SUBTASK 3.1 GEOMORPHIC DESIGN

FINAL REPORT

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EXECUTIVE SUMMARY

Research Aim and Scope

Approximately 40% of operating mines in West Virginia are surface mines, producing around 50 million tons of coal each year (WV Office of MHS&T, 2011). Federal regulations that have been designed to control environmental impacts associated with surface mining are becoming increasingly stringent. The West Virginia Department of Environmental Protection (WVDEP) Division of Mining and Reclamation and United States Environmental Protection Agency (EPA) recently have delayed or temporarily suspended surface mining permits because of the implementation of more rigorous standards relating to reclamation and post-mining land use. As the demand for energy continues to increase, there is a need to find an alternative to the typical surface mine reclamation techniques used today in Appalachia.

The short-term outcome of this project was to assess the feasibility of coal companies to implement geomorphic design into surface mine reclamation in Appalachia. Many other considerations were studied throughout the duration of this project. Laws and regulations were also evaluated to determine where geomorphic design may be applied in Appalachian surface mining. With regulations becoming more stringent and changing frequently, implementing geomorphic ideas into the steep terrain of Appalachia while adhering to current regulations is a challenge.

The long-term outcome of this research was to incorporate Carlson®'s Natural Regrade® with GeoFluv™ software to create a geomorphic design for a sample surface mine in southern West Virginia. This followed with evaluation of the conceptual landforms with seepage and slope stability analysis to determine the safety, constructability, and long-term performance of the proposed site.

While this innovative reclamation design approach has been used with success in semi-arid regions of the United States, as well as throughout the world, the approach has not been utilized in West Virginia. One main purpose of this project was to analyze the effectiveness of geomorphic reclamation on surface mines in West Virginia as well as a comparison of the features of the completed geomorphic valley-fill design contrasted to an approximate original contour variance valley-fill design. By creating a geomorphic reclamation design for a site in West Virginia, data could be collected and compared directly to traditional designs in order to determine and assess advantages and disadvantages of implementing this innovative surface reclamation technique in Appalachia.

A safety analysis as well as a cost analysis was also performed to compare both a traditional valley-fill design and the completed geomorphic valley-fill design so that any significant cost increases or decreases could be assessed. Stream analysis including the length of original streams, length of created streams, stream classification, and stream type was performed to identify complete drainage systems. All of the numerous aspects that were analyzed between the traditional and geomorphic valley-fill designs in return yielded an accurate analysis of the benefits and/or disadvantages of the nontraditional reclamation approach as well as the ability to implement this geomorphic reclamation design method in West Virginia. Following the comparison, it was found that the AOC variance valley-fill design was intended to ensure slope stability, control drainage, complement the drainage pattern of the surrounding terrain, and prevent stream sedimentation. The prototype geomorphic design consisted of:

- slope shapes exhibiting uniform benches
- planar slopes having unvarying contours
- drainage ditches located along the perimeter and/or center of the fill

However, the traditional, planar reclamation method following the Approximate Original Contour (AOC) can be improved to appear more natural and decrease the drawbacks associated with it.

Features of the resulting Natural Regrade® design include:

- long-term stability due to dynamic equilibrium
- suggested reduction in maintenance due to stability
- projected reduced cost due to strategic placement of fill material

- more aesthetically pleasing valley-fill due to a diverse natural habitat with ridges and valleys.

These landform designs add variability and aid in establishing a site with a long-term hydrologic balance. The geomorphic landform reclamation approach has potential to extend beyond current industry practices and will improve environmental impacts, flood control, water quality, and human safety.

The fluvial geomorphic principals are being researched to aid in reclamation alternatives to AOC designs. Following the development of the geofluvial landform design the research progressed to an analysis investigating the differences in seepage and slope stability between the AOC method and geomorphic designs. The objective here was to compare and contrast effects of the analysis results and determine benefits and contrasts of each method.

Laboratory testing was carried out according to ASTM standard test methods. The scope of the testing performed involved grain size distribution analysis, hyrometer analysis, saturated shear strength testing under an *in situ* consolidation load, Atterberg limits including plastic and liquid limits, compaction at three predetermined compaction energies, and rigid wall permeameter hydraulic conductivity testing. Data was evaluated and analyzed to find to what degree the material particles moved under certain hydraulic gradients and if the particle movement affected the shear strength of the samples. The objectives of the testing were to understand the movement of small diameter soil particles at a valley fill and ensure an efficient, durable slope design using deterministic and sensitivity factor of safety analysis on several modules of GeoStudio™.

The computational modeling involved geomorphic design for a proposed valley fill in southern West Virginia using commercial software following the Geofluv® method. A comprehensive seepage and slope stability analysis was then developed using the SEEP/W, SIGMA/W, and SLOPE/W modules of GeoStudio2007 for assessing the groundwater flow characteristics of the fill rock, a deformation analysis, and the resultant limit equilibrium analysis of slope stability (factor of safety). These analyses were performed for both the AOC and geomorphic fill designs.

A seepage and slope stability analysis was performed using commercial geotechnical engineering software. The program GeoStudio® 2007 using the SEEP/W, SIGMA/W, and SLOPE/W modules was used to assess the groundwater flow characteristics of the fill rock, a deformation analysis, and the resultant limit equilibrium analysis of slope stability (factor of safety based). These analyses were performed for both the AOC and geomorphic fill designs.

Analysis criteria were chosen as a way to compare the results of the two fills in order to investigate if an advantage to one fill design was apparent. If an advantage of was apparent, the magnitude of the advantage was quantified using a percent difference in results.

Synthesis of Results

Mine Safety Aspects

The geomorphic landform valley-fill design of the sample site optimizes heavy equipment utilization in order to minimize worker exposure to potentially dangerous slope profiles, creates safer and more stable land profiles, and minimizes groundwater infiltration into underground mine working thus reducing mine inundation possibilities.

Fluvial geomorphic landform design has the potential to decrease operator exposure time in dangerous conditions by minimizes the amount of earthwork that has to be performed. In traditional reclamation practices, the soil has to be moved once during the mining process and again during reclamation. In the geomorphic landform design of the sample site, the soil that is removed during mining is transported directly to a location that was previously mined and is used to create valley-fill landforms. Thus it cuts down on total distance traveled and the number of hours needed to complete the reclamation process making the geomorphic landform design safer for site workers.

The design tool Natural Regrade® using GeoFluv™ was used to apply the geomorphic landform design principles to the sample surface mine site that is located in the southern West Virginia coalfield region. The area was characterized by a system of steep-sloped ridges and valleys. A boundary line was drawn along the perimeter of the property; then the valley-fill was divided into subwatersheds in order to create a natural appearance and balanced design. A majority of the default settings in Natural Regrade® were used in order to create the geomorphic landform design for the sample site due to the lack of on-site data because of current mining. However, two of the global settings that were drastically changed for the sample site were that the 2 yr, 1 hr rainfall changed from 0.6 in to 1.41in and the 50 yr, 6 hr rainfall changed from 2.0 in to 4.03 in. The default rainfall values are based on semi-arid regions of the United States where precipitation is lower as opposed to the higher precipitation region of the United States in which the sample site is located, based on type II storm and precipitation data.

Stream channels were created within each subwatershed boundary and geomorphic landform design principles were then applied to each subwatershed. Once all of the subwatershed designs were created using Natural Regrade® with GeoFluv™ they were combined so that the valley-fill design was complete. All of the data for each analyzed subwatershed was compiled so that a proper analysis of the total design was completed.

The geomorphic valley-fill design allowed 1300 ft of original stream length to remain undisturbed compared to the traditional valley-fill design and almost 33,000 ft or 6.25 miles of stream length (type A and type C channels as defined by Rosgen) was created on the property. In four of the six subwatersheds, only one channel was needed to satisfy the drainage density requirement due to the watershed area and the length the main channel. Even though only one channel was created, the valley-fill created using Natural Regrade still had a greater amount of stream length within the same area compared to the original stream length.

The data collected from the AOC variance valley-fill design and the geomorphic landform valley-fill design created using Natural Regrade® with GeoFluv™ were compared.

The AOC variance valley-fill design was intended to ensure slope stability, control drainage, complement the drainage pattern of the surrounding terrain, and prevent stream sedimentation.

The design consisted of:

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Features of the resulting Natural Regrade® design include:

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These landform designs add variability and aid in establishing a site with a long-term hydrologic balance. The geomorphic landform reclamation approach has potential to extend beyond current industry practices and will improve environmental impacts, flood control, water quality, and human safety.

Through the analysis of numerical modeling results, it was found that the geomorphic fill design has advantages with respect to water movement through the fill and water storage within the fill. The geomorphic fill had an advantage in the behavior of groundwater seepage for the majority of the time frame of the transient analysis, as well as in regards to slope stability.

The geomorphic fill had peaks in advantage in water velocity at the toe of 1291.1% at year 3 and 1646.6% at year 7, peaks in advantage in water flux at the toe of 405.4% at year 3 and 1141.7% at year 7, peaks in advantage in maximum hydraulic velocity of 482.1% at year 3 and 1273.7% at year 7, and a peak in advantage in storage of2 4.3% in year 6 . For each of these criteria, the magnitude of the advantage for the geomorphic fill was much higher than the magnitude of any advantage for the AOC fill. This advantage was a result of the geomorphic fill moving water through the fill at a faster rate. This advantage in seepage could translate into an advantage in contaminant transport by water having less contact time with the fill material.

For the numerical modeling of the slope stability analysis, it was found that the height of the piezometric line had a profound influence on the factors of safety. When an area was saturated, the factor of safety decreased, sometimes below 1.0 as in the piez. 2 toe scenario of the AOC valley fill design. If the piezometric line was not elevated to the area of the selected failure plane, then the factor of safety remained unchanged. Additionally, steeper slope angles decreased factors of safety. Two initial saturation conditions were modeled for the cumulative analysis. The saturation conditions were applied in SEEP/W, and SIGMA/W computed *in situ* stresses to be input into SLOPE/W for a factor of safety computation. The initial saturation condition of the gravity segregated durable rock underdrain was significant. The initial saturation altered the volume of water retained within the structure, and ultimately altered the factors of safety that resulted. The factors of safety vary from one hydraulic condition to the next, but did not necessarily increase or decrease accordingly. The result is an effect of the varying areas of increased pore pressure. The result of the SEEP/W analysis produced outputs that accumulated water storage within each fill in different areas, which resulted in varying factors of safety. Both cumulative analysis that were run for the geomorphic design and the valley fill proved that the initial condition could vary the factor of safety. The change in the factor of safety was not always in favor of either condition from a structural standpoint. The significance of the initial saturation condition was that the water storage areas within the fill changed, and altered the factors of safety.

The cumulative analysis for the geomorphic valley fill alternative design yielded the highest factors of safety. Most cases produced factors of safety over 2.0. The most likely reason for these high factors of safety is that the geomorphic design had shallower slopes, and drained well. Geomorphic landform design can be utilized to reduce infiltration volumes by shortening runoff travel distances, increasing runoff water removal from a design site. A completed design should retain less water than the modeled results show because of vegetative cover and quick surface runoff. Both initial saturated and unsaturated conditions yielded high factors of safety. The failure locations were sought out to find the lowest factors of safety for the structure. The geomorphic landform profile described in section 13.4 still retained its structural integrity even when high volumes of water are being stored within it. None of the factors of safety even under the most critical circumstances tested yielded factors of safety under 1.0 for the geomorphic design. Even though the original ground dimensions vary for the two profiles, the surface dimensions are identical except for the near the toe. The results prove that the geomorphic design can remain very stable under different conditions and geometries.

Sometimes, in an effort to "tie in" boundary elevations with water channel elevations, GeoFluv™ generates slopes that are not structurally sound. One such slope was analyzed, and it was found that it was by far the weakest structure addressed in the numerical modeling. It was referred to as the "critical slope." None of the factors of safety under any scenario analyzed for the critical slope yielded a factor of safety over 1.0. The factors of safety of this structure were expected to be low. The analysis of the critical slope was intended to illustrate that GeoFluv® does not consider slope stability, and can produce slopes that are not stable. GeoFluv® does enable the designer to alter many components of the design to mitigate the slope stability problems that may occur due to rapid elevation changes.

The AOC design was typical with its bench cuts and planar slopes. Regulations require that slope factors of safety must remain above 1.3. The analysis performed showed that the design could withstand *insitu* loads and slope angle under most conditions analyzed. Elevated pore pressures tended to result at the toe of the slope, and decreased the factor of safety. The most critical scenario was a totally saturated toe which yielded a factor of safety of 0.50.

The SEEP/W analysis yielded results that implied that the structure drained well for the AOC valley fill design. There were small areas of water storage accumulation and elevated pore water pressures, but nothing which caused the factor of safety to drop below 1.0 for the cumulative analysis. For the cumulative analysis, the lowest factor of safety for the AOC valley fill design was 1.22 at the toe of the slope at an initially unsaturated durable rock underdrain condition.

Geomorphic design decreases erosion potential and therefore decreases maintenance demands. The proposed AOC design would be adequate if it remained sufficiently drained. If particle transport can occur and alter toe pore pressures, it is possible that some small slope failure may occur. The gradations that were found for the unweathered well graded sand fill material showed that particle transport would not be a significant concern.

By observation of the data, the material does not need a significant amount of compaction in order to achieve a high dry density, but it does need the accompanying moisture content to achieve it.

The shear strain curves revealed that much of the residual strength is retained within the sample. The reason the samples retained their strength is likely a result of the creation of the unweathered material. The geometry of the particles of the sample is angular from being blasted unweathered rock. The angular nature of the material increases the friction between shear planes and resists displacement. This insight is beneficial when considering slope stability. Slopes constructed with this material would be expected to have slope angles of 30 degrees or greater and the material would tend to be free draining.

While observing the summary of the gradations produced by the as received grain size distribution, the pre-permeability test specimens, and the post-permeability specimens, the following conclusions were reached:

The results of the particle transport analysis indicate that the unweathered sandstone material reaches an aggregated equilibrium with very similar gradation after several pore volumes of water are permeated. The results imply that introducing a range of compaction energy can alter soil properties and have performance implications on earthen structures. Layered construction known as “lift construction” could assist in better quality control of the compaction energy applies to earthen structures to more precisely manage the aggregation phenomena. The amount of compaction energy for the 34% Proctor compaction and standard proctor samples seems to have broken up the aggregated particles, then when they were permeated, became more aggregated. After the permeation occurred, all three compaction energies approached a similar gradation, but diverged somewhat as the particle size decreased. The specimens began diverging in similarity around 40% finer.

A geomorphic fill showed a distinct advantage in the durability of the earthen structure geometry addressed. To further analyze the comparison between a geomorphic and AOC fill, probabilistic analyses could be performed to more thoroughly account for spatial variability. Spatial variability was only taken into account in these models as a sensitivity analysis. Field conditions of a slope structure would have a great deal of spatial variability both in compaction and in initial water content affecting soil strength and phreatic surface elevations.

The AOC valley fill design would be adequate if it remained sufficiently drained. If particle transport can occur and alter toe pore pressures, it is possible that some small slope failure may occur. The gradations that were found in the fill material indicate particle transport probably would not be a concern for the laboratory tested unweathered sandstone.

Geomorphic design is expected to decreases erosion potential and therefore decrease maintenance demands, however, in order to fully address this potential benefit of geomorphic landform design, a thorough cost analysis with regard to construction techniques in AOC and geomorphic landform design would need to be investigated.

By analyzing each fill individually, collecting results, and comparing those results, conclusions about the comparison of an AOC fill and geomorphic fill were collected. When looking at the comparison of results between the two fills, the conclusions were as follows:

When looking at the summary of the percent changes from the AOC fill to geomorphic fill, the following conclusions were made:

In every category, the geomorphic fill showed an advantage for the majority of the time steps. The greatest advantage was seen in the velocity at the toe. The next highest advantage was seen in water flux at the toe and maximum hydraulic velocity. Storage showed an advantage for the geomorphic fill for the majority of the model, but with a lower magnitude of advantage. If the percent differences for each criterion and each time step were totaled, it was seen that the geomorphic fill had an overall advantage throughout the entire 10 year model.

Finally, a comparison of the slope stability results provided the following conclusions:

For all failure modes, both the AOC fill and geomorphic fill had a factor of safety greater than the valley fill design standard of 1.3.

The geomorphic fill, however, had a higher factor of safety in each case. Almost all factors of safety were above 2.0, whereas the factors of safety for the AOC fill ranged from 1.3-1.5. This was a result of the geomorphic fill having a less steep slope and draining better than the AOC fill, producing less stress from seepage.

All of these conclusions pointed to supporting the idea of the geomorphic design of valley fills having advantages over Approximate Original Contour design.

An area that needs to be investigated to fully compare the differing design techniques is the construction and lifetime cost of implementing a geomorphic fill versus an AOC fill. With the very limited amount of work that has been done with geomorphic fills in the region of central Appalachia, this research has provided a sound initial analysis to compare with previously used design techniques. Further research must be done in order to make a fully informed decision as to whether or not geomorphic design would be feasible to implement in the reclamation of surface mines in central Appalachia.

The following two appendices present the full body of this study. Appendix A titled *The Integration of Geomorphic Design into West Virginia Surface Mine Reclamation* contains a full presentation of the research into development of a geomorphic analysis of a candidate valley fill design for West Virginia. Appendix B titled *Soil Analysis and Subsequent Slope Stability Analysis of Geomorphic Landform Profiles versus Approximate Original Contour Applied to Valley Fill Designs* fully addresses the laboratory soil testing, seepage analysis, and ground slope stability analysis of the geomorphic designs put forth in Appendix A.