Synergistic effects of rock fragment cover and polyacrylamide application on erosion of saline-sodic soils

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ABSTRACT

Many erodible and unstable bare soil slopes were exposed under rainfall during the tidal flat reclaimed to be farmland in the coastal provinces of China. There is an urgent need for erosion control methods that are not only efficient and effective long term but also economical and environmentally friendly for slopes with saline-sodic soils. A combination of rock fragment cover (RC) and polyacrylamide (PAM) might be a potential choice. We investigated the synergistic effect of RC and PAM amendment rates on infiltration, runoff, and erosion processes for slopes of 15° with saline-sodic soils that were subjected to two 60-min simulated rainstorms with an intensity of 60 mm/h under laboratory conditions. Nine treatments with three RC (0%, 15%, and 30%) and three PAM applied rates (0, 0.4, and 1.0 g/kg) in the upper soil layer were all exposed to two sequential rains of deionized water, and these two rainfall events (E1 and E2) were 4 h apart. The results showed that the embedded rock fragment cover decreased the infiltration rate (IR) and increased the runoff rate, which increased sediment yield rate (Rs) in rainfall E1. In E2, RC had a significant ($P < 0.05$) negative impact on the sediments yield rate by blocking the runoff in the rill. The PAM amendment significantly ($P < 0.05$) increased the IRs for both rainfall erosion processes, but the IRs were reduced with the PAM application rates increasing from 0.4 to 1.0 g/kg. PAM significantly ($P < 0.05$) decreased the soil loss in E1 and E2. The positive effect of RC on mean Rs in E1 was restrained as the PAM application rates increasing to 1.0 g/kg. An application rate of 0.4 g/kg was recommended for improving infiltration and controlling erosion because the increased infiltrated water could dissolve soil salt and transport it to drainage ditch though the underground pipes. The optimized combination formula had a PAM application rate of 0.4 g/kg and RC of 15% after taking the two sequential rainfall events into account.

1. Introduction

Reclamation of saline tidal flats has been an indispensable practice in Jiangsu Province in China for over a long period, and it will play a more crucial role for the coastal areas faced with population and cultivated land demand increasing (Liu and She, 2017a). In Jiangsu Province of China, approximately 2 million hectares of tidal flats have been reclaimed and cultivated since the construction of the Fan-Gong Dike in the 11th century A.D. (She et al., 2014). With the acceleration of urbanization and population growth occurring in the coastal provinces, the exploitation will play an increasingly important role in coastal development strategy. In the process of reclaiming the tidal flats with supporting water conservancy construction, many exposed excavated slopes will be built, including the banks of ditches, drainage channels,

streams and rivers. Considering that the region's rainfall is abundant but the soil has high sodium salinity and poor structure, these slopes would likely be more erodible and unstable, which would possibly result in collapse due to salinity lowering the aggregate stability of soil (Al-Uzairy, 2015). As a result of the soil slope erosion and destruction, the ditch banks lose soil at up to 140 kg/m² annually in the most recently reclaimed farmland according to the field investigation (She et al., 2014), and some kinds of constructions used for soil desalinization might lose efficacy due to the soil scouring beneath the construction. Under natural conditions, soil slopes can be protected by growing vegetation effectively. Effective vegetation protection requires dense cover, and after local field observations, it was confirmed that the local vegetation cover was not dense enough in a larger area due to the high soil salt contents and inadequate levels of salinity tolerance in plants

(She et al., 2014; D. Liu et al., 2015; Z. Liu et al., 2015). Except for natural vegetation protection, the constructed slope protection, such as a concrete cover, is widely used, although it is neither energy-efficient nor environmentally friendly.

RC is an alternative artificial slope protection measure that has been proven to be effective in numerous studies (e.g., Poesen et al., 1994; Jomaa et al., 2013) under certain climate characteristics and soil conditions in both field experiments (Wang et al., 2013) and laboratory experiments (Zavala et al., 2010). The rock fragments can be supplied from the gravels that are already present at the reclamation site as waste leftover from the reclamation of tidal flat constructions. Therefore, these rock fragments could potentially be converted to slope protection material from construction waste. On the other hand, the effect of RC on runoff and soil losses is complex and can vary from negative to positive depending on topsoil structure (Poesen and Ingelmo-Sanchez, 1992), vertical position (Poesen et al., 1990) and size (Agassi and Levy, 1991; Poesen and Lavee, 1991) of the rock fragment as well as the soil surface slope (De Ploey, 1981), among other factors. This effect could be influenced by rock fragment parameters changing over time during individual rainstorms (Liu and She, 2017a). Most recent studies have focused on the effect of stone or gravel mulch cover on the hydrological and erosional response of agricultural soils (Cerdà, 2001), but the effect of these covers on slopes with saline-sodic soils has not been investigated thoroughly.

Soil erosion can be influenced by many interacting factors, including rainfall intensity and duration, soil properties, topography, land cover, spatial scale, and initial and antecedent soil conditions (Hancock et al., 2008; Neave and Rayburg, 2007; Rudolph et al., 1997; Poesen et al., 1994). Surface sealing and crusting also have important effects on the erosion progress (Singer and Shainberg, 2004). Sealing and crusting can decrease the IR, which increases the runoff and potential for soil loss (e.g., Le Bissonnais et al., 1998; Neave and Rayburg, 2007). Rock fragments placed on top can potentially protect soil surfaces from raindrop impacts and reduce surface sealing to some extent (Poesen and Lavee, 1994). However, it was also found that surface sealing increased when stones were embedded in the soil surface layer than when placed on the soil surface (Poesen, 1986). Based on the different rock fragment positions and the percentage in the top layer, Valentin (1994) substantiated the laboratory results and developed two simple models that could determine the effect of rock fragments on the infiltration. The models indicated that infiltration coefficients of soils under free rock fragment covers would be higher compared to bare soil, which showed that free rock fragments play a protective role in surface sealing. The latest research results of our team indicated that RC between 40% and 60% could reduce soil loss over the sum of two sequential soil erosion events and the second rainfall erosion event alone, while RC could not protect the slope for the first soil erosion event. It was also proposed that the benefits of RC might be augmented by combining them with other protective measures, such as adding polyacrylamide (PAM) (Liu and She, 2017a). To research the synergistic effects of RC and PAM on erosion could test their suggestions and confirmed the conclusions. The application of PAM influences the infiltration and runoff progress, and the interaction of rock fragments and PAM has not been sufficiently researched. This study might reveal the interactions of two slope protection measures between physical way of RC and chemical conditioner of PAM that are both widely applied in practice.

PAM has been used to stabilize soil structure with high efficiency, which leads to increased infiltration, reduced erosion, and a reduction in water use (Lentz and Sojka, 1994; Lentz et al., 1996; Trout et al., 1995). Laboratory and field studies with anionic PAM (Shainberg et al., 1990; Agassi and Ben-Hur, 1992; Levy et al., 1992) have demonstrated that small amounts of PAM (10–20 kg·ha^{-1}) added to the soil were effective in stabilizing soil structure, which maintains good permeability and reduces runoff and soil erosion. The addition of PAM significantly increased the percentage of > 4-mm aggregates compared to the untreated aggregates. However, PAM was more effective at stabilizing the light- to medium-textured soils than clayey soils (Miller et al., 1998). Many studies have shown that PAM can be used to maintain adequate infiltration under high intensity rainfall (Levin et al., 1991; Shainberg et al., 1990; Smith et al., 1990), especially with electrolytes in the water. The hydraulic conductivity was higher with the PAM dissolved in the saline water compared to deionized water (Shainberg et al., 1990). The soil in the study area contained a very high content of salt (with the exchangeable Na content of 4.6 cmol·kg^{-1}) and might increase the positive effect of PAM on infiltration.

For soils that lack structural porosity, including the coastal saline-sodic soil in this study, a positive relationship between RC and interrill sediment yield existed when fragments are embedded well in a surface seal developed on a topsoil with a textural porosity (Poesen et al., 1994). The positive effect of RC on sediment yield was partly derived from the decrease of IR (Liu and She, 2017a). The IR can be reduced by the embedded rock fragments in topsoil without structure porosity (Poesen et al., 1994), but it can be increased by adding PAM on the soil surface (Abrol et al., 2013). As the preliminary study showed, the position of rock fragments could be changed by the erosion progress (Liu and She, 2017a). We hypothesized that with the stabilization of aggregates caused by relatively high PAM application rate treatment and the viscous spots formed on the slope surface, the rock fragments is unlikely to be replaced by the concentrated flow due to reduced soil erosion and strengthened soil surface stability. Our own preliminary study (Liu and She, 2017a) showed that RC could be used to control soil loss for the slopes of saline-sodic soil; however it was effective only with high covers of 40%–60% on the slopes of 15°, and the soil loss could be increased under the RC of 10%–20%. We also hypothesized that combined with the aggregates stabilization by PAM, a lower RC would reach to similar protective effect of a higher RC applied alone as in the preliminary study for soil conservation. Thus, the objectives of this research were to (i) investigate the complex and dynamic interactions between soil loss and runoff which vary differently with two kinds of soil amendments, (ii) reveal the mechanism through which granular PAM was effective for improving the protective effect of RC on this particular type of soil, and (iii) optimize a combination formula of dry granular PAM dosage and RC according to the purpose of the application (to improve IR, control erosion or taking the two sequential rainfall events into account).

2. Material and methods

2.1. Study area and soil

The study area is located in a coastal reclamation region of eastern Dongtai City (32°33′–32°57′N, 120°07′–120°53′E) of Jiangsu Province, China (Fig. 1). It is a low-lying flat area besides the Yellow Sea, and its altitude ranges between 1.4 and 5.1 m. This area lies in a transition zone between the subtropical and warm temperate zone, the mean daily temperature is 15.0 °C with a minimum temperature of −7.5 °C in February and a maximum of 35.9 °C in July. The total annual rainfall is 1060 mm, and the annual potential evapotranspiration is 880 mm. A sullage-puddled soil containing a silt loam texture is the dominant soil type in the reclamation region.

The soil was taken from the study area so the slope erosion affected by PAM application and RC could be investigated systematically in laboratory rainfall simulation experiments. To help the experiment reflect the actual situation better, the soil was taken from the 100-cm layer below the surface of a typical reclamation ditch bank in August 2013. Then, it was air-dried for months, passed through a 4-mm sieve, and thoroughly mixed before used. The soil contains organic matter with 3.26 g/kg, a sodium (Na) ion content of 1.60 g/kg. The clay, silt, and sand contents were 2.3%, 40.3%, and 57.4%, respectively, and the texture was silt loam (USDA classification). The EC$_{1:5}$ (soil electrical conductivity of a 1:5 soil: water suspension) of this soil is 4.3 mS/cm,