have a moisture content of 14%, sieved through a 0.5 mm aperture, and filled into the scouring trough. In filling the soil, the soil was compacted, and 5cm was loaded each time, totalling 10cm. The dry bulk density of the soil on the slope surface in the scouring trough was controlled to be about $1.35 g\cdot cm^{-3}$. After filling, use tools to scrape the surface flat. The schematic diagram of the test setup and soil filling is shown in Fig. 1. Then insert disposable chopsticks on the slope. The water supply equipment used constant water pressure to control the scouring intensity. The scouring intensity was controlled by the water pressure gauge on the controller of the scouring instrument and by the pressure relief valve. After the test started, sediment samples were collected at the outlet of the scour tank. Then, the runoff sediment samples were weighed every 2 minutes for a cumulative total of 10 weighings, starting from the beginning of the flow production and lasting for 20 minutes. After completing the scouring test, each scouring sample in the water basin was left to stand for 24 hours. Then, the water was removed, and the other liquids were poured into an aluminium box. Finally, the sediment was moved to an oven at 105° for continuous drying, and then the content of the sediment was determined. The test was repeated for each group.

2.5 Data processing

The erosion reduction effect of willow piles on sediment was calculated using the following equation[17]:

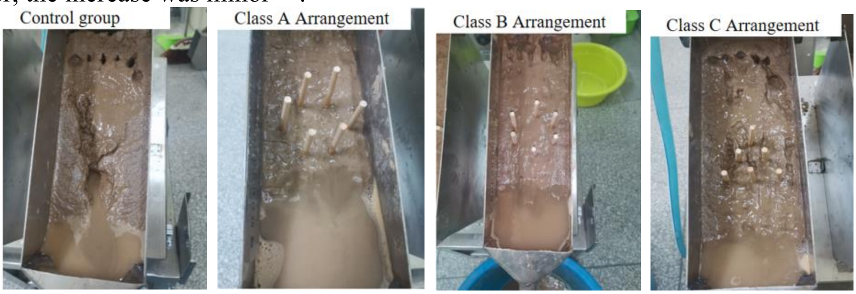
$$E=[(Y_b-Y_v)/Y_b]\times 100\% \tag{1}$$

Where E is the erosion reduction effect; Y_b and Y_v are the cumulative amount of sediment, g, for bare slopes and slopes with different arrangements of willow piles, respectively.

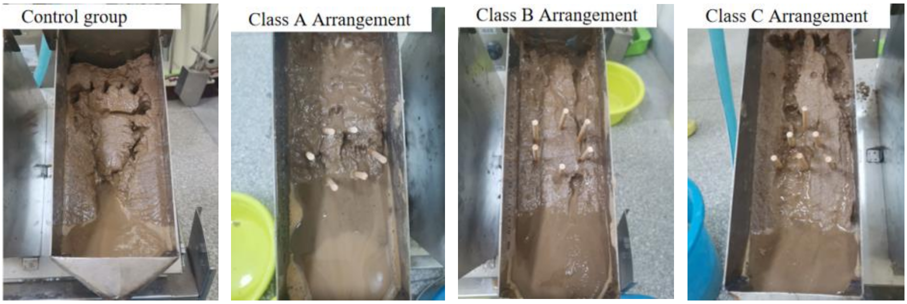
3 Results and analysis

3.1 Effect of different arrangements on slope scour erosion

Fig. 3 shows the slope scouring process of the willow pile in different arrangements with a scouring intensity of 1.8 L·min^{-1}. The test scouring time was 20 min. At the beginning of the scouring stage, the top of the slope was mainly impacted by the needles of the needle-type scouring table. Moreover, it caused severe erosion on the top of the slope. With the generation and penetration of runoff, a rill gully was gradually formed on the slope along the runoff channel. Undercutting erosion and headward erosion appeared at the head of the gully. With the continuous action of the runoff, the erosion is intensified to form the incised gully. In the first 10 min of scouring, the slope appeared to be an apparent erosion phenomenon. The bare slope (control group) had the most severe scouring erosion. The erosion area is the largest. The maximum width is 2.34 cm. The length has reached the middle and upper part of the slope. The gully erosion occurs. In the last 10 minutes of the scouring process, the erosion length gradually extended to the upper part of the slope. The maximum width reaches 4.73 cm. The gully erosion is intensified. There is a localized slumping phenomenon. When the treatment measures are laid on the slope, the erosion is regulated to a certain extent. Both show a noticeable attenuation effect, inhibiting the slope gully erosion. The slope surface only causes local slice erosion around the piles in the Class A arrangement. The slope forms a gully with a width of 1.75 cm and a length of 1.75 cm running through the whole slope surface in the Class B arrangement. The slope surface forms two large erosion gullies with lengths running through the whole slope surface in the Class C arrangement. The maximum widths are 2.1 cm and 3.15 cm respectively. The most obvious effect is the Class A arrangement. The Class B arrangement has a better regulatory effect. The worst effect is the Class C arrangement. Under other scouring intensities (not listed due to limited space), the slope erosion pattern is the same as that of 1.8 L·min^{-1}. With the increase of scouring intensity, the slope erosion is intensified. However, the increase was minor[17].



(A)Current status of the slope after 10 min of scouring

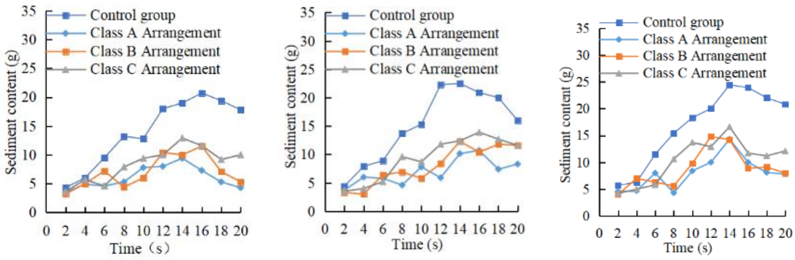


(B)Current status of the slope after 20 min of scouring

Fig. 3. Comparison of slope scour of three types of willow pile assemblies at a scouring intensity of 1.8 L·min^{-1}

3.2 Sediment content of slope scour under different release intensities and arrangements

Fig. 4 shows the change of slope sediment content under different water scouring intensities and arrangements. Under the same water scouring intensity, the sediment content on the slope surface shows a fluctuating tendency of first increasing, then decreasing. Then, it increases and then decreases with the increase of scouring time. The analysis of the scour erosion map shows the slope surface after levelling is relatively smooth in the pre-scouring period of runoff. The water flow resistance is negligible. The increase in sediment content is slight. Scouring continues, and the slope surface gradually produces a drop can, the water flow resistance on the slope increases. The flow velocity decreases. The amount of eroded sediment also decreases. As the fall develops, the slope gradually runs through to form a fine gully. The delicate gully erosion process gradually formed trace erosion, and the gully wall collapsed gully erosion. The amount of sediment increased dramatically. At the end of the test, the development of the incised gully was stabilized. The gully bed was gradually smoothed. Sediment volume also decreased as the resistance decreased. The results of one-way ANOVA showed that the sediment content under the three types of arrangement was significantly different from the control group ($p<0.05$). It indicates that vegetation cover has a significant effect on slope sediment content. With the increased scouring intensity, the slope scour amount also showed an increasing trend. Nevertheless, the difference between the B and C arrangements of ways gradually decreased. This is consistent with the study of Wei Xia et al. [18].

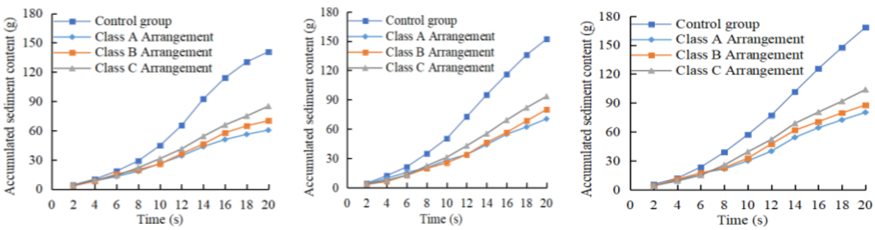


(A)1.8 L·min^{-1} (B)2.4 L·min^{-1} (C)3.0 L·min^{-1}

Fig. 4. Variation of sediment content on slopes with various arrangements of willow stakes at different water scouring intensities

3.3 Cumulative scour on slopes with different discharge intensities and arrangements

The increased vegetation on the slope leads to increased water infiltration and a decrease in runoff, reducing sediment accumulation. As the scouring intensity increases, the scouring rate and duration of the slope surface also increase, enhancing the ability of runoff to erode and transport soil particles [17]. Consequently, the cumulative sediment content increases with more extraordinary scouring intensity. Under identical experimental conditions, the cumulative sediment content can reflect the effectiveness of unusual combinations of willow piles. Fig. 5 shows that the average accumulated sediment content for the control group (averaged across different scouring intensities) is 153.6g. Class A, B, and C arrangements are 70.3 g, 79.2 g, and 94.0 g, respectively. With longer runoff duration, all arrangements show increased accumulated sediment content with a steeper curve between 8-14 minutes because of the saturation-induced soil looseness leading to increased erosion sediment amounts on the slope surface. The overall trend observed for cumulative sediment content indicates that Class A arrangement has the most significant regulatory effect on slope trenching erosion, followed by Class B and then Class C. This finding aligns with previous results regarding slope erosion.



(A)1.8 L·min^{-1} (B)2.4 L·min^{-1} (C)3.0 L·min^{-1}

Fig. 5. Variation of cumulative sediment content on slopes with various arrangements of willow piles at different scouring intensities

3.4 Analysis of erosion reduction effects of sediment

There are many research results on vegetation erosion of slope erosion sand production. The influencing factors include vegetation type, layout pattern, rainfall, and scouring intensity[6,19]. Therefore, this investigation analyzes the influence of willow piles on the erosion reduction effect of slope erosion and sand production by different arrangements and scouring intensities. As shown in Fig. 6, the erosion reduction effect of willow piles on slope sediment under each arrangement mode decreased with increased scouring intensity ($R^2 > 0.9$, $p < 0.01$). The comparison revealed that the erosion reduction effect of scouring intensity on the average cumulative sediment content of slopes with various combinations of willow piles was 54.2%, 50.0%, and 38.8%. The magnitude of cumulative sediment erosion reduction effect under each arrangement: Class A > Class B > Class C. Class A was superior to classes B and C. Two-factor ANOVA is shown in Tables 1 and 2 below. The results show significant differences between the scouring intensity and the three types of arrangement of A, B, and C on the sediment erosion reduction effect on the slope ($p < 0.05$). Therefore, the inhibition of slope incision gully erosion by class A arrangement is more excellent than other arrangement ways and has the most apparent effect on slope erosion reduction.

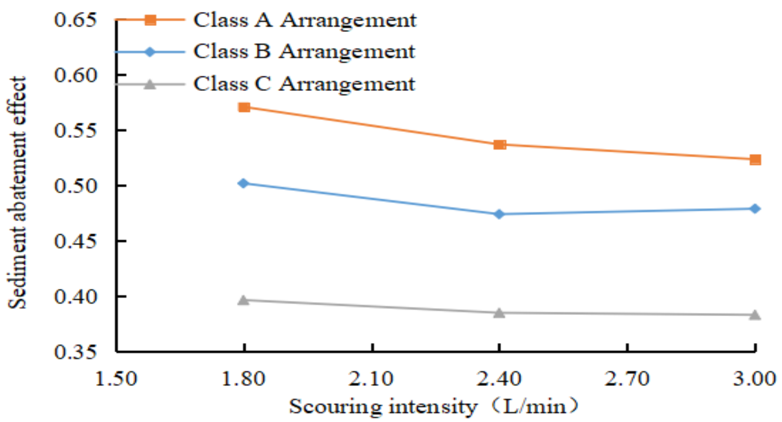


Fig. 6. Erosion-reducing effects of various arrangements of willow piles under different water scouring intensities

Table 1. Effect of different arrangements and scouring intensities on the erosion and sand production of willow piles on erosion-reduced slopes.

scouring intensity/ ($L\cdot min^{-1}$)	Class A arrangement	Class B arrangement	Class C arrangement
1.8	57.07%	50.18%	39.66%
2.4	53.69%	47.40%	38.51%
3.0	52.35%	47.89%	38.32%

Table 2. Results of two-factor ANOVA.

source of variation	SS	cf	MS	F	P-value	F crit
arrangement	0.001379	2	0.00069	7.877535	0.040998	6.944272
Scouring intensity/ $(L \cdot min^{-1})$	0.036921	2	0.018461	210.8181	8.83E-05	6.944272
inaccuracies	0.000350	4	8.75E-05			

4 Conclusion

Indoor scouring experiments were used to investigate the energy dissipation and erosion reduction effects of three arrangements of willow piles (hexagonal corners facing upstream, edges facing upstream, and triangular corners facing upstream) on slope erosion under different scouring intensities in this investigation. The main conclusions are:

(1) After 20 min of slope scouring, the control group slopes produced incised gullies and collapsed. All three willow pile arrangements showed erosion around the piles on the slopes. It is recommended to increase the grass plants to prevent erosion; however, the overall erosion was suppressed to a certain extent.

(2) With the increased scouring flow rate, the sediment mass and cumulative sediment content under each arrangement method showed an increasing trend. The erosion reduction effect showed a decreasing trend. The average cumulative sediment content of the bare slope in the control group (the average value under different scouring flow rates) was 153.6 g. The average cumulative sediment content under the three types of arrangements A, B, and C were 70.3 g, 79.2 g, and 94.0 g, respectively.

(3) The erosion-reducing effects of willow piles on the average cumulative sediment content of slopes under the three modalities were 54.2%, 50.0%, and 38.8%. The average cumulative sediment content attenuation effect: the Class A arrangement > the Class B arrangement > the Class C arrangement. That is, the moderating effect of the class A approach on slope sediment was optimal in this investigation.

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