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Method of mitigating the surface erosion of a high-gradient mudstone slope in southwest Taiwan

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Abstract Soft mudstone dominates the rock mass at southwest Taiwan. Mudstone slakes significantly when it meets water due to a short diagenetic period and poor cementation. Gulleys are visible on the surface of mudstone slopes after rainfall. The low slaking durability resistance of the mudstone causes not only geographical badland but also erosion problems on the highway slopes in the mudstone area. An effective countermeasure for protecting the mudstone slope must contribute to a reduction in surface erosion; facilitate drainage from the slope surface during rainfall; and incorporate a high-strength structure to fight against swelling stress, preserve vegetation, and contribute to slope stabilization. In this study, a new slope erosion countermeasure, the soil-tyre-vegetation method (STV), was applied to an excavated mudstone slope in southwest Taiwan. STV utilizes waste tyres, H-beams, and geotextile. Waste tyres are good for preserving the soil for vegetation on mudstone slopes, mitigating slope erosion. The H-beams support the weight of the vegetation and the soil-filled tyres. The geotextile prevents the loss of fine-grain soil and guarantees drainage from the slope during heavy rainfall. The experimental results for a mudstone slope with a slope angle of 45° showed that STV protected the mudstone slope and improved the condition of the vegetation on it.

Introduction

Mudstone is a fine-grained sedimentary rock that is considered a weak rock. It is prone to rapid weathering and slaking due to its sensitivity to water absorption and desorption. The strength of the mudstone decreases significantly upon contact with water, and this is a significant factor in the weakness of mudstone (Lee et al. 2007b; Doostmohammadi et al. 2009; Naohiko and Ömer 2011). In addition, when mudstone is exposed to alternate wetting and drying cycles, its cementing agents often break down, resulting in mechanical erosion (Peter and Shahid 2011).

In the foothills of southwest Taiwan, Neogene debris comprising sedimentary rocks with short diagenetic times dominate the parent rocks. Typical rocks include sandstones, mudstones, alternating sandstone–mudstone, and some gravel. The region with weak mudstone extends to Chiayi, Tainan, and Kaohsiung. Mudstone behaves as a hard rock when it is in a dry state, but it softens, swells, and slakes when it absorbs water. Thus, it has a low resistance to changes in water content. Mudstone is formed through the long-term compaction of large amounts of silt and clay, and has low permeability. When a mudstone slope suffers heavy rainfall, the water infiltrates into cracks in the surface soil, reaching the fresh mudstone interface and causing seepage, which then induces the weathered soil layer to slide (Lee et al. 2008). Rainfall also causes runoff and

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scours the bare mudstone slope. Following runoff erosion, gullies, and erosion pipes are often visible on the mudstone slope.

In southwest Taiwan, mudstone slopes are rapidly eroded at an average rate of 9 cm/year during the rainy season (May–September), but almost no erosion occurs in the dry season (October–April). In addition, the weathered layer approximately 10 cm below the surface of the mudstone slope has a higher water content, lower density, larger void ratio, and a higher salt concentration. Thus, the weathered layer is removed by rapid slaking and erosion induced by heavy rainfall during the rainy season (Higuchi et al. 2013). Moreover, the rainfall is concentrated on southwest Taiwan during the rainy season. Small collapses and mudslides occur when a typhoon or heavy rainfall occurs in the mudstone region. Due to the environmental wet/dry interaction, badlands with developed gullies and bare ground constitute the typical terrain of southwest Taiwan. Figure 1 shows the landscape of a typical badland in southwest Taiwan.

Over the last decade, a network of expressways has gradually been constructed in Taiwan. Freeway Nos. 3, 8, and 10, as well as Expressway Nos. 82, 84, and 86 were constructed in the mudstone region. Because large numbers of high-gradient slopes were cut as part of this large-scale construction project, soil–water conservation on mudstone slopes has become a major traffic safety issue. Mudstone slopes have low erosion resistance and are not conducive to the growth of vegetation. This absence of slope protection leads to an increase in bare mudstone slopes and slope collapses. Lee et al. (2007a) indicates that the slope protection methods commonly used by road management agencies to protect the mudstone slopes in southwest Taiwan include vegetation, grille beam, fabric

Fig. 1 Landscape of a typical badland in southern Taiwan (Tan-Liao district, Kaohsiung)

form, shotcrete, green coating, stone masonry, and gabions. However, erosion of the surfaces of mudstone slopes cannot be avoided using these methods, and visible mudstone failures have occurred along the south section of Freeway No. 3. Although the above methods cannot protect mudstone slopes well, Lu et al. (2010) considers vegetation to be the best of these methods of protecting mudstone slopes. Thus, in the work described in the present paper, we proposed and tested a new soil-tyre-vegetation method (STV) to mitigate erosion and scouring of mudstone slopes. The vegetation grid elements used in this method consist of H-beams with waste tyres and bags of vegetation placed in the open spaces of the grid to increase the erosion resistance of the mudstone slope. STV was initially applied to a 35° mudstone slope in 2004, and long-term observations of soil erosion indicated that erosion of the mudstone slope was reduced by more than 90 % when the slope was protected by STV (Yang et al. 2006; Lee et al. 2007a, 2008). This indicates that STV worked effectively as a slope protection method. In this study, STV was applied to a 45° mudstone slope to gauge the applicability of this slope protection method to a high-gradient slope.

Mudstone in southwest Taiwan

Distribution and index properties

Mudstone is a general term for sediments that are primarily composed of silt and clay and are just compacted clay soils without a durable binder (Goodman 1993). Under long-term compaction, mudstone has low permeability and runoff infiltrates find it difficul to infiltrating into the rock mass. Gutingkeng mudstone is a Pliocene marine sedimentary rock with a short diagenetic period that is mainly distributed in the foothills of southwest Taiwan. The apparent colour of intact Gutingkeng mudstone is grey or dark grey. The distribution of Gutingkeng mudstone has been recorded in many articles (Chen et al. 1984, 1996; Yang et al. 2006; Lee et al. 2007a, b, 2008), and is shown by the area inside the red dotted line in Fig. 2. Gutingkeng mudstone is distributed from Yuchin, Tainan in the north to Kangsan, Kaohsiung in the south. The western boundary extends from Hsinhua to Kuanmiao in Tainan to Kangsan in Kaohsiung, while the eastern boundary stretches from Yuchin and Nanhua in Tainan to Chishan in Kaohsiung, leading to a mudstone region 1,400 km^2 in size (Chen et al. 1984). Table 1 indicates that Gutingkeng mudstone particles consist of silt (55–79 %) and clay (16–42 %), and Fig. 3 shows the typical grain size distribution (Lee and Chen 2009). The slaking index (Id2) of Gutingkeng mudstone is about 50.0 %, and it is classified as a

Fig. 2 Geological map of the mudstone area in southwest Taiwan (modified from Chen 2000)
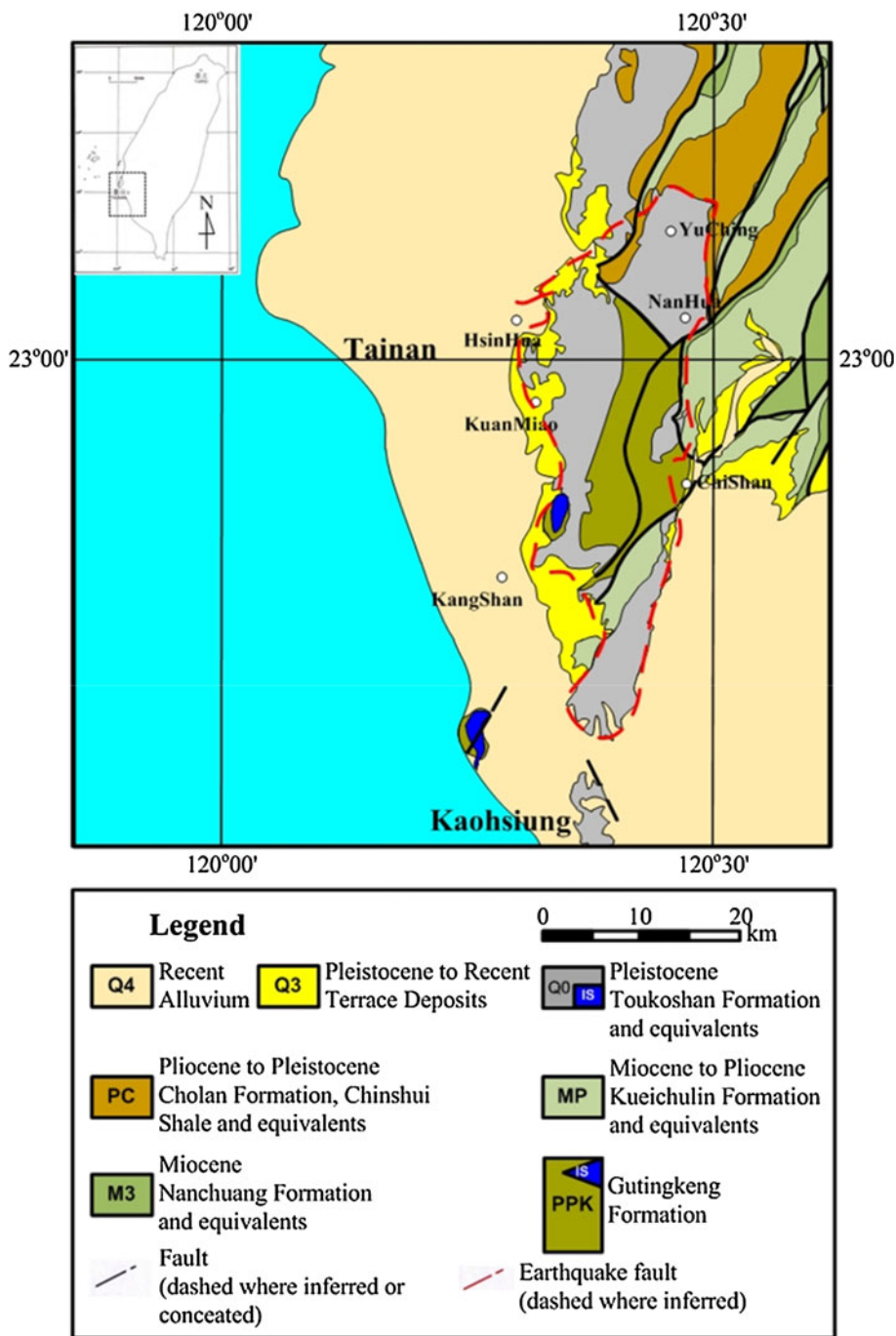

**Table 1** Properties of Gutingkeng mudstone (Lee and Chen 2009)

G_s	Void ratio, e	γ_d (kN/m³)	Atterberg limits (%)		Particle size distribution (%)			USCS
			LL	PL	Sand	Silt	Clay	
2.67	0.21	17.36	24.00	7.40	2	55	16	CL-
2.77	0.51	24.23	42.20	25.40	23	79	42	ML

low-durability rock according to Gamble's classification (Lee et al. 2007b).

In addition, mudstone exhibits extreme variations in strength under wetting or drying conditions. It behaves as a hard rock in a dry state, but softens significantly when it absorbs water. In the latter case, mudstone undergoes a considerable volume change and breaks down. Swelling
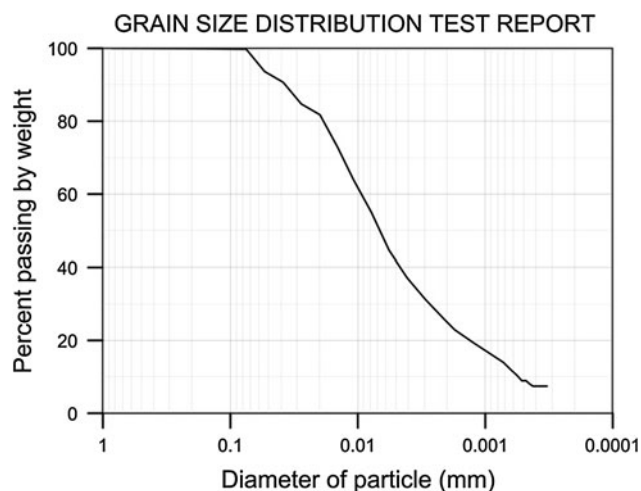
**Fig. 3** Typical grain size distribution of Gutingken mudstone (Lee and Chen 2009)
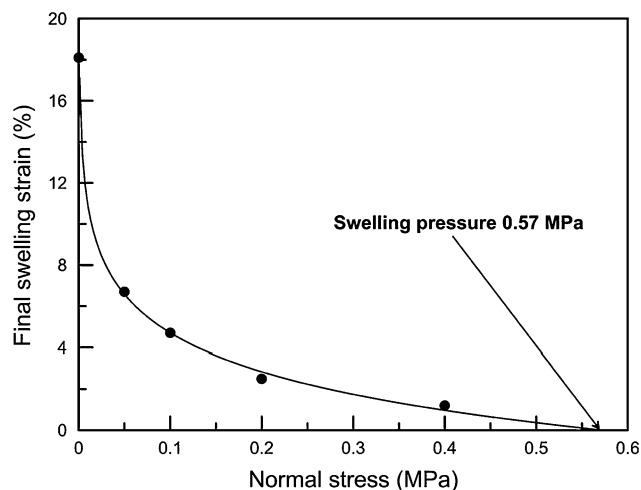
Fig. 4 Swelling test results for Gutingken mudstone

and slaking occurs, leading to a reduction in strength (Bjerrum 1967; Osni and Lázaro 2002).

In this study, laboratory swelling tests were carried out in order to understand the swelling characteristics of mudstone. Figure 4 shows the swelling test results, which show that the swelling pressure of Gutingkeng mudstone is 0.57 MPa.

This swelling is due to the gradual destruction by the water of the diagenetic bonds between mudstone particles. The distance between the particles also increases (Bjerrum 1967; Lee et al. 1994). Figure 5a shows that, before the compression test took place, the particles were initially arranged in a sheet structure. Figures 5b, c are photomicrographs of mudstone particles on a sliding surface after triaxial tests performed under failure conditions. In Fig. 5b, the diagenetic bonds of the mudstone particles have not been destroyed by the water content (0 %), so the particle crushing
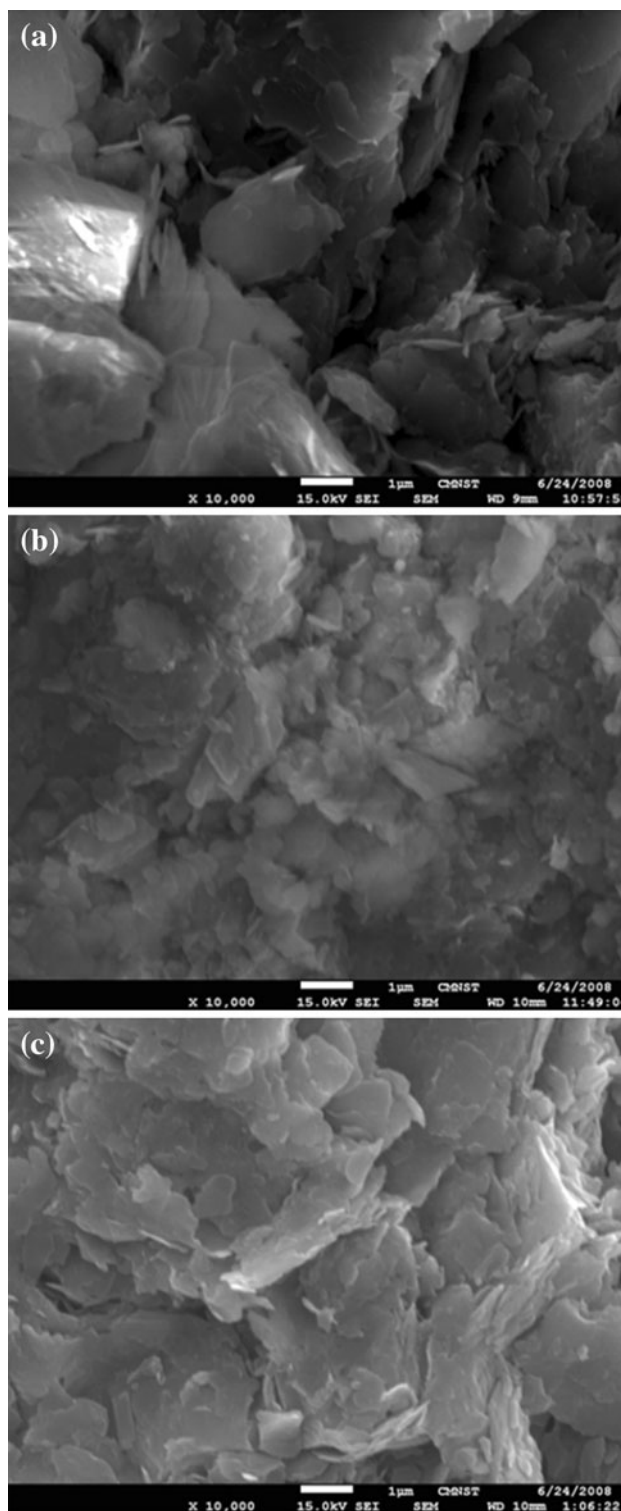
Fig. 5 Mudstone particles on a sliding surface after triaxial tests performed under failure conditions. **a** Untested, **b** water content 0 %, **c** water content 4–6 %

phenomenon is visible under compression. In Fig. 5c, the diagenetic bonds between mudstone particles have been destroyed by the water content. Therefore, sliding between

mudstone particles is the main failure mechanism under compression, and particle crushing is not significant.

Erosion and failure characteristics of a mudstone slope

Gutingkeng mudstone easily swells and has low durability. Thus, runoff often scours mudstone slopes and causes many mudstone slopes to collapse during the rainy season in southwest Taiwan. Furthermore, bare mudstone slopes are not conducive to the growth of vegetation. Thus, badlands are the most significant geological landscape in the mudstone region.

Chen et al. (1984) found that south-facing slopes have more scours than north-facing slopes, and observed severe erosion on long and gentle slopes. In addition, the annual erosion depth of bare mudstone slopes exceeds 10 cm, and the infiltration depth of rainfall is less than 50 cm. The gradient of a bare mudstone slope is generally in the range 30–60°, with slope gradients of 35–45° occurring with the greatest frequency. Lee et al. (2008) investigated 117 mudstone slope failures along the south section of Freeway No. 3. Based on the lithology, these slopes were classified as sandstone slopes (28 sites), sandstone and shale inter-bedded slopes (44 sites), mudstone slopes (34 sites), and conglomerate slopes (11 sites). Among these, the sandstone and shale interbedded slopes had the highest failure rate of 37.6 % (44/117). The mudstone slopes had a failure rate of 29.1 % (34/117). However, the ratio of the number of slope failures to the highway length for a specified rock mass showed that the mudstone slope was 4.93 sites/km, which was the worst among the specified rock masses. For the sandstone and shale interbedded slopes, the ratio was 3.07 sites/km. Moreover, the 34 mudstone slopes included 20 surface erosions, 12 shallow slides, and 2 slide ditch cracks.

In the badlands, the water infiltration rate changes rapidly over short periods of time due to the swelling and deflocculation of clay. Gullies accelerate the erosion and scouring on the near-surface of the mudstone slope. Moreover, the development and interconnection of erosion

Fig. 6 Failure development on a mudstone slope (plot based on Faulkner 2013)
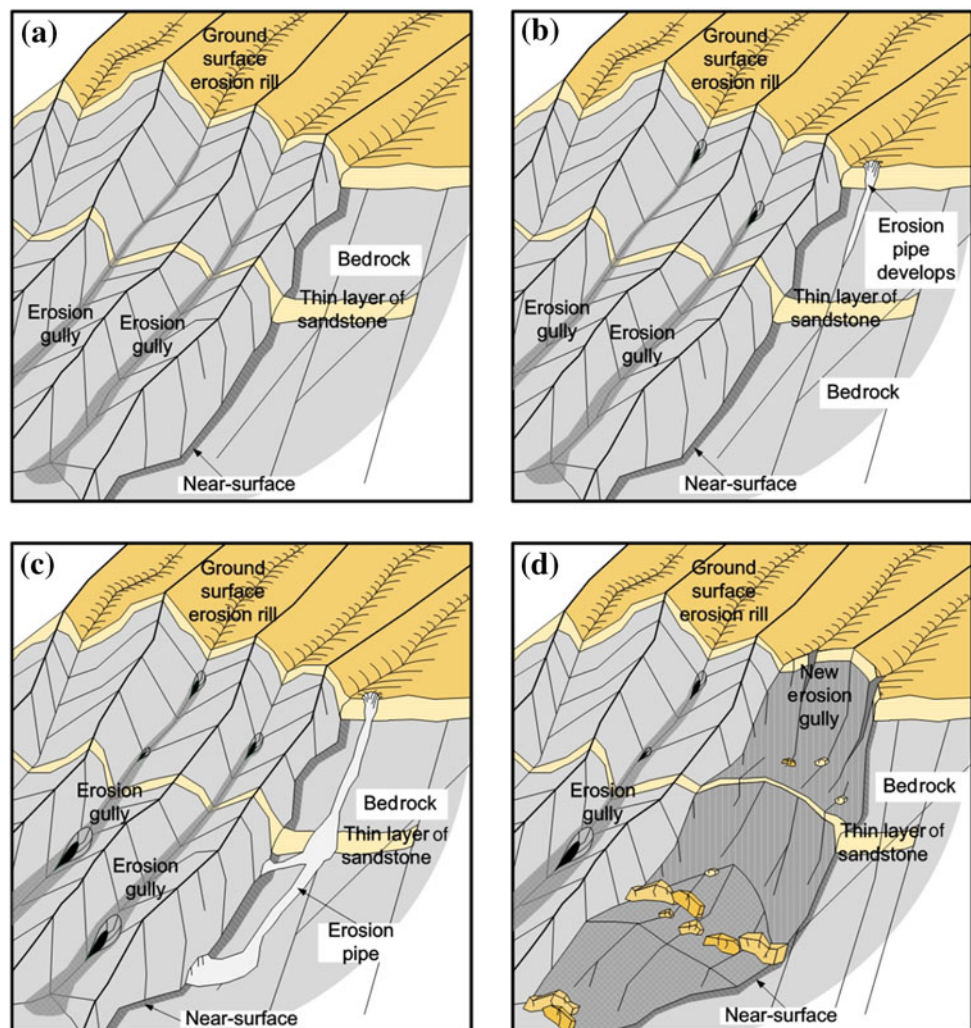
pipes in the mudstone slope gradually leads to large underground pathways, and thus to slope failure (Faulkner 2013). Figure 6 shows the failure process of a mudstone slope. A bare mudstone slope has many erosion gullies (Fig. 6a), and near the surface is a weathered layer. Rainfall scours the mudstone slope surface directly, and infiltrates into the rock mass along the weak planes (Fig. 6b), leading to the development of erosion pipes. Subsequently, the infiltrating water gradually erodes deeper and deeper, extending the length of the erosion pipes (Fig. 6c), and flowing out of near-surface regolith pores. Figure 6d shows the shallow mass with erosion pipes sliding due to rainfall/runoff scours. A new bare surface then develops on the mudstone slope. This new surface again suffers erosions and scours under the influence of rainfall/runoff, causing further slope failure.

The soil-tyre-vegetation method (STV)

Because water weakens mudstone significantly, "avoid water" must be the guiding principle of a mudstone slope protection method. Lee et al. (1996) suggested that the slope height and angle must be considered when choosing a mudstone slope protection method. The mudstone slope must be partitioned into multiple stages to stabilize the


Fig. 7 Sketch of the application of STV to a 35° mudstone slope (Lee et al. 2007a). **a** Vertical section, **b** cross-section
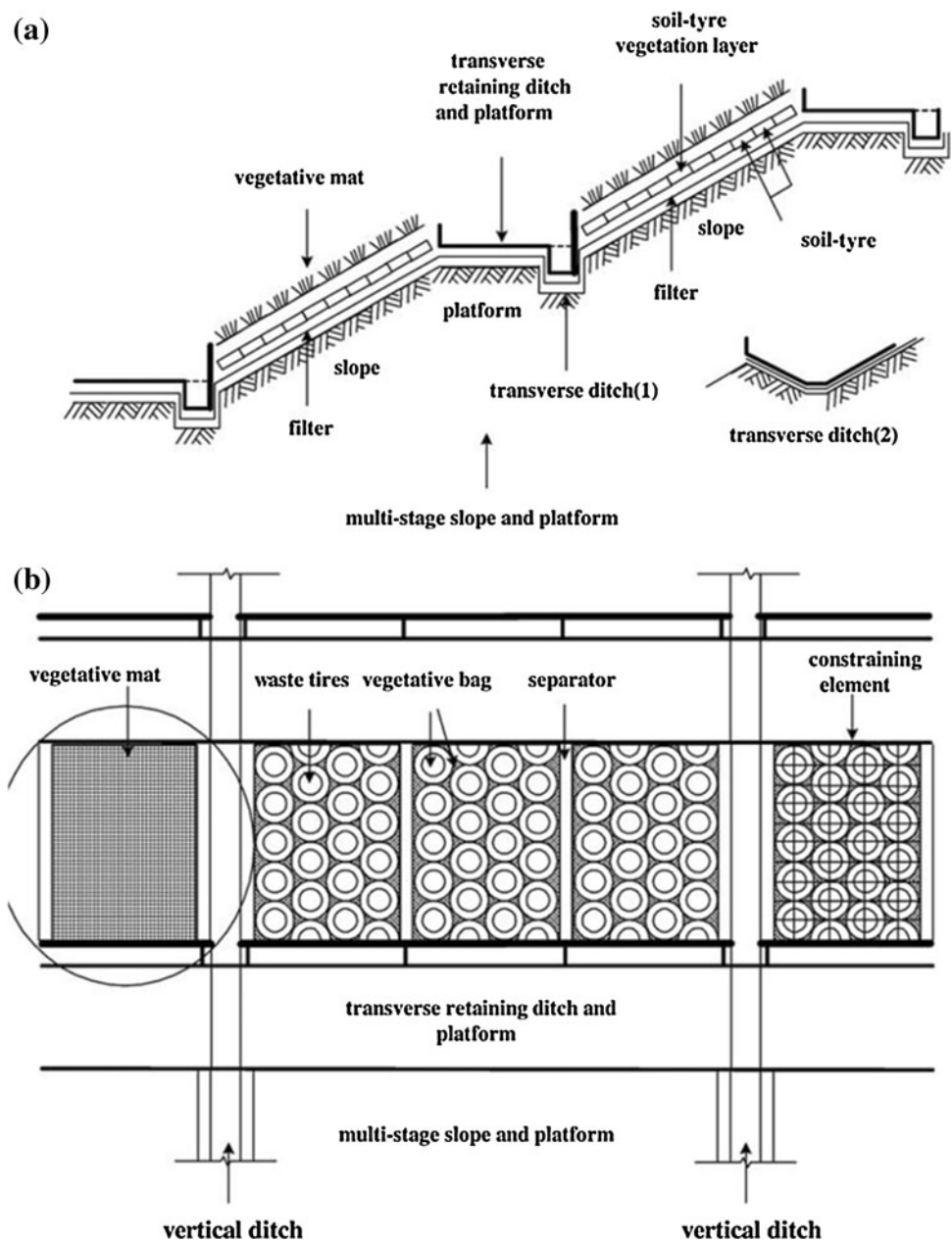
Table 2 Soil erosion as measured on a 35° mudstone slope (modified from Lee et al. 2007a)

Date (day/month/year)	Cumulative rainfall (mm)	Soil erosion (g/m^2)						
		Original slope	STV slope					
			D_1	D_2	E_1	E_2	F_1	F_2
17/12/2004	96	860	424	192	274	146	300	216
10/04/2004	167	232	58	136	13	50	41	75
22/05/2005	252	1716	178	33	12	52	114	50
24/06/2005	1,188	11,486	193	26	47	61	149	107
16/07/2005	64	595	276	34	25	76	86	121
26/07/2005	723	4,897	86	39	9	86	148	28
08/09/2005	869	6,393	55	16	27	10	56	9
26/11/2005	194	1,486	22	7	12	5	24	4
Total	3,553	27,665	1,775		905		1,528	
Reduce percentage (%)	–	–	93.58		96.73		94.48	

The subscripts 1 and 2 denote the upper slope and lower slope, respectively
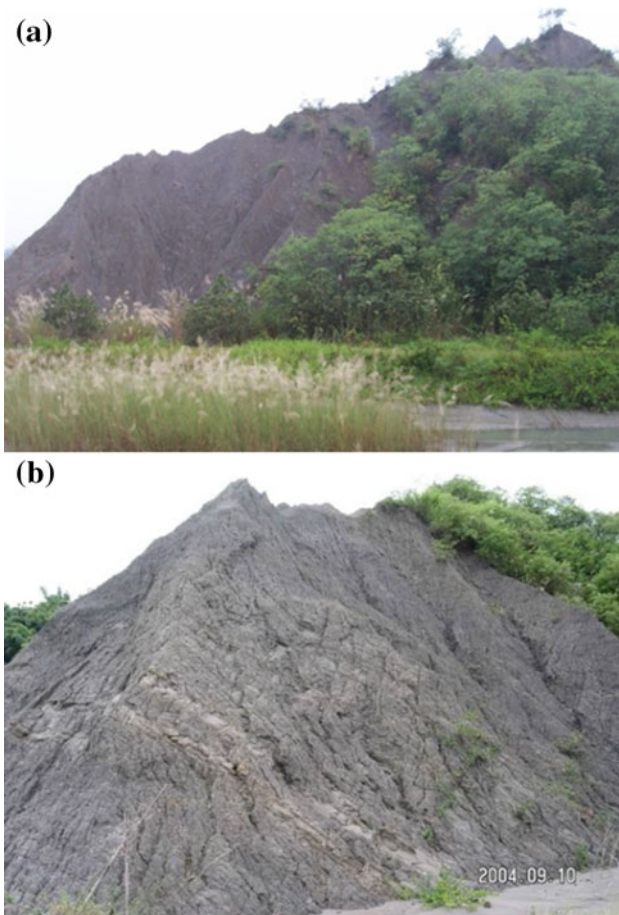
Fig. 8 Test mudstone slope. **a** Far view, **b** close-up view

slope and to reduce slope erosion. The height of each slope stage should be about 5 m. When the angle of the slope exceeds 40°, artificial structures must be created to protect the slope. Therefore, when designing a good mudstone slope protection method, we must:

1. Include a surface drainage system to constrain the flow path of water runoff.
2. Incorporate a method of preventing the loss of fine grains and keeping surface water off the slope.
3. Decide on the appropriate slope length and height (high and long slopes should be partitioned into multiple stages).
4. Provide the structure with adequate strength to counteract the swelling pressure of the mudstone.
5. Utilize countermeasure structures that are light enough that they do not induce slope failure due to their weight.
6. Consider the concepts of ecology and landscaping when designing the slope protection structures.

Based on these aforementioned principles for mudstone slope protection, a soil-tyre-vegetation method (STV) was proposed as a hard countermeasure to stabilize the mudstone slope, and was initially applied to a 35° mudstone slope (Yang et al. 2006; Lee et al. 2007a) (Fig. 7). STV consists mainly of waste tyres, H-beams, and geotextile. The initial construction step involves placing a filter layer onto the newly excavated mudstone slope. Grid elements are then constructed with the H-beams, and the waste tyres are placed in the open spaces of the grid, on top of the filter layer. To improve slope vegetation, bags of vegetation are placed in the tyres to act as a vegetative zone. This helps to prevent erosion and weathering on the slope. The grid element of STV is relatively lightweight, easily repaired, and takes only a short time to construct.

Table 2 shows erosion measurements taken from a 35° mudstone slope protected by STV, which was investigated

during 2004 and 2005. The test slope is separated into seven regions (A–G). In the table, only results for the regions D, E, and F are shown, which were protected by STV. During the study period, the accumulated rainfall throughout the test period was 3,553 mm. Table 2 also shows that STV protects the mudstone slope effectively: the total amount of slope erosion was 27,665 g/m^2 on the original mudstone slope which was left unprotected during 2004 and 2005; however, upon applying STV, the erosion

was less than 2,000 g/m^2, indicating a reduction in erosion of more than 90 %.

Application of STV to a high-gradient mudstone slope

In previous sections, we mentioned that the most common mudstone slope gradients in southwest Taiwan are 35–45°. Since we have seen that STV can effectively restrain erosion

Fig. 9 Sketch of the STV on the 45° mudstone slope. **a** Vertical section, **b** cross-section
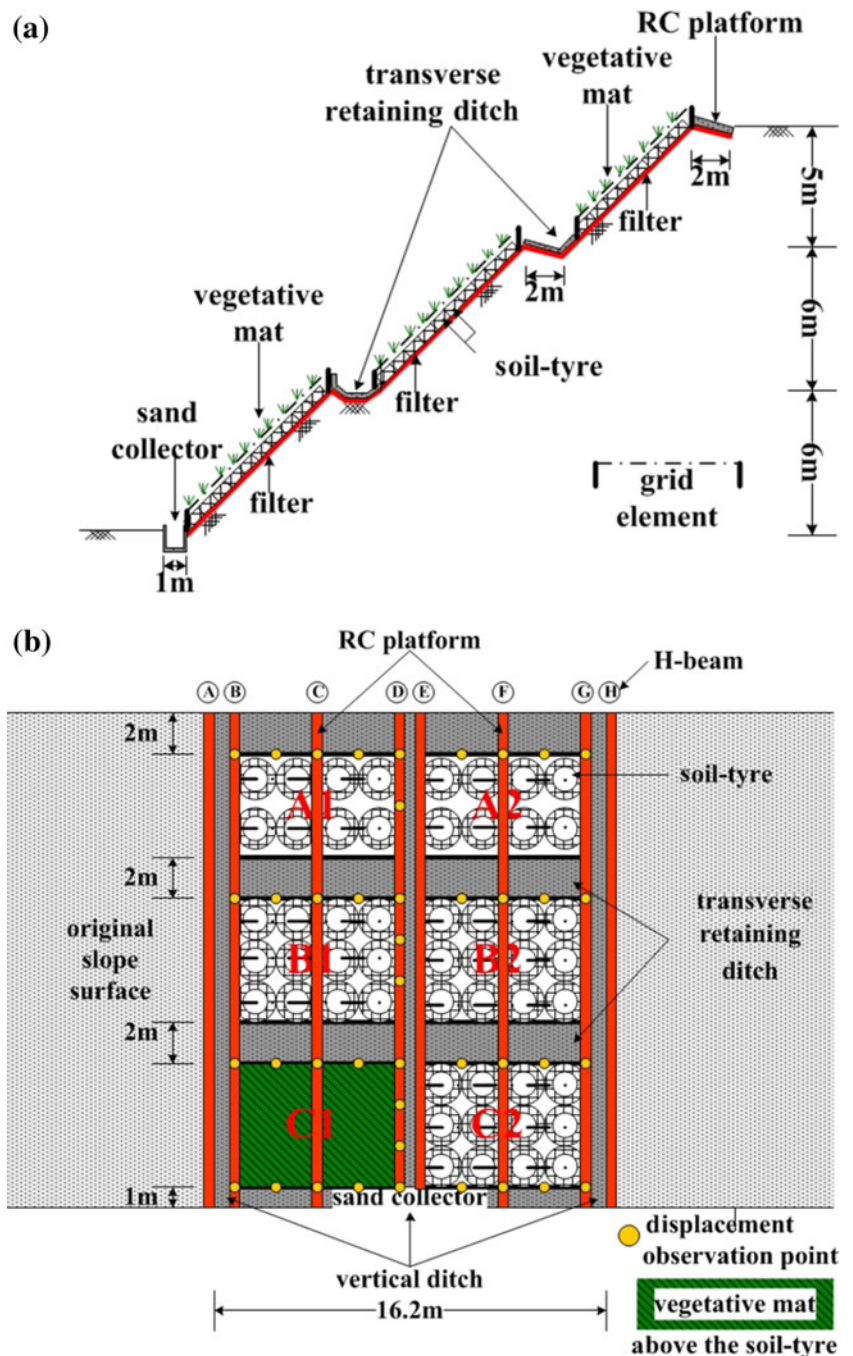
Table 3 Procedure for STV

Step	Brief summary	Detailed summary
1	Shape the slope surface	Divide the slope into three stages with designed heights and gradients
2	Add the filter layer	Place the filter layer above the slope surface (the filter layer includes the fabric drainage sheets and the geotextile to avoid the loss of fine particles and facilitate water drainage)
3	Install the grid elements	Install the grid elements above the filter layer using H-beams
4	Construct transverse ditches and RC platform	Construct transverse ditches on the slope using H-beams and concrete. Build the RC platform at the top of the slope and the sediment pool at the toe
5	Set waste tyres and vegetation bags	Place waste tyres in the grid elements and fill the tyres with bags of vegetation
6	Build longitudinal ditches	Construct longitudinal ditches using H-beams and concrete
7	Place the vegetation mat	Place the geotextile over the tyres and a straw mat on the grid

and weathering on a 35° mudstone slope, the present study investigated the use of STV on a mudstone slope with a gradient of 45°. The efficacy of STV at protecting the slope from erosion was investigated by monitoring soil erosion and the displacement of the grid elements.

Design and construction method

Figure 8 shows pictures of the selected mudstone slope prior to STV construction. The strike of the slope was N35°E, and the dip angle of the slope was 45°SW. The slope had two sets of joints (A and B). The strike of joint A was N60°W and the dip angle was 85°SW, while the strike of joint B was N24°E and the dip angle was 65°NW. The slope was partitioned into multiple stages. The slope angle of each shaped slope partition was 45°. The slope protection work covered an area of 390 m². Figure 9 shows a sketch of the STV on the mudstone slope with a dip angle of 45°. The test slope was partitioned into three stages. The height of the slope in the first and the second stages was about 6 m, and about 5 m in the third stage. Two-metre-wide transverse ditches were placed at each stage to intercept the surface runoff. A 3-m-wide RC platform was set up on top of the test slope to bear the weight of the grid element and to prevent runoff water from infiltrating into the surface mudstone from the top of the slope, causing erosion problems. In addition, three longitudinal ditches were also dug on the slope surface to drain water from the transverse ditches during the rainy season. This was done to avoid erosion problems caused by water overflowing from the transverse ditches and then flowing to the lower slope. Finally, a 1-m-wide sediment pool was set up at the slope toe. The STV construction procedure is listed in Table 3, and an outline is shown in Fig. 10.

Stability of the STV method

Because the 45° test slope was larger and higher than the 30° test slope, it was essential to understand the stability of a high-gradient mudstone slope. Thus, in this study, 20 displacement monitoring points were placed on H-beams B, C, D, F, and G, as shown by the yellow points in Fig. 9b. A fixed point was set on the road near the test slope, and the relative coordinates of each observation point were then measured. The deformations of the STV's grid elements were determined by observing the monitoring points at different points in time. Figure 11 shows the displacements of the grid elements during the rainfall in April–June 2006. The recorded displacements were very small. The largest displacements were recorded at the RC platform and for H-beam G; however, these displacements were still only about 10–12 mm, with barely any lateral displacement (6 mm). This lateral displacement was caused mainly by the erosion that occurred on the bare slope adjoining the STV test slope during the rainy seasons. Therefore, the grid elements remained stable during rainfall, despite the high slope gradient.

Erosion resistance of the STV method

The erosion resistance of the STV-protected high-gradient mudstone slope was investigated. Table 4 shows that from April 1 to May 20 in 2006, the amount of erosion was 2,000 g, with a cumulative rainfall of 222 mm. However, the erosion reached 21,000 g from May 21 to June 22 in 2006, when the cumulative rainfall was 893 mm. The cumulative rainfall increased roughly fourfold, while the amount of erosion increased tenfold. The considerable erosion that occurred from May 21 to June 22 may have been largely due to the fact that the vegetation bags were difficult to fix in the waste tyres on the steep slope. In addition, the heavy rainfall seriously eroded the soil for the
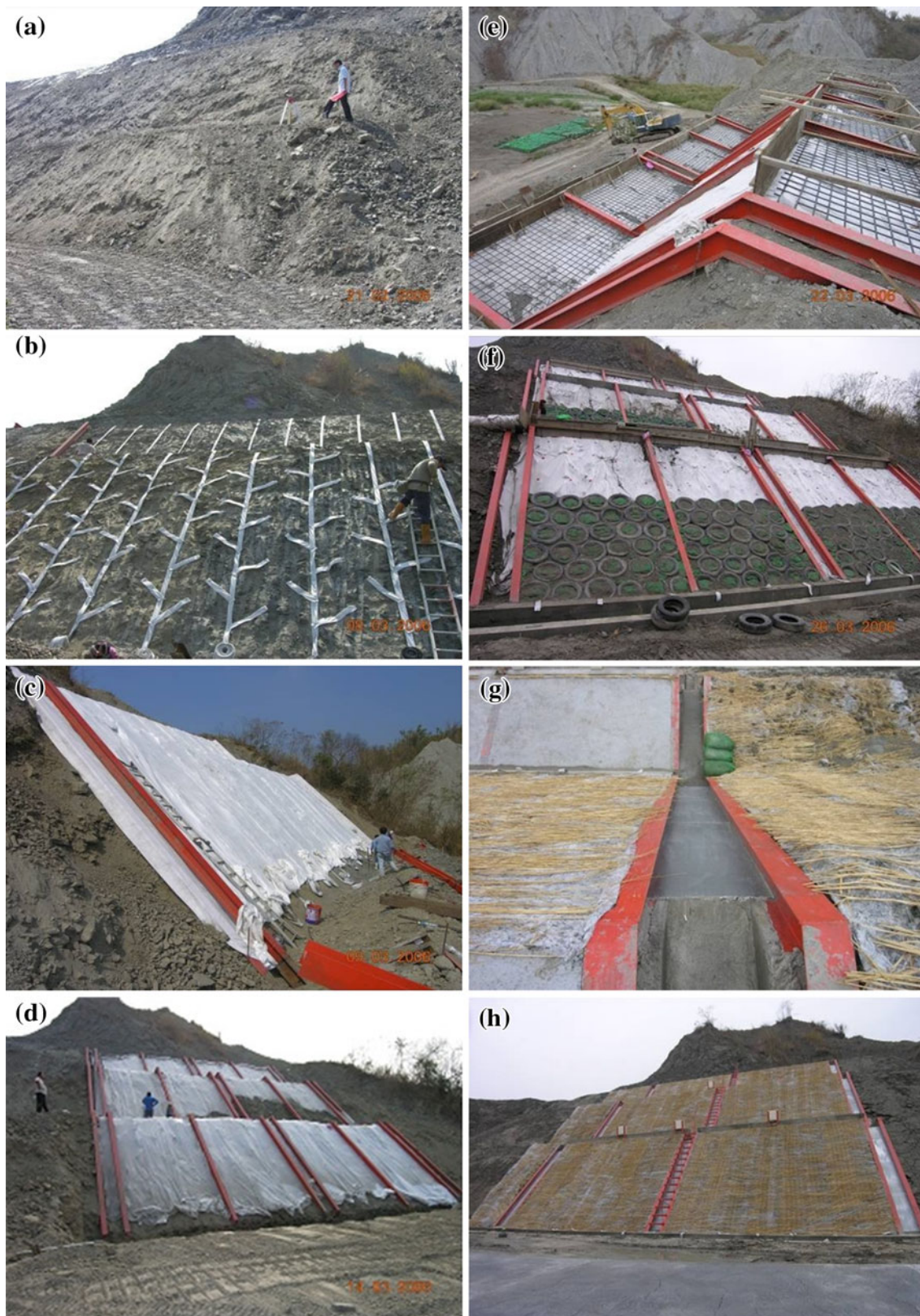
Fig. 10 Field implementation. **a** Shaping the three-stage slope and the platform, **b** installing the fabric drains, **c** placing the geotextile sheet, **d** installing the grid elements, **e** constructing transverse ditches and the RC platform, **f** placing waste tyres in the grid and bags of vegetation in the tyres, **g** constructing longitudinal ditches, **h** placing the vegetative mat on the grid and completing the work
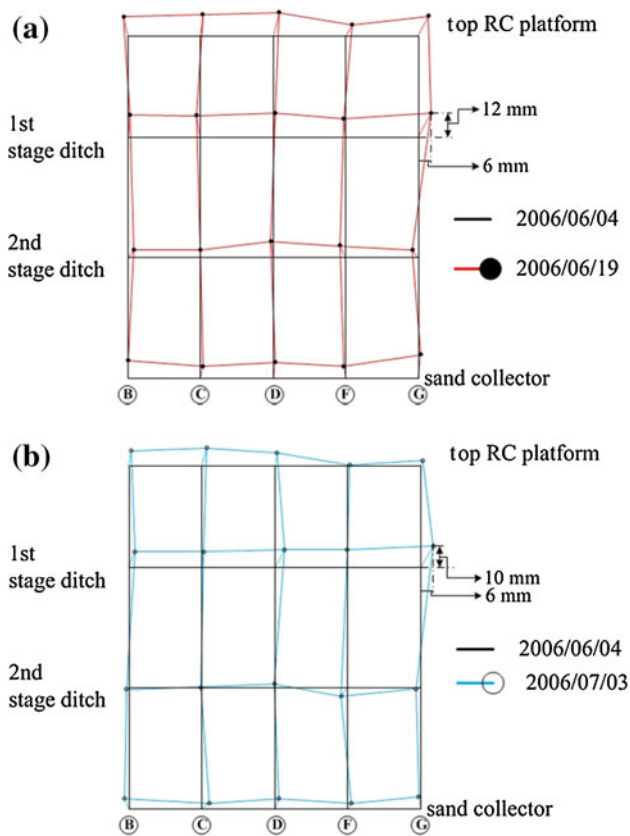
Fig. 11 Displacement of the STV H-beam grid elements. **a** First set of measurements, **b** second set of measurements

Table 4 Soil erosion measured on the 45° mudstone slope

Period (day/month/year)	Cumulative rainfall (mm)	Soil erosion (g/m^2)
01/04/2006–20/05/2006	222	2,000
21/05/2006–22/06/2006	893	21,000

vegetation. Moreover, under the heavy rainfall, the adjoining bare slope surface (that did not have STV protection) was seriously eroded. The eroded soil flowed into the transverse ditches and the sediment pool, affecting the erosion data. According to the design principles of the STV, the filter layer is situated between the vegetation zone and the original mudstone surface in order to protect the surface. Thus, the loss of soil from the tyres affects the vegetation zone. However, the problem of soil erosion in the tyres can be solved by stabilizing the vegetation bags.

Long-term observations of the 45° mudstone test slope

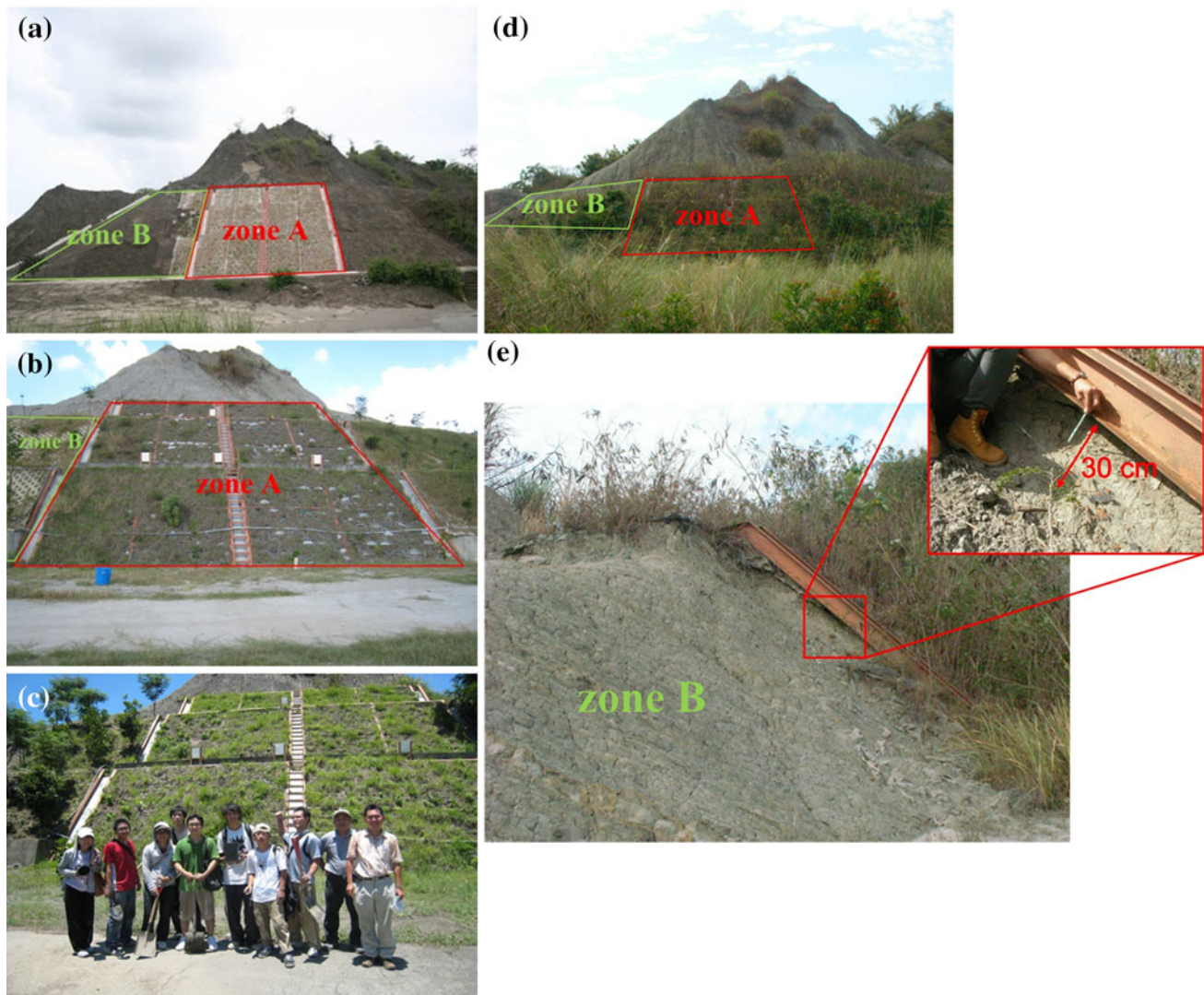Figure 12a shows the condition of the test slope 3 months after the completion of the STV (June 2006). The bare region of the mudstone slope (zone B) showed significant erosion and collapse, but the test slope (zone A) suffered no failure phenomena under STV protection, even though no plants were observed at that time. Figure 12b shows the condition of the test slope in May 2008. The bare region (zone B) had been protected by a conventional nylon bag carpet. The condition of the test slope indicated that both the new STV and the conventional nylon bag carpet effectively protect the mudstone slope and provide an environment conducive to vegetation growth. Figure 12c shows the test slope in July 2010. The mudstone slope is still stable and vegetation is growing well under the protection of both STV and the nylon bag carpet.

Figure 12d, e shows photographs of the test slope in February 2012. The growth of the vegetation shown in Fig. 12d indicates that STV can significantly improve the vegetation on the mudstone slope. Further, the STV structure was still stable. However, Fig. 12e shows that the bare region (zone B)—protected by a nylon bag carpet—collapsed due to the rainfall in 2010 and 2011. This meant that the mudstone slope was exposed again and suffered rainfall erosion and scouring. The erosion thickness was almost 30 cm, and this observation shows that the new STV can provide protection for a longer period than the conventional nylon bag carpet when used on a high-gradient mudstone slope. Since 2006, the STV has resisted rain erosion and maintained the stability of this mudstone slope.

Conclusion

In this study, the STV method was applied to a high-gradient mudstone slope to provide protection from erosion. After continuous rainfall in April and May 2006, the STV grid elements had deformed by only 0.6 cm horizontally. Therefore, the grid elements of STV showed high stability on the high-gradient mudstone slope. In addition, the amount of soil erosion increased significantly because of the loss of soil from the bags of vegetation in the tyres, as well as the erosion of soils from the neighbouring bare mudstone slope. Therefore, the problems of soil loss and scouring on the high-gradient mudstone slope can be solved by applying STV if its vegetation zone can be stabilized, making it conducive to effective vegetation growth. The test results for the 45° mudstone slope show that STV works well on longer and steeper mudstone slopes.

The grid elements in STV are constructed from H-beams, waste tyres, and bags of vegetation. Using these H-beams, the volume of concrete required can be decreased. The soils in the bags of vegetation were taken from the alluvial soils of the eroded mudstone slope. Thus, local soils can be used to construct an STV. Meanwhile, using waste tyres protects the mudstone slope but also contributes to waste recycling. In

Fig. 12 Changes in the 45° mudstone test slope. **a** June 2006, **b** May 2008, **c** July 2010, **d** February 2012, **e** scouring of the bare mudstone slope

addition, based on the changes observed in the condition of the test slope over time, STV can provide long-term protection of a 45° mudstone slope. This protection is possible for three reasons: (1) STV uses multiple stages to shorten the slope length, which reduces surface erosion; (2) waste tyres constitute a later of vegetation that can reduce the amount of bare mudstone surface; (3) the filter layer reduces the loss of fine soils from the mudstone slope. Therefore, this new STV method is an effective and ecological technique for protecting mudstone slopes.

To summarize, the STV method is a new slope erosion countermeasure, that can significantly reduce the amount of erosion of a bare mudstone slope. It utilizes waste tyres and local geomaterial to form a vegetation zone. Although it was developed to solve erosion problems on mudstone slopes, this method could also be applied to slopes consisting of other soil types.

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