Design of Stable Concave Slopes for Reduced Sediment Delivery during Geomorphic Reclamation

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Abstract: This paper is a synthesis of previous published works that have arisen out of an investigation of the stability and sediment control considerations in reclaimed mine lands. Methods currently exist to estimate both the mechanical slope stability of the slopes and the hillslope sediment delivery. However, these methods require input parameters that are obtained from laboratory or field measurements, or through empirical relationships, many of which were not developed for mine lands. Further, these methods have been developed for slopes that are planar in cross section or profile, and existing studies would suggest concave slopes may reduce surface erosion and sediment. This synthesis addresses the following: a) soil characterization and mechanical stability of steep reclaimed slopes with a low compaction surface layer, b) hydrology curve number and revised universal soil loss equation (RUSLE) erodibility (K) factor for Appalachian surface coal mining reclamation sites, c) testing of the SEDCAD model performance for applicability for steep-sloped reclaimed mine lands, and d) superior mechanical stability and erosional resistance of concave slopes relative to planar slopes.

Introduction

A research project recently funded though the U.S. Bureau of Mines, Applied Science program (Eric C. Drumm and John S. Schwartz “Reforestation of Steep Reclaimed Slopes: Stability and Sediment Control Considerations” US Office of Surface Mines, Applied Science Program, June 2008- May 2011) has identified several contributions which may be of use to others in the geomorphic reclamation of mine lands. These contributions have been published, and are referenced as below.

Soil Characterization and Mechanical Slope Stability of Steep Reclaimed Slopes with a Low Compaction Surface Layer

The quick and healthy establishment of forest and ground cover is an important consideration for the successful restoration of the mine-land and for the long-term erosion control. While mine reclamation incorporates compaction procedures to ensure stability of the restored slopes, the high levels of compaction may have negative impacts on tree survival. The Forest Reclamation Approach (FRA), now promoted by the US Office of Surface Mining, is a reclamation method that employs minimally compacted soils in the slope surface to enhance tree survival. The FRA was investigated on steep slopes ($> 20^{o}$) at three reclaimed coal mining sites in the Appalachian region of East Tennessee (Jeldes et al. 2010, Hoomehr et al. 2013, Jeldes et al. 2013a). The analysis of several modes of failures suggested that the governing failure mode is shallow and contained within the loose surface layer. It was shown that the field measurement of the angle of repose, coupled with the use of the infinite slope method, represents an effective means to rationally verify the stability of steep slopes constructed with low surface compaction. In addition, field measurements of the highly variable unit weight are not required for long-term analyses (Jeldes et al. 2013a). The method was extended to allow for the evaluation of a) seismicity and b) field variations in moisture content (Jeldes and Drumm 2011, Jeldes et al. 2014a). While stability analyses showed that seasonal increments in the stability of steep FRA slopes due partial soil saturation are possible and the static long-term stability is a lower bound of the real field performance, seismic spectral response analyses illustrated the rare cases where stability may be compromised during dynamic loading.

Hydrology Curve Number and Revised Universal Soil Loss Equation (RUSLE) erodibility (K) factor for Appalachian surface coal mining reclamation sites

A series of full scale field experiments were used to quantify the hydrology curve number (CN) and Revised Universal Soil Loss Equation (RUSLE) erodibility (K) factor for Appalachian surface coal mining reclamation sites, and appropriate values were recommended (Hoomehr et al. 2013, 2014). Three study sites in East Tennessee included active mining operations on steep slopes (> 20^o) where after mining, approximate natural hillslope contours were reconstructed using loose spoil materials on top of slope, at shallow depths of 1-2 m, following the Forest Reclamation Approach, now promoted by the US Office of Surface Mining.

The CN and the K factor are critical input parameters for the SEDCAD model used for developing surface mining permits. CNs were estimated by the traditional NEH-4 (Part 630) method for three study sites in East Tennessee, in additional to the asymptotic and frequency matching techniques. It was found that an initial abstraction (λ) of 0.2 best fits the data. CNs generated by the asymptotic method provided an estimate with a practical range between 58.5 and 60, and based on this method representing larger storms the range should be used for hydrological modeling. The CN range is lower than one would expect from surface-mine sites, suggesting infiltration influenced the measured rainfall-runoff relationships.

Average cumulative erosivity for the three study sites during the monitoring period was measured as 5,248.9 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$. The K factor ranged between 0.001 and 0.05 $t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$, with the highest values occurring immediately following reclamation site construction as rills developed (June - August 2009). The K factor for two study sites with about an 18-20 mm spoil D_{84} were above 0.01 $t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$ during rill development, and below 0.003 $t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$ after August 2009 for the post-rill development period. During rill development the K factor is almost 4 times the post-rill development period's value. It appears larger size fractions of spoils influence KC factors on low-compaction steep slopes reclamation sites. Although site spoils were loose, steep slopes generated overland flow in excess of infiltration and initiated rill formation.

Testing of the SEDCAD Model Performance for Applicability for Steep-sloped Reclaimed Mine Lands

The Sediment, Erosion, Discharge by Computer Aided Design (SEDCAD) program is extensively used in the mining industry for engineering site layout plans with best management practices (BMPs) for erosion control. For the same study used to estimate the hydrology CN and erosion K factor, this study (Hoomehr and Schwartz 2013) compared measured sediment yields with SEDCAD modeled outputs. SEDCAD model inputs included site derived hydrologic Curve Number (CN) of 59, and average erodibility K factors ranging from 0.001 to 0.034 $Mg \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$ varying based on pre- and post-rill development periods, and mining site. SEDCAD overestimated sediment yields as a function of erosivity (R) up to 1.6 times greater than the minimally measured yields, in two of the three study sites. A sensitivity analysis of input parameters found CN selection can greatly affect modeled outputs for sediment yield. For example, a 40% deviation in selecting a CN would double the computed sediment yield. Results from this study provide design engineers using SEDCAD a better understanding of the uncertainty with model outputs in order to improve selection and design of erosion BMPs on surface coal mining sites.

Superior Mechanical Stability and Erosional Resistance of Concave Slopes relative to Planar Slopes

While constructed slopes are traditionally designed to be planar in cross section, in nature curvilinear slopes with concave shapes are naturally formed as a result of evolutionary processes leading towards a state of erosion and sediment transport equilibrium. It has been understood for some time based on field studies that concave slopes produce less sediment than planar slopes; however, not all concave shapes are mechanically stable and the mathematical description of concave slopes for mechanical stability is complex and not likely to be adopted in practice. To overcome this difficulty an approximate mathematical solution defining the geometry of critical concave slopes (FS ≈ 1) for frictional soils with self-weight was developed (Jeldes et al. 2013b), and an approach to design concave slopes for any given FS, for both long-term and short-term stability was demonstrated (Jeldes 2014, Jeldes et al. 2014b). It was demonstrated that these concave slopes yield 15-40% less sediment than planar slopes of equal FS, regardless of soil erodibility and weather conditions, and that the stability of concave slopes is not significantly influenced by errors in the construction when typical high accuracy GPS construction equipment is employed (Jeldes 2014, Jeldes et al. 2014b). On the other hand, while mechanically stable, the proposed concave slopes may not be in a full equilibrium state from a water erosion perspective; therefore, based on the assumptions inherent to the RUSLE2 erosion model, concave profiles in water erosion equilibrium were obtained (Jeldes 2014, Jeldes et al. 2014c), and those concave slopes that satisfy both erosion equilibrium and a desired degree of mechanical stability were identified and mathematically described.

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