Chapter 5
Hillslope Stability in the Yellow River Source Zone

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Abstract Tectonic uplift is the primary control upon the low relief yet moderately undulating plateau landscapes that make up much of the source zone of the Yellow River. Steep ravines and gullies are restricted to mountain ranges at the northern and southern margins. This contrasts starkly with the deeply dissected landscapes at the eastern margin of the Qinghai–Tibet Plateau. Although the high elevation induces low mean annual temperatures, diurnal temperature ranges are high. Precipitation is sparse but concentrated, and gales are frequent. Hillslope processes such as landslides, debris flows, solifluction and soil erosion are extensively developed in the region. This chapter presents an overview of hillslope stability in the Yellow River Source Zone. First, the landscapes and topography of the Yellow River Source Zone are introduced. Landslide, debris flow, soil erosion (aeolian and rill/gully) and freeze-thaw processes are shown to be key drivers of patterns and rates of grassland degradation. Human activities and climate change are key agents

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G.J. Brierley et al. (eds.), *Landscape and Ecosystem Diversity, Dynamics and Management in the Yellow River Source Zone*, Springer Geography,
DOI 10.1007/978-3-319-30475-5_5

of landscape change. The influence of vegetation management upon hillslope stability and in reducing geological disasters is demonstrated. Vegetation plantation and increased vegetation cover enhance the mechanical and hydrologic effects of hillslope protection, increasing soil shear strength and interception of rainfall.

Keywords Hillslope stability · Hillslope process · Landslide · Debris flow · Solifluction · Soil erosion · Hillslope protection by vegetation · Soil and water conservation · Land use

5.1 Introduction

The source zone region of the Yellow River is characterized by a wide range of landscapes with considerable variability in hillslope form and process (Nicoll et al. 2013). The diverse geologic settings generate stark contrasts between mountainous regions, vast plateaus and dissected landscapes at the margins of the Qinghai–Tibet Plateau. Endogenic processes have created profound variability in relief—both absolute and relative. Tectonic uplift of the plateau has induced a sharp altitudinal decline at the eastern margin, demarcating the transition between the first two terrain (topographic) steps in China (Brierley et al. 2016a, Chap. 1). Atop this geologically defined template, climatic factors induce marked within-regional variability in exogenic processes, both horizontally and altitudinally. There is also a significant imprint of former environmental conditions upon the contemporary landscape, such as extensive glacial and periglacial features. Human activities and climate change have altered the distribution and effectiveness of geomorphic processes, greatly accelerating soil erosion, and modifying the depth and extent of permafrost. Collectively, these factors have brought about significant spatial and temporal variability in hillslope processes. In turn, hillslope processes facilitate and impact upon many other relationships, such as vegetation distribution and land use potential, and resulting patterns of human activities. Human relationships are quite different, for example, on the bare hillslopes and dissected landscapes at the plateau margin relative to the grassland and wetland areas that are found across many depositional basins and valley floors (which themselves have a marked altitudinally induced gradient in land use potential).

This chapter presents an overview of hillslope forms and processes in the source zone of the Yellow River. The term 'plateau landscape' suggests hillslope processes that are relatively benign and innocuous. However, the plateau is far from flat, with an intriguing complex of plains and undulating hills inset within an array of mountain ranges (see Brierley et al. 2016b, Chap. 3). Hillslope gradients across most areas of the upper Yellow River reflect long-term weathering, surface erosion and the history of fluvial incision processes. This chapter starts by summarizing regional terrains and their associated hillslope characteristics. Hillslope evolution is then framed in relation to the broad (long-term) geological setting. Human interactions with hillslope processes are then discussed, initially assessing factors that have accentuated the distribution and rate of soil erosion, before considering management actions to address concerns for hillslope instability, focusing particularly on vegetation planting.

5.2 Topographic Setting and Primary Hillslope Patterns in the Yellow River Source Zone

The Yellow River Source Zone lies in the eastern part of the Qinghai–Tibet Plateau. The altitude of the region ranges from 2500 to 5500 m (Fig. 5.1). The Kunlun Mountains and Bayan Har Mountains lie to the west and south-west. The Buqing Mountains are aligned along the northern boundary, whilst the north-west–south-east-aligned Anyemaqen Range lies to the east. Among these mountains, Maqinggangri is the highest peak. More than ten peaks are higher than 5000 m. Contemporary glaciers sit at the crest of extreme high mountains at elevations above 6000 m. Elevation differences between peaks and valley floors often extend beyond 2000 m. Above 4800 m plant cover is sparse, dominated by lichens (Cheng et al. 2006; Zheng and Wang 1996). Areas between 4400 and 4800 m are characterized by grassland meadows with alpine *Kobresia humilis* and sedge dominant. Alpine swamp with grassland meadows dominated by *Kobresia tibetica* and *Carex alrofusca* are distributed from 4200 to 4400 m (Zheng and Wang 1996).

The Yellow River Source Zone is part of the Naqu-Maduo plateau within the Qinghai–Tibet Plateau (Brierley et al. 2016a, b, Chaps. 1 and 3). It has an average

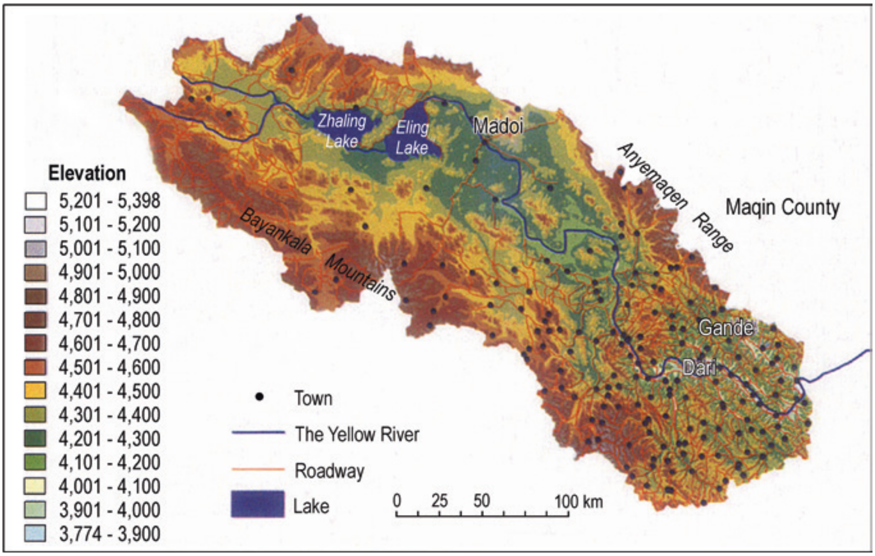


Fig. 5.1 Topography of the Yellow River Source Zone (modified from Zhang et al. 2006a)

altitude of about 4500 m (Zhang et al. 2006a). The interior area comprises an upland plain and lake basin with broad valleys. There are some undulating (rounded) mountains and high-altitude hills with a gentle gradient, but only limited areas of steep mountains and gullies. The whole terrain is inclined from the north-west to the south-east, with river and lake systems aligned along the strike of grabens within this fault-block terrain (Zhang et al. 2006a). Many rivers are ephemeral, characterized by markedly seasonal flows and sandy valley floors. Both freshwater and salt-water lakes are evident. Terraces, piedmont platforms and alluvial fans are found along the margins of the graben basins. Mountains and hills are gently undulating in the east and south of the source zone. Broad valleys and lake basins are found in the west and middle part. Extensive flat plains are evident in the northern part.

Interactions between topography (relief, hillslope angle/length, etc.), climate (hydrology and vegetation cover), geology (weathered materials and soils) and human impacts generate quite different catenas in differing areas of the upper Yellow River. Two examples are presented in Figs. 5.2 and 5.3. Adjacent to Zhaling Lake in Maduo County, the contemporary Yellow River is inset alongside various floodplain, terrace, piedmont and fan features (Fig. 5.2; Cheng et al. 2006). The flat-topped nature of valley floor units reflects the imprint of history—extended phases of valley evolution associated with ancestral versions of the Yellow River, and subsequent patterns of valley infilling and incision associated with climate history. Adjacent mountains make up just a small proportion of this landscape. Ironically, the source zone has little exposed bedrock, and reworked sediments drape much of the landscape (alluvial, colluvial and aeolian stores).

Quite different hillslope relationships are evident in Guide County, but the key driver of hillslope form remains the same, as hillslope morphologies are largely determined by the imprint of valley evolution processes. Here, the dominant influence has been the long-term history of valley infilling of the Guide Basin, followed by relatively rapid incision by the Yellow River and associated tributaries (Pan 1994; Zhao and Liu 2003; Fig. 5.3). Basin fills that separate the gorges along

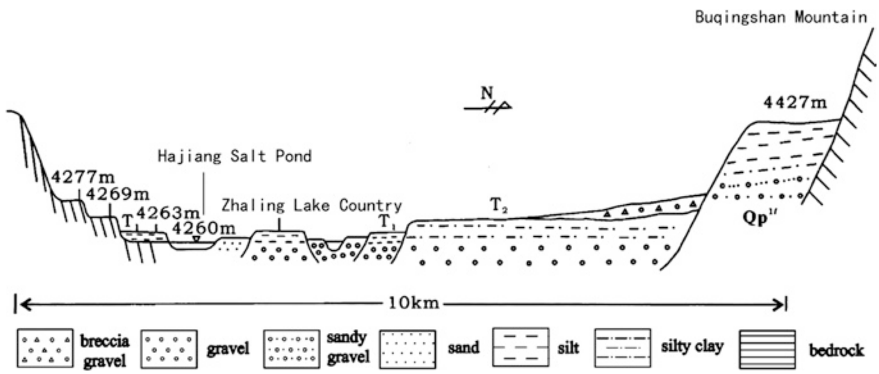


Fig. 5.2 Transverse sections of the valley of the Yellow River near Zhaling Lake, Maduo County (modified from Cheng et al. 2006)

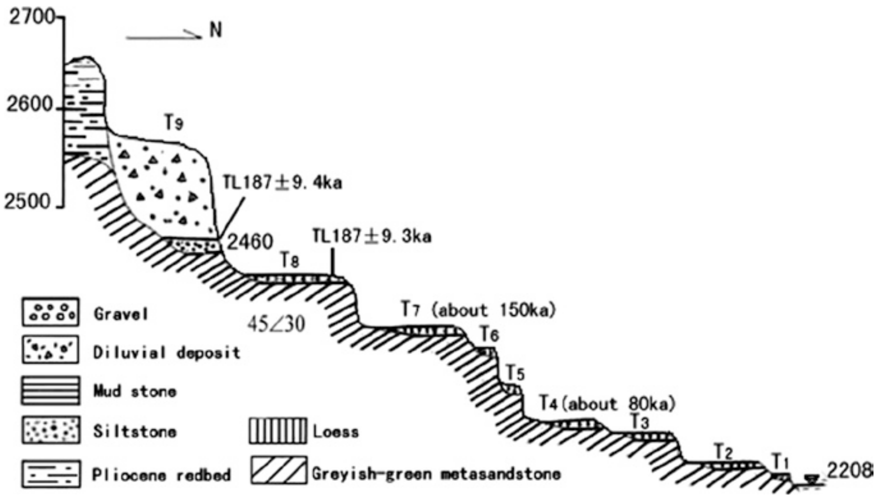


Fig. 5.3 Synthetic cross section of the valley fill of the upper Yellow River at Nina, Guide Basin (modified from Zhao and Liu 2003)

the upper Yellow River result in near-vertical cliffs of Tertiary and Pleistocene aged valley fill deposits (lacustrine, fluvial and aeolian deposits) that line the margin of the incised trunk stream and its tributaries (Brierley et al. 2016a, Chap. 1). Gravel and sand deposits are often hundreds of metres deep.

Unfortunately, systematic appraisals of hillslope process relationships across differing landscape settings of the Yellow River Source Zone are unavailable, hindering our capacity to assess linkages to flow pathways, soil types, vegetation patterns and other abiotic and biotic associations. As shown in Tane et al. (2016, Chap. 13), these are vital considerations in establishing process-based understandings to inform management applications. For now, it is important to simply consider the stark contrasts in landscape settings evident in Figs. 5.2 and 5.3. In the area around Maduo, characteristic of many of the basin fills of the upper Yellow River, landscapes have very subdued relief, the imprint of the long-term sedimentation history lingers and hillslope processes are slow and subtle. In contrast, incised and dissected landscapes at the margin of the Qinghai–Tibet Plateau are characterized by many near-vertical cliffs, whether comprised of bedrock in gorge settings, or cemented alluvial and lacustrine materials in the terraces of incised basin fill deposits. The latter landscapes are prone to dramatic collapse via landslide activity, especially in response to earthquakes or major storms (e.g. Guo et al. 2014; Ouimet et al. 2007).

Permafrost melt and the role of the 'active layer' exert a critical influence upon hillslope processes and forms at higher altitudes of the plateau (especially above 4100 m). Changes to the depth and extent of the active layer that is subjected to repeated freeze-thaw processes impact upon hillslope instability via solifluction and gelifluction processes.

5.3 Hillslope Processes: Landslides, Debris Flows and Solifluction

In general terms, the level of geologic hazard associated with hillslope failure in the source zone of the Yellow River is low, with process activity accentuated locally in high mountain areas and along the trunk stream of the Yellow River itself (Zhang et al. 2003; Fig. 5.4). Contemporary uplift of the plateau and enhanced rates of

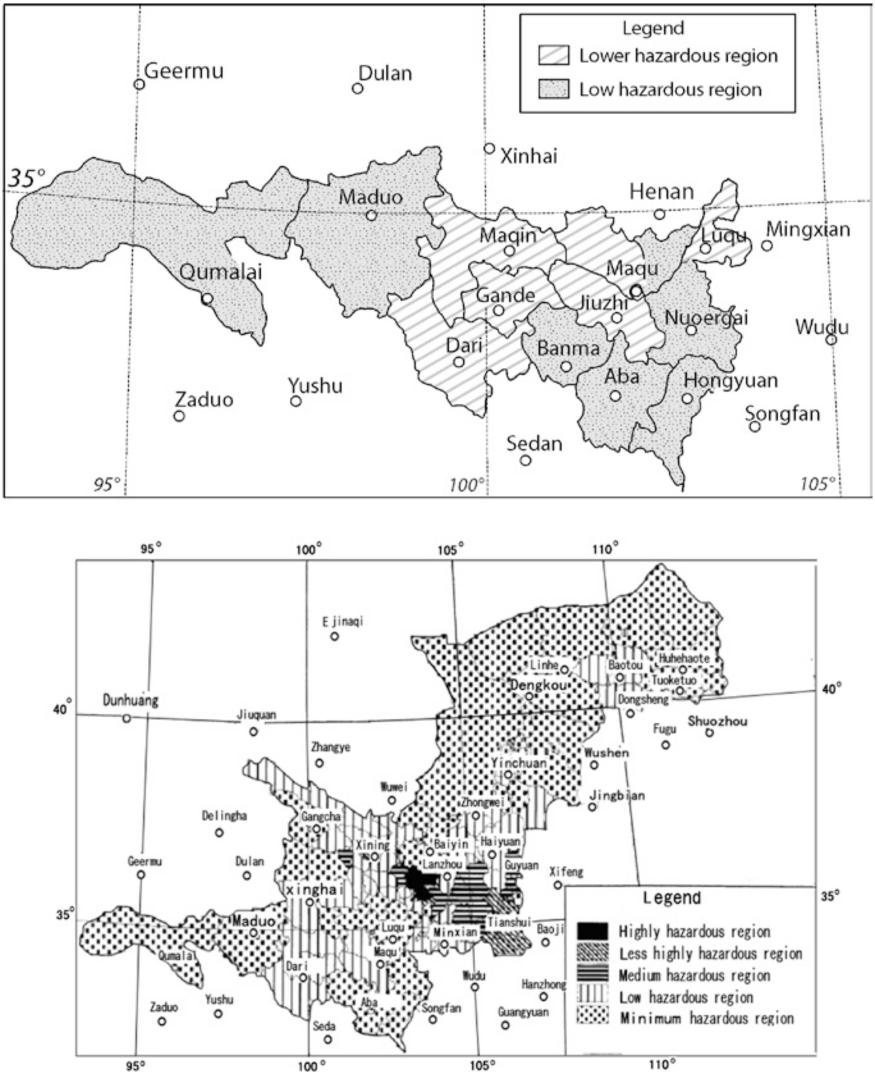


Fig. 5.4 Risk of geological hazards of hillslope failure by collapse, landslide and debris flow activity in the upper reaches of the Yellow River (modified from Zhang et al. 2003)

weathering create extensive areas of talus hillslopes which provide materials for debris flows (Zhang et al. 2006b). Landslides are linked closely with contemporary tectonic movements (Li et al. 2007, 2008a, b; Zhang et al. 2006b). Heavy rainstorms trigger many landslides in the rapidly saturated silty soils, especially in areas where soluble salts are prominent (Li et al. 2008a, b). Elsewhere, high rainfall events and summer snow melts that concentrate water and debris in colluvial depressions or along steep valley floors induce debris flows among Quaternary deposits (You and Jing 1980; Zhang et al. 2000).

Widespread permafrost generates fragmented substrates within the active layer of hillslope soils. Freeze-thaw and frost heave generate many mass hillslope slips by solifluction and gelifluction processes (Fig. 5.5; Yang and Tong 2010). Solifluction processes are prominent in high-altitude areas, whereas shallow landslides and landslips are prominent on the loess hillslopes in the north-eastern part of the plateau (see Hu et al. 2013). Many areas of talus slope are subjected to severe frost weathering and wind erosion. The large number of talus slopes reflects the action of wind erosion and frost weathering, especially at high altitudes (Cheng et al. 2006). Large quantities of bare rock on steep hillslopes are prone to collapse via landslide and debris flow activity. These geological disasters are widespread and frequent (Chen et al. 2007; Xu and Huang 1997).

Fig. 5.5 Solifluction lobes on the hillslope at Huashixia in Qinghai Province

5.4 Soil Erosion

Soils of the upper Yellow River are generally infertile, thin, coarse grained and loose. Soil formation processes occur very slowly and resistance to soil erosion is limited in these mountainous environments with dry climates and fragile ecosystems. As such, they have limited integrity, low water-retention and are very prone/vulnerable to erosion (Han et al. 2011; Zeng et al. 2004; Zhang et al. 2006a). The main soil types in the region are alpine cold desert soil, alpine meadow soil, alpine steppe soil, mountain meadow soil, grey cinnamonic soil, chestnut soil, boggy soil and aeolian sandy soil (Zeng et al. 2004; Zhang et al. 2006a).

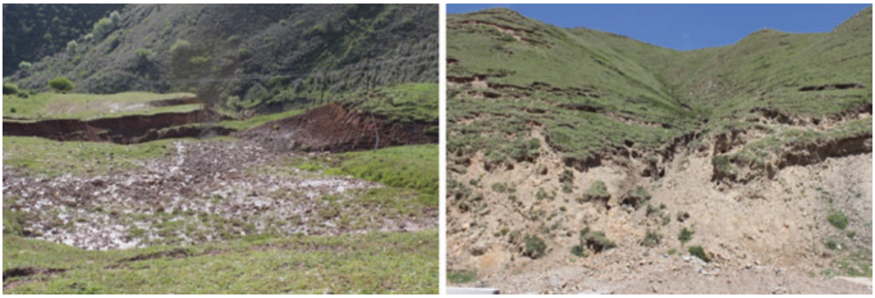
Freeze-thaw erosion, water erosion, wind erosion and gravitational erosion are the primary agents of soil erosion in the region (Yan et al. 2004). Freeze-thaw processes operate over most of the Yellow River Source Zone, especially in higher-altitudinal areas to the west. Freeze-thaw cycles reduce the strength and integrity of the ground, loosening soil particles, so they are more readily moved by wind and water erosion processes (Fan and Cai 2003). Strong frost weathering has led to extensive exposure of bare rocks and gravels on hillslopes (Fig. 5.6). In contrast, erosion in the lower areas to the east is dominated primarily by water and wind processes.

Wind speeds increase from the south-east to the north-east and with altitude. Westerly winds are most prominent. Gale conditions are experienced on 75–128 days per year, with wind speeds up to 30 m s^{-1} (Zeng and Feng 2009). Wind erosion is less pronounced in areas with high underground water level and with better soil and water conditions where ground cover is maintained. Desertified pastures and drying swamps/lakes are subject to localized wind erosion (see Li and Wang 2016, Chap. 8). Wind erosion is especially pronounced in Gonghe, Guinan and Maduo counties (Yan et al. 2004). In areas with little ground cover and abundant medium–fine-grained sands, even lower wind speeds can trigger significant soil erosion.

Talus slope formed by frost weathering in the Yellow River source zone

Talus slope formed by frost weathering in the source zone of the Yellow River

Fig. 5.6 Talus slopes in the Yellow River Source Zone generated by freeze-thaw processes



Grassland degradation and gully development impacted by overgrazing

A gully in the source zone of the Yellow River

Fig. 5.7 Examples of grassland degradation and gully development in the Yellow River Source Zone

Rill and gully erosion is distributed across the Yellow River Source Zone, but it is especially prominent in loess deposits that have accumulated atop the north-eastern corner of the Qinghai–Tibet Plateau. The prominence of relatively loose colluvial, aeolian and alluvial deposits presents abundant scope for incision and channel expansion (Li and Pan 2009; Fig. 5.7). As headcut erosion eats back into the hillslope via network extension, it generates large volumes of sediment. However, given the relatively steep and incised channels, sediment delivery ratios are exceptionally high.

Several factors have aggravated soil erosion in recent years (e.g. Feng et al. 2006; Wang et al. 2013; Zhang et al. 2006a). Since the 1980s, human activities and climate change have brought about extensive vegetation degeneration, transforming areas of previously flourishing hygrophilous vegetation which is well adapted to cold environments into sparse drought-enduring vegetation (Dai et al. 2014; Liang et al. 2007; Pan and Liu 2005; Xu et al. 2012; Yang et al. 2005; Wang et al. 2004). Increased areas of bare soil, associated with overgrazing and rodent removal of topsoil have exposed calcisol horizons that do not favour plant establishment (Li et al. 2016, Chap. 7; Tane et al. 2016, Chap. 13). Decreased herbaceous cover reduces soil moisture, water retention and soil cohesion, leaving soil particles exposed to erosion. This increases the area of bare patches that are prone to further run-off and wind erosion (Fan and Cai 2003; Wang et al. 2008).

Infrastructure development, especially road construction, has locally increased the prevalence of steep and bare hillslopes, increasing susceptibility to landslides following intense rainfall events (Fig. 5.8). These processes inhibit prospects for vegetation establishment and recovery, decreasing prospects for water conservation whilst enhancing conditions for soil erosion (Yan et al. 2004). Proactive management of vegetation cover is required to address erosion problems before they become too severe.

Bare slope caused by road construction *Hillslope failures associated with road construction*

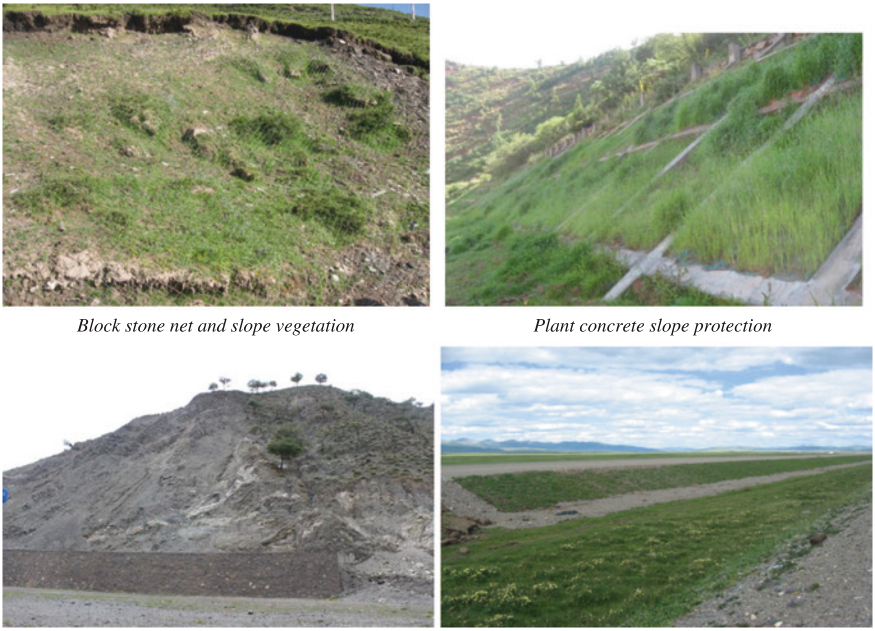
Fig. 5.8 Hillslope instability associated with road construction in the Yellow River Source Zone

5.5 Approaches to Hazard Reduction on Hillslopes of the Yellow River Source Zone

Hillslope processes such as landslides, debris flows and solifluction are key agents of grassland degradation, desertification and soil erosion in the Yellow River Source Zone. Hillslope instability damages infrastructure and property, decreases agricultural productivity and threatens human safety. Protection of grasslands and associated ecosystems is a high-priority issue in this largely undeveloped region.

In many areas, artificial measures need to be taken to mitigate the effects of landslides (Fig. 5.9). Commonly used engineering measures include grouting, anchoring, soil nailing walls, retaining walls and load reduction. Increasingly, these hard engineering measures have been supplemented by a range of soft (environmentally friendly) measures such as hillslope protection by vegetation. Hillslope protection by vegetation is beneficial for both prevention/reduction of geological hazards and the protection and restoration of ecosystems. Often hard and soft measures are used in combination, with deep layer reinforcement using soil nails and rock bolt, and shallow layer reinforcement using vegetation (Hu et al. 2013; Li et al. 2014; Wang and Chen 2003; Zhou and Zhang 2003). Compared with traditional hillslope protection measures, vegetation has the advantages of being cheap, fast and long-lasting, whilst also increasing biodiversity and providing carbon credits (Yang et al. 2007). However, plants struggle to establish and survive on steep, rocky hillslopes, so protective planting is only effective on shallow hillslopes.

Figure 5.10 presents an overview of the influence of vegetation cover upon hillslope stability. Shrubs and herbs that are well adapted to the cold and dry environment of the north-eastern part of Qinghai–Tibet Plateau can significantly enhance soil strength on hillslopes, reducing soil erosion and shallow landslides (Hu et al. 2009, 2013; Li et al. 2006, 2008a, b; Zhang et al. 2006a; Zhu et al. 2008). Hillslope stability is enhanced by vegetation through soil reinforcement by shallow root, anchorage by taproots, lowering of pore water pressure, interception of rainfall, and reduced rain splash erosion. Roots enhance hillslope stability (e.g. Operstein and Frydman 2002; Wu et al. 1988). Plant



Block stone net and slope vegetation *Plant concrete slope protection*

Road protection at the base of a talus slope *Roadbed hillslope protection by vegetation*

Fig. 5.9 Measures to address concerns for hillslope instability associated with road construction in the Yellow River Source Zone

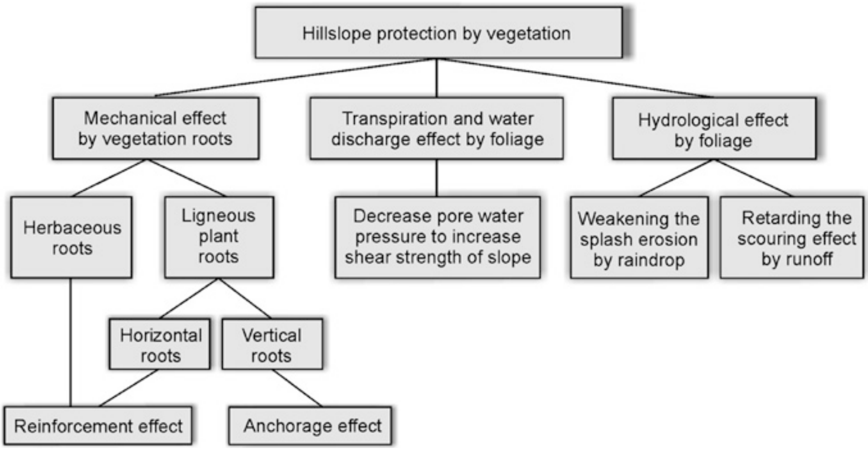


Fig. 5.10 Influence of vegetation in strengthening hillslope stability (modified from Fu 2011; Wang et al. 2005; Zhou and Zhang 2003)

root structure influences the reinforcement effect. Deep tap roots have an anchoring role, whilst horizontal roots have a traction role (Li et al. 2003). Shallow herbaceous roots significantly reinforce and strengthen surface soil layers (Li et al. 2003; Xiao 2004; Zhou et al. 2012). Greater vegetation cover also reduces run-off erosion and the generation of rills and gullies, regulates local climates and increases biodiversity (Gong 2011; Lv et al. 2010; Zhu and Li 2006). Vegetation cover intercepts rainfall and reduces rainsplash, reducing flow and sediment concentration and the effectiveness of sheet flows (Zhu and Li 2006). Increases in effective surface roughness enhance the infiltration rate along roots and improve the water storage capacity of soils by enhancing soil structure (Xiao et al. 2006). Dissipation of flow energy and greater retention of run-off not only decreases surface erosion on hillslopes, but also reduces prospects for incision and the initiation and expansion of rill and gully networks, and their extension into hillslopes. Leaf area index and other indicators of plant coverage have a positive correlation with the amount of rainfall interception and absorption (Hu and Shao 2002; Wen et al. 2005; Fang and Dai 2001). Herbaceous cover also increases the roughness of hillslope surfaces, reducing run-off velocity, changing run-off patterns and reducing soil erosion (Li et al. 1992; Wu et al. 1988).

5.6 Concluding Remarks

Land use change and infrastructure development are key influences upon, and in turn are greatly affected by, geological hazards in the Yellow River Source Zone. Efforts to prevent disasters and protect society on the one hand must be accompanied by ecologically sensitive measures that protect or enhance environmental conditions on the other. These concerns are all the more pressing in areas that have accentuated sensitivity to climate change, such as permafrost zones.

To date, research on hillslope forms, processes and patterns across the Qinghai–Tibet Plateau remains in its infancy, limiting prospects to develop and implement effective and comprehensive management plans and practices.

Vegetation can play a key role in hillslope management in the region. Locally adapted plants can effectively protect and control disasters associated with surface water loss and soil erosion, reducing impacts of shallow landslide and debris flow activity. At the same time, these practical, adaptable and relatively cheap (low cost) measures have environmental benefits and create no pollution. Importantly, these measures must be adapted in locally sensitive ways, harmoniously supporting community livelihoods and well-being across the region.

Acknowledgments This work was supported by grants from the National Natural Science Foundation of China (Grant No. 41162010, 41572306), Provincial National Natural Science Foundation of Qinghai (Grant No. 2014-ZJ-906), Program for Changjiang Scholars and Innovative Research Team in University, Ministry of Education of China (IRT13074) and International Science & Technology Cooperation Program of China, MOST (2011DFG93160). The authors thank students and colleagues who supported this work, in particular: Lei Haochuan, Zhao Yujiao, Liu Changyi, Li Huatan, Zhao Dan, Li Yanting, Zhu Haili and Li Guorong.

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