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Can rock fragment cover maintain soil and water for saline-sodic soil slopes under coastal reclamation?

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ABSTRACT

Seeking a potential erosion control method for saline-sodic soil slopes under coastal reclamation is essential. We investigated the effect of rock fragment covers (*RC*) on the rainfall partitioning, infiltration and runoff processes, and the erosion processes for saline-sodic slopes of 15° and 30° subjected to a 50-min simulated rainstorm with an intensity of 92 mm h^{-1}. Six rock fragment covers (0%, 10%, 20%, 40%, 60% and 80%) were investigated. Soil was packed in 200 cm × 100 cm × 30 cm flumes, divided into two to create two replicates for each treatment. Two sequential soil erosion events, *E1* followed by *E2*, were induced under two rainstorms that were 24 h apart. Results showed that, in general, *RC* had a positive effect on the runoff rate for both slopes. A logarithmic relationship existed between the steady-state infiltration rate and the *RC*. For the gentler slopes, an *RC* between 40% and 60% could protect the soil from erosion for *E2* and *E1* + *E2* events, but did not do so for the *E1* events alone. For the steeper slopes, the *RC* had no effect on soil losses for the *E2* and *E1* + *E2* events, but increased the soil losses for the *E1* events. As the situation of rock fragment changed from *Situation 1: well embedded into the soil surface* to *Situation 4: submerged in water*, the relationship between *RC* and soil loss became more complex and might change over time from a positive to a negative one. The results suggested that the effect of *RC* on runoff and soil losses was influenced by the change of rock fragment situations over time during individual rainstorms. The benefits of *RC* might be augmented by using them in combination with another protective measure.

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1. Introduction

Reclamation of coastal saline tidal flats has been a frequent practice for coastal countries faced with a lack of cultivated land and an increasing population. Such reclamation is not without its problems. For example, in Jiangsu Province, China, the reclamation of tidal flats involves the construction of many water channels or drainage ditches in order to facilitate soil desalinization and to both conserve and transport water resources. The soil slopes of these water channels suffer from severe rainfall erosion (Liu et al., 2015; She et al., 2016). The soil desalinization process takes about 30 years to yield agricultural land of minimal acceptable quality depending on the soil type and local environmental conditions (Xu et al., 2013). Hence, these saline-sodic soil slopes need to be protected from rainfall erosion for a long time. Soil slopes are often protected by growing vegetation. However, local field observations confirm that it is difficult to obtain a high enough level of vegetation cover in order to protect the channel slopes due to the high salt contents of the soil and inadequate levels of salinity tolerance of the plants. The use of a constructed slope protection, such as a concrete cover, is neither energy-efficient nor environmentally friendly. Based on numerous published studies (e.g. Poesen et al., 1999; Jomaa et al., 2013) and our own preliminary study (She et al., 2014), we concluded that a cover of rock fragments could potentially protect the slopes. These rock fragments are already present at the reclamation site as a waste left over from the reclamation of tidal flat constructions. However, while stone or gravel mulches have been used on other soils in order to reduce soil erosion, their use on saline-sodic soil slopes does not appear to have been investigated.

The presence of rock fragments on or within soils could change the soil hydraulic properties (Mehuys et al., 1975; Bouwer and Rice, 1984). In the case of soils containing rock fragments, hydraulic properties are difficult to determine directly (Ma et al., 2010). Bouwer and Rice (1984) proposed that the saturated hydraulic conductivity (*K*) of a stony soil could be calculated from the saturated *K* of the soil matrix surrounding the stones and the void ratios of the stony soil and of the soil alone. Ma et al. (2010) tested an analytical method proposed by Ma et al. (2009) that determined the hydraulic properties of soils containing rock fragments and showed that the saturated *K* values of stony

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soils decreased with increased rock fragment content. Similarly, Novák et al. (2011) found that the hydraulic conductivities of saturated stony soils decreased nonlinearly as a function of the relative stone content.

During a rainstorm, soil aggregates are broken down by raindrop impact, slaking, and clay dispersion. The loose particles plug soil pores that enhance the compaction of the soil surface to create a surface seal (Warrence et al., 2002). Rock fragments can potentially protect soil surfaces from raindrop impacts and reduce surface sealing to some extent (Poesen and Lavee, 1994). However, Poesen (1986) found that surface sealing was greater when stones were embedded into the soil surface layer than when the stones were placed on the soil surface. Based on the position and the percentage of rock fragments in the top layer, Valentin (1994) substantiated the laboratory results of Poesen (1986) and developed two simple models that could determine the role of the rock fragments. The models indicated that infiltration coefficients of soils under free rock fragment covers would be higher than those of the bare soils, thereby illustrating the protective role of free rock fragments against sealing.

The role of rock fragments in affecting soil erosion processes has been studied intensively in recent years (Poesen et al., 1990; Cerdà, 2001; Jomaa et al., 2012a; Shi et al., 2013; Jomaa et al., 2013). Poesen et al. (1990) and de Figueiredo (1998) found that placing rock fragments on the slope surface resulted in increased infiltration rates and decreased runoff volumes. However, as implied above, Poesen et al. (1990) indicated that the rock fragments embedded in the soil surface would reduce infiltration rates and increase runoff amounts due to the effects on surface sealing. Jomaa et al. (2012a) indicated that rock fragments protect soils from raindrop impact and reduce overland flow rates, thus reducing its sediment transport capacity, and both roles reduce soil erosion. However, to the best of our knowledge, there have been no studies on rock fragment effects on soil erosion processes when the soil is more prone to dispersion as in the case of saline-sodic soil slopes under coastal reclamation. Therefore, such a study is needed. The aims of this study were (1) to quantify how the level of rock fragment cover affected rainfall partitioning and sediment transport for this particular type of soil (i.e., saline-sodic), and (2) to compare the effects of different rock fragment covers on soil erosion processes under multiple erosion events, i.e., under different antecedent conditions. Knowledge of the rock fragment effects on water migration and slope erosive characteristics is essential in guiding coastal reclamation, soil conservation and optimal land resource utilization.

2. Material and methods

2.1. Study area

The study area was a coastal reclamation area in the Tiaozini reclamation region near Dongtai City (32°33′–32°57′N, 120°07′–120°53′E), Jiangsu Province, China (Fig. 1A and B). The study area had been under reclamation since 2012 (Fig. 1C). This region is adjacent to the Yellow Sea and is only 1.4–5.1 m a.s.l. It is situated in a climatic transition zone between subtropical monsoon and warm temperate zone and has a mean annual rainfall of 1060 mm. The mean annual temperature is 15 °C and the mean annual potential evapotranspiration is 880 mm.

The study area was the source of the soil used in laboratory rainfall simulation experiments in which the effects of rock fragment cover on soil and water losses could be investigated systematically. The soil was collected in August 2013 from the upper 100 cm layer of the banks of a reclamation ditch. The soil was a sullage-puddled soil with a silt loam texture. The collected soil was air-dried, passed through a 4-mm sieve, and thoroughly mixed. The basic properties of the soil are shown in Table 1. According to the criteria defined by Thorne (1954), the soil was a saline-sodic soil (EC > 4 mS cm^{-1} and ESP > 15). The soil, with a high sodium salt content, is highly susceptible to erosion by rainfall. Consequently, newly excavated drainage ditches in the study area fill with massive amounts of eroded material within just one year.

2.2. Experimental setup

Rain was simulated by a Sprinkler Rainfall Device. This device produces simulated rainfall with a fall height of 4 m, and at an intensity that can be varied by adjusting pressure gauges. Heavy rainstorms (>60 mm h^{-1}) occur frequently in this study region. Therefore, a rainfall intensity of 92 mm h^{-1} was selected in this study to simulate those naturally occurring intense storms. Deionized water was used to simulate the water quality of rainwater.

A metal flume (200 cm long, 100 cm wide, 30 cm deep) packed with soil was used to investigate the slope erosion processes. The metal flume was divided into two so that the soil in both sides (200 cm long, 50 cm wide and 30 cm deep) of the flume was subjected to identical treatments that could be considered as replicates of that treatment. Similar experimental split-plot designs have been used in other field studies (e.g. Descroix et al., 2001; Mandal et al., 2005). It should be noted that using a soil in the small flume in this study would not give a complete picture of slope erosion processes occurring under field conditions. However, this type of study enables systematic studies to be carried out under controlled conditions that enable insights into the changes in certain slope erosion processes to be achieved. The metal flume was set on a framework that could be inclined to create different slope gradients. The range of exposed excavated soil slopes in the reclamation area of Jiangsu province was 5°–40°; thus, two typical slope gradients were selected, i.e., *S1*, which represented a gentler slope (15°), and *S2*, which represented a steeper slope (30°).

Each simulated rainfall experiment included two separate erosion events *E1* and *E2*: a typical rainfall simulation lasting for 50 mins (*E1*), followed by a further simulated rainfall of 50 mins applied 24 h later (*E2*). The main reason for this separation was to consider the effect of the rock fragments on soil and water losses under different initial conditions. In the field, the first rainstorm in a rainy season typically falls on a soil with low water content where the soil is not covered by a well-formed seal, particularly if the soil is on the banks of a newly excavated, or re-excavated, ditch. In subsequent storms, sealing has occurred albeit with some destruction due to drying, and the water content is likely to be higher. In our first storm, we used air-dried soil and no seal was present. In the second storm, the antecedent water content should be close to saturation while the seal formed during the first storm would be largely intact. These two sets of initial conditions represent the two extremes that could be found in the field.

Therefore, each rainfall simulation experiment first involved preparing the flume with both sides of the divided flume prepared identically. A 4.5-cm thick layer of gravel was used to cover the base of the flume. This layer was then covered with a 0.5-cm thick layer of cotton, which prevented soil particles from entering the gravel layer but allowed the free drainage of water and permitted air to escape. Two 5-cm thick soil layers were uniformly packed into the flume to give a bulk density of 1.3 g cm^{-3}. Note that the surface of the lower soil layer was raked before packing the upper one to ensure continuity between the two soil layers. The upper soil layer was manually tilled to achieve a similar surface roughness in all of the rainfall simulation experiments. Irregularly shaped rock fragments were then well-embedded into the soil surface. The packed flume was positioned under the rainfall simulator, adjusted to the intended slope gradient, and exposed to rainfall for 50 mins. At the end of the erosion event, *E1*, the slope surface was carefully covered by a clean plastic sheet to prevent evaporation and destabilization. The second erosion event, *E2*, began 24 h after *E1* had ended, after removing the plastic cover.

The rock fragments used in this study came from the waste material left over from construction during the reclamation of the tidal flats. Primarily these fragments were used as a porous layer within the constructions and consisted of an igneous rock material. The fragments used in

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