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**AUTOMATED SYSTEM TO IMPROVE LEVELNESS OF RECONSTRUCTED SOIL**

V. S. Bodapati, L. G. Wells

**ABSTRACT:** Extraction of coal, ores, and minerals from the earth by surface mining has occurred for many years and has always presented a significant challenge with regard to restoration of productive soil to mined areas. Federal and state regulations require that land should be returned to pre-mine productivity or reclaimed as per specific standards following mining. Excessive compaction of reconstructed soil caused by traffic of heavy earth moving equipment has been an enduring challenge regarding successful restoration of soil. A mechanical system was previously designed and developed to reconstruct soil to a depth of 1.22 m (48 in.) while completely avoiding equipment traffic. This article describes modification of the ‘Soil Regenerator’ prototype system to increase its capacity and improve levelness of reconstructed soil. The modifications included: a) remounting the blade to facilitate sidewise soil displacement, b) adding a blade extension which is moved by a hydraulic cylinder, and c) installing a soil surface sensing system to control position of the blade extension.

Soil reconstruction capacity was increased by 118% and surface levelness of reconstructed soil was improved. The standard error of vertical deviation from prescribed surface elevations of six 1.83-m wide segments of reconstructed soil was 11 cm. Soil reconstructed with the system prior to the modifications was characterized by numerous mounds and depressions (>25 cm) owing to uneven metering of soil. An automatic system to control soil displacement blade width in response to soil level sensor measurements was determined to function correctly in approximately 60% of instances examined. Malfunctions generally resulted in inappropriate blade retraction which corresponded to lower-than-specified elevations of reconstructed soil surfaces.

**Keywords.** Soil compaction, Soil reclamation, Soil levelness.

Coal has been mined in the United States since 1740, but surface mining did not become widespread until the 1930s (NRC, 1981). Vast areas of land are stripped of vegetation so that measures must be implemented to prevent excessive soil erosion and contamination of streams (NRC, 1981). After mining, overburden must be reconstructed to ensure viable re-vegetation of the landscape and a return to pre-mining land use and productivity (SMCRA, 1977).

The main problem with surface mining is that it drastically disturbs the earth’s surface and changes its physical properties. It can affect the environment by leaving behind a scarred earth surface, increasing run-off laden with sediment or even polluting underground water resources (Haan and Barfield, 1978). Federal and state regulations were enacted to ensure that surface mined land is adequately reclaimed by setting standard guidelines and regulatory procedures.

The Surface Mining Control and Reclamation Act of 1977 (SMCRA, 1977), Public Law 95-87, is the primary federal law that regulates the environmental effects of coal mining in the United States. SMCRA grew out of concern about the environmental effects of surface mining and created two programs: one for regulating active coal mines and the second for reclaiming abandoned mined lands. Permitting and performance standards for surface coal mining and reclamation of prime farmland were implemented. Surety bonds were required to ensure compliance with the regulations. SMCRA also set forth specific requirements for restoration of prime farmland when such land was disturbed by mining. Prime farmland was generally designated as land suitable for production of row crops, i.e. corn, soybean, small grains, etc.

The foremost requirement of SMCRA for land designated as prime farmland is that it be reclaimed to equivalent or higher levels of crop productivity than that of the surrounding prime farmland that has not been subjected to mining. Several important requirements were set forth within these regulations pertaining to prime farmland (SMCRA, 1977). First, the A- and B-soil horizons must be segregated and stored separately upon removal, where the A-horizon is topsoil and the B-horizon is subsoil. Secondly, these horizons must be replaced during reclamation to develop a uniform depth of 1.22 m of rooting zone with 0.30 m of topsoil (A-horizon) over 0.92 m of subsoil (B-horizon). Thirdly, overburden material must be graded to approximate pre-mining contour and the post-mined landscape must blend…

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into the surrounding undisturbed terrain (SMCRA, 1977). Section 515(b)(7) outlines minimal requirements for removal, storage, and replacement of A-horizon (top soil) and subsoil (B-horizon plus a part of C-horizon). Crop production studies usually follow soil replacement and surety bonds are released only if target yields are met within a specific time frame.

Scrapers were widely used in early post-SMRCA surface mining operations because of their efficiency in moving soil. Scrapers were used to excavate and segregate topsoil or A-horizon soil and subsequently excavate B/C-horizon soil to the depth of restoration required by SMCRA (Martin et al., 1982). However, it soon became apparent that the use of scrapers in reconstructing soil produced highly compacted and unproductive soil. Alternative methods using bulldozers, wheel loaders, and trucks were subsequently developed that produced less compacted reconstructed soil. Preventing excessive compaction of soil by equipment during reconstruction operations remains difficult to achieve (Hooks, et al., 1992).

Dunker et al. (1988) measured penetration resistance in prime farmland soils reconstructed in western Illinois using two methods; a) placement of mixed A- and B-horizon with a bucket wheel excavator, and b) placement of B-horizon with bucket wheel excavator and placement of 45 cm of topsoil using scrapers. Surfaces for both methods were graded by small bulldozers. Penetration resistance at a depth of 64 cm (25 in.) was 30% greater when scrapers were used to place topsoil. Corn yield was slightly greater when topsoil was added, however, yield from both reconstruction methods was approximately 60% that of un-mined soil from that location.

Dunker et al. (1995) studied the effect of deep tillage in alleviating adverse compaction of soil during replacement using scrapers. They applied tillage treatments using chisel implements reaching 20 to 35 cm and subsoiler treatments reaching depths from 80 to 120 cm. In four of five years after tillage, corn yield from plots tilled to 120 cm (47 in.) was not significantly different from an undisturbed soil nearby, while yield was significantly lower in all the other tillage treatments.

Hooks et al. (1992) studied methods of soil reconstruction which attempted to minimize adverse compaction. Plots were constructed whereby subsoil was placed on graded spoil using scrapers and trucks. In one treatment, subsoil was placed by scrapers in layers 10 to 20 cm deep with requisite scraper wheel traffic. In the other treatment, trucks dumped subsoil onto graded spoil and bulldozers leveled the surface. Topsoil [20 cm (8 in.)] deep was placed atop the plots by three methods. On the scraper plots, scrapers deposited topsoil along opposite boundaries of the plots and bulldozers spread the topsoil across the plots. In one set of truck plots, trucks hauled topsoil onto the plots, while on the other, trucks dumped topsoil at opposite boundaries. Penetration resistance was highest in the scraper placed plots and lowest in the truck plots where traffic was minimized. Average corn and soybean yield measured over six years was highest in the truck-with-minimum-traffic plots and lowest in the scraper plots. Yield from truck-with-minimum-traffic plots was slightly less than, but not significantly different from yield from an undisturbed nearby soil.

These studies show that limiting traffic on soil during reconstruction was the most important factor in minimizing soil compaction and restoring crop productivity. Specifically, the use of trucks to place subsoil onto graded soil was advantageous. However, since removal and stockpiling of topsoil requires the use of scrapers, the low-traffic strategies also require the use of shovel excavators and trucks. The Soil Regenerator (Fulton et al., 2002) was designed and developed at the University of Kentucky as a system which could be used with only scrapers to reconstruct soil with minimal compaction. Soil cone index measured immediately after reconstruction using the ‘Soil Regenerator’ ranged from 0.02 to 0.2 MPa (Fulton and Wells, 2005.)

**University of Kentucky Soil Regenerator**

Fulton et al. (2002) proposed a concept for reconstructing soil after surface mining which utilized a powered auger in front of a modified conventional bulldozer blade. A modified semi-universal blade was mounted in front of a D7 Caterpillar bulldozer. The right side of the blade was straightened to promote lateral soil displacement from left to right as the bulldozer moved forward. The blade was 3.4 m wide and 1.7 m high. The helical auger was 2.2 m long with a diameter of 91 cm and a pitch of 61 cm. It was supported by using pivoting structure which was raised and lowered by hydraulic cylinders to control auger height independent of blade height. Most of the power available from the bulldozer engine (rated at 150 kW) was required by the running gear so an auxiliary engine mounted on the rear of the bulldozer was used to produce about 75 kW needed to operate the hydraulic motor which powered the auger.

Scrapers were used to place soil atop a graded base in long windrows. The spiral action of the auger agitated the soil in front of the blade and displaced it from left to right to fill a void beneath the auger extending beyond the blade and adjacent to the windrow. As the bulldozer pushed into the windrows, the auger displaced the soil perpendicular to the direction of travel.

The design concept envisioned the auger displacing soil as the bulldozer moved forward into a windrow and soil rose up the blade. All of the soil in the windrow would be displaced to the void beneath the auger extending beyond the right end on the blade. When the auger height was set at the same elevation as the top of a previously deposited soil layer, that layer would be extended leftward. Thus, if a scraper deposited a windrow 0.3 m deep and 3.7 m wide and the bulldozer moved forward at 1.6 km/h, the soil reconstruction rate would be 1776 m$^3$/h.

Testing of the Soil Regenerator prototype revealed that the actual soil reconstruction rate was approximately 330 m$^3$/h (430 yd$^3$/h) (Fulton et al., 2002) and later work on a surface mine suggested that a reconstruction rate of 610 m$^3$/h (800 ft$^3$/h) could be achieved if critical improvements to the system were implemented (Fulton and Wells, 2005). The auger was not capable of displacing soil at the rate of engagement as the bulldozer moved forward. Furthermore, because of variation in the volume of soil deposited in the windrows, maintaining a level surface of reconstructed soil was difficult. When too little soil was being displaced to fill the void beneath the auger, a depression in the reconstructed soil surface was created. Conversely, when too much soil was being displaced, excess soil was pushed beyond the right end of the auger forming a mound. Finally, it became apparent that the bulldozer lacked sufficient traction to push soil into the auger at a continuous, steady pace. These deficiencies are
the motivation in this paper for modifying the prototype to increase capacity and improve surface levelness of reconstructed soil. This paper describes modifications and enhancements of the system and presents the results of testing to evaluate performance of the modified system.

The objectives of the study were:
- to design and fabricate a modified prototype mechanism for reconstructing cropland soils following surface mining without allowing traffic on the upper 1.22 m of soil (A- and B-horizons),
- to design and fabricate a control system to increase capacity and improve performance of the modified mechanism, and
- to test and evaluate the performance of the modified prototype with respect to operational capacity and levelness of reconstructed soil.

DESCRIPTION OF THE SYSTEM

MODIFIED BLADE DESIGN

The blade described by Fulton et al. (2002) was mounted perpendicular to the bulldozer’s axis of symmetry and thus soil was moved from the front of the blade to the berm entirely by the action of the auger. This resulted in a substantial suppression of the soil reconstruction rate. To overcome this suppression, the blade was remounted at an angle of 96° relative to bulldozer heading (fig. 1) to facilitate lateral displacement of soil as the bulldozer blade moved forward. The powered auger was placed in front of and parallel to the blade and the elevation of the auger relative to the blade remained adjustable between 58 and 132 cm. This new configuration utilized the powered auger primarily to level the soil surface instead of displacing soil from the front to the side of the blade.

Secondly, an extension was added to the right end of the blade which was adjusted by extending or retracting a hydraulic cylinder. The blade extension moved along tracks mounted inside the blade framework (fig. 1). A solenoid directional control valve operated a hydraulic cylinder which moved the extension in and out. When soil accumulated at the end of the auger, the extension was retracted to create more space for soil beneath the auger. Conversely, when too little soil was conveyed rightward to fill the void beneath the auger beyond the blade, the extension would move outward to reduce the space for soil beneath the auger. The sensors, which determined the existence of depressions or mounds in the reconstructed profile, along with an automatic control system to determine whether to extend or retract the blade extension, are described below.

SURFACE-SENSING ARMS WITH INCLINOMETERS

Figure 2 shows a frontal view of the modified Soil Regenerator. A windrow of soil is depicted in front of the blade and soil reconstructed on the previous pass is shown at the left. As the bulldozer moves forward, soil is pushed up the blade, then pushed and augured into the void between the windrow and the previously reconstructed soil. Two soil surface sensing arms are shown mounted on the auger support structure extending to the left of the blade. Inclinometers were attached to the arms which measured the angle of each arm relative to a datum. The arm mounted nearest the bulldozer was positioned inboard of the end of the auger and its datum was the angle corresponding to the end of the arm being level with the bottom of the auger. A depression forming near the end of the auger would allow the inboard arm to drop below the bottom of the auger. If the inclinometer sensed an angle greater than the datum, the control system would cause the blade extension to move outward. Excess soil transported by the auger beyond its end would form a mound beyond the end of the auger. When the outboard arm rose above the bottom of the auger, the control system would cause the blade extension to move inward.

The sensing arms [13 × 76 mm (0.5 × 3 in.)] and mounting hinges were fabricated with mild steel. Inclinometers (model H4A1-70-V, Reiker, Inc., Ashton, Pa.) were used to measure the respective angles of the sensing arms relative to specified reference points or datum. This input was fed into a PMD-1208 LS data acquisition device (M.C.C., 2006a) which controlled the extension of the hydraulic cylinder through a solid state relay.

Figure 1. Rear isometric view of modified blade showing: (a) blade extension cylinder, (b) right auger support assembly lifting cylinder, (c) blade extension, and (d) inboard and outboard soil surface sensors.
Figure 2. Frontal view of the modified Soil Regenerator illustrating operation in which soil previously deposited in a windrow on a graded base is engaged and displaced leftward into a void formed by the previously reconstructed soil and the windrow. The outboard soil surface sensor detects excess soil accumulating at the end of the auger (A) and causes the blade extension to move inward. Insufficient soil beneath the auger is detected by the inboard soil surface sensor (B), causing the blade extension to move outward. Situations A and B cannot occur simultaneously.

**BLADE EXTENSION DYNAMIC CONTROL SYSTEM**

Figure 3 shows a block diagram of the control system. Supply regulators (5 V dc) were used to supply a constant voltage for the inclinometers. The feedback transducer completed the closed loop control by reading blade position. Inclinometer outputs were connected to Pins 1 and 2 of the PMD data acquisition device. Pin 3 of the PMD is a common ground if it is configured in a single-ended operational mode. The two grounds of both these sensors were tied together to pin 3. The 12-V dc power supply was reduced to produce a 5-V dc output voltage using the voltage regulator LM340T-5. The third sensor being used for feedback was the linear transducer that was mounted parallel to the blade extension. This transducer measured the position of the blade extension and was connected to Pin 4 of the PMD.

**BULLDOZER HYDRAULIC CIRCUIT**

Figure 4 shows a schematic diagram of the hydraulic circuit utilized on the bulldozer. The auger lifting cylinders were connected in series and the circuit was controlled by a closed-center, manual, 4-way, and 3-position control valve. The blade extension cylinder circuit was controlled by a solenoid operated, closed-center, 4-way, and 3-position control valve and included a manual flow control valve to adjust speed of blade extension movement. The hydraulic motor which turned the auger shaft was powered by a separate pump mounted on the auxiliary engine. A manual reversible flow control valve was used to control auger speed and direction of rotation.

Visual Basic (M.C.C., 2006b) control software was developed to monitor the position of the two soil surface sensing arms and to determine the position of the blade extension cylinder for optimizing surface levelness. The software allowed the user to operate in either dynamic mode or manual override mode. The dynamic mode used the logic described in detail by Bodapati (2008). Manual override allowed the user to ignore the dynamic nature of the software and either stop, extend, or retract the blade at the stroke of a button.

![Figure 3. Functional block diagram of the blade extension dynamic control system.](image)

![Figure 4. Schematic of the hydraulic circuit controlling the auger lift cylinders and the blade extension cylinder.](image)
The control software was written to control blade extension position in response to the inboard and outboard sensor angles. The null angle (datum), resulting in no blade extension movement, for both sensors was $60^\circ$. When the outboard sensor angle was $\geq 60^\circ$, excess soil beyond the end of the auger was indicated and the software initiated action to move the blade extension inward, if the inboard sensor angle was also $\geq 60^\circ$. If the inboard sensor angle was $<60^\circ$, insufficient soil to fill the void beneath the auger was indicated and the software initiated action to move the blade extension outward, regardless of the outboard sensor angle.

**EXPERIMENTAL METHODS**

**DETERMINING SOIL RECONSTRUCTION CAPACITY**

Performance of the Soil Regenerator blade width control system was determined via trials performed on a test strip constructed as illustrated in figure 5. The strip was approximately 61 m (200 ft) long and 3.7 m (12 ft) wide. Approximately 1.8 m (6 ft) of the strip was left in place to simulate a previously-deposited berm whose surface was to be matched in each performance trial. The remaining soil was deposited in a windrow parallel to but displaced from this berm (see fig. 5). Different patterns of random mounds and depressions were created within the windrow using a skid-steer loader.

Each trial consisted of forming a berm of reconstructed soil approximately 45.7 m (150 ft) long. The height and width of the berm was approximately 0.6 and 1.8 m (2 and 6 ft), respectively. The auger height was set at the minimum of 0.6 m (2 ft) so that the tractor operator would not be required to control the height of the auger during the trials. Also, reconstructing soil 0.6 m (2 ft) deep required less tractive pushing capacity of the bulldozer and thus, the performance of the control system was not affected by stalling of the bulldozer during the trials.

The bulldozer operator started the dynamic control system by selecting the start button on the Visual Basic program. Data from the two sensor arms and the feedback transducer was recorded in a designated file for each trial at 1 Hz. Manual override controls on the Visual Basic program allowed extension or retraction of the blade cylinder to be controlled or stopped by circumventing the control system.

Time required for bulldozer movement during the deposition of each trial berm was recorded. Soil reconstruction rate was determined by dividing the approximate volume of soil placed by the system ($51\text{ m}^3$) by the elapsed time recorded for each trial berm.

**DETERMINING BLADE EXTENSION DYNAMIC CONTROL SYSTEM PERFORMANCE**

During each trial, the outputs of the two surface-sensing inclinometers, the blade position transducer, and time were recorded. The times when the auger passed by markers placed at 9.1-m (30-ft) intervals along the length of strip were also measured with a stopwatch and recorded. Thus, by starting both the data logger clock and stopwatch at zero at the beginning of each trial, the times corresponding to the Soil Regenerator passing by each transect location could be determined using the stopwatch. Transducer readings logged between the first and last transects could thus be determined by referencing the time intervals measured using the stopwatch.

Table 1 shows an outline of the parameters that were set at the beginning of each field trial. Time taken for full extension (61 cm) and retraction of the blade were measured and blade speed was calculated. The inboard and outboard transducer angles were inputs to the Visual Basic blade position control program which determined the increments or decrements of blade movement. Control system performance was determined by comparing the direction of movement and blade position recorded throughout each trial with that prescribed by the control software in response to measured outputs of the surface-sensing and blade position transducers. Successful operation occurred when the control system produced correct blade movement in response to transducer outputs. For instance, if the inboard transducer output rotated downward and the blade position was less than fully extended, then the blade should have moved outward or extended. The results of each trial were analyzed to determine the degree of operational success. Control system performance was also quantified by calculating the deviation of the elevation of the trial berm surfaces from the corresponding prescribed elevations. prescribed elevation
Table 1. Summary of times of blade movement, blade speeds and transducer angles for experimental trials.

<table>
<thead>
<tr>
<th>Trial No.</th>
<th>Blade Move Inwards Time (s)</th>
<th>Blade Move Outwards Time (s)</th>
<th>Blade Speed Inwards (cm/s)</th>
<th>Blade Speed Outwards (cm/s)</th>
<th>Inboard Transducer Angle (degrees)</th>
<th>Outboard Transducer Angle (degrees)</th>
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<tr>
<td>1</td>
<td>19</td>
<td>10.5</td>
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was determined as 0.6 m (2 ft) above base grade measured at each transect.

**SURFACE LEVELNESS OF RECONSTRUCTED SOIL**

Surface elevations of reconstructed soil were measured at 9.1-m (30-ft) intervals along the berm length using surveying instruments (fig. 6). Elevations were determined at 0.3-m (1-ft) intervals on transects perpendicular to direction of bulldozer travel and included measurement of base elevations. Fourteen (14) elevations were recorded on each transect, with the first and last measurements corresponding to the upper and lower base elevations, respectively. Thus, elevations 1 through 14 in each transect characterized the cross-section of the soil berm at the location of the transect. Nominally, elevations 1 through 6 characterized the portion of the berm which was not deposited by the trial passes of the Soil Regenerator, i.e. that portion of the berm remained more or less undisturbed during the trials.

The task of the Soil Regenerator in each trial was to construct a soil berm such that elevations 7 through 13 would be 0.6 m (2 ft) higher than a line connecting elevations 1 and 14 at each transect.

**RESULTS AND DISCUSSION**

**SOIL RECONSTRUCTION CAPACITY**

Table 2 presents a compilation of soil reconstruction capacity measured in construction of each trial berm. Measured soil reconstruction rates were substantially lower in the first trial. Increased reconstruction rate after trial 1 was apparently due to improvement of operator efficiency as the trials were executed. The mean reconstruction rate of 643 m$^3$/h (841 yd$^3$/h) was 96% greater than the rate of 330 m$^3$/h (430 yd$^3$/h) reported by Fulton et al. (2002) even when the depth of soil placement was limited to 0.61 m (2 ft). If trial no. 1 is discounted as an anomaly, then the mean reconstruction rate is 720 m$^3$/h (942 yd$^3$/h), which is 118% greater than the unmodified prototype. This rate (vs. the mean rate in table 2) is equivalent to continuous reconstruction of a soil berm 1.22 m (48 in.) deep and 1.83 m (72 in.) wide at a speed of 0.32 km/h (0.20 mi/h). Thus, the modifications of the Soil Regenerator, including implementation of the blade control system, clearly increased soil reconstruction capacity.

**CONTROL SYSTEM PERFORMANCE**

Figure 7 shows the performance of the control system as recorded during field trial no. 1. At the beginning of the trial ($t = 0$ s), the end of the moveable blade extension was 25.4 cm beyond the end of the fixed blade. The initial outboard and inboard sensor angles were 66° and 64°, respectively. The following is an explanation of the events depicted in figure 7:

- During $t = 0$ to 3 s, both transducer angles remained constant (>60°) while the blade moved inward to 20.6 cm. This movement was an apparent malfunction of the control system.
- During $t = 34$ to 42 s, the inboard sensor angle decreased to 0° and the outboard sensor angle decreased to 22°. The blade moved outward to 55.9 cm at $t = 62$ s, which was a correct response of the control system.
- During $t = 62$ to 351 s, the outboard transducer angle increased but remained <60°. The inboard transducer angle steadily increased to >60° while the blade extension moved inward to 52.1 cm. Then during $t = 351$ to 362 s the blade extension moved abruptly inward to 27.4 cm while the inboard transducer angle remained <60°. These
movements, especially the latter one, were apparent malfunctions of the control system.

- During $t = 410$ to $427$ s, the inboard transducer angle increased to $72^\circ$ while the outboard transducer angle also increased to $>60^\circ$. The blade extension moved inward to 13.5 cm, which was a correct response of the control system.
- During $t = 427$ to $443$ s, both transducers decreased to $<60^\circ$ and the blade extension moved outward to 28.4 cm, which was a correct response of the control system.
- During $t = 443$ to $557$ s, both transducers oscillated above and below $60^\circ$, while the blade position did not change. This probably indicated a correct response by the control system, although it was not considered in determining the correctness percentage reported for this trial.
- During $t = 557$ to $571$ s, the inboard transducer angle decreased to $27^\circ$ while the outboard transducer angle remained $<60^\circ$. The blade extension moved outward to 44.2 cm, which was a correct response of the control system.
- During $t = 571$ to $633$ s, the inboard transducer angle increased to $65^\circ$ while the outboard transducer angle remained $<60^\circ$. The blade extension moved inward to 24.1 cm, which was an apparent malfunction of the control system.
- During $t = 633$ to $641$ s, both transducers decreased to near $0^\circ$ and the blade extension moved outward to 51.6 cm. This was a correct response of the control system.
- Finally, during $t = 725$ to $751$ s, the inboard transducer angle decreased to around $45^\circ$ while the outboard transducer angle increased to $>60^\circ$. The blade extension moved inward to 23.9 cm, which was a correct response of the control system.

The control system responded correctly to sensor measurements in six of ten events described above for field trial no. 1. Thus, the control system achieved a 60% success percentage for this trial.

Similar analyses of five additional trials are combined with these results in figure 8. Figure 8 shows that the best performance was for trial 3 (83% success) and the worst performance was for trials 2 and 4 (45%). At first look, the average success rate of 57% does not seem to indicate good performance of the control system. However, the control system increased reconstruction capacity and resulted in improved levelness of reconstructed soil surfaces as will be shown later.

The cause-and-effect behavior of the blade extension control system suggests the possibility of modeling system response and using stability analysis to improve system performance. There were substantial complexities of behavior, however, which prevented attempting such modeling and analysis at this juncture. First, modeling the complex soil behavior within the system was beyond the scope of this effort. Modeling conveyance of soil by the auger into the void at the end of the blade was observed to be highly dependent upon soil accumulation in front of the blade as well as soil physical properties affected by texture and water content. Furthermore, a spatial characterization of soil in front of the blade would be highly stochastic in nature. Finally, these preliminary results strongly suggest that our first priority should be to identify and eliminate causes of apparent sensor malfunctions and then proceed to modeling and testing the system with a more predictable medium such as gravel or dry sand.

Future improvements to the system should include:
- increasing bulldozer power,
- installing stops to control lowermost blade elevation,
- minimizing malfunction of the blade control system which results in inappropriate inward blade movement and resulting depressions in reconstructed soil profiles, and
- automation of bulldozer blade height and auger height control.

**Surface Levelness**

Figure 9 shows the results of surface levelness measurements for trial no. 2. The results for all trials were similar so only the results from this trial will be explained in detail. Each of the solid curved lines represents the elevations measured along the transect of the reconstructed berm. These transects were spaced 9.1 m (30 ft) apart along a 45.7 m (150 ft) long reconstructed berm as was illustrated in figure 5. Transect heights on the extreme left and right side correspond to the respective elevations of the base upon which the berm was constructed. Thus, the base elevation sloped downward approximately 20 cm across the berm width of approximately 400 cm. Additionally, figure 9 indicates that elevations of profile 6 were approximately 1 m higher than those of profile 1. Thus, the lengthwise slope of the berm was approximately $1/45.7$ or 2.2%.

![Inbound Transducer](image1.png)

**Figure 7.** Typical data recorded from soil surface sensors and control program output during operation of the modified Soil Regenerator for field trial no. 1.

![Correct Response](image2.png)

**Figure 8.** Percentage of correct response and execution by the blade extension control system during six (6) field trials.
The dotted lines corresponding to each of the six berm transects represent the prescribed heights of the reconstructed berm between lateral displacements 183 and 366 cm. These elevations were determined by constructing lines parallel to and 61 cm above straight lines connecting elevations at 0- and 396-cm lateral displacement of each transect. The differences in elevations between the solid and curved lines for each profile represent the error of the Soil Regenerator in reconstructing the prescribed berm profile. It should be noted that the horizontal scale is compressed relative to the vertical scale by a factor of 1.5 in figure 9 to improve clarity. Thus, deviations of the actual elevations from the prescribed or target elevations are magnified.

Figure 9 indicates that most measured elevations were below those prescribed for specific lateral locations. Only the extreme left and right elevations of transects 1 and 2 were higher than prescribed. Standard errors of estimates were computed using measured and prescribed elevations for the seven points shown between lateral displacements 183 and 366 cm.

Table 3 presents the standard errors of estimate for the prescribed versus measured berm transect profiles. Standard error was computed for each trial/transect combination from seven pairs of measured versus prescribed surface elevations. Total standard errors for each trial (right column) were computed using $6 \times 7 = 42$ pairs. Finally, the grand total standard error was computed using $6 \times 7 \times 6 = 252$ pairs.

Trial no. 2 was chosen to illustrate the efficacy of the Soil Regenerator in reconstructing a prescribed soil surface because the standard error for this trial was approximately the same as that for all the trials, 11 cm. Thus, in these tests, the Soil Regenerator reconstructed soil surfaces approximately 11 cm below the prescribed elevation when the prescribed height of reconstructed soil was 61 cm.

The general tendency of reconstructed soil elevation being lower than that prescribed agrees with the previous observation that malfunction of the blade control system generally resulted in inappropriate inward movement of the blade, creating soil deficit beneath the auger. Given the mean success rate of the blade control system indicated in figure 8 (57%), it appears that the corresponding average non-success rate of 43% has the effect of responding inadequately to soil deficit beneath the auger and lowering-than-expected reconstructed soil elevation. Improvements of the system should therefore be concentrated on minimizing inappropriate movement of the blade inward and facilitating more rapid outward movement of the blade when the inboard sensor indicates soil deficit beneath the auger.

Operation of the system was constrained to perform at a lower efficiency due to the use of a D7 Caterpillar bulldozer manufactured in 1975. While an auxiliary engine was used to drive the auger, the bulldozer lacked sufficient traction force to continuously displace soil laterally when reconstructing the soil berms. A more powerful tractor (possibly a D8 or D9 Caterpillar) would definitely improve system operation and allow an operator to monitor soil reconstruction more effectively. Additionally, modification of the blade support linkage to prevent the bottom of the blade from going below the bottom of the bulldozer tracks would also free an operator from maintaining correct blade elevation during soil reconstruction.

Automatic control of both bulldozer blade height and auger height would free the operator of these demanding tasks. This could be accomplished via GIS mapping and a GPS-based control system. These capabilities would free the operator to concentrate on steering the bulldozer along the

Table 3. Standard errors of estimate (cm) for actual reconstructed surfaces vs. prescribed surfaces for six (6) transects on each of six (6) trial soil berms reconstructed using the Soil Regenerator.

<table>
<thead>
<tr>
<th>Transect</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Total</th>
</tr>
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<tr>
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<td>15</td>
<td>16</td>
<td>4</td>
<td>6</td>
<td>17</td>
<td>6</td>
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<td>10</td>
<td>15</td>
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<td>11</td>
</tr>
<tr>
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<td>9</td>
<td>11</td>
<td>12</td>
<td>15</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
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<td>7</td>
<td>9</td>
<td>11</td>
<td>6</td>
<td>18</td>
<td>10</td>
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<tr>
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<td>9</td>
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</tr>
<tr>
<td>Trial 6</td>
<td>8</td>
<td>6</td>
<td>10</td>
<td>7</td>
<td>6</td>
<td>30</td>
<td>12</td>
</tr>
</tbody>
</table>

Grand total 11
optimum path for displacing soil from windrows into reconstructed soil.

**CONCLUSIONS**

Based on this study in which we have modified a Soil Regenerator system to improve its reconstruction capacity and surface levelness of reconstructed soil, the following conclusions could be drawn:

- **Modification of the Soil Regenerator system** resulted in improved reconstruction of soil profiles. The modifications included: a) remounting the blade and powered auger at an angle of 96° relative to bulldozer heading, b) installation of a movable blade extension, and c) installation of a system to control blade extension position in response to soil-level sensors mounted both inboard and outboard of the end of the powered auger. The modified system increased capacity of soil reconstruction by 118% to 720 m³/h (942 yd³/h), as measured, excluding trial no. 1.

- A blade extension position control system was designed and implanted. The blade position control system was determined to function correctly in 57% of instances examined. Malfunctions were predominantly inappropriate movement of the blade inward and creation of undesired soil deficit beneath the auger. These malfunctions resulted in lower-than-desired elevation of reconstructed soil profile surfaces.

- Total standard error of estimate of actual versus specified soil surface elevation was 11 cm (4.3 in.) below prescribed elevation across a berm width of 1.83 m (6 ft). This level of accuracy should be acceptable for most cases of reconstructing soil on specified contour elevations.

**REFERENCES**


