



Report

A new ecological control method for Pisha sandstone based on hydrophilic polyurethane

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Abstract: The Pisha sandstone-covered area is among the regions that suffer from the most severe water loss and soil erosion in China and is the main source of coarse sand for the Yellow River. This study demonstrated a new erosion control method using W-OH solution, a type of hydrophilic polyurethane, to prevent the Pisha sandstone from water erosion. We evaluated the comprehensive effects of W-OH on water erosion resistance and vegetation-growth promotion through simulated scouring tests and field demonstrations on the Ordos Plateau of China. The results of simulated scouring tests show that the water erosion resistance of W-OH treated area was excellent and the cumulative sediment yield reduction reached more than 99%. In the field demonstrations, the vegetation coverage reached approximately 95% in the consolidation-green area, and there was almost no shallow trenches on the entire slope in the treated area. In comparison, the control area experienced severe erosion with deep erosion gullies appeared on the slope and the vegetation coverage was less than 30%. This study illustrated that W-OH treatment can protect the Pisha sandstone from erosion and provide the vegetation seeds a chance to grow. Once the vegetation matured, the effects of consolidation-growth mutual promotion can efficiently and effectively improve the water erosion resistance and ecological restoration.

Keywords: erosion resistance; field experiment; growth promotion; sediment yield; water and soil conservation

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1 Introduction

Pisha sandstone, formed in the Mesozoic Era, is widely distributed in semi-arid area in Shanxi, Shaanxi provinces and also in Inner Mongolia Autonomous Region within the Yellow River Basin in China. It covers an area of approximately $16.7 \times 10^3 \text{ km}^2$ (Ni et al., 2008; Ma and Zhang, 2016). The Pisha sandstone can be divided into bare, sand-covered, and soil-covered Pisha sandstones according to the top materials. The average annual erosion modulus in the Pisha sandstone-covered area can reach up to 30×10^3 – $40 \times 10^3 \text{ t}/(\text{km}^2 \cdot \text{a})$ and the area is the sediment source of the Yellow River. As Pisha sandstone is predominantly intermingled with other rocks with different grain sizes (e.g., muddy sandstone, sandy mudstone and some gravel and shale), it

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possesses some unique characteristics. For example, it can be as hard as a solid rock when it is dry. However, it becomes soft and muddy once exposed to water and is thus prone to wind and water erosions (Zhen et al., 2016).

Since the 1950s, many measures have been taken to fight against the wind and water erosions mainly including biologicals and engineering (Li et al., 2015). The biological measures include forest shelter-belts, windbreak and sand fixation forests, slope protection plants, and seabuckthorn flexible dams (Zhang et al., 2009; Yang et al., 2013, 2014). The engineering measures include terracing, trenching, ditching, etc. (Wang et al., 2007). Nevertheless, they can hardly achieve the expected comprehensive goals of controlling erosion, promoting vegetation growth, and stabilizing steep slopes (Xiao et al., 2014).

Recently, integrated and multivariate approaches have been adopted to prevent wind and water erosions. For example, Wu et al. (2011) studied a type of polyurethane as an ecological sand fixation agent. Liang and Wu (2016) further studied the fixation effects of polyurethane. Liu et al. (2011) introduced organic polymers as soil stabilizers. Su and Zhang (2012) introduced the EN-1 curing agent to protect sandstone slopes. Some other researchers (Wang et al., 2005; Zhang et al., 2012) tried new consolidation materials as well. Unfortunately, most of these aforementioned methods have not been applied to the Pisha sandstone in the fields. Inspired by the work that used a novel hydrophilic polyurethane (W-OH) to control desertification and to achieve ecological restoration (Wu et al., 2009; Gao et al., 2011), this study introduced a W-OH method combined with vegetation measures for protecting Pisha sandstone from erosion.

2 Materials and methods

2.1 Experimental area

The experimental site, situated in the middle of Erlaohugou on the Ordos Plateau, Inner Mongolia Autonomous Region, China ($39^{\circ}47'38.79''\text{N}$, $110^{\circ}36'2.74''\text{E}$; Fig. 1), is within the bare Pisha sandstone area. The area has an arid and semi-arid temperate continental monsoon climate with cold winter and hot summer. The mean annual precipitation is about 400 mm with 70%–80% falling in July to September. The area is mainly dominated by water and gravity erosion. The overall vegetation coverage is less than 20%.

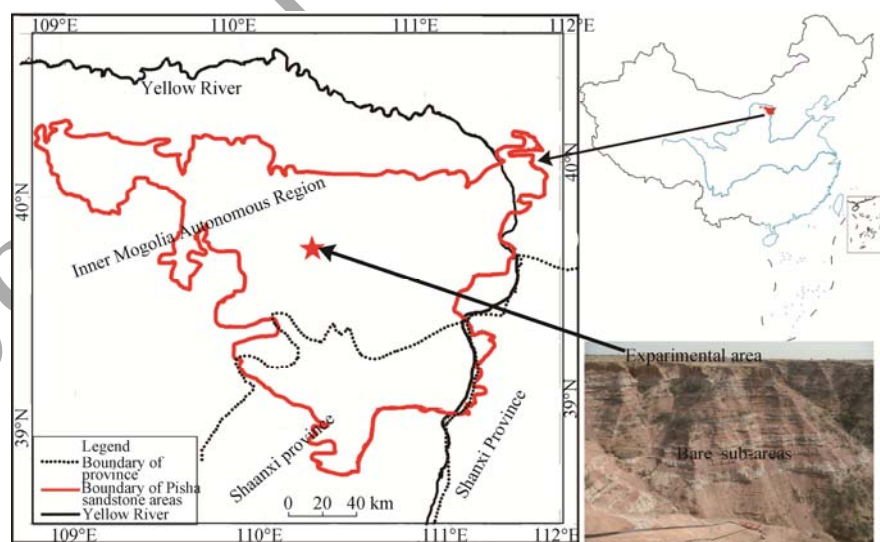


Fig. 1 Location of the study site and types of Pisha sandstone sub-areas

2.2 Materials

W-OH is a type of hydrophilic polyurethane produced by Toho Chemical Industry Co. Ltd., Japan. It can rapidly react with water to form an elastic gel with strong adhesion capabilities. It

does not contain any heavy metal ions and thus has no harmful effect on plants and animals (Wu et al., 2009).

2.3 Scouring test

To evaluate the erosion resistance of Pisha sandstone slopes treated with W-OH solution, we conducted simulated scouring tests on two slopes: an original hard Pisha sandstone slope (slope angle, 43° ; S1) without vegetation coverage and a quicksand slope (slope angle, 34° ; S2) with some vegetation. The experimental area was isolated by iron sheets from the surrounding environment. The iron sheets were 15 cm high with 5 cm above the ground. Each experimental slope was divided into the treated area and the control (not treated) area and the control area was separated by iron sheets as well. The experimental design is shown in Figure 2. The 6% and 3% of W-OH solutions were sprayed on the surface of treated areas of S1 and S2, respectively. The spraying amount was 3 L/m^2 . The scouring test started after the surface was completely dry. The scouring flow was controlled at approximately 3 L/min and the scouring process lasted for 1 h. We repeated the scouring process for three times and selected a typical one for analyses. The sediment yield was collected by barrel at the bottom of the slopes. We collected the sediment yield every other minute over the entire scouring process and obtained 30 collections. Then we mixed all collections to form a representative sediment sample and dried it in an electric oven at 105°C to a constant weight. The morphological changes on the slopes were documented by taking pictures.

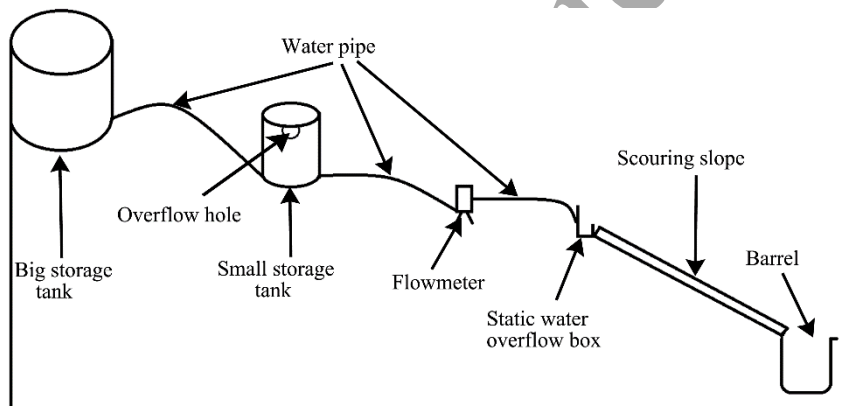


Fig. 2 Illustration of the field scouring test. The length of the scouring slope is 4.0 m and the width is 1.0 m.

2.4 Field demonstration

A 5-month field demonstration was conducted on a Pisha sandstone slope from May to September 2014 to monitor the effects of W-OH solution. The slope was 43.5 m long with a vertical height of 29.9 m and an average gradient of 44.5° (Fig. 3a). We surrounded the experimental area with iron sheets and divided the area into A and B parts. Part A was set as the control and part B was treated with W-OH solutions. According to the slope gradient and potential for vegetation growth, we further divided B into consolidation-waterproof (B1), consolidation-growth promotion (B2), and consolidation-green (B3) sub-sections (Fig. 3b). The three sub-sections were treated with W-OH solutions in different concentrations. The slope angles of sub-sections B1, B2, and B3 were greater than 60° , 30° – 60° , and less than 30° , and the concentrations of the solutions sprayed were 8%–10%, 4%–5%, and 3%, respectively. W-OH solutions were artificially sprayed (Fig. 3a) and the sprayed amount was controlled at 2.0 – 3.0 L/m^2 to ensure the penetration depths reaching 5–8 mm. There were four barrels installed at the slope bottom to collect the eroded sediments and runoff. The seeds of local bushes and grasses, such as *Buchloe dactyloides* and *Pseudostellaria maximowicziana* (Zeng et al., 2013), were sowed in B2, B3 and the similar areas in A. The B was treated with W-OH solutions. Micro-irrigation systems were constructed to guarantee the water supply for the vegetation growth. A meteorological station, and a water and sediment monitoring station were set up to collect the rainfall intensity, temperature, humidity, wind, sediment, etc.

The sediment yield and vegetation growth (Zhang et al., 2009) were recorded after each rainfall event. The vegetation coverage digital pictures, taken with a focus on a 50 cm×50 cm area, were measured using Adobe Photoshop.

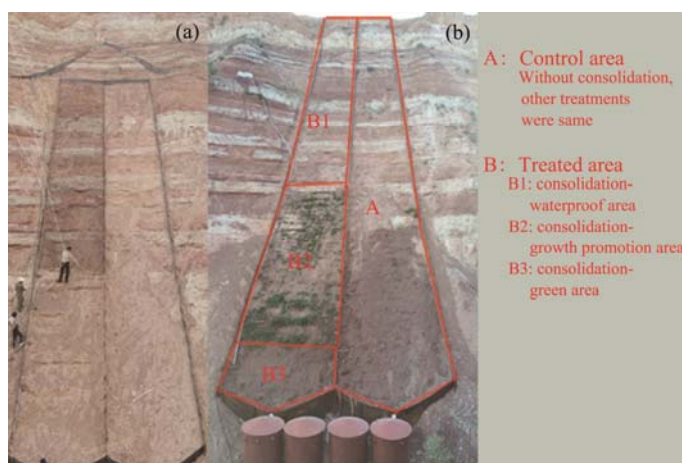


Fig. 3 Experimental area in Erlaohu Gou on the Ordos Plateau, Inner Mongolia Autonomous Region, China. (a) spraying W-OH solutions, (b) the experimental design and control partition.

3 Results and discussion

3.1 Sediment yield

As shown in Figure 4a, the sediment yield from the control area of slope S1, an original hard Pisha sandstone slope with an angle of 43° without vegetation coverage, increased dramatically first and then gradually decreased with scouring time. The peak value of sediment yield, approximately 3200 g/min, appeared at 10 min after the process started. The formation of erosion gullies at the early stage of scouring led to the increase of sediment yield. For the area treated with the 6% W-OH solution, the sediment yield had some fluctuations in the scouring process but the value of the collection was less than 7.0 g/min.

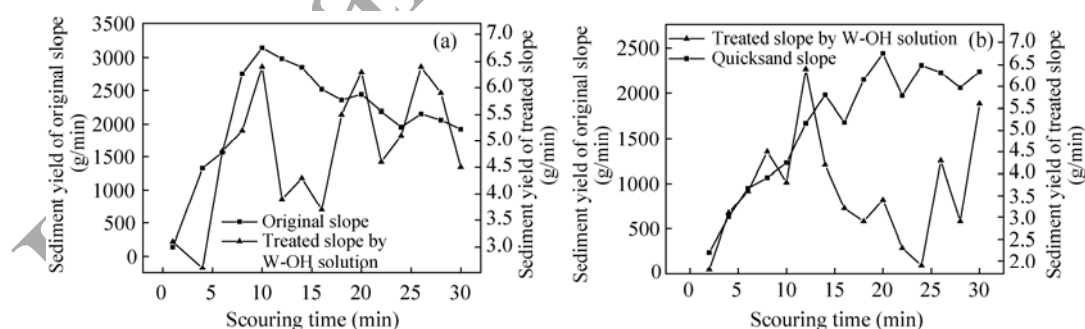


Fig. 4 Sediment yield on two different Pisha sandstone slopes. (a), an original hard Pisha sandstone slope (S1; slope angle of 43°) without vegetation coverage; (b), a quicksand slope (S2; slope angle of 34°) with some vegetation.

The sediment yield process of the control area of S2, a quicksand slope with an angle of 34° with some vegetation, presented a different trend (Fig. 4b) in comparison with S1. Specifically, the sediment yield increased relatively gradually at the beginning of the scouring process and then became stable at about 20 min after the process started. For the treated area of S2 (i.e., treated by 3% W-OH in Fig. 4b), the sediment yield presented a similar trend with that in treated area of S1. The sediment yield was also less than 7.0 g/min in the entire process.

3.2 Runoff and sediment yield

After each rainfall event, we collected the sediment in the barrels. We found that the sediment yield tended to increase with increasing rainfall intensity in both treated and control cases (Table 1). But, the difference between the treated case and the control case was rather large. For example, at the rainfall intensity of 41.2 mm/h, the sediment yield of the control case reached approximately 1895.7 kg with the average unit loss of 11.8 kg/m², while the sediment yield of the treated case was only 11.9 kg with the average unit loss of only 0.074 kg/m². It means that the W-OH treatment has reduced the erosion by 95%. These results indicate that the consolidation layer formed by W-OH has greatly enhanced the erosion resistance of Pisha sandstone slopes.

Table 1 Results of the experimental and control areas in rainy days from July to September

	1 Jul	22 Jul	28 Jul	2 Aug	12 Aug	22 Aug
Rainfall (mm)	16.4	8.6	23.2	35.6	20.6	34.4
30-min rainfall intensity (I_{30} , mm/h)	26.0	4.4	15.6	41.2	26.8	20.0
Rainfall erosion force (MJ·mm/(hm ² ·h))	94.8	9.4	77.2	373.3	131.0	133.3
Sediment yield in experimental area (kg)	8.6	0.0	1.8	11.9	0.4	1.6
Sediment yield in control area (kg)	216.1	42.0	27.3	1895.7	52.1	18.7
Reduced sediment yield (%)	96.0	100.0	93.4	99.4	99.2	91.4

3.3 Vegetation and W-OH treatment

Again as shown in Figure 3b, Part A was the control and Part B was divided into three sub-sections. The performance of the consolidation layer in protecting the slopes was dependent on the thickness of layer and the concentration of W-OH solution as well. For the steeper portion of the slope under B1 treatment, a few cracks appeared (Fig. 5a) even under the consolidation layer reaching the maximum penetration depth of 8 mm. Cracks occurred because the residence time of the W-OH solution was short. In addition, the steeper slope was not very smooth and was difficult to guarantee a uniform W-OH spraying. As a result, water-eroding and gravity collapsing forces led to minor damage to the consolidation layer in some places. Consequently, the number and the magnitude (i.e., depth and width) of the grooves increased gradually. Continuous expansion of the grooves with time and with rainfall intensity eventually resulted in the collapse of the entire slope.



Fig. 5 Comparison between the consolidation-waterproof (B1) and consolidation-green (B3). (a) cracks in the consolidation-waterproof section; (b) comparison between A and B (also among B1, B2, and B3) in September, 2014. (1)–(5) are cracks appeared in sections under different treatments.

In the consolidation-green area (i.e., B3) where the concentration of the sprayed solutions was the smallest (approximately 3%), vegetation grew quickly from May to August (Fig. 5b). When heavy rainfall occurred from July to September, the vegetation had already grown up and the mature vegetation played an important role in reducing the erosion force of raindrops and water flow. Therefore, just a few small erosion gullies appeared in the treated area.

In the case of B2 (i.e., consolidation-growth promotion), as the vegetation coverage increased, the plants became more effective in protecting the weathered Pisha sandstone from further

erosion. In the treated area, the vegetation coverage reached approximately 95% and the average height of vegetation reached 50–60 cm with the average root length reaching 50 cm at the end of September (Fig. 6). However, in the control area, the vegetation coverage was only 26% and the average height of the vegetation was only 10 cm. The vegetation not only increased the roughness of the slope surface and effectively reduced the kinetic energy of raindrops and flow velocity of water, but also played a role in improving soil permeability (Zhao et al., 2014). In brief, W-OH treatment can protect the Pisha sandstone from erosion and provide the vegetation seeds a chance to grow. Once the vegetation matured, consolidation-growth mutual promotion effect took place.

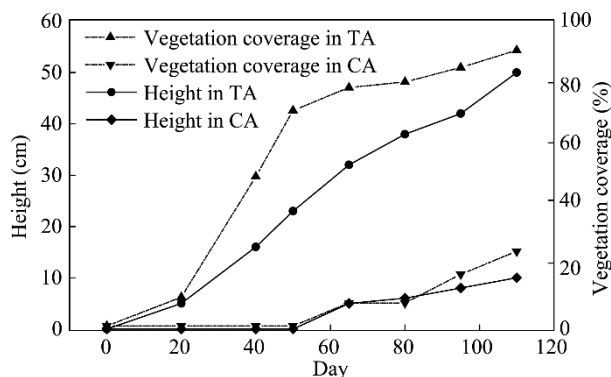


Fig. 6 Vegetation coverage and height in the treated area (TA) and control area (CA) from May to September 2014

4 Conclusions

Generally speaking, under W-OH treatment the sediment yield reduction reaches approximately 99% compared with that in control slopes mainly due to the consolidation effects of W-OH treatment. The field demonstration results show that the W-OH treatment reduced the erosion by 95%, indicating that the consolidation layer formed by W-OH has greatly enhanced the erosion resistance of Pisha sandstone slopes. This study illustrated that W-OH treatment can protect the Pisha sandstone from erosion and provide the vegetation seeds a chance to grow. Once the vegetation matured, consolidation-growth mutual promotion effect took place. But, we should admitted that the comprehensive effects of combining W-OH with vegetation measure were evaluated only in a short experiment time (from May to September 2014) and the need is thus pressing to evaluate the long-term effects.

Acknowledgements

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