



10-30-2019

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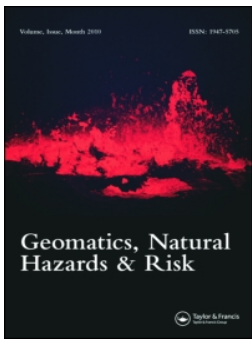
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Xu, Rui; Li, Xunchang; Yang, Wei; Jiang, Chao; and Rabiei, Minou, "Use of Local Plants for Ecological Restoration and Slope Stability: A Possible Application in Yan'an, Loess Plateau, China" (2019). *Petroleum Engineering Faculty Publications*. 8.
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To cite this article: Rui Xu, Xunchang Li, Wei Yang, Chao Jiang & Minou Rabiei (2019) Use of local plants for ecological restoration and slope stability: a possible application in Yan'an, Loess Plateau, China, *Geomatics, Natural Hazards and Risk*, 10:1, 2106-2128, DOI: [10.1080/19475705.2019.1679891](https://doi.org/10.1080/19475705.2019.1679891)

To link to this article: <https://doi.org/10.1080/19475705.2019.1679891>



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Published online: 30 Oct 2019.



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Use of local plants for ecological restoration and slope stability: a possible application in Yan'an, Loess Plateau, China

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ABSTRACT

This paper aimed to screen the potential species suitable for ecological restoration and slope stability from local natural growing plants in China Loess Plateau under a semiarid climate. As part of the field investigations of local natural growing plants, potential species, which are suitable candidates for ecological restoration and slope stability, were nominated in the hilly-gullied region in the Yan'an area. The results showed that *Artemisia* spp. is the best candidate to form a stable root-soil composite system to support the loose loess and reinforce the loose soil, particularly suitable as pioneer plant in the initial stage of loess slope ecosystem reconstruction. Field root pull-out test and direct shear test for soil without roots and root-soil composite systems were conducted to analyse the reinforcement effect of *Artemisia* spp. The results from quantitative analysis of the slope protection effect showed that the slope safety factor could be obviously improved by the growth of *Artemisia* spp. As the survey, test, stability analysis and case study shown, *Artemisia* spp. can effectively prevent the occurrence of loess flow slides and shallow landslides, which has extensive application prospect.

ARTICLE HISTORY

Received 22 July 2019
Accepted 4 October 2019

KEYWORDS

Artemisia spp.; loess slope; slope stability; vegetation; root-soil composite system

Introduction

In recent years, the occurrence of slope failure and soil erosion induced by local environment, such as seasonal heavy rainfall, has been increasing all around world especially in arid and semiarid region worldwide (Eab et al. 2014). Due to the fragile ecological environment and the influence of human engineering activities, the loess slope geological disasters such as soil erosion and landslides have been reported frequently in China Loess Plateau (Figure 1(a)), which covers $6 \times 10^5 \text{ km}^2$ over the northern Shaanxi province and extensive areas of the Shanxi, Gansu, Ningxia and Henan provinces (Wang et al. 2015; Hu et al. 2018).

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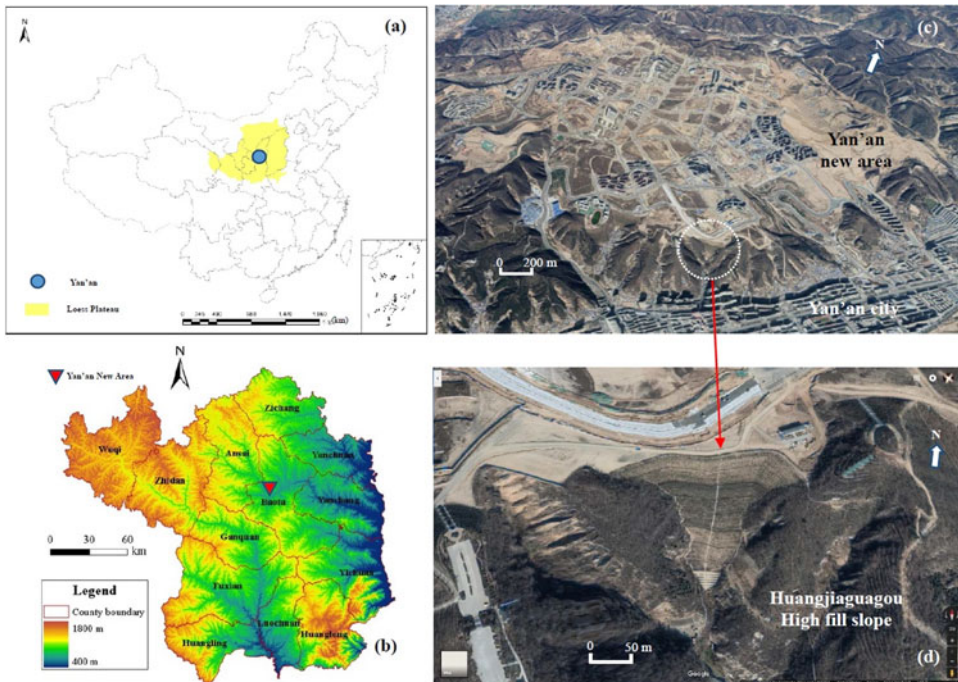


Figure 1. Location of study area. a) Location of Loess Plateau and Yan'an, b) Location and topography of Yan'an area (including Yan'an city and other counties), c) Yan'an new area (Satellite image from Google Earth), d) Huangjiaguagou high fill slope (Satellite image from Google Earth). Source: Juang et al. (2019)

Loess has distinctive physical and mechanical properties (Hessel and Asch 2003; Jefferson et al. 2003; Acharya et al. 2011; Shroder et al. 2011; Wang et al. 2013), such as high porosity, sets of vertical joints and metastable structure failure (loess water collapsibility), so that the Loess Plateau is one of the regions prone to soil erosion and geological hazards in China (Sun 1989; Dijkstra et al. 1994; Derbyshire et al. 2000; Derbyshire et al. 2001; Li et al. 2013a; Li et al. 2013b, Hu et al. 2018), where about 20% of the Chinese population lives.

On the other side, in Yan'an area (Figure 1(b)), the man-made engineering activities to expand the urban areas due to the growth of economy and population may exacerbate the environmental destruction and geological disaster (Liu and Li 2014). The Yan'an area has experienced several geological disasters in the past. For example, in July 2013, a heavy rainfall in Yan'an area induced more than 8000 landslides (about 0.22 landslides/km²), most of which within the loess flow slides and killed 45 residents (Wang et al. 2015). These loess slope geological disasters not only pose a serious threat to the life of local residents but also worsen the problems of soil erosion and natural environment deterioration, which would be feeding back into the still fragile loess slope and induce new geological disasters.

Therefore, the enhancement of geological disaster treatment and environmental protection is one of the most important tasks in China Loess Plateau, especially in Yan'an area. Traditional geological hazard treatment methods, such as anti-slide pile, anchor, retaining wall, satisfy the safety requirements and have been widely used in loess slope engineering.

The instability of loess slope can be mitigated by the traditional method of treating slope, but the negative impact that they will have on the appearance of its surrounding environment is of a concern. A soil-bioengineering approach is an alternative which is the use of live materials such as plants, vegetation and grasses in protection of the slope against failure and soil erosion (Eab et al. 2014, 2015). With the theory of soil-bioengineering, one solution may be the combination of engineering technical projects and ecological restoration measures, which must be also locally applicable (Marco 2007). These researches show that the contents of soil-bioengineering are not related to the mere use of vegetation for stabilizing purposes, but they focus on broader environmental concerns (Bischetti et al. 2014). There is an emphasis on the necessity to reconcile both natural hazard control and ecological restoration (Rey et al. 2019).

With the development of soil-bioengineering, the concept of slope ecological protection has emerged and the relevant practices of soil-bioengineering are arising in recent years (O'Loughlin 1974; Gray and Leiser 1982; Gray and Sotir 1996; Greenwood et al. 2006; Barker 1995; Niu et al. 2016; Sidle and Bogaard 2016). The significance of plants in water and soil conservation has been generally an accepted and established approach (Ren 2004; Zhang et al. 2007; Evette et al. 2009; Burylo et al. 2011; Eab et al. 2014, 2015), but vegetation growing on a slope has traditionally been considered to have a minor effect on slope stability. However, in some cases, this assumption may not be correct, and a growing body of research suggests that the loess slope protection by vegetation is an effective method for restoration ecology and geological disaster prevention (Waldron 1977; Cislighi et al. 2019; Nguyen et al. 2019).

There are three main slope protection effects of vegetation: hydrologic effect of stems and leaves, soil reinforcement of roots and ecological restoration. Stems and leaves can effectively reduce surface erosion of loess slope in rainfall, mainly with rainfall interception effect and rainfall reallocation effect by plant stems and leaves, the effect of reduction in raindrop splash erosion by foliage, and plant residues and surface runoff retardation effect by plant aboveground residues. The developed root system can not only effectively enhance the survivability of vegetation, but also form a stable root-soil composite system to protect slope with reinforcement effect by fibril roots, anchorage effect by taproots and traction effect by horizontal roots.

Many researchers focus on the relationships between slope stability and slope plants worldwide (Stokes, Norris, et al. 2008; Stokes, Sotir, et al. 2010), including the study in Loess Plateau (Li and Li 2011; Ji et al. 2012; Ma et al. 2012; Zhang et al. 2014; Fu et al. 2016; Liu et al. 2017). The stability of loess slope protection by vegetation can be affected by the complex interactions of factors beyond geological engineering conditions, such as local soil characteristics (Charlafti 2014), plant traits, human activity and climate (Stokes et al. 2009). Because the distribution of the plant species is local, there are complex interactions of factors, as there are in any part of the technology promotion and application, where obstacles tend to be complicated and localized. In the international literature, data on the effect of slope plant can be found and generalized for similar environments, and many researchers agree that those values need to be localized for any specific project. Study on loess slope stability

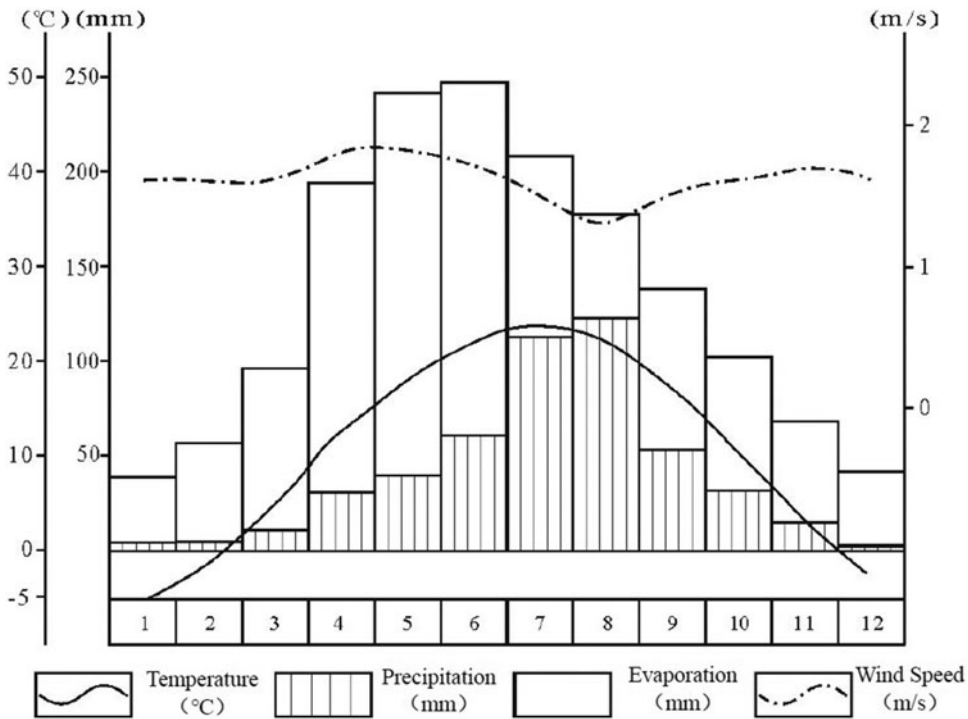


Figure 2. Statistics of meteorological factors (monthly average) in the area of Yan'an since 1970.

by vegetation requires the screening for right plants adapted to local environmental strains.

In this paper, the engineering geological characteristic and the vegetation community structure were studied through field investigation in Yan'an area. The vegetation community structure was analysed by data statistics to screen out the potential species for ecological restoration and slope protection. The results present the findings of an exploratory analysis into the use of native *Artemisia* spp. for ecological restoration and slope stability. Field root pull-out test and direct shear test for soil without roots and root-soil composite systems were conducted to analyse the reinforcement effect of *Artemisia* spp. The results from quantitative analysis of the slope protection effect showed that the slope safety factor could be obviously improved by the growth of *Artemisia* spp. As the survey, test, stability analysis and case study shown, *Artemisia* spp. can effectively prevent the occurrence of loess flow slides and shallow landslides, which has extensive application prospect.

Materials and methods

Study area

Situated in Northern Shaanxi Province on the south-central part of the Loess Plateau ($35^{\circ}21' - 37^{\circ}31' N$ and $107^{\circ}41' - 110^{\circ}31' E$) (Lü et al. 2012), the Yan'an area overlooks the middle reaches of the Yellow River, the cradle of Chinese Civilization, and covers an area of about $3.7 \times 10^4 \text{ km}^2$. This survey, of more than 300 natural loess slopes

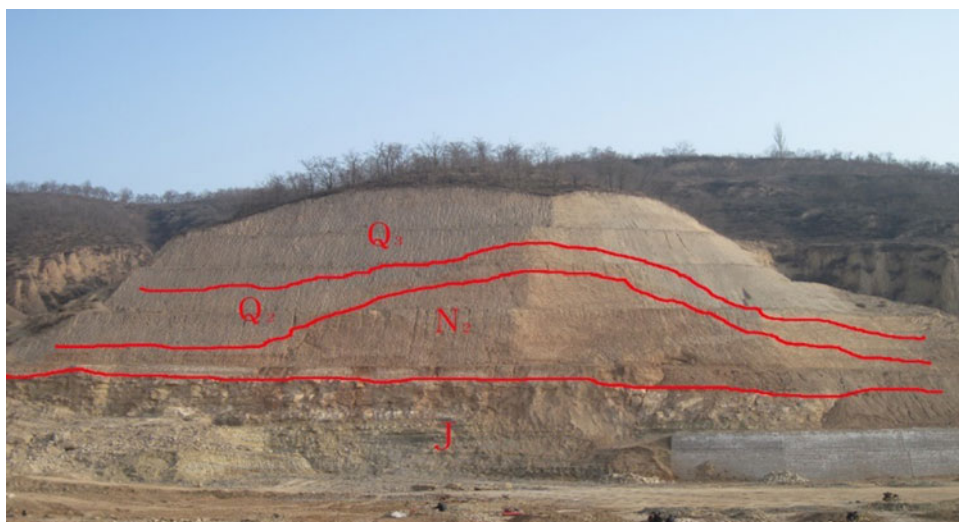


Figure 3. Typical strata of loess slope in Yan'an in this survey.

and very few artificial slopes, began in 2014 and continues to present day, has been expanded from Yan'an city (Baota county) to other 11 counties (Figure 1(b)).


Yan'an has a semiarid continental climate that borders on a steppe climate, with cold, dry and moderately long winters, and hot, somewhat humid summers. Spring and autumn are short transition seasons in between. The monthly 24-hour average temperature ranges from -5.5°C (22.1°F) in January to 23.1°C (73.6°F) in July, and the annual mean is 9.90°C (49.8°F). The mean annual precipitation is 511 mm (20.1 in) of precipitation, and more than 70% of the annual precipitation may fall in a few heavy rainstorms between June and September (Figure 2). The greatest single storm event within a 24-h period was 139.9 mm in 1981, and the maximum monthly rainfall was 577 mm in July 2013. Moreover, the rainfall events with high intensities and shorter durations play dominant roles in causing soil and water loss in the study area and then induce various geological hazards. However, with strong evaporation and arid climate, this region has a weak ecological environment in general, and it is difficult to breed and propagate plants.

In Yan'an area, elevations generally increase from south-east to north-west with an altitude between 500 and 1600 m.a.s.l. There is a huge difference between daytime and night-time temperatures because of the climate and geographical condition. The geomorphic landscape is usually characterized by gullies, where the gravity erosion such as slide and collapse is very active.

In general, the stratum in Yan'an is deposited in sequences of sandstone (J), mudstone (N) and thick-bedded eolian Pleistocene loess (Q). The Pleistocene loess (Q) is, in order from old to young formations, Late Pleistocene Wucheng Loess (Q1) in some regions, Middle Pleistocene Lishi Loess (Q2) and Early Pleistocene Malan Loess (Q3) with a thickness of about 10–30 m (Figure 3). In particular, the Malan loess (Q3) has a well-distributed particle size, is porous (commonly with porosities of more than 50%) and possesses unstratified structures, obvious perpendicular fissures, large bearing capacity, collapsibility and structural behaviour. These characteristics make

Table 1. An example of the field book completed during the survey.

Location: Road between Louping and Nangou		Survey area: $1 \times 1\text{m}^2$	
Slope /Aspect	72°/85°	Altitude (m)	1073
E	109°18'12.8"	N	36°37'4"
Soil erosion	Rain or wind	Soil humidity	Medium
Dominant species	Artemisia spp.	Coverage	40%
Soil characteristics	Colluvial loess, tawny, crumbly topsoil and dense loess below 3–4 cm, distributed evenly, plasticity		
Physiognomy	Low hill		
Number	Species	Quantity	Height (cm)
1	Artemisia ordosica	12	30
2	Jujube	1	50



the Malan loess (Q3) sensitive to water infiltration. Water increases the bulk weight of the Malan loess and reduces its shear strength. As a result, shallow loess flow slides and landslides frequently occur along the loess slopes (Wang et al. 2015).

Vegetation survey

Considered as the most basic measure of plant–environment relationships, vegetation community structure is a collection or association of plant species within a designated geographical unit, which forms a relatively uniform patch, distinguishable from neighbouring patches of different vegetation types. The components of each plant community are influenced by soil type, topography, climate and human disturbance.

In order to characterize the topography and physiognomy of the Loess Plateau, field investigations were carried out in loess hilly and gully region, mainly in spring, summer and early autumn. In order to get more statistic of local natural plants and analyse vegetation community structure, the investigators mainly drive along the country roads and then take a walking deep into loess hilly and gully where it is usually hard for car to get in. Representative loess slopes were chosen for the survey, with thick loess cover and well-grown natural plants. At each investigation site, we considered a quadrat of $1 \times 1\text{ m}$ for the investigation and took photographs. With ruler and shovel, we could cut an outline of the investigation quadrat ($1 \times 1\text{ m}$) on the slope. It was ensured that the distance between the investigation point and the upper or lower edges of slope is not less than 1.5 m. The information that was collected throughout the survey included the following: (1) The latitude, longitude, slope gradient, hydrogeological condition, etc.; (2) the statistics of plants, such as dominant families, genera and vegetation density as well as growth characteristics; and (3) photographs and videos. The data were analysed using statistical methods. Typical investigation point and simple field book are exemplified in Table 1.

Soil section survey

In the process of vegetation survey, the status of the soil section was examined using some typical samples of natural loess slope. The dry excavation method was carefully conducted along the plant's growth position in both directions of slope's elevation and section. In order to measure, record and assess the root distribution and

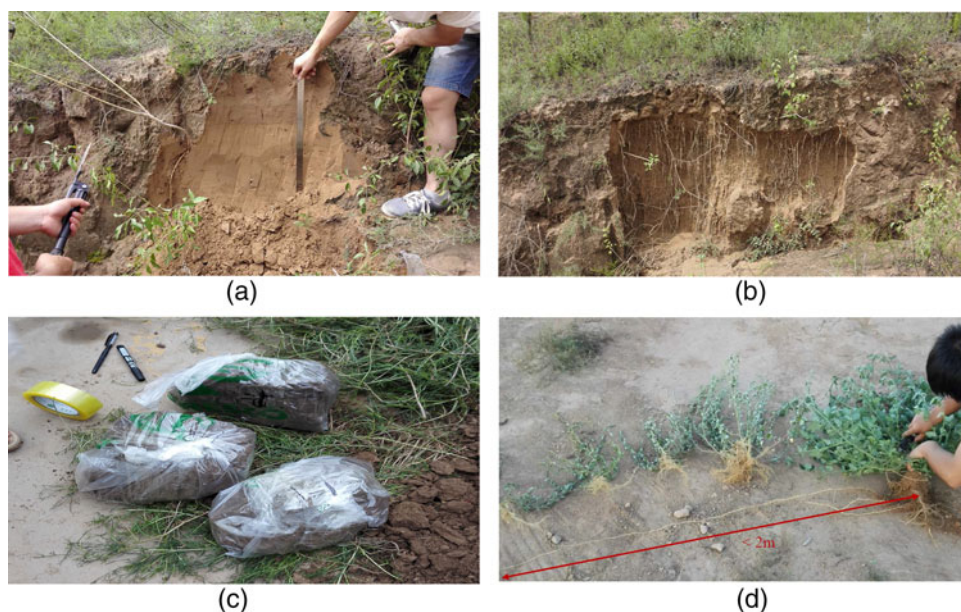


Figure 4. Typical section investigation process on some loess slope. a) Excavation and recording procedure, b) Root distribution in a section, c) Soil sampling, d) Plant sampling.

architecture characteristics with original natural state, the excavation should be no less than the root depth.

After the soil section survey, the soils without roots and root-soil composite system samples were excavated out carefully from the soil section. Then, plastic bags were used to envelop all blocks of soil samples immediately, and they were individually put into the testing cases and were taken back to the laboratory for direct shear tests and moisture content tests. Typical section excavation and sampling process on some of the slopes mostly covered with *Artemisia* spp. are shown in [Figure 4](#).

Field root pull-out test

Root-soil mechanical interaction is a key to loess slope stability, so we conducted field root pull-out test to analyse the reinforcement effect of dominant species during the process of the vegetation survey. To implement the experiment, a equipment for field root pull-out test was designed. Its tripod is portable and adjustable to irregular slope, and can support a force of up to 1.8 kN. The guy wire of the winch passes through a centring guide which is mounted at the top of the tripod. A force transducer with a max support of 1.5 kN and a displacement transducer with ranging accuracy of millimeter are installed in this equipment. The history data can be stored automatically in the transducer, or can also be send to a laptop computer that instantly stores the data and generates a displacement versus force graph. Afterwards, the peak in the generated graph indicates the maximum force required for a plant to be uprooted. The equipment for field root pull-out test is shown in [Figure 5](#).

These tests were performed under similar weather and soil conditions. No rain showers had occurred during the previous days so that the soil was mostly dry and

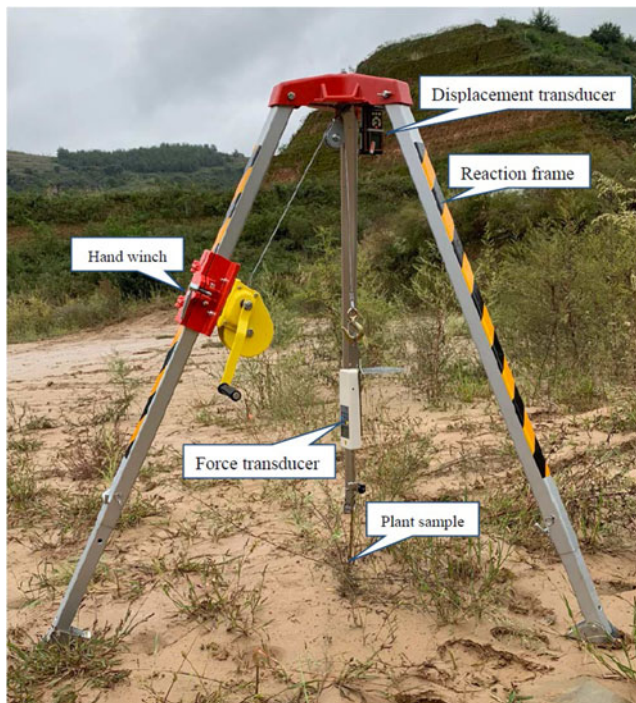


Figure 5. Equipment for field root pull-out test.

dense (most soil moisture content is about 15%~18% according to moisture content tests). Each selected plant was identified with a specific number, and the ground surface around the plants was cleared to facilitate the setting of the equipment. In the next step, the lengths of the plants were measured with a yardstick and the diameter of each stem was taken using a Vernier calliper. The pull-out process is performed at a constant rate of uplift (about 100 mm/min). The test was continued until the entire root system was pulled out of the soil. Additionally, the root characteristics of the plants were measured on site after the pull-out test. In total, 103 pull-out tests, in similar conditions, performed for 11 species, including five species of *Artemisia* spp. (*Artemisia ordosica* (*Artemisia ordosica* Krasch.), *Artemisia hedinii* (*Artemisia hedinii* Ostenf. et Pauls.) and *Artemisia sacrorum* (*Artemisia sacrorum* Ledeb.), *Artemisia annua* (*Artemisia annua* Linn.), *Artemisia dracunculus* (*Artemisia dracunculus* Linn.)) and other six species of Herb, which were the most common species on natural loess slopes in this survey. The data generated during the pull-out test would be analysed statistically in order to get a better understanding of the maximum uprooting resistance of different species.

Soil direct shear test

It is well known that root-soil interactions can effectively improve slope stability. Most studies have shown that the physical and mechanical parameters of soil without roots are obviously lower than the parameters of root-soil composite systems (Waldron 1977; Wu et al. 1979; Waldron and Dakessian 1981; Ziemer 1981;

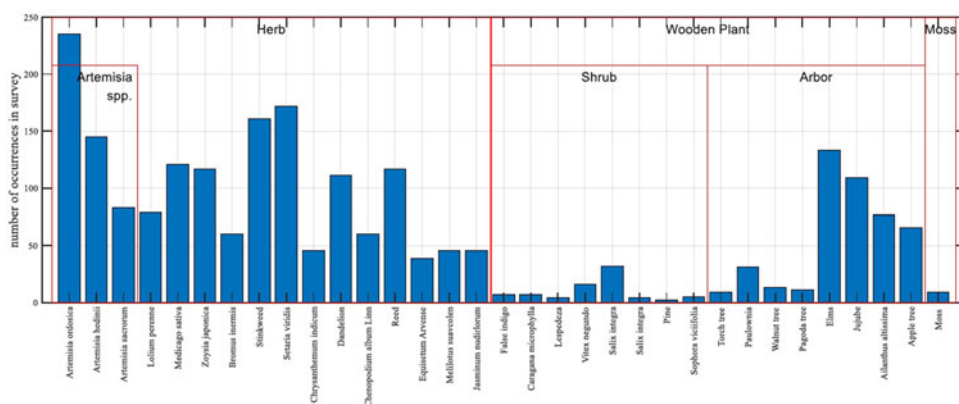


Figure 6. The number of occurrences in survey.

Ekanayake and Phillips 1999; Nilaweera and Nutalaya 1999; Operstein and Frydman 2000).

As the *Artemisia* spp. was one of the most common species during the survey, the six blocks of soil without roots and the six blocks of root-soil composite system samples, from the slopes mostly covered with *Artemisia* spp. (*Artemisia ordosica* (*Artemisia ordosica* Krasch.)) in the same area, were sent back to the laboratory for indoor soil test, mainly including moisture content test and direct shear test. First, the moisture content of soil was measured. Then, the soil samples for large direct shear test were obtained with the rigid steel-cutting ring (sample diameter 300 mm, height 150 mm) from the blocks of soil, and four samples were taken from each block of soil. At last, direct shear tests were conducted on each sample under four vertical pressures (50, 100, 200 and 300 kPa). The process was performed at a constant shear rate (0.8 mm/min). The test was continued until the sample was completely destroyed.

Case study

In addition to general constructions such as building and roads, there is a large-scale project on going in the Loess Plateau, which is part of the campaign to remove the upper level of the mountains to fill in the valleys to create flat land for more constructions (Li et al. 2014). This is one of the largest projects in the Yan'an new area (Figure 1(c)), which started in April 2012 and is expected to double the city's current area by adding 78.5 km² of flat ground (Bai et al. 2014). The location and topography of Yan'an and Yan'an new area, as well as typical high fill slope formed by removing the tops of mountains to fill the valley, are shown in Figure 1c. This will enhance the probability of the hazards associates with the changes in the rock and soil structure. As shown in Figure 1(d), Huangjiaguagou high fill slope is located on the edge of Yan'an new area, which was once a several hundred meters deep natural gully. We continued to investigate the local natural growing plants in Huangjiaguagou high fill slope since 2014. With this case study, the relative dominance of local pioneer plant was investigated. Moreover, the change of diversity of species in an ecological

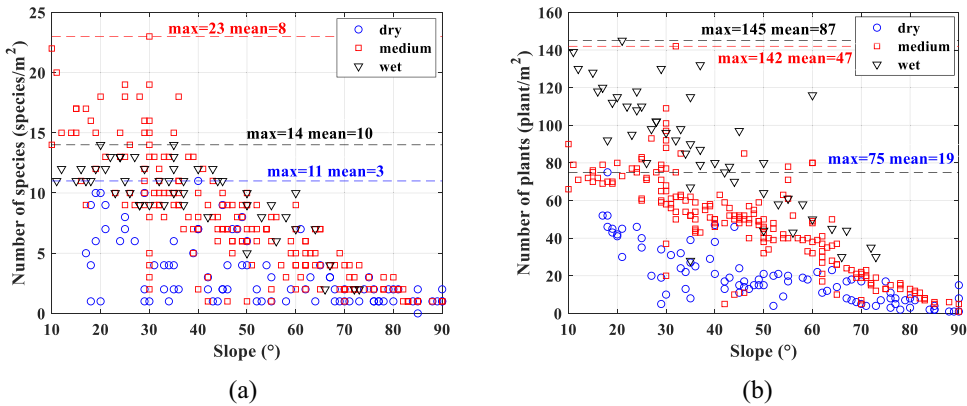


Figure 7. Statistics of species, plant number, soil moisture and slope. a) statistics of species, soil moisture and slope and b) statistics of plant number, soil moisture and slope.

community, as well as the slope protects effect of local pioneer plant, can be further analysed.

Results

Vegetation community structure

The statistics of plant species is one of the most important indexes of vegetation community structure. In this survey, although a great diversity of plants was observed, only 33 main plant species on natural loess slope in Yan'an area were analysed, including 15 species of Herb, nine species of Shrub, eight species of Arbor and 1 species of Moss. The statistic on the number of occurrences of main vegetation species in surveys is listed in Figure 6.

The above statistics indicate that the vegetation species diversity in Yan'an is below the medium level, which accords with the slope vegetation composition characteristics of loess plateau semiarid areas. The main vegetation species statistics is also indicative of the dominance of Herb, and therein *Artemisia* spp., mainly including *Artemisia ordosica* (*Artemisia ordosica* Krasch.), *Artemisia hedinii* (*Artemisia hedinii* Ostenf. et Pauls.) and *Artemisia sacrorum* (*Artemisia sacrorum* Ledeb.). These are the main varieties of loess slope naturally growing vegetation and repeated most often in the data statistic, which are the potential species for ecological restoration and slope protection in Yan'an area.

The state of plant community is directly affected by the local slope habitat with many influencing factors, such as slope height, slope degree, slope aspect, soil thickness and soil matrix. Figure 7(a) illustrates the number of species, and Figure 7(b) illustrates the number of plant in every slope. Based on the data analysis shown in Figure 7, the main influencing factors in this study appear to be the slope and soil moisture. Generally, the number of species as well as plants declines obviously with less soil moist and deeper slope, such as the statistical mean value shown in Figure 7. However, with regard to the statistical max value shown in Figure 7(a), the number of species in 'wet' condition is less than that in 'medium' condition of soil moisture.

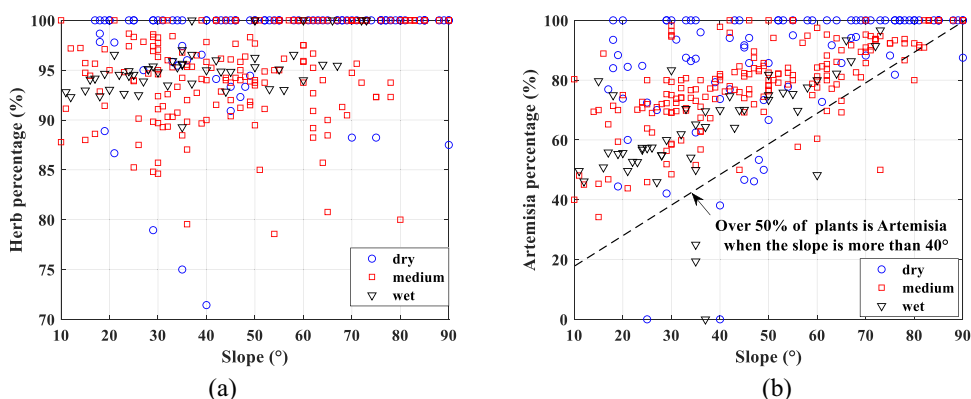


Figure 8. Proportion of some plant. **a)** proportion of Herb and **b)** proportion of Artemisia spp.

The reason, soil moisture is the main factor of plant growth, but some local drought-tolerant species may not stand the long-term high soil moisture environment.

Loess in Yan'an is a porous (commonly with porosities of more than 50%) formation and possesses unstratified structures, with obvious perpendicular fissures, collapsibility and structural behaviour. These characteristics significantly reduce the soil's capacity to store water and nutrients at ordinary times, which dries out most plants. On the other hand, the loess's sensibility to water infiltration significantly increases the bulk weight of loess and reduces its shear strength during the heavy rainfall, so shallow loess flow slides and landslides frequently occur along the loess slopes; then, soil erosion, as well as land degradation, is aggravated. Therefore, the soil's capacity to store water and nutrients is one of the most important influencing factors. The 'soil moist' of the root zone layer, recorded in vegetation investigation, presents a good reflection of above influencing factors on the soil's capacity to store water and nutrients. Similarly, the 'slope' is another most important influencing factor, which is often viewed as direct parameter impacting the slope stability, plants attachment, soil erosion as well as above factors.

Growth characteristics

As mentioned before, the vegetation species diversity in Yan'an is below the medium level, which accords with the slope vegetation composition characteristics of loess plateau semiarid areas. The drought and freezing-tolerant plant types are the main varieties of loess slope vegetation. However, there are significant differences in growth status between plant species. For example, Herb accounts more than 70% of the total number of plants were seen in all slopes under this investigation (Figure 8(a)), and a considerable part of Herb is Artemisia spp. (Figure 8(b)). Moreover, as shown in Figure 8(a,b), this trend of high proportion of Herb and its Artemisia spp. is even more marked with less soil moist and more slope.

Artemisia spp. is the main species of loess slope naturally growing vegetation in the data statistic, which is the potential species for ecological restoration and slope protection in Yan'an area. Study on its slope protection effect, as well as growth characteristics, plays an important role in loess slope stability and ecological restoration.

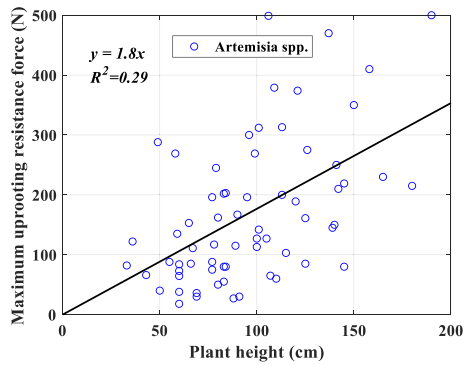


Figure 9. Statistics of *Artemisia* spp. Height.

Field root pull-out test

The collected data from the pull-out test plus the most correlating variable of the plants' morphological properties and the maximum uprooting resistance are shown in Figures 9–12, together with the linear curve fitting and coefficient of determination (R^2).

As Figures 9–11 show, among these correlating variable of the plants' morphological properties, maximum taproot diameter ($R^2 = 0.61$) is most relevant to maximum uprooting resistance force, so the relationship between maximum taproot diameter and maximum uprooting resistance force was chosen to analyse the differences between species. In general, the root density is one of the most major factors to influence the ultimate uprooting resistance, but maximum taproot diameter also could be the factor to reflect indirectly the influence degree of root density, easier for statistics and analysis. In some studies, maximum uprooting resistance force is the same parameter as shear strength to compare the qualification of the species to be used in loess slope protection (Florineth 2012). The greater the maximum uprooting resistance force (or shear strength) of a single plant, the stronger its ability to reinforce soil shear strength (Gray and Sotir 1996; Zhu et al. 2008; Hu et al. 2009; Yang et al. 2009). Comparing Figure 11 with Figure 12, *Artemisia* spp. show a better performance than other Herb ($R^2 = 0.04$) in uprooting resistance, which is important in engineering applications, so that *Artemisia* spp. has great potential in ecological restoration and slope protection in Yan'an area.

Soil direct shear test

Indoor soil test, mainly including moisture content test and direct shear test, was conducted for both *Artemisia ordosica* (*Artemisia ordosica* Krasch.) root-soil composite systems and soil without roots. The results showed line relationships between shear strength and vertical pressure. The results were derived from 48 samples, the number of tested replication was 6, and root area ratio (RAR) after test averaged 0.3%. According to the moisture content tests of 12 samples, average soil moisture content is 16.85% and 16.75% for *Artemisia* spp. root-soil composite systems and soil without roots, respectively. The reinforcement effect of topsoil with *Artemisia*

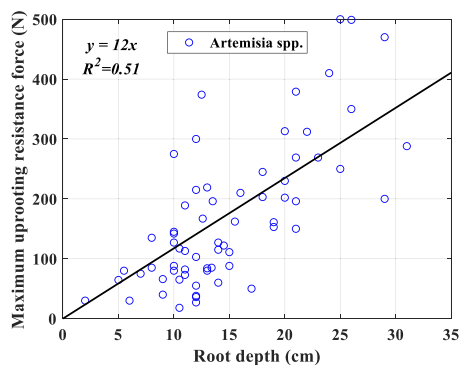


Figure 10. Statistics of *Artemisia* spp. root depth.

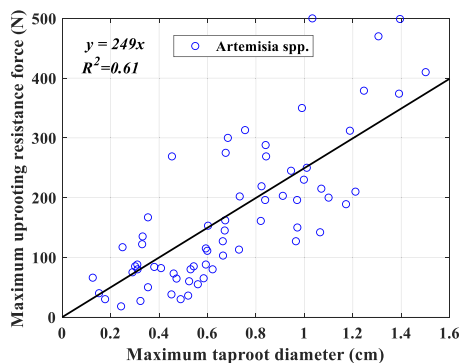


Figure 11. Statistics of *Artemisia* spp. root diameter.

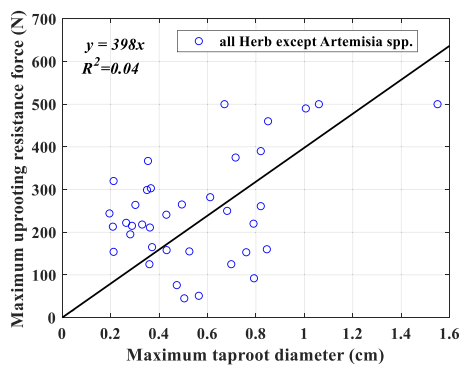


Figure 12. Statistics of Herb root diameter.

ordosica (*Artemisia ordosica* Krasch.) roots through the direct shear tests is shown in Figure 13. In this figure, values of shear strengths are shown as a function of the vertical stress. Both cohesion force and internal friction angle of the root-soil composite system for *Artemisia ordosica* (*Artemisia ordosica* Krasch.) are notably greater than those of the soil without roots, with an incremental cohesion force value of around 34.45% (from 8.95° to 10.26°) and internal friction angle value of around 14.64% (from 4.18 to 5.26) greater than soil without roots, respectively.

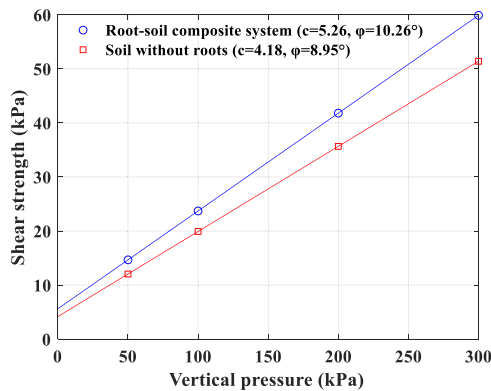


Figure 13. effect of reinforcement with *Artemisia ordosica* (*Artemisia ordosica* Krasch.) roots.

Discussion

Relative dominance of Artemisia spp. on loess slope

The harsh conditions, such as geology, soil and climate, produce an unfavourable environment for plants grown in Yan'an area, where common slope-protecting plants in other parts of China can be difficult to grow on loess slope. Besides the plant adaptation to the severe environment in Yan'an area, species colonization is a great potential risk with the introduction of alien species.

Therefore, it is necessary to screen out local native plants to choose potential species, which are suitable for ecological restoration and slope protection in Yan'an area. Among these plant species on natural loess slope in this vegetation survey, *Artemisia* spp. found to be the main species of loess slope naturally growing vegetation. As above statistical analysis showed, *Artemisia* spp. quantity decreases with the increase of gradient or the decrease of soil moisture as all other species, but the relative dominance of *Artemisia* spp. increases on loess slope, accounting for about over half of all the plants with the slope more than 40° (Figure 8), which shows that *Artemisia* spp. has a better adaptability to surrounding and its advantage will be more obvious with habitat destruction.

Taking Huangjiaguagou high fill slope as an example, the relative dominance of *Artemisia* spp. was further analysed. As shown in Figure 14(c), Huangjiaguagou high fill slope is located on the edge of Yan'an new area, which was once a several hundred meters deep natural gully (Figure 14(a)). In July 2015, shortly after this high fill slope was completed, we carried out a field survey on it and analysed its environment changes, aiming to identify the potential species for ecological restoration and slope protection. Taken in July 2015, photographs of Figure 14(a) give a visual representation of the situation. Soil erosion and desiccation in this slope were very serious. Most of the artificial cultivated plants with good care, such as cypress (*Platycladus orientalis*), have shrivelled and died. On the other hand, wild *Artemisia* spp., almost the only species, has completely covered the entire slope (Figure 14(b)) like many other investigation slopes.

Various reasons contribute to the relative dominance of *Artemisia* spp., with its strong resistance to cold, drought, barren and salinity believed to be the primary



Figure 14. Huangjiaguagou high fill slope. a) An overview of the slope (July 2015), b) the growth state of plants (July 2015) and c) the growth state of plants (July 2016).

ones. Secondly, the root distribution characteristic is another limiting factor for plant growth in Yan'an area. Although *Artemisia* spp. is one of the hardy herbaceous plants that belongs to the daisy family Asteraceae, the roots of *Artemisia* spp. have the characteristic of woody plants, including long, thick, sturdy and woody taproot as well as developed lateral root, which can adapt to the local harsh environment of soils and slope. *Artemisia* spp. usually has a root length of over 0.5 m, more than its height of the plant (Figure 4(b)), and considerable part of *Artemisia* spp. species can be over 2 m in this survey (Figure 4(d)), which can form a more stable root-soil composite system, resulting in stronger uprooting resistance (Figure 11) to allow themselves to take root in the loose loess. Moreover, *Artemisia* spp. can fully use water and nutrients in barren loess with its developed root system.

Loess slope ecological protection of *Artemisia* spp

Yan'an area is the worst vulnerable eco-environment, soil erosion and loess geological disaster area in China, where loess slope geological disasters seriously aggravate the problems of soil erosion and natural environment deterioration, which, in turn, would be feeding back into the fragile loess slope and induce new geological disasters. The best way to avoid this vicious circle is loess slope stabilization by vegetation to fundamentally improve slope stability and environment. *Artemisia* spp. is the main species on natural loess slope due to its viability, which is the suitable species for ecological restoration and slope protection. The hydrologic effect of stems and leaves, soil reinforcement of roots and ecological restoration of *Artemisia* spp. is significant. *Artemisia* spp. can effectively reduce surface erosion of loess slope in rainfall. The developed root system can not only effectively enhance the survivability of *Artemisia* spp., but also form a stable root-soil composite system to greatly improve the

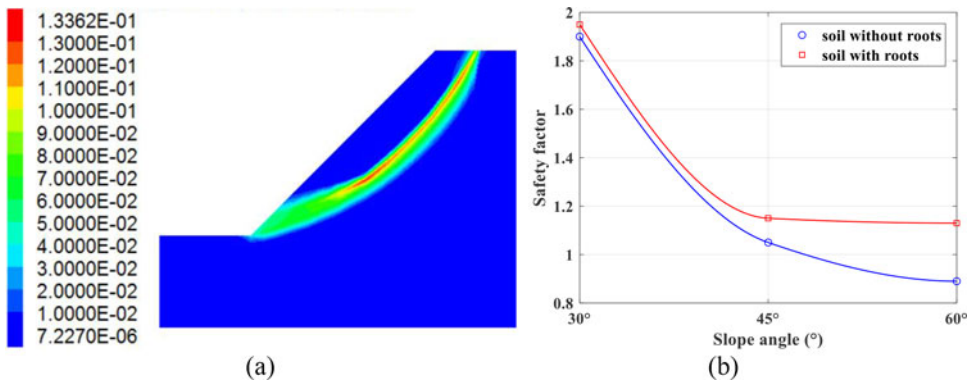


Figure 15. Numerical modelling. a) contour of max shear strain increment and b) safety factor as function of slope angle.

mechanical parameters of soil, such as cohesion force and internal friction angle, as above large direct shear test shown (Figure 13).

Compared to other species, another important advantage of *Artemisia* spp. is an obvious effect of ecological restoration. The vegetation surveys for many years in a row have shown that the community structure of the ecosystem can be restored by *Artemisia* spp. It is all known that the diversity of species in an ecological community is the core of ecosystem stability, sustainability and rehabilitation. Although *Artemisia* spp. is an absolute majority in most steep loess slopes, the relative dominance of *Artemisia* spp. will keep decreasing with time. Through two-year observations (2015–2016) and comparison in community structure of Huangjiaguagou high fill slope, it can be seen that plant species remarkably increased from a single *Artemisia* spp. (comparing Figure 14(b, c)).

The developed root system of *Artemisia* spp. not only reduces soil erosion and desiccation, and improves the stability of the slope, but also improves soil's ability of fertilizer and water conservation and then encourages suitable habitats for microorganisms. With the improvement of soil condition, various kinds of other plants, which might not once survive in this barren soil, are able to grow well. This illustrates the ecological restoration and reconstruction of loess slope are gradually improved because of the ecological plasticity of *Artemisia* spp. Therefore, *Artemisia* spp. is particularly suitable as pioneer plant for loess slope ecosystem reconstruction without special maintenance, and then, the diversity of species in an ecological community can be increased effectively by natural growth or human interaction in this improving process of soil.

Loess slope stability protection of *Artemisia* spp

It is well known that root-soil interactions can effectively improve slope stability. As shown in Figure 13, both cohesion force (c) and internal friction angle (ϕ) of the *Artemisia* spp. root-soil composite system are notably greater than those of the soil without roots, with an incremental cohesion force value of around 34.45% and internal friction angle value of around 14.64% greater than soil without roots, respectively. On the other hand, of the plants analysed in our field root pull-out test,

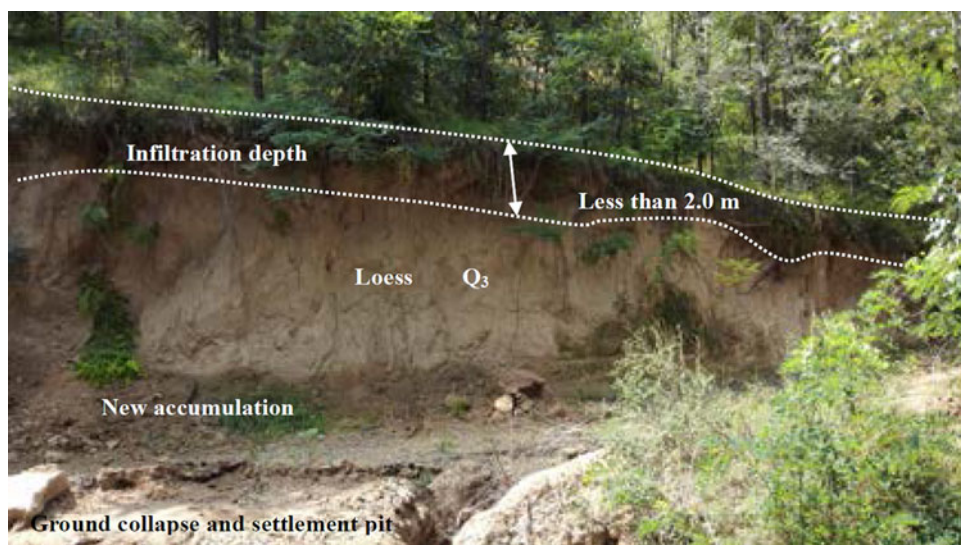


Figure 16. Infiltration depth of slope (August 2015).

Artemisia spp. has obviously more stable performance than other plants in uprooting resistance (Figure 11), which is an indicator for the stability of the soil-root composite systems and expresses the stabilizing effects of plants on the soil.

The quantitative analysis of the slope protection effect of *Artemisia* spp. was provided by the calculation of the safety factor (F_s) of different slopes by a classical shear reduction method with the software FLAC in 2D. The model is shown in Figure 15(a). The safety factor (F_s) was determined based on strength reduction technique which consists to decrease the shear strength of the soil matrix until failure occurs. A detailed description of this kind of procedure can be found in previous works (Kokutse et al. 2016; Nguyen et al. 2018). In this slope model of 10-m height, the effects of the roots are modelled by increasing the cohesion force and internal friction angle value of slope topsoil as shown in Figure 13. We examined the influence of different angles α of a slope ranging from 30° to 60° ($\alpha = 30^\circ, 45^\circ$ and 60°). As simulation results shown in Figure 15(b), an improvement of the slope's stability, with the slope protection effect of *Artemisia* spp., is easily perceptible. It is all known that mild or moderate slope (smaller inclination) is more stable than a sharp (peaked) slope. More importantly, the more slope angle, the better are the slope protection effect of *Artemisia* spp. Simulation results show an improvement of the safety factor from the slope angle from $30^\circ, 45^\circ$ to 60° , and the safety factor increased respectively by 2.63%, 9.52% and 26.97% with the slope protection effect of *Artemisia* spp.

Of course, the selected plants for slope protection should not only have better mechanical properties (Figures 11 and 13) but also be suitable for the characteristics of local geological disaster, such as rain-triggered shallow slider. Yan'an is a geological disaster-prone and vulnerable eco-environmental area. Besides soil erosion, loess slope failure, including landslide and loess flow-slide, is the most severe problem of geological disaster in Yan'an. Loess flow slide is the most common hazard following rainfall, characterized by a small thickness, narrow-long shape,

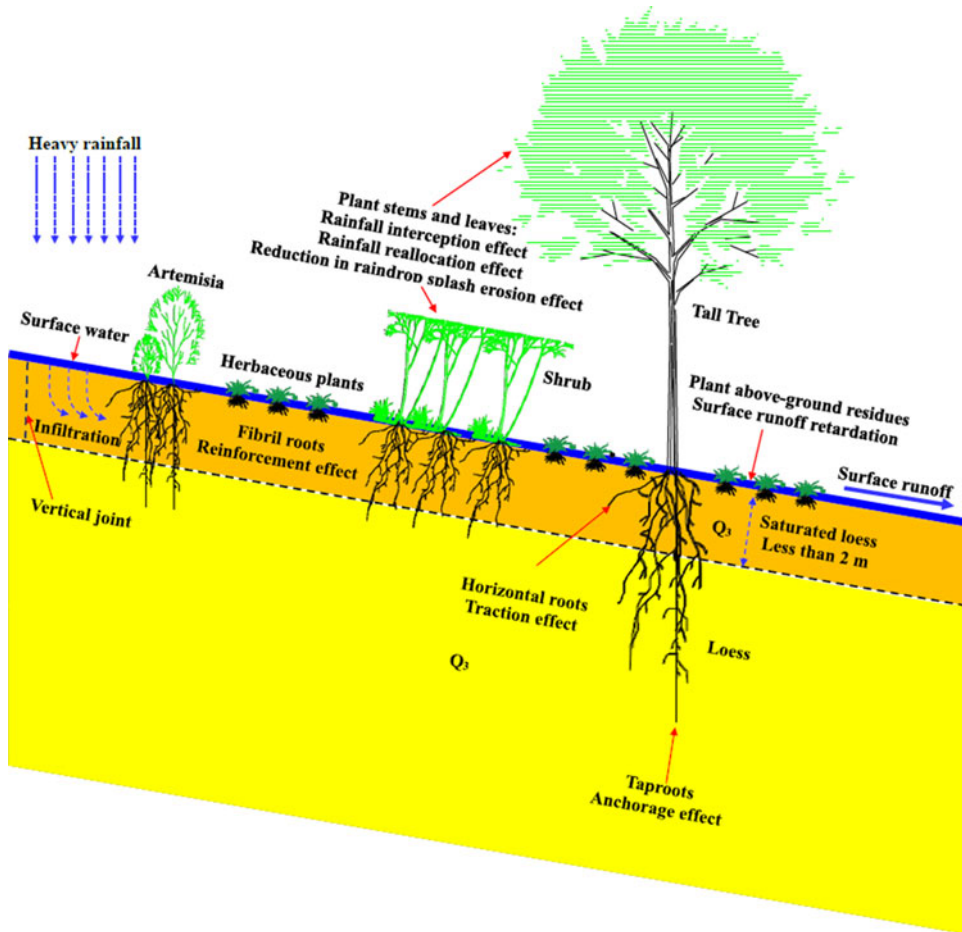


Figure 17. Vegetation strategies of loess slope protection in Yan'an.

rapid surface runoff and high water content (meeting or exceeding the liquid limit), and the occurrence of loess flow slide is closely related to rainfall intensity, infiltration depth and weak strength of the saturated loess (Wang et al. 2015). Based on previous researches (Dai et al. 1999; Billard et al. 2000; Tu et al. 2009; Zhang and Liu 2010), the loess flow slides are usually induced by rainfall and occur in a surface layer of completely saturated loess with a depth of <2 m, corresponding to a surface layer of completely saturated loess. The consequence of an infiltration depth of <2 m was essentially consistent with our investigation in Yan'an area (Figure 16).

Because the water content of loess is the main controlling factor of the shear strength, the loess flow slide usually occurred under a certain thickness of saturated, consistent with the infiltration depth of loess slope under heavy rainfall. It is well known that plants are beneficial for preventing soil erosion with hydrological and mechanical effects, but vegetation growing on a slope has traditionally been considered to have a temporary and limited effect on a slope stability, because the roots of some grasses (e.g. *Setaria viridis* (*Setaria viridis* (Linn.) Beauv.)) and bushes (e.g.

Sabina vulgaris (*Sabina vulgaris* Ant.) generally only extend <50 cm in depth, much less than infiltration depth of loess in rainfall. However, our field investigation showed that the root length of most *Artemisia* spp. is usually more than its plant height (Figure 4(b)), and many perennial *Artemisia* spp. species, having been growing for a year or two, can reinforce deeper loess mass and effectively prevent the occurrence of loess flow slides as well as shallow landslides with over 2-m root system as an anchor for the overlying materials. Although many trees also have longer and stronger roots than many other plants in Yan'an area, their great weight makes themselves difficult to stick on the steep and loose slope, as Figure 16 shows that trees can only grow on the platform on top of the slope, consistent with the statistics of species (Figure 7). Moreover, the environment requirements of trees, such as water, nutrients and soil condition, are much more than *Artemisia* spp. Therefore, *Artemisia* spp. is particularly suitable as pioneer plant for loess slope ecosystem reconstruction and slope stability protection.

In conclusion, the conceptual vegetation strategies of loess slope protection in Yan'an are suggested in Figure 17. As this figure shown, all kinds of plants can protect slope with soil reinforcement of roots. For example, herbaceous plants have only shorter and superficial roots which can hardly reinforce deeper soil, but the reinforcement effect by their fibril roots can maximize ground cover and associated interception to reduce the effects of rainsplash and runoff in rainfall. So it is an appropriate strategy that we should use all kinds of plants as many as possible for ecological restoration and slope protection, especially selected *Artemisia* spp. that can effectively prevent the occurrence of loess flow slides and shallow landslides (with slip planes less than 2 m deep). Despite the importance of species diversity, it should be noted that many species, such as shrubs and trees, are restricted to the lower and wetter parts of slope, as these species are hardly adapted to high steep slopes (Figure 5) the barren areas where protection against soil erosion, shallow landslides, loess flow slides and debris flows is most required (Wang and Lee 1998; Zhou and Zhang 2003; Guo et al. 2004; Li et al. 2007; Hu et al. 2013).

Because *Artemisia* spp. has a better adaptability to surrounding and its advantage will be more obvious with habitat destruction, *Artemisia* spp. accounts for about over half of all the plants if the slope is more than 40° (Figure 8). Therefore, *Artemisia* spp. is particularly suitable as pioneer plant for loess slope ecosystem reconstruction without special maintenance. However, the species diversity in an ecological community is beneficial to the ecosystem stability, sustainability, and rehabilitation (Figure 17). Besides *Artemisia* spp. without special maintenance, some selected plants, such as shrubs and herbs, should be sown and watered at the beginning of growth until their relatively longer roots ensure that they are able to extract water from depth, sustaining their growth. And if necessary, the engineering measures, such as geocell and drainage network, are suggested to ensure plants survival in high steep slopes.

Conclusions

This paper has presented a long-term investigation of the local natural growing plants in the hilly-gullied region in the Yan'an area since 2014 and aims to screen the

potential species suitable for ecological restoration and slope stability in China Loess Plateau under a semiarid climate. The conclusion can be highlighted as follows:

- a. With investigation statistics, it is found that the drought and freezing tolerant plant types are the main varieties of loess slope vegetation. Among these, *Artemisia* spp. is the main species of loess slope naturally growing vegetation in Yan'an area and has a better adaptability to surrounding;
- b. Through the long-term observation of the evolution process of slope, the ecological restoration and reconstruction of loess slope are gradually improved with the ecological plasticity of *Artemisia* spp. This illustrates that *Artemisia* spp. is particularly suitable as pioneer plant in the initial stage of loess slope ecosystem reconstruction;
- c. The reinforcement effect of *Artemisia* spp. root-soil composite system was considered through the field root pull-out test and soil direct shear test. The results from quantitative analysis of the slope protection effect showed that the slope safety factor (F_s) could be obviously improved by the growth of *Artemisia* spp.
- d. *Artemisia* spp. may reinforce deeper loess (up to about 2 m) and effectively prevent the occurrence of loess flow slides and shallow landslides, which has extensive application prospect.

In future studies, more detailed analysis on the complex correlation among the factors will be addressed by continuous measurements of the relationship among community structure, soil erosion and long evolution process of slope.

Acknowledgements

Finally, the authors would like to thank Professor Vamegh Rasouli, University of North Dakota, for valuable comments on an earlier draft of this paper

Disclosure statement

No potential conflict of interest was reported by the authors.

Author's contributions

R. X. and X. C. L. involved in study design and conduct; R. X. involved in data collection, management and analysis, and R. X., W. Y., and M. R. involved in interpretation; R. X. and M. R. prepared manuscript, reviewed or approved; and R. X. and C. J. revised the manuscript.

Funding

This work was supported by the Fundamental Research Funds for the Central Universities (No. 310826171013, 310826172203) and Natural Science Foundation of Shaanxi Province (No. 2018JQ4044). The award of a China Scholarship Council (CSC) Visiting Scholar grant to Rui Xu (No. 201706565054) supported the development of this paper at The University of North Dakota.

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