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COMPACT – A Reclamation Soil Compaction Model Part II. Sensitivity Analysis and Applications

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Abstract

COMPACT, a physically based, event-oriented compaction model, was developed as a management or research tool to evaluate the influence of a surface mining system on compaction of soil material during reclamation. Two systems of area mining reclamation operations were simulated by COMPACT. The first system involved scrapers and bulldozers and the second also included trucks. Scrapers or trucks were used to pick up and deposit the soil material. Bulldozers were then used to shape the site for reclamation. The simulated results were compared with measured results and show how equipment patterns and soil parameters can affect overall soil compaction. This simulation model allows equipment, soil material, and operational parameters to be changed easily so managers and researchers can understand the soil compaction processes at surface mine sites.

Keywords. Soil compaction, Modeling.

Introduction

Simulation of vehicle movement and its influence on bulk density within the soil profile can be very useful to individuals who need to evaluate various surface mining reclamation systems for their effectiveness. Compaction affects plant growth and groundwater infiltration and flow. Understanding the relationship between equipment parameters, patterns of operations, and the resulting soil compaction would reduce costs and increase the success of reclamation systems.

The objective of this study was to assess the capability of COMPACT (<u>C</u>ompaction of <u>O</u>verburden by <u>M</u>achinery <u>P</u>rocesses <u>A</u>ssociated with <u>C</u>ontemporaneous <u>T</u>ranslocation) (described in Part I of this article, Bingner and Wells, 1992) to simulate bulk density within the soil profile of surface mining reclamation sites.

Description of the Surface Mining Systems Simulated

To verify that COMPACT determines bulk density throughout a reclamation site's soil profile with reasonable accuracy, comparisons were made from observed data from two surface mining systems. Albrecht and Thompson (1982) performed a study on several mining systems on sites located in the farmland of the midwestern U.S. Their objectives included an evaluation of the effects of surface mining on the soil characteristics of the reclaimed fields. The soil characteristics studied included bulk density, texture and fertility. Two surface mining sites, the Brazil Mine and the Power Mine, were chosen from that study as suitable for simulation by COMPACT. Each system used different equipment techniques in mining and reclaiming each site. The measured data from the plots on these sites were used as a comparison with the simulated data.

Brazil Mine Site Description

The Brazil Mine was located in West central Indiana on a permit area covering about 67 ha which has gently rolling slopes of 0-2%. The topsoil material of the mined area was removed by scrapers to a depth of 30.5 cm and stored, then replaced on the reclaimed field in a windrow about 1.5 times the scrapers width. Bulldozers then distributed the soil material from the windrow for final grading of the field. Windrowing was performed so minimum scraper traffic could be maintained over a reclaimed field.

A loader and 45 t end-dump trucks were used to remove the subsoil material to a depth of 3 m. The loader removed the subsoil material and loaded the trucks for transport around the mine site. After the trucks deposited the subsoil material in the reclaimed field, bulldozers were used to level the material before the topsoil material was deposited. Subsoils were replaced in the fall of 1978 and the topsoils were replaced in the spring of 1979.

After the final grading of the topsoil, the field was chisel-plowed and disked. The field was planted in wheat and harvested in the summer of 1980. Sunflowers were seeded after the wheat, with growth of various grasses continuing that were seeded with the wheat. This was the condition of the field at the time of sampling by Albrecht and Thompson (1982).

Two plots were placed in the reclaimed field with the dimensions of 30.5 m by 122 m. One plot (2) was reconstructed from an Ava series soil while the other plot (4) was from an Iva series soil. These soils are silt loams with slight differences in each. The Ava Series is somewhat poorly drained while the Iva Series is moderately well drained. The Iva soils also have a high available water capacity and slow permeability while the Ava soils have moderate available water capacity and very slow permeability. Ava soils formed in a thinner deposit of loess and contain a fragipan unlike the Iva soils.

Article has been reviewed and approved for publication by the Power and Machinery Div. of ASAE.

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Power Mine Site Description

The Power Mine was located in Southwest Missouri near Montrose on a permit area covering about 388 ha. The topsoil material of the mined area was removed by scrapers to a depth of 30.5 cm and transported to a stockpile area for about one year. Subsoils were also removed by scrapers to a depth of 122 cm and stockpiled for almost one year. The subsoils and topsoils were replaced onto the reclaimed area by scrapers and graded by bulldozers.

Two 30.5 m by 122 m plots were placed on the reclaimed field and sampled. Plot 1 was sampled one week after the soils were replaced. Plot 2 was sampled two years after the soils were replaced. Plot 2 was disked and planted in wheat in the fall of 1979. Instead of harvesting the wheat on Plot 2, the wheat was plowed under. In November 1980 both plots were seeded with alfalfa.

The soil types of the plots were a mixture of Hartwell and Deepwater soil series. The Hartwell Series consisted of deep, somewhat poorly drained soils on nearly level land. The surface layer is a silt loam 25 cm thick. The subsoil has two parts, the upper part is a firm silty clay loam and the lower part is a silt loam. Total subsoil depth is 69 cm. A perched water table could possibly form on the firm clay subsoil during wet periods of the year. Also, because of the clay, permeability is slow and available water capacity is moderate.

The Deepwater Series consisted of a deep, moderately well drained soil on gently sloping land. The surface layer is a silt loam 46 cm thick. The subsoil is classified as a silty clay loam with a depth of more than 152 cm. The permeability is moderate and the available water capacity is very high.

Inputs Selected for the Mine Sites

User inputs and GASP IV (Pritsker, 1974) inputs are required for COMPACT. GASP IV is a simulation language that contains ANSI FORTRAN 77 standard subroutines. The user inputs required for the model were obtained from Albrecht and Thompson (1982), from available literature concerning the soils, and from the manufacturer's literature concerning the equipment used in the reclamation operations. The GASP IV inputs chosen from Pritsker (1974) included specifying files, file entries, initial parameter values, etc., and are described by Bingner (1988).

The simulated layout of the Brazil Mine and the Power Mine included a field selected for soil removal and a reclamation field selected for final subsoil and topsoil placement. The Brazil Mine also included a field for topsoil storage that was used for final topsoil placement at the reclamation field after subsoil placement. Lift increments were produced at a field from the leveling of placed soil, which increased the elevation of the field. Lift increments at the Brazil Mine were produced in the subsoil from leveling all the soil piles dumped from the trucks and in the topsoil from scraper deposition. Topsoil and subsoil placement on the reclamation field at the Power Mine were simulated by placing each removed layer from the soil removal field directly on the reclamation field in 0.3 m lift increments, using scrapers, without any storage time. Three simulated plots or crossing-section areas were distributed around the reclamation field at each mine site to determine any spatial variability of the compaction produced by the

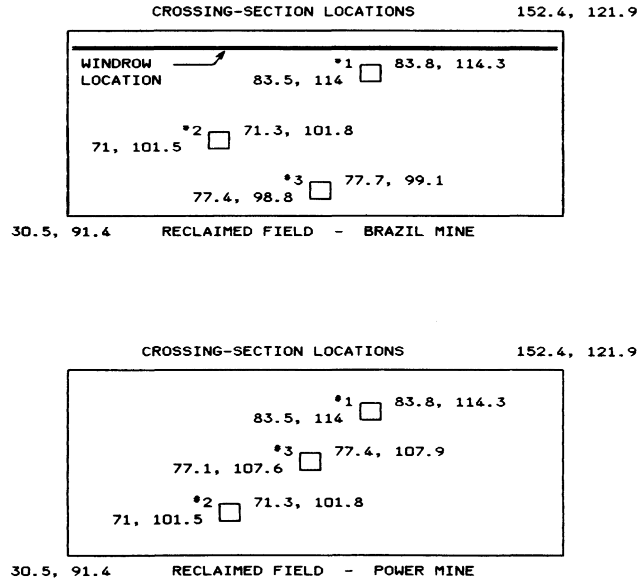

Figure 1–Position of the crossing-section locations (x, y in meters) at the reclaimed field for the Brazil and Power mine sites.

traffic patterns of the vehicles. Crossing-section areas are defined as small areas within a field that records information of vehicles passing across it. The distance between these fields was determined not to be an important compaction consideration for the systems simulated at the Brazil and Power Mine sites.

For each field an initial elevation at the start of the simulation was required. At the excavation field for each mine, the initial elevation was chosen as 30.5 m as was the topsoil storage field for the Brazil Mine. The initial elevations at the reclamation fields for the Brazil and the Power Mine sites were 27.4 m and 29.2 m, respectively.

For these simulations there was only one type of soil for each field at each mine site. If more than one type of soil was present, then each field could have their own soil parameters that describe the soil material as reclamation operations are performed.

The density at a known stress, ρ_o, the known stress, σ_o, the compression index, C_v, the known degree of saturation when related to the bulk density, S, and the slope of the bulk density versus the degree of water saturation curve at a given stress, k_w, were all determined from Larson et al. (1980) for each of the site's soil type. The Brazil and Power Mine sites were both determined to be similar to the Typic Hapludolls soil suborder of the Mollisol order. This was based on the nearest match for both soils of the sand, silt, and clay contents as reported by Larson et al. (1980) that contained the necessary parameters for the equations. The slope of the secondary compression curve (SCC), C_s, was determined from Lambe and Whitman (1979) for organic soils. Although the soil at the Power Mine site would be more typical of an Aquic Hapludolls soil order, all of the parameters necessary were not reported by Larson et al. (1980) and thus the soil order was not considered in this study. The parameters used for this study were:

ρ_o = 1.37 g/cm^3 $\quad$ k_w = 28.2 × 10^4

σ_o = 98 kPa $\quad$ C_v = 0.31

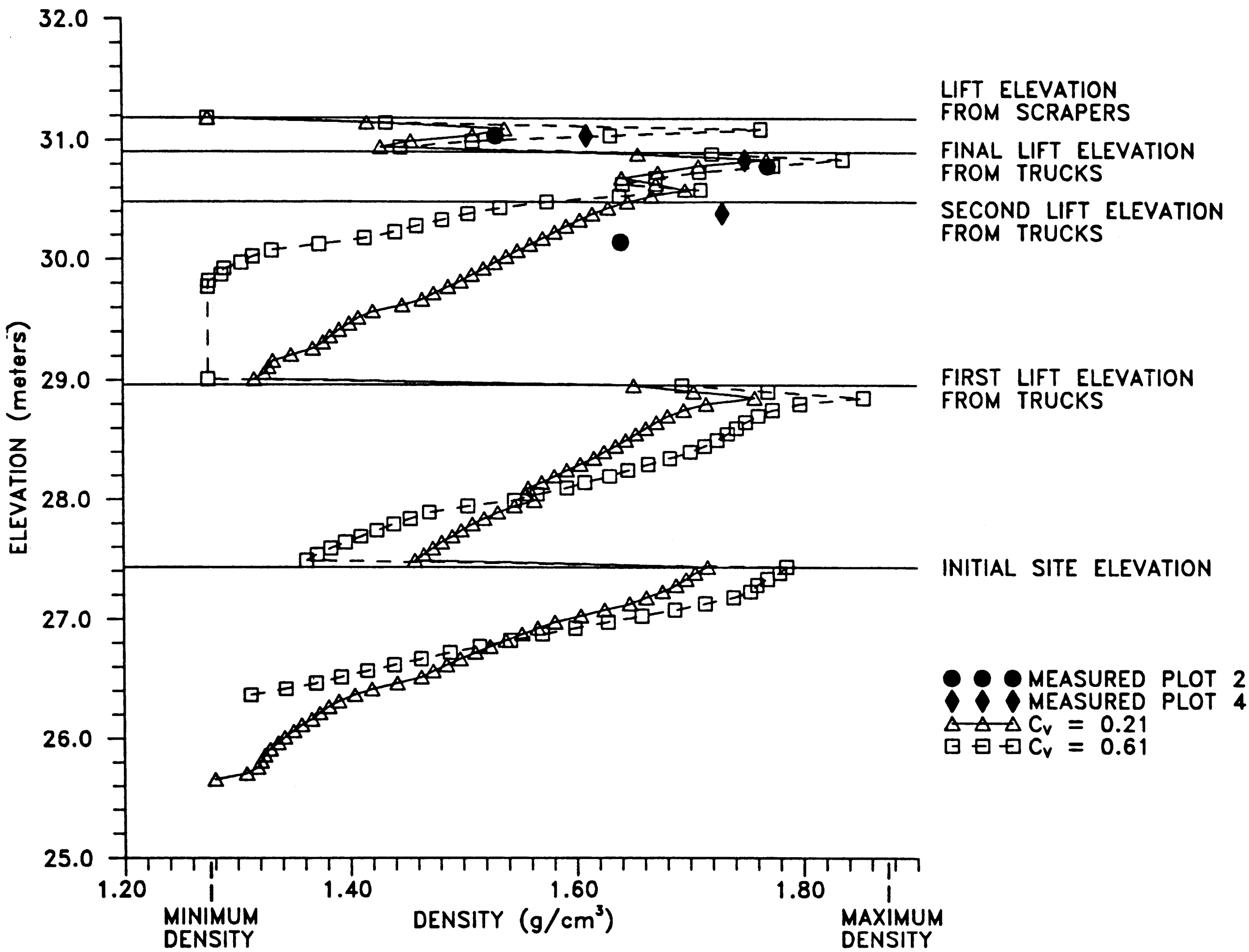

Figure 2–Sensitivity analysis of the slopes of the virgin compression curve, C_v, at the Brazil Mine site.

S = 59.1 C_S = 0.04

Each mine site had three monitored crossing-section areas or locations chosen at various points around the site (fig. 1). This would show any variability in vehicle movement, from the amount that a vehicle crossed the crossing-section areas, and the resulting affects on density. At the end of the simulation, the area's load history and soil profile would be combined to determine the density profile of the crossing-section area that would have been caused by machinery traffic passing above.

RESULTS

The results from the systems simulated for the Brazil and Power Mine sites (figs. 2-4) show how the model responds to the inputs selected for each system. Actual bulk density measurements are shown from each site to compare how the model, COMPACT, performed in simulating bulk density for various elevations of the soil material. A sensitivity analysis could be performed on many of the parameters of COMPACT, but this analysis was limited to the degree of saturation, S_m, the slope, C_v, of the virgin compression curve (VCC), and the density, ρ_o, at a known stress as described in Part I of this article (Bingner and Wells, 1992). All parameters and inputs to the model remained unchanged, except the value being changed, for each of the sensitivity analyses. The parameter values used for these results, when another parameter value was varied, were C_v equal to 0.31, ρ_o of 1.37 g/cm^3, and a S_m of 70%.

The degree of saturation was a variable that was unknown at the time of soil replacement and could have a significant effect on the resulting density. Therefore, several values were chosen for a sensitivity analysis of the degree of saturation using the information from the Brazil Mine. The values C_v and ρ_o are values that were chosen depending on the type of soil. Since the soil types studied did not correspond exactly to that of Larson et al. (1980), the parameters for the various soil types could not be chosen with certainty. In any engineering problem involving consolidation the choice of the slope of the VCC is very difficult. By varying these parameters, an indication of the response of the model as density is computed can be shown.

The output from COMPACT produces a report that shows the combined crossings of the vehicles from any point within a crossing-section. By combining all the values that occur within a crossing-section at a depth below the crossing-section, an average density profile for the crossing-section can be shown. Repeated crossings of the crossing-section by vehicles affects the density at the

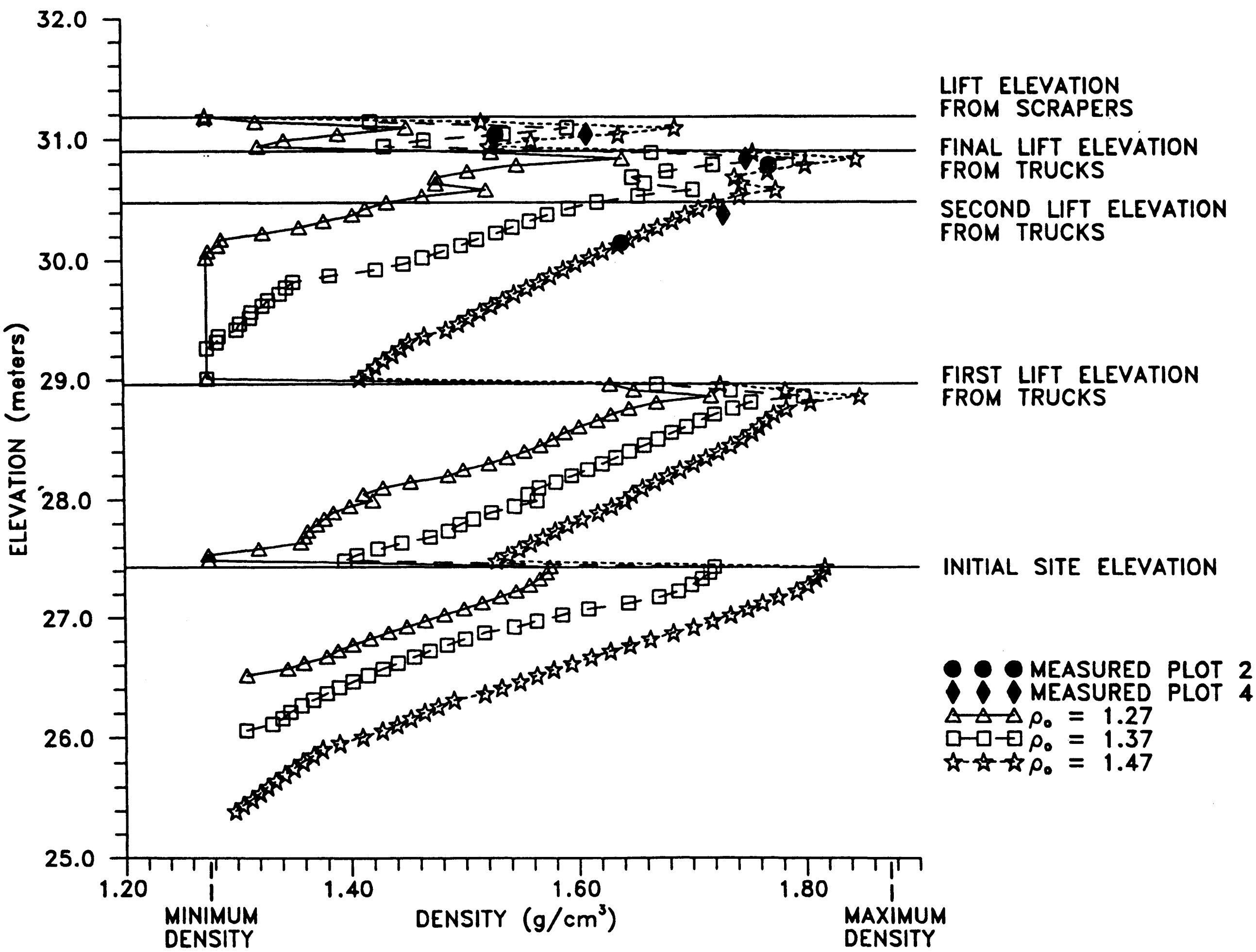

Figure 3–Sensitivity analysis of the density at a known stress, ρ_0, at the Brazil Mine site.

surface and throughout the soil profile. Thus, the density associated with an elevation may not be assumed to be caused only from a vehicle's initial passing at that surface elevation. COMPACT does not show if the density reported has been affected by only one vehicle or subsequent vehicles that might pass the crossing-section.

Sensitivity Analysis

Slope of the Virgin Compression Curve (C_V). At the Brazil Mine, C_V was varied with values of 0.21 and 0.61 (fig. 2). This variation encompassed the range of C_V values for the various soils described by Larson et al. (1980). Figure 2 demonstrates that as C_V increases, the density will be greater near the top of each lift elevation. As the vehicle pressure decreases into the lift increment, the density decreases faster for higher values of C_V. An increase in C_V is expected to produce this result, while holding all other parameters the same.

The pattern of the density profile shows there are several compacted layers contained in the soil, which is expected when material is being placed, in mainly a loose state, at surface mine sites At the Brazil Mine site, the trucks produced two lift increments of 1.5 m each and a third lift increment of 0.4 m. The lift increments were produced by the trucks dumping their loads into soil piles. Bulldozers would then completely level the field before more trucks would dump their load for the next lift increment. The small, third lift increment was produced by trucks only dumping onto part of the field, since the excavation operations had stopped, and the bulldozers leveled those soil piles over the entire field. The final lift elevation was produced by the scrapers depositing topsoil in a windrow so bulldozers could level the field for a lift increment of 0.3 m. The format of figure 2 will be followed in all the density profile figures that follow.

Density at a Known Stress (ρ_0). The known stress, ρ_0, was varied in the analysis with the values 1.27, 1.37, and 1.47 g/cm^3. Figure 3 demonstrates that soil density increases as ρ_0 increases. The compacted layers of ρ_0 equal to 1.47 g/cm^3 are deeper and the density profile lines are more uniformly shaped within the lift elevations than the other values.

Degree of Saturation (S). The sensitivity analysis of the model for degrees of saturation of 50% and 90% are shown in figure 4. This shows that as the degree of saturation increases, the density increases throughout the soil profile.

Brazil Mine Results. The sensitivity analyses did show that the model is sensitive to the parameters evaluated, but not which parameter is optimal for the soil condition at the mine site at the time the material was placed. Since there was no reason not to use the parameters suggested by

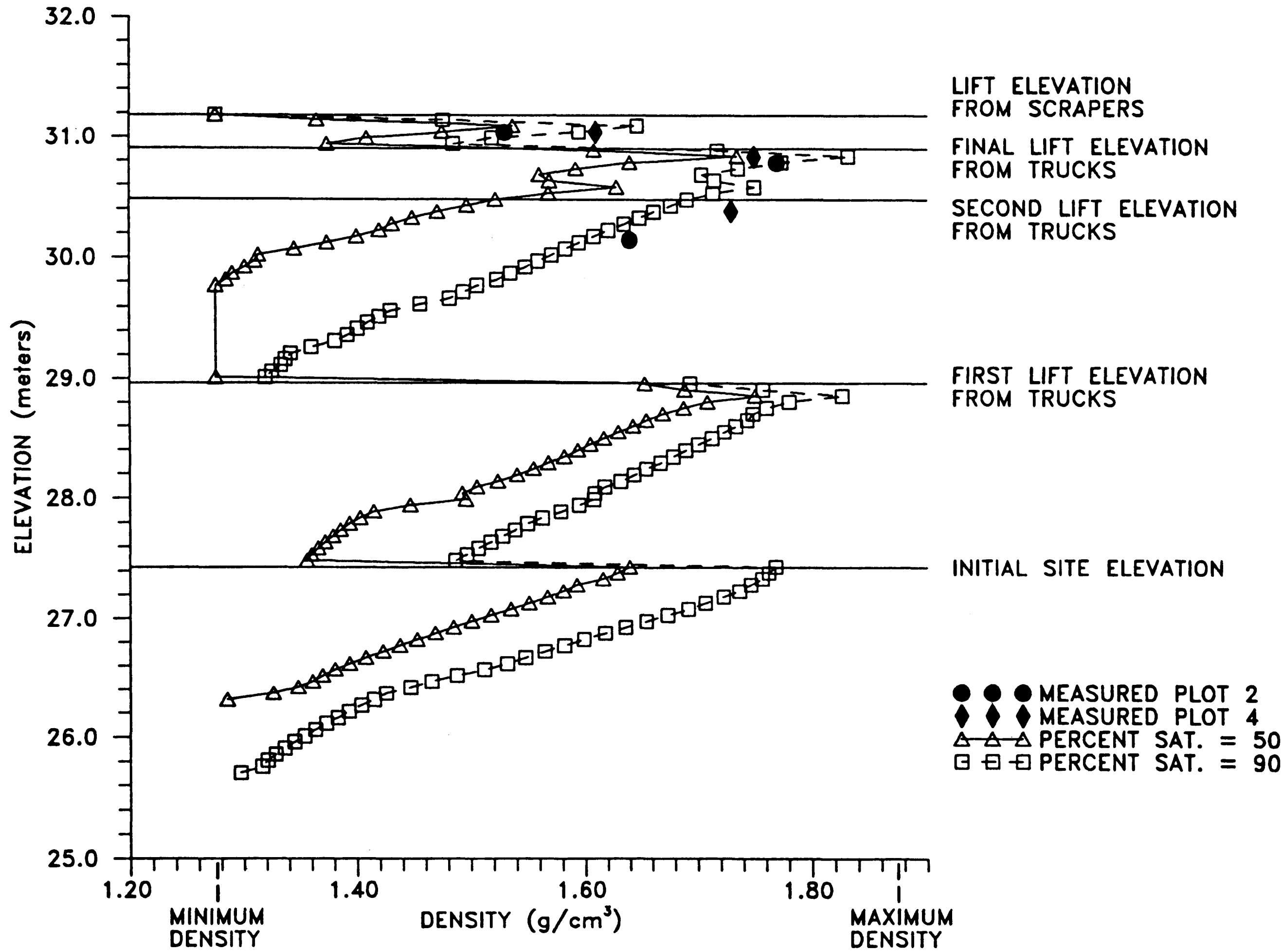

Figure 4–Sensitivity analysis of the degree of saturation at the Brazil Mine site.

Larson et al. (1980) as described earlier for the assumed soil type, those parameters were used for the detailed comparison of the measured results.

The parameters used in the analysis of the Brazil Mine were as described previously with a degree of saturation of 70%. Figure 5 shows the results of the model when 0.3 m square crossing-sections are at three different points in the field. Figure 5 does show differences in the density profile around the field, but the trends all seem to be similar. For example, the density increases with depth near the surface of each crossing-section and then decreases with depth. Location 3 does have a sharp increase of density at 30.3 m which could be caused by increased vehicle traffic at that point. Other peaks of density that occur in all the crossing-sections of each location were produced by the trucks near the top of the last lift increment and the initial site elevation or at the original ground surface before placement of the soil material. The original ground surface could be either the elevation of the site before mining or the elevation of the spoil base upon which soil was placed, depending on how the system was described.

Although the initial site elevation was not initially in a loose state, the density determinations assumed this elevation to be in a loosely compacted state. Since no field measurements were taken there, this would provide a view of how far the surface contact pressure would affect the density into the soil profile. COMPACT is currently configured so the density of the soil material cannot be affected by the value of the density of soil material below it. Any density from 27.4 m and below will only have been affected by the trucks or possibly the bulldozers.

Power Mine Results. Results of COMPACT from the Power Mine with crossing-sections located at three various points in the field are shown in figure 6. Figure 6 shows COMPACT overpredicted the measured density at all elevations for each location. The scrapers deposited four, 0.3-m layers in the field. Bulldozers provided minor leveling of each layer before another layer would be deposited by the scrapers. At the top final layer, density is low near the surface and increases cyclically with depth into the third layer at 30.1 m for all but location 3. The density then decreases in the third layer until the top of the second layer when density again increases to a peak at 29.7 m. The density profile then varies again through the second and first layers for locations one and two until the original ground surface is attained and the density gradually decreases. Location three shows that the maximum density is attained throughout layer two and into the first layer. The trend that is clear in all the locations is that density

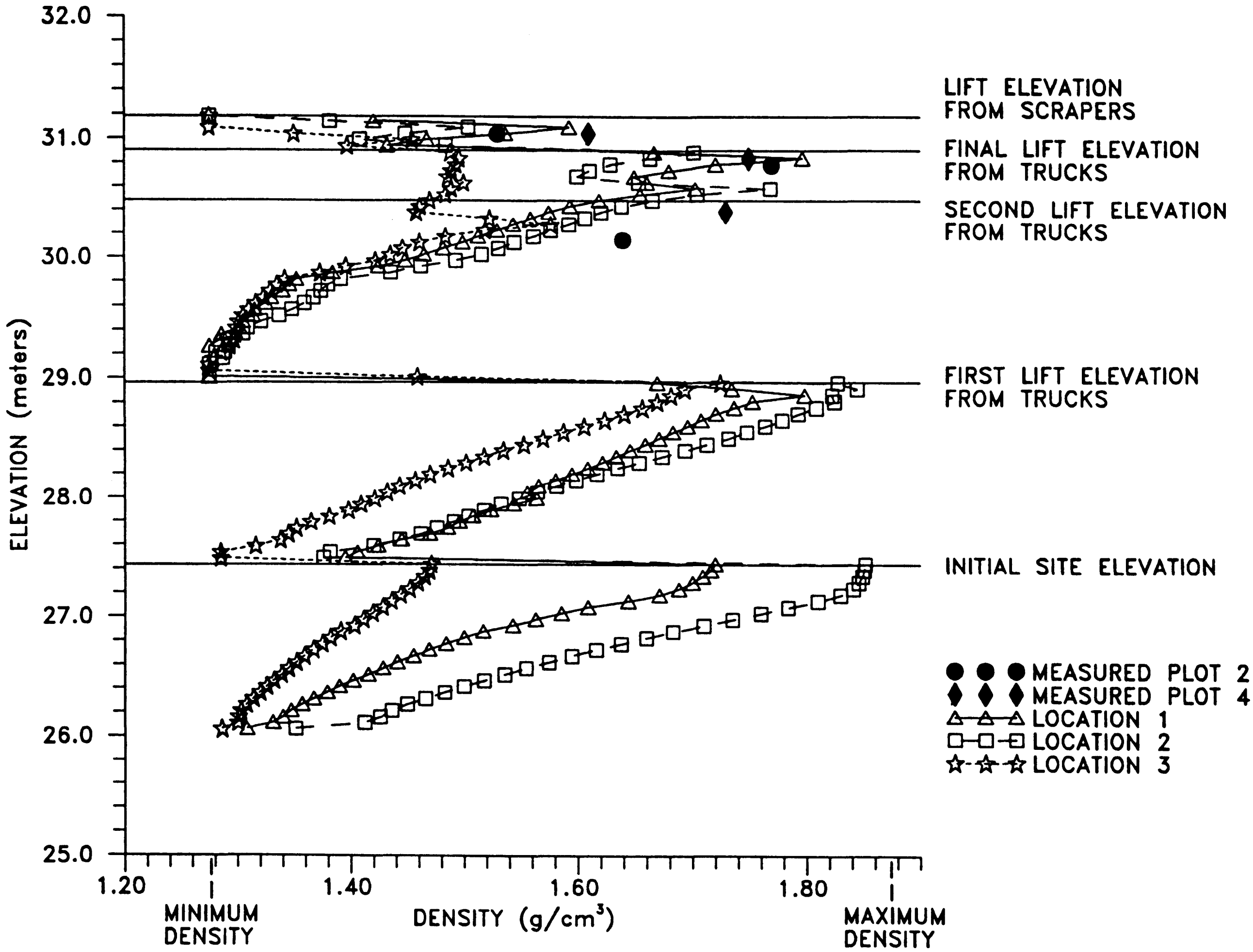

Figure 5–Density profile beneath three locations (crossing sections) at the Brazil Mine site.

increases with depth at the Power Mine until the original ground surface.

Discussion

The results demonstrated how COMPACT simulated the density of soil. While the results do not particularly agree with the measured results, some trends and observations can be made to apply to actual situations. The density with depth profile for all the locations simulated for the Brazil Mine (fig. 5) show compacted layers being produced by the vehicle traffic. The static weight of soil is not included in the computation of the density profiles. This would result in the density profile approaching a minimum density that is greater than is indicated in the figures. Static weight would not be much of a factor in the first meter under the vehicle, but could effect the results several meters into the soil. For the purpose of this model, this was not considered a major factor, but could be easily included in future developments of the model.

The three locations at the Brazil Mine site show there was variation of the density profile around the mine site. Location 3 produced a density profile that has lower density near the surface then the other locations. The density profiles from the second through the first lift increment show a less drastic change. Location 3 was situated the furthest from the windrow produced by the scraper. The farther away from the windrow the less chance there would be of a bulldozer pushing material over the crossing-section and driving back to the windrow. Since the pattern of the trucks dumping soil is uniform over the field, the variation in vehicle movement should be less among the three locations.

When the simulated results are compared to the measured, consideration must be made that the model is predicting results immediately after all of the reclamation operations were completed on the field. The measured results were in fact sampled over one year after the reclamation operations of replacing the soil had been completed. Also, the field had been chisel plowed, disked, planted, and replanted by the time the measured plots were sampled. Obviously, chisel plowing and disking would affect the density from the surface to 0.3 m or 0.6 m into the ground. What these effects are cannot be determined from the report by Albrecht and Thompson (1982).

The difficulty in obtaining accurate parameter values for the virgin and secondary compression curves was characterized by the soil at the site being substantially mixed from the procedures used in removing the subsoil. Mixing resulted from removing the subsoil from depths of up to 4.57 m below the surface and depositing this material

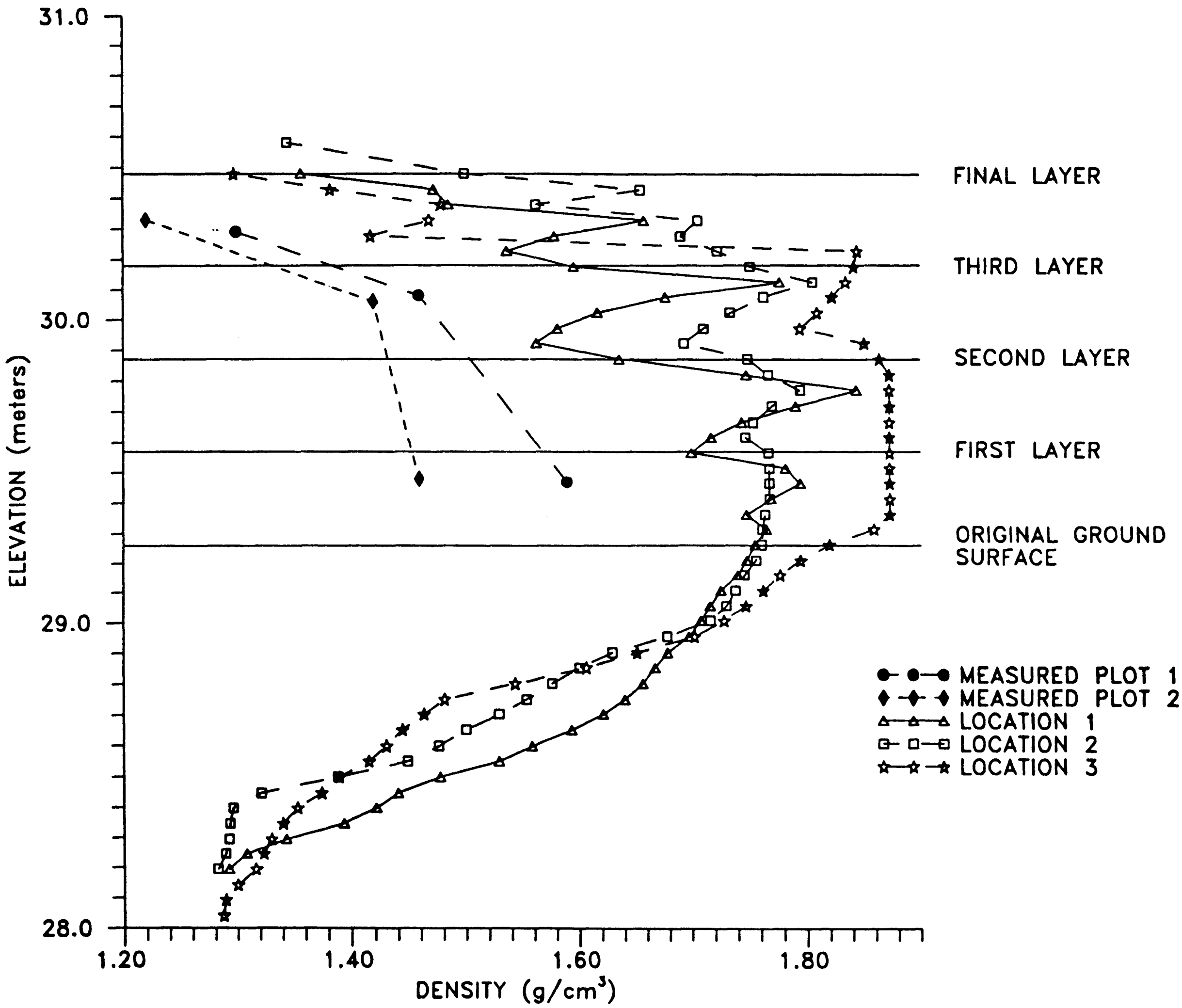

Figure 6–Density profile beneath three locations (crossing sections) at the Power Mine site.

alongside material from overlying depths. The soil texture from this mixture would be noticeably different from the soil texture of a natural soil. Albrecht and Thompson (1982) reported this soil texture change. They attributed some of the density changes in the soil profile to the changes in soil texture.

From the sensitivity analyses it was shown that the parameters studied affected the model as might be expected, but unless accurate parameters can be determined for each soil type studied then only estimates can be made for the parameters. Further sampling of a site to determine the parameters for the virgin and secondary compression curves would be the ideal method of testing the model's accuracy. However, as long as the model can predict trends and relative values, the model would be useful in studying traffic and the influence it has on compaction at surface mine sites.

Density profiles from the Power Mine show a distinct difference from results produced by the the Brazil Mine. For the simulated results at the Power Mine, figure 6 shows there are several compacted layers within 1.2 m of depth that result from the scrapers and bulldozers placing and grading the subsoil. The initial elevation of the field, before reclamation operations began, was 29.3 m. The scrapers deposited the subsoil onto the field in 4-0.3 m layers. The top of the field after reclamation operations were completed was at an elevation of 30.5 m. Since the compacted layer from 29.3 m and below is contained in the original subsoil, the densities produced in this layer would mainly be from the scrapers driving over the field to deposit the subsoil. The trend of the simulated density profile for the Power Mine is for the compacted layer's maximum densities to increase with depth throughout the entire subsoil material. This agrees with trends produced by the measured results showing an increase in the density with depth.

The scrapers also were simulated such that each pass that they made, to deposit the layer, passed over the same points at the site as with previous layers. This would produce a high density profile at the locations of the vehicle tracks but the density would be at a minimum at other locations in the field. Actual scraper movement would not be over the exact same location and thus the average density of the field may be higher.

The difference between actual and predicted results at the Power Mine site can be explained with similar reasons as those given for the Brazil Mine site, such as choosing the right soil type and parameters for the associated relationships in the virgin and secondary compression curves. The mixing of the soil was less of a problem at the Power Mine then the Brazil Mine because the scrapers were able to remove and replace the soil layers exactly as they occurred naturally. This would lead the reclaimed site to have conditions similar to the natural sites, only the densities would be different. Albrecht and Thompson (1982) found that by replacing the soil so the conditions were near natural, the effects of compaction compared to the other systems they studied, were reduced.

Variation of Soehne's concentration factor with the density of soil that a vehicle passes needs validation. Intuitively, there should be a relationship between the density and the concentration factor. The method presented is a reasonable and simple relationship suitable for modeling the machinery and soil interaction.

The model assumes that the effect of the pressure from a tire or track is limited to the width of the tire or track. In reality, this effect extends beyond the width of the tire or track. This assumption was made to simplify the model.

Equations that the model uses are only approximations of actual processes and interactions that occur with soil material as it is being compacted. The model does not address all of the possible interactions between the soil material and the vehicles, but only serves as a starting point for further study.

Summary and Recommendations

A model was developed to simulate the compaction of soil resulting from the vehicle traffic that occurs during surface mining reclamation operations. The model showed a responsiveness to soil characteristics as machinery moved over a reclamation site. The model also showed an effect on the soil density caused by different systems of soil replacement.

Input parameters chosen to describe soil conditions at the time of compaction can greatly affect the results of the model. Degree of saturation, slope of the VCC, and density at a known stress as used in the compaction equations were parameters chosen to determine how the model responds to soil conditions. The Brazil Mine site showed a uniform response for the levels of degree of saturation and the density at a known stress. Varying the slope of the VCC showed that a greater slope increases the density near the surface of a vehicle passing but attains the minimum density of soil at a shallower depth than with smaller slopes of the VCC.

While not all systems now used by surface mining companies can be simulated. the model can be expanded to include other systems. This study does show that an understanding can be made of how equipment can alter the density of a soil profile and permits the determination of the reclamation operations that will reduce compaction. A framework has been developed by the model for further research into the problem of compaction caused by the machinery used by surface mining systems.

As faster and more efficient computers become available, increasingly complex systems can be developed. If computational speed and economic costs are not a factor, then further changes can immediately be made. By understanding the processes involved in the compaction of the soil, improvements can be made in scheduling the reclamation operations of a surface mine.

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