ANALYSIS OF THE DENSIFICATION OF RECLAIMED SURFACE MINED LAND

A Thesis

by

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ABSTRACT

Analysis of the Densification of Reclaimed
Surface Mined Land. (May 1977)
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Knowledge of the settlement characteristics of reclaimed surface mined land is of great importance if rigid structures are to be constructed on mined land spoil material. As surface mined coal and uranium are exploited as energy resources, knowledge of overburden settlement characteristics becomes even more important. Geologic and engineering investigations have been conducted to determine the amount and rate of settlement at the Alcoa lignite mine near Rockdale in east central Texas.

Geologically, the study area is located within the mudstones, clays, silts, sands, and lignites of the Eocene Calvert Bluff Formation of the Wilcox Group. Deposition of the main lignite seam at Alcoa occurred in a marsh within an interchannel basin on the upper part of the delta. As the basin subsided, the marsh was replaced by a lake of variable water depth which gradually filled in with clays and laminated clay-silts. These deposits were in turn covered by overbank and levee deposits associated with meandering channels. Lignites associated with the channel overbank deposits are thin and discontinuous, reflecting the influence of the channel.

In engineering terms, the overburden at Alcoa may be classified as overconsolidated low to high plasticity clays and silts and as well sorted sands, which would place them as soils rather than rocks.

Laboratory measurements indicate the dominant mechanism of initial redensification is one of plastic deformation of the soil aggregate, and is dependent on the maximum precompression and the water content of the soil. Immediately after mining the soil is fluffed an estimated 24 to 47 percent. Over time, the soil redensifies, but will remain fluffed permanently by 7 to 23 percent of the initial overburden thickness. Hydrologic conditions affect the eventual amount of redensification, since partially saturated soils with the groundwater level below the depth of mining become more dense than fully saturated soils in which the groundwater table is at the surface. Since the addition of water strongly affects the amount and rate of redensification, the effect of long term soil moisture changes under foundations or pavements may have a great influence on their stability and rate of settlement.

Measured settlement rates change from 312 ft/yr for a day old spoil pile, to 0.221 ft/yr for reclaimed land 2-1/2 years old, to virtually no settlement for land mined ten years ago. Differential settlement is on the order of 0.100 ft/yr for stations 350 ft apart, and on the order of 0.020 ft/yr for stations 5 to 15 ft apart. It is estimated that approximately 75 percent of all settlement will occur within one year after mining, 80 percent within the first five years, and most of the rest over the next 1000 years. The comparison of laboratory and field measurements indicates good agreement on the amount and rate of settlement.

ACKNOWLEDGEMENTS

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INTRODUCTION

Statement of Problem

Plummer wrote in 1932, "When the oil fields are exhausted, the lignite beds will take their place as the future fuel, lubricant, and power producing resource of the state (Texas)." This statement by Plummer is now being proven by extensive lignite exploration and exploitation programs (Table 1). Texas has been blessed, not only with large oil and gas reserves, but with large lignite resources covering approximately one million acres underlain by some 10.7 billion tons of lignite, having an energy content equivalent to 37.7 billion barrels of oil (Kaiser, 1974). Much of this land may be mined for use in mine-mouth power plants as the present rate of exploration indicates great interest in the resource.

Since mining is an interim land use, the suitability of the land after reclamation for use in agriculture or for development is important. The Texas State Legislature enacted into law Senate Bill #55, which was signed by Governor Briscoe in 1975, in order to "prevent adverse affects to society and the environment resulting from unregulated surface mining operations." Governmental regulation of surface mining has led to much research into reclamation, most of which has centered on revegetation of land for agricultural use. Very little work has been done on the settlement characteristics of the disturbed land as it redensifies. Knowledge of the settlement characteristics is vital if rigid structures such as houses, barns, or roads are to be

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The citations on the following pages follow the style of the Bulletin of the Association of Engineering Geologists.

TABLE 1. Estimated land requirements of lignite fueled electric generating plants in Texas.

Plant	Capacity (Megawatts)	Area Disturbed Yearly (acres)**	Location
Alcoa	360	100	Rockdale, Milam County
Big Brown	1150	580	Fairfield
Monticello +	1800	900	Titus County
Martin Lake *	3000	1500	Rusk County
Forest Grove *	750	380	Henderson County

\+ Partially completed at present time

* Under development

** Estimated assuming an eight ft thick lignite seam constructed on reclaimed land.

In order to avoid confusion, it is necessary to define several words as they will be used in this thesis. Densification is the decrease in volume of a soil mass due to compressive stress and may result from loading or drying. Redensification is the densification of a soil that was in a denser state, and has been disturbed as in a strip mine operation. Settlement is the adjustment of the land surface as a result of densification or redensification. In generally accepted mining terminology the change in volume of the overburden due to disturbance by mining is called "swell". In engineering terminology, swell may also mean an increase in volume due to a moisture change in expansive soils or due to a decrease in effective stress. To avoid problems in terminology, the term "fluff" is used to designate the increase in volume of the disturbed overburden. This author recommends the adoption of the term "fluff" to describe the increase in volume of overburden due to mining.

Objectives

The primary objective of this study is to determine the characteristics of disturbed, loose overburden materials as they redensify following mining. The objective is met through the following subobjectives:

1) by measuring the total settlement, amount and rate, of reclaimed land in the field;
2) by measuring the differential settlement of the disturbed land, over both short and long distances;

3) by determining the stratigraphy of the study area as related to the engineering and settlement characteristics of the disturbed land; and
4) by developing an empirical procedure for predicting settlement characteristics of disturbed soils.

Significance of This Work

This analysis of the redensification of reclaimed, surface mined land and the settlement characteristics of uncompacted soils will be significant to the redevelopment of surface mined land. Increased exploitation of lignite is disturbing large land areas in the State. If rigid structures are to be built on reclaimed land, knowledge of the overall settlement characteristics of loose spoil material and the ability to predict settlement of these materials are important.

GEOLOGIC INVESTIGATION

Location of the Study Area

The study area is located at the Alcoa lignite mine in the southern tip of Milam County, in east central Texas, near the town of Rockdale (Figure 1). Regional strike of the geologic units in the area is N 40°E, with dip being $1/2^{\circ}$ to 2° southeast. Stratigraphically, the study area is contained entirely within the outcrop area of the Eocene Calvert Bluff Formation of the Wilcox Group. Locally the Calvert Bluff consists of unconsolidated sands, mudstones, interbedded sands and mudstones, and lignite.

Previous Work

Stratigraphically, the Calvert Bluff overlies the meanderbelt deposits of the Simsboro Sand (McGowen and Garner, 1970), and is overlain unconformably by the braided stream deposits of the Carrizo Sand (Figure 2). Intermixing of time-rock and rock terms has caused some confusion concerning the terminology of the Lower Eocene, Upper Paleocene Series. The problem originates from the use of the Ostrea thirsae oyster banks to define the base of the Wilcox Group (Murray, 1955). This is in contradiction to the Code of Stratigraphic Nomenclature (1961), which states that groups, which are rock units, should be defined on the basis of mappable lithology and not on the basis of faunal content. The boundaries for the time units, time-rock units, and rock units shown in Figure 3 are generally accepted, but terminology for the units still varies. Rock units comprising the Calvert

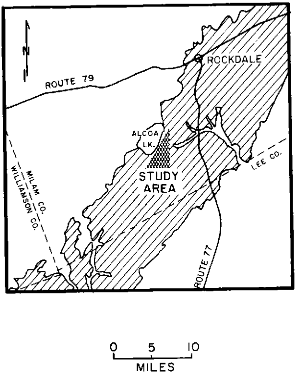

FIGURE 1. Location of the study area. Striped area is the Calvert Bluff outcrop from the Geologic Atlas of Texas, Austin Sheet.

Eocene Series	Jackson Group	Whittsett Formation Manning Formation Wellborn Formation Caddell Formation
	Claiborne Group	Yegua Formation Cook Mountain Foundation Stone City Formation Sparta Sand Weches Formation Queen City Sand Reklaw Formation Carrizo Sand
	Wilcox Group	Calvert Bluff Formation Simsboro Sand Hooper Formation

FIGURE 2. Stratigraphic section showing the relationship of the Calvert Bluff to surrounding units (After Kaiser, 1974).

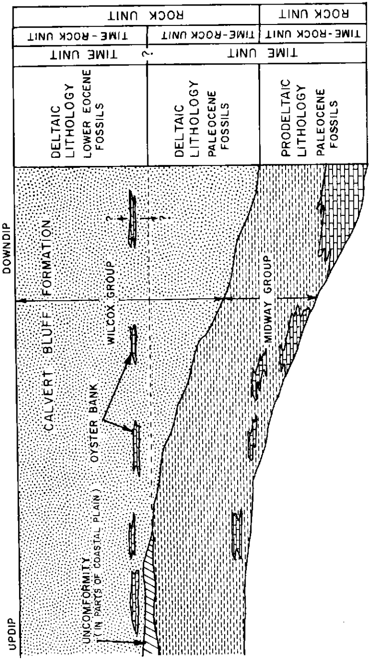

FIGURE 3. Generalized cross section of Wilcox and Midway rocks indicating time, time-rock, and rock categories (After Fisher, 1961).

Bluff are considered to be either of member status of the Rockdale Formation (Plummer, 1932), or of formation status within the Wilcox Group (Stenzel, 1953), the latter being more widely accepted.

Various origins of Wilcox lignites have been described as coastal plain (Plummer, 1932), or fluvial, lagoonal, and deltaic (Fisher, 1968). Since the mode of origin of the lignite affects the composition and the morphology of the lignite bodies, an understanding of the depositional environments of lignite would be helpful in planning exploration and exploitation programs. The depositional environments of coal and lignite have been studied in both ancient and recent settings.

Plummer stated in 1932 that, "lignite layers (in the Rockdale Formation) can be explained only by a constant shifting of river beds over a flat, swampy coastal plain." Plummer visualized meandering rivers heavily laden with water and sediment, with major channels 25 to 30 miles apart. Lakes and lagoons would initially be present between the channels and their levees. As the lakes and lagoons filled up with sediment, they would be replaced by marshes 10 to 15 miles wide. The marshes would in turn be covered by lakes and lagoons as the area subsides, then by the deposits of the shifting channel, creating a coarsening upward sequence.

Coleman (1976) has described a modern case of coastal peat accumulation of the Giana and Surinam coast of South America, where laterally extensive mangrove swamps and open marshes flourish in the hot, humid climate. Peat deposits over 160 ft thick have been measured in the freshwater marshes that interfinger with the more woody mangrove swamp deposits, as well as with the mud flats and beach sands.

Wilcox lignites in east Texas have been described as fluvial in origin (Kaiser, 1974), with deposition of the lignite occurring in a freshwater forested swamp on the alluvial plain of the river. The grain size of the sediments decreases upward in each cycle, with the lignite being associated with the finer overbank deposits. The lignites are moderately low in ash and sulfur, and contain a high percentage of woody material. In morphology, deposits may be 5 to 15 miles wide and extend 5 to 10 miles downdip. A modern example of fluvial deposition exists in the Mississippi River alluvial plain, between the Bayou Teche and the Mississippi River (Frazier, 1967).

Wilcox lignites in south Texas have been described as lagoonal (Kaiser, 1974). The lignites originated in a salt marsh environment, and contain up to 50 percent ash and 2 percent sulphur on a dry weight basis, along with very little woody material. Stratigraphically, the lignites are part of a coarsening upward, progradational barrier-strandplain-beach sequence, are associated with the lagoonal muds, and should be elongated along strike.

Kaiser (1974) has described central Texas lignites as deltaic in origin. A delta is a complex environment, with geomorphological features including delta plain marshes, crevasse splays, channels, levees, interchannel basins, and lakes. The relationship of these features shifts as the delta subsides and channnels change course. Peat accumulates in a variety of places on the delta, including the channel mouth, the meanderbelts of the distributaries, abandoned subdeltas, and in the interchannel basins. The two latter cases are the most important.

Abandoned subdeltas can be areas of accumulation for blanket peats of wide lateral extent. Coleman (1976) has described the case of the West Bay subdelta of the Mississippi River, where a crevasse splay opened in 1839, forming a subdelta and filling the bay with sediment. The splay was subsequently abandoned and vegetated by a freshwater marsh. As long as the growth of vegetation keeps pace with subsidence, peat accumulation will continue. If subsidence exceeds the growth of vegetation, the marsh deposits may be covered by marine muds or another crevasse splay. Lignites deposited thus will generally have a low ash content since there is little detrital input from either the river or tidal channels, be predominantly non-woody due to a marsh origin, and be of wide lateral extent.

The interchannel basin is another important site of lignite accumulation on the delta. Kaiser (1976) has suggested that the commercial lignite deposits at Alcoa accumulated in an interchannel basin analogous to the modern Des Allemands-Barataria basin of the Mississippi delta (Figure 4). Maximum peat accumulation occurs in the upper part of the basin, in areas away from the effects of the Gulf and the active channels. As long as peat accumulation keeps pace with subsidence, peat deposits in swamps and marshes continue to thicken. When subsidence exceeds accumulation, swamps and marshes may first be covered with interchannel lakes, where fine grained material from flooding accumulates. These may in turn be covered by coarser grained crevasse splay deposits. When these splays are abandoned, marshes may once again become established. In this way a coarsening upward sequence of deposits is developed, leading to the inverted Christmas tree pattern evident in electric logs.

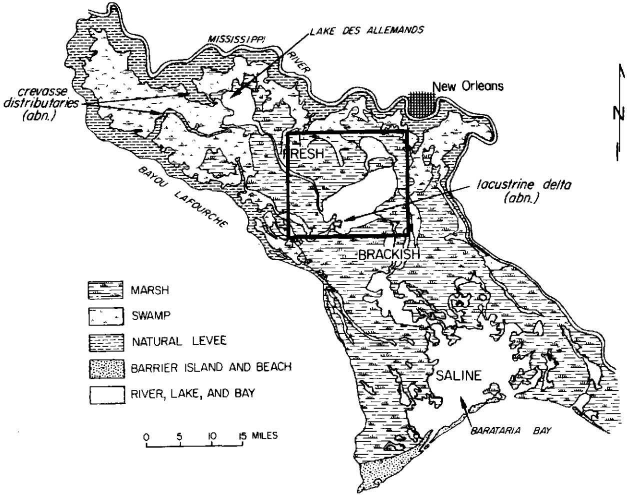

FIGURE 4. Des Allemands-Barataria basin of the Mississippi delta, with the boxed in area representing a modern analogue to the Calvert Bluff depositional system of the main Alcoa lignite (After Kaiser, 1976).

Several factors support Kaiser's (1976) interchannel basin interpretation of the main lignite seam at Alcoa. Regionally, the Calvert Bluff in east central Texas represents a component facies of the Rockdale Delta System, one of seven principal depositional systems mapped by Fisher and McGowen (1967) using subsurface logs and cores. The position of the Calvert Bluff within the delta system has been investigated using palynology and the mapping of sand bodies. Palynology of the main lignite at Alcoa indicates the alternation of hardwood swamp and freshwater marsh conditions (Atlee and others, 1968). Through analog with modern deltas, this suggests a location on the upper delta plain. This location is also suggested by the channel geometry shown in the sand percent map (Figure 5). In the area adjacent to the outcrop of the Wilcox, the channel geometry is straight to slightly bifurcating, as in the upper part of a modern delta. In addition, analyses of the Rockdale lignites indicate average ash contents of 12 percent and average sulfur contents of 1.5 percent on an air dried basis (Kaiser, 1974). These are consistent with an origin on the low energy parts of a delta, and tend to preclude a lagoonal origin, since lagoonal lignite should have a higher ash content due to the higher energy of the environment of deposition.

Method of Study

A major purpose of this study is to investigate the environment of deposition of the Calvert Bluff lignites at Alcoa. The exposures present in the high wall at the Alcoa mine provide an excellent opportunity to meet this goal. The geologic investigation was accomplished

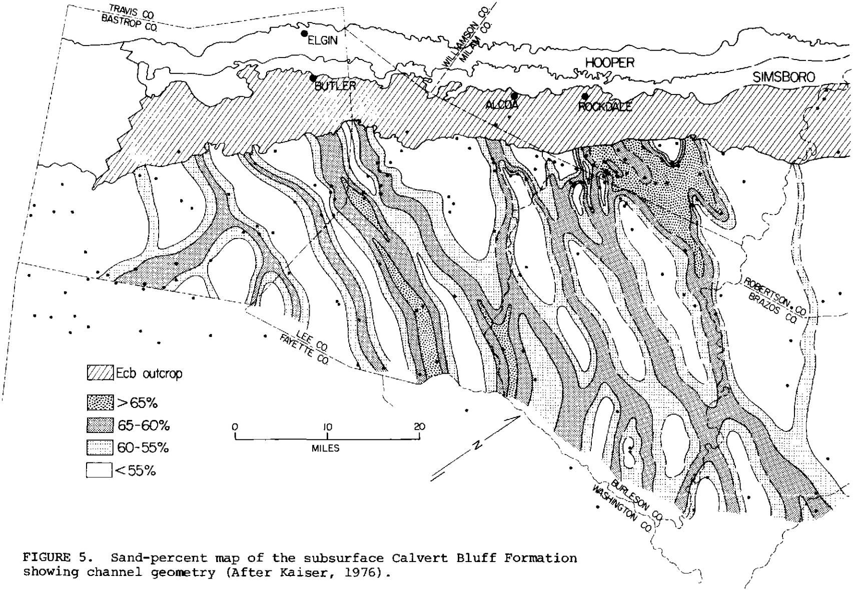

FIGURE 5. Sand-percent map of the subsurface Calvert Bluff Formation showing channel geometry (After Kaiser, 1976).

by measuring and describing the exposed strata, noting relationships between sediments, and making environmental interpretations on the basis of observed data and inferred facies relationships. Described sections were used in conjunction with photographs of the high wall in order to construct a geologic cross section of the pit.

Description and Discussion of Geology

The morphology of the lignite bodies at Alcoa is varied, as shown in the geologic cross section (Figure 6). The major lignite seam is widespread, being traceable for at least ten miles along strike and two miles along dip, the limits being determined by the limits of exploration and not by the absence of lignite. The seam generally ranges between 5 and 16 ft thick, but is absent in several places, due either to erosion by channels or local faulting. In most places more than one lignite is present in the section. These lignites range from a few inches to more than 6 ft in thickness. The variation in thickness and continuity reflect changes in the stability of the environment of deposition.

The limited data available on the morphology of the lignite bodies do not rule out the possibility of any of the major environments of lignite accumulation. Deposition in the coastal plain, interchannel basin, lagoon, or fluvial backswamp could all produce lignite deposits at least ten miles along strike, two miles along dip, and 16 ft thick. The thinner, less persistent lignites could be associated with the less stable portions of any of these environments. A more detailed morphologic study might be more conclusive if it delineated

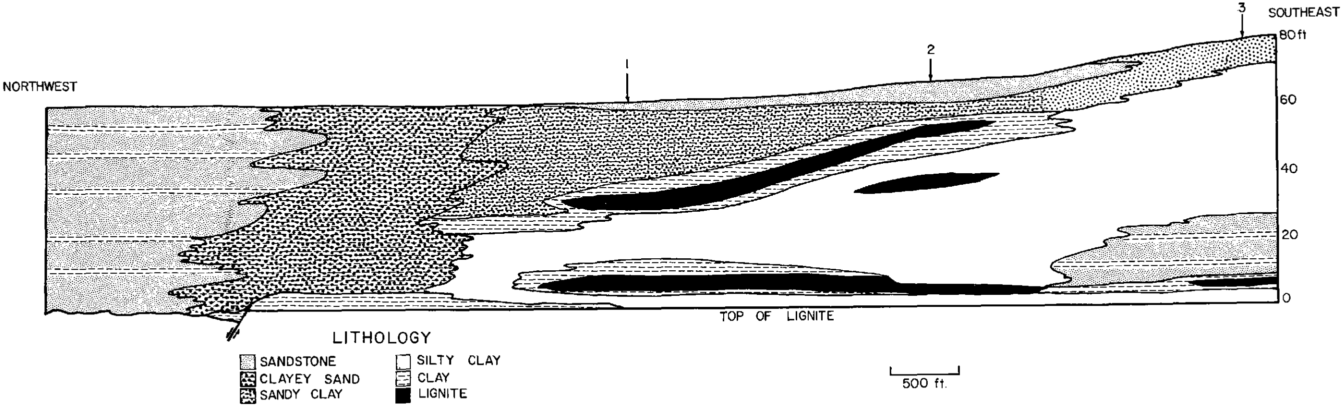

FIGURE 6. Generalized geologic section of the main pit at Alcoa. The section is oriented along strike.

channels, beaches, or other bounaries to the lignite accumulation, but this is not possible with the available data.

The composition of the lignite provides clues to its environment of deposition. Lignite of the main seam is brown-black, predominantly massive and banded, and contains variable amounts of pyrite. The lignite may be described as the xyloid type, containing more than 50 percent anthraxylon, which is derived from the woody parts of plants (Fisher, 1963). Woody fragments and leaf imprints are present in the main seam, but not in the abundance which might be associated with a fluvial backswamp environment. As noted earlier, lignites in the Rockdale area are relatively low in ash and sulfur. This tends to support an origin in a low energy part of the delta over a higher energy lagoonal origin.

The types of sediments associated with the lignites and their relationship to the lignite bodies are determined by the depositional framework. It should be possible to determine the environment of deposition of the lignite by studying the progressive change in sediments above and below the lignite deposits. Descriptions of these sediments are found in Figures 7 to 9 and Appendix A. In general the sediments consist of coarsening upward cycles of lignite, clay, clay-silt laminae and clay-silt-sand laminae.

Although it is not exposed, drilling records indicate clay below the lignite. Immediately above the lignite is normally a gray or black clay which varies in thickness and organic content (Figure 10). This clay layer may contain a few sand or silt lenses. It is overlain by 4 to 5 ft of wavy discontinuous silt-clay laminae (Figure 11).

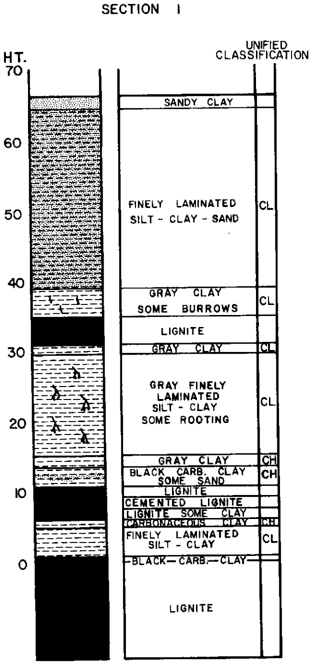

FIGURE 7. Geologic Section 1 based on pit exposures 2500 ft north of the spoil pile. The height is measured in ft from the top of the main lignite.

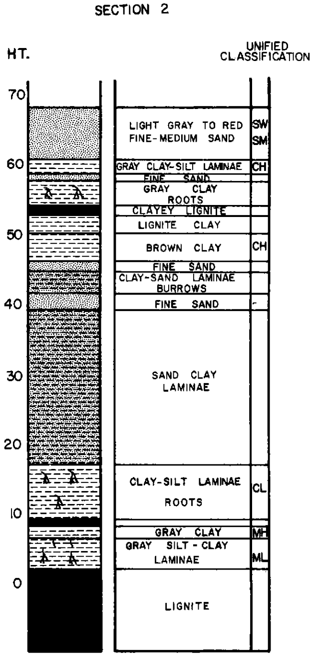

FIGURE 8. Geologic Section 2 based on pit exposures 800 ft north of the spoil pile. The height is measured in ft from the top of the main lignite.

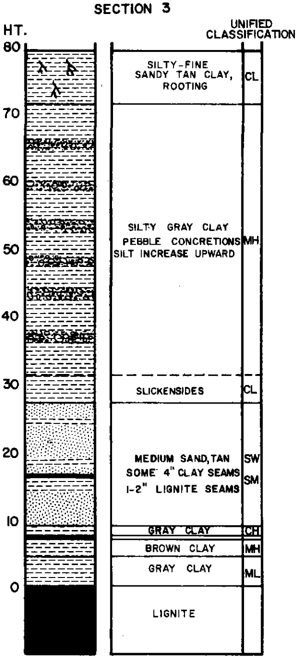

FIGURE 9. Geologic Section 3 based on pit exposures at the far south end of the main pit, 1500 ft south of the spoil pile. The height is measured in ft from the top of the main lignite.

FIGURE 10. Black carbonaceous clay overlying the main lignite seam.

FIGURE 11. Silt-clay laminae above the main lignite seam. Note the wavy, discontinuous laminae. The lens cap is 2 in. in diameter.

These laminae may be broken into discontinuous blebs (Figure 12) or disturbed by rooting or burrowing (Figure 13). The silt-clay laminae grade upward into another clay, which then is followed by a lignite to complete the cycle.

The thick clays and undisturbed laminae over the lignite indicate rapid deposition. Pauses in deposition are indicated by rooting, burrowing, or the subaerial drying which resulted in the discontinuous blebs (Figure 13). Rooting and subaerial drying indicate a shallow and variable water depth. On the basis of the sequence of sediments, the interchannel basin and the abandoned subdelta both seem to be possible environments for the deposition of the main lignite seam. Rooting, burrowing, subaerial drying, and rapid deposition are possible in both environments. In the interchannel basin subsidence may exceed the growth of vegetation and a lake may form. The vertical sequence in the lake could consist of poorly stratified clays deposited below the wave base followed by discontinuous silt-clay laminae, then muds (Visher, 1965). Variations in the level of the lake could account for rooting and subaerial drying. Upper lignites in the sequence are less extensive and thinner due to the influence of meandering channels which entered the area after the deposition of the main lignite.

At least two sequences may follow peat deposition on an abandoned subdelta, a marine transgression or a new crevasse splay. In the case of a marine transgression, the expected vertical sequence is sand or silt laminae followed by marine muds with bioturbation being very common. This is an unlikely sequence, since it is not observed in the highwall. The alternative is deposition of crevasse splay deposits

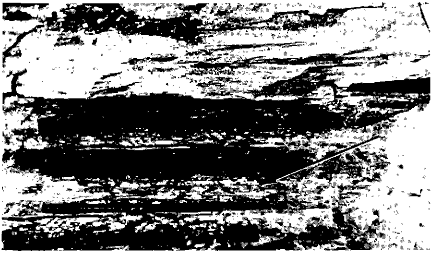

FIGURE 12. Blebs of silt-clay laminae (arrow) above the main lignite seam. Note the parallel laminations within the blebs and the recurring cycle of deposition. The pen is 6 in. long.

FIGURE 13. Bioturbated silty clay above the upper lignite in Geologic Section 1. Note the burrow (arrow), which is about 1-1/2 in. long.

over the subsiding subdelta. This would be a coarsening upward sequence formed by meandering distributaries. A principal problem with this interpretation is that meandering distributaries contemporaneous with the immediate post-lignite deposition are not seen in the long outcrop. On the basis of the sediments associated with the main Calvert Bluff lignite seam at Alcoa, the interchannel basin is the most likely environment of deposition for the main seam.

Following deposition of the main lignite seam and its overlying lacustrine deposits, the character of sedimentation changes greatly. This is reflected by the three major channel deposits which are exposed in the operating mine, one each at the extreme north and south ends of the pit, and one approximately in the middle. These deposits are approximately 50 ft thick, up to 200 ft wide, and exhibit crossbeds up to 10 ft thick. The channels postdate the main lignite seam and its immediately overlying sediments, and are contemporaneous with later deposition. For example, the sands in the lower part of Section 3 (Figure 9, p. 20) appear to be related to the southern channel (Figure 14). The sands in Section 1 (Figure 7, p. 18) are overbank and levee deposits related to the middle channel which is located approximately 500 ft northwest of the section. The northern channel deposit lies unconformably over the lignite (Figures 15 and 16). Minor channels up to 50 ft wide and 10 ft thick are also noticeable in the pit as areas of seepage (Figure 17). Lignite seams deposited contemporaneously with the channels are thinner and less continuous than the main seam due to the unstable environment of the channels.

FIGURE 14. Channel sands with crossbeds at the south end of the main pit. For scale, the line is 25 ft.

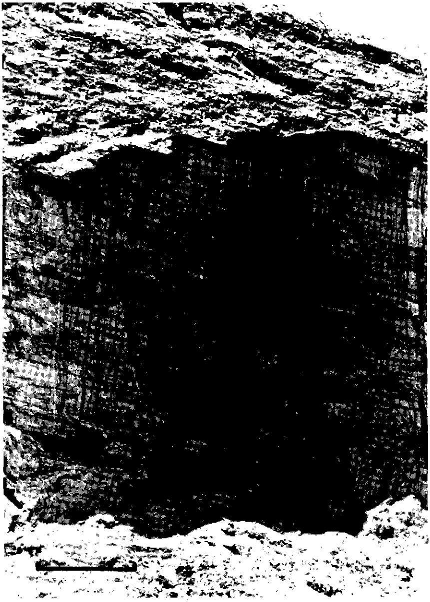

FIGURE 15. Channel sands at the north end of the pit. For scale, the line is ten ft.

FIGURE 16. Unconformable contact (arrow) of the northern channel and the lignite. For scale, the picture is about 8 ft wide.

FIGURE 17. Minor exposed channel showing seepage into the pit. Striations are due to the dragline and are not large crossbeds. The scale bar is 20 ft.

Clay Analysis

The bulk clay mineralogy of four samples was determined using the x-ray diffraction technique (Table 2). For each sample, two fractions were x-rayed, one a powder mount of the whole sample, the other a slide of the clay fraction (<2 microns). The clay fraction was obtained by sedimentation. It was magnesium saturated, poured on a slide, and allowed to equilibrate with ethylene glycol. It was then x-rayed, heated to 300° C, x-rayed, heated to 550° C, then x-rayed a final time. Two slides were made of the sand, one a sample of the whole sand, since there was very little material in the clay fraction. The dominant minerals present in the samples were smectite, kaolinite, quartz, mica, chlorite, feldspar, and vermiculite (Table 2).

Summary of Geologic Results

Based on the geologic investigation of the Alcoa lignite mine, the following conclusions are considered justified:

1) The Calvert Bluff lignites at Alcoa were deposited in an interchannel basin position on the upper part of the delta. This position is indicated by the palynology and composition of the lignites, the mapping of the associated subsurface sands, and the sequence of sediments accompanying the lignite.
2) The depositional cycle consists of a marsh followed by development of a lake, which is then filled in with muds and silt-clay laminae. This infilling is followed by

TABLE 2. Mineralogy of selected samples as determined from the relative intensities of principle peaks.

Sample	Smectite (percent)	Mica (percent)	Quartz (percent)	Kaolinite (percent)	Chlorite (percent)	Other (percent)
1-u	45	7	16	27	5	0
16-A	55	4	16	20	5	0
2-u	17	9	45	29	0	0
Sand < 2 um	67	0	13	20	0	0
Sand	21	5	10	56	3	4*/5**
Houma	52	8	29	11	0	0

* Feldspar

** Vermiculite

development of another marsh. Lignite deposits are the result of the organic accumulation in the marsh.

3) The development of lignites deposited after the main seam at Alcoa was influenced by the presence of channels crossing the area. As a result, these lignites are thinner and less continuous than the main seam, and the accompanying sediments are coarser grained.

ENGINEERING INVESTIGATION

Present Status

Considerable literature already exists on the subject of mine-land reclamation. The mining industry is concerned about such topics as: government regulation, reclamation efficiency, ameliorating the effects of mining on the environment, and the reestablishment of vegetation on mined land. Papers on topics such as improving reclamation potential by using better mining techniques in order to minimize cost and maximize coal extraction (Saperstein and Secor, 1973); the problem of revegetation on toxic soils (Sutton, 1973); the use of sewage sludge for improving plant growth (Schulze, 1973); the environmental impact of mining on water quality and groundwater movement (Pennington, 1975); preventing stream sedimentation (McCarthy, 1973); and many others are to be found in the literature.

Some idea of the direction of research effort and interests may be gained by looking at the 100 papers presented at the three Research and Applied Technology Symposiums on Mined-Land Reclamation (1973, 1974, 1975). The papers may be separated into six categories: soil development-revegetation, economics and methods of mining and reclamation, hydrologic studies, planning -management, case histories, and the relation of surface mining to governmental agencies and regulations. Thirty-two percent of all papers fall into the soil-revegetation category with many others making at least some mention of revegetation. Economics and methods of mining and reclamation, the second most common category, accounted for 18 percent. Planning-management of mining and reclamation accounts for 12 percent, and government regulation and its relation to mining accounts for 9 percent. No papers dealt with the problem of the settlement of mined land or with the densification of spoil piles.

Research into the problem of densification has been of limited extent for several reasons. Much reclaimed land has been used solely for agricultural purposes or is held and owned by the mining company, so the problem of building structures has not occurred. Any theoretical approach to the problem of predicting densification is hampered by mathematical complexities. In addition, laboratory tests are hard to perform due to difficulties in measurement of pore water and pore air pressures. Despite those difficulties, the study of settlement characteristics of reclaimed land is of significance if Senate Bill #55, calling for reestablishment of "natural conditions consistent with the anticipated subsequent use of the affected land," is to be satisfied.

A few studies have dealt with the settlement of reclaimed land. Limited measurement of settlement rates have been done in the field in England, where it was found that most measurable settlement occurred within the first five years after reclamation (Mathewson, personal communication). Reconnaissance laboratory work done by Clary and Mathewson (1975) indicates that a 100 ft thickness of disturbed overburden could be expected to settle 3.5 ft in 2 to 5 years and 2.5 ft over the next 30,000 years. These indications are encouraging because if they can be proven and documented then it may be possible to place structures on reclaimed land soon after reclamation. Clary (1975) emphasized the need for field and differential settlement investigations to verify his results.

In order to better understand the process and theory of densification, it is necessary to review the literature on consolidation and "Consolidation Theory."

The decrease in volume of a soil mass, due to an increase in effective stress, by the squeezing out of pore fluids is defined as the process of consolidation. Terzaghis' (1943) development of the mathematical treatment of consolidation, "Consolidation Theory", marked the beginning of modern soil mechanics. The basic assumptions of the theory are complete saturation, small strains, the validity of the theory of effective stress, and the validity of Darcy's law. Consolidation theory has been well developed in many texts and papers, including Terzaghi (1943), Taylor (1948), Bishop and Henkel (1962), Crawford (1964), and Lambe and Whitman (1969). The theory is widely employed in engineering practice to predict the settlement of structures on saturated soils. If the actual settlement is compared with predicted settlement, it is generally found that the total amount of settlement is within reasonable agreement, but the rate of settlement may vary widely.

Partially saturated soils have also received a great deal of study since troublesome soils have caused extensive, costly damage to roads and foundations, either by swelling (Mathewson, et al., 1975) or by collapse (Jennings and Knight, 1957). The movement of water in partially saturated soils is of great interest due to its role in swelling or collapse and has been studied theoretically (Lytton, 1969) and predicted numerically using the computer (Lytton and Kher, 1968). Computer methods for predicting swelling have been used with success in research efforts (Lytton and Watt, 1970). Swelling and collapse have also been predicted with some success using the double consolidometer test (Jennings, 1965). In general, partially saturated soils are more difficult to study than saturated soils since the partial differential equations relevant to partially saturated soils are more difficult to handle than those of Terzaghi's theory and experiments measuring both pore air and pore water pressures are difficult to perform.

The practicing engineer frequently avoids problems of settlement of partially saturated soils by artificially compacting the soil. As a result, much of the work done on partially saturated soils has dealt with the consolidation of artificially compacted soils, which do not exhibit the classical consolidation curve on a log time-settlement plot. Instead when loaded, they show an initial compression followed by a creep process dependent on the viscosity of the soil skeleton. This behavoir has been described using Terzaghi's Theory, where it has been modeled as a linear Kelvin element, consisting of a spring and dashpot in parallel by Taylor (1948), and as non-linear Terzaghi Theory, where it has been modeled as a non-linear Kelvin element, consisting of a non-linear spring and non-linear dashpot in parallel by Barden (1965b). The permeability of partially saturated soils to air has been investigated by Yoshimi and Osterberg (1963) who found high air permeabilities in excess of 90 percent water saturation. No theory for predicting settlement on partially saturated soils is presently in wide use outside of the research community.

Material Investigation

Samples were collected from the pit at sites of described sections (Appendix A) for testing and classification purposes. The materials collected are uncemented sediments and can be referred to as rock in geologic terms or soil in engineering terms. To a geologist, soil most often connotes the weathered mineral material at the surface which supports plant life, while to the engineer a rock is something hard and lithified. To avoid confusion and to conform with the general literature, the materials studied will be referred to as soils, as used in the engineering sense of an unlithified mineral aggregate. Testing included the determination of natural moisture contents, Atterberg limits, specific gravity, and the degree of consolidation.

The Atterberg limits (Lambe, 1951) were determined for samples containing greater than 12 percent material passing the 200 sieve, and were used to determine the classification according to the Unified Classification System. The results (Table 3, Figure 18) show most of the soils may be classified as CL or CH, with several being classified as ML, MH, or SW-SM. The relations of the soil type to the stratigraphy is shown in Figures 7, 8 and 9 (pages 18, 19 and 20).

Fresh samples were weighed in the field, then dried overnight in an oven at 110° C in order to determine the natural moisture content. The results (Table 3, Figure 19) indicate the majority of the soils are dry of their plastic limit.

Specific gravity measurements were obtained by two methods, direct measurement (Lambe, 1951) and by indirect calculation from the shrinkage limit data. Except for sample 2-u, the specific gravity is in the

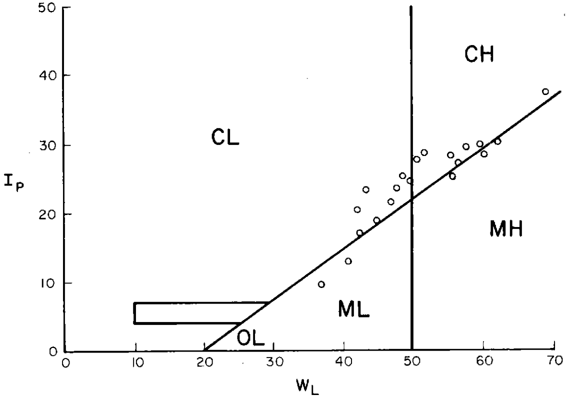

FIGURE 18. Plasticity index, I_p - liquid limit, w_l, relationship for the analyzed soils. The relationship of these two variables allows the soils to be classified according to the Unified Classification System as inorganic clays, C, as inorganic silts, M, or as organic soils, O. The soils are also classified as high compressibility, H, or low compressibility, C. Thus a highly plastic inorganic clay would be classified as CH.

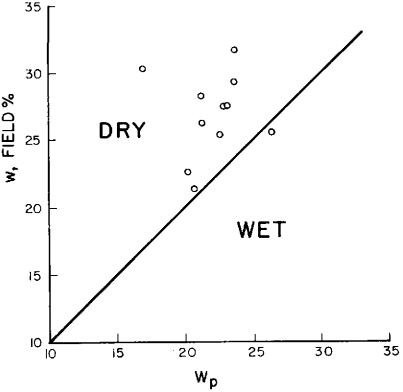

FIGURE 19. Natural moisture content, w, compared to the plastic limit, w_p.

TABLE 3. Material properties of analyzed soils.

Sample	Atterberg Limits (percent)				Unified Class.	Natural Moisture Content	Specific Gravity *	Specific Gravity **	Field Density (pcf)
	LL	PL	PI	SL					
Houma	63.7	22.9	40.8	-	CH	-	-	2.69	-
1-u	44.8	26.1	18.7	19.5	CL	21.4	2.53	-	-
2-u	59.8	29.8	30.0	6.1	CH	-	2.27	-	127.3
4-u	40.8	27.9	12.9	-	ML	18.7	-	2.46	125.0
5-u	59.9	31.7	28.2	-	MH	22.3	-	2.45	-
6-u	56.4	29.3	27.1	-	CH	23.7	-	2.70	116.9
A-2	49.8	25.6	24.6	22.7	CL	26.4	2.53	-	103.4
A-3	55.6	27.4	28.2	20.3	CH	21.4	2.52	-	-
A-4	69.2	31.8	37.4	-	CH	23.7	-	-	-
A-5	42.2	25.4	16.8	-	CL	22.6	-	-	-
A-6	42.0	21.5	20.5	-	CL	20.8	-	-	-
A-7	36.8	27.4	9.4	-	ML	23.0	-	-	-
A-8	55.6	30.3	25.3	-	MH	17.0	-	-	-
A-9	50.6	22.7	27.9	-	CH	20.1	-	-	-
A-10	-	-	-	-	SW-SM	-	-	-	-
A-11	57.5	27.7	29.8	-	CH	23.1	-	-	-
A-12	62.2	32.1	30.1	-	MH	-	-	-	-
A-13	-	-	-	-	SW-SM	-	-	-	-
A-14	27.8	24.3	23.5	17.9	CL	-	2.56	-	-
A-15	43.4	20.0	23.4	15.3	CL	-	2.51	-	-
A-16	48.4	23.0	25.4	-	CL	-	-	-	-
A-17	-	-	-	-	SW-SM	-	-	-	-
A-22	51.4	22.6	28.8	-	CH	-	-	-	-
A-23	-	-	-	-	SW-SM	-	-	-	96.1
A-25	46.8	25.3	21.5	-	CL	-	-	-	-
Reclaimed Land	-	-	-	-		-	-	-	96.0

* Calculated from shrinkage limit.

** Measured with pycnometer

range of 2.45 to 2.70. Sample 2-u has a calculated value of 2.27, which is probably too low due to an inaccurate shrinkage limit.

Two undisturbed soil samples, 2-u, 4-u, were tested in the consolidometer to determine the maximum precompression pressure (Lambe, 1951). Under the maximum pressure obtainable with the consolidometer used, the two soils appear to be entirely on their recompression curves. An estimate of the maximum precompression is on the order of 25 to 30 tsf. Present maximum overburden pressure is on the order of 5 to 6 tsf, so the soils are highly overconsolidated. This is also indicated by the fissured nature of the clays as well as by their low moisture contents.

Bulk density measurements at natural moisture contents were calculated for the two undisturbed specimens. Bulk density values for four additional samples were obtained by driving thin-walled sampling tubes. Values of bulk density ranged from 96 to 127 lb/ft^3 (Table 3).

As discussed earlier, the mineralogy of selected samples from the Alcoa mine was determined using x-ray diffraction (Table 2). In addition, a sample of the Houma soil was tested in order to compare it to the Alcoa soils. As seen in the results (Table 2, p. 29) it closely resembles some of the Alcoa samples.

Laboratory Testing

Procedure

Laboratory testing is designed to simulate the mining process and thus allows the prediction of the amount and rate of settlement to be expected in the field. In the mining process, the soil is first broken up by the action of the dragline into lumps ranging in size from sand size to more than a yard in diameter. These are deposited in a pile, and loaded as the height of the pile is increased (Figure 20). The soil is again loaded as the next pile in line is dumped, then again as the next line of piles is dumped. Finally, the upper part of the spoil pile is artificially compacted by the action of the bulldozer reshaping the soil during reclamation. Water may be added to the soil either from surface infiltration of precipitation, or by a rise in the groundwater table. Water aids in the redensification process, as evidence in Figure 21, where circumferential cracks formed around a puddle of water due to a difference in rates of redensification caused by the downward movement of water.

In the lab, the process of mining is simulated by grating a clod of soil through a cheesegrater (Figure 22). The grated soil is placed in a consolidometer at natural moisture content, then loaded either incrementally or by a single load. At some time during loading, water may be added to the soil to attempt to saturate it.

Two different sequences of loading and wetting were used on the grated samples. In the first sequence, the sample was cheesegrated and placed in the consolidometer with the arrangement shown in Figure 23. The top piece of aluminum foil was intended to prevent excessive drying. It was then loaded incrementally with $\Delta\sigma/\sigma=1$, starting at $\sigma=0.1$ tsf. The success of the aluminum foil in preventing drying during the seven day test may be seen by comparing initial and final water contents of the grated, multiple load samples (Table 4). A second series of tests conducted on the grated samples started with

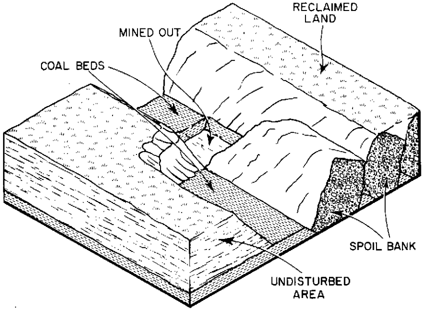

FIGURE 20. Block diagram of the mining process showing unmined area, open pit, spoil banks, and reclaimed land.

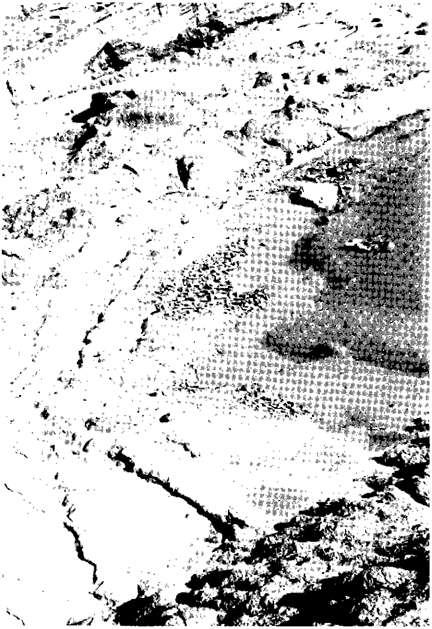

FIGURE 21. Circumferential cracks formed around the edges of a puddle of water due to differential redensification.

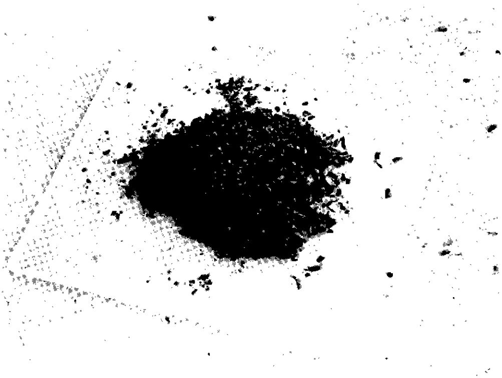

FIGURE 22. Soil as it appears after cheesegrating. Grated pieces are up to 0.2 in. long.

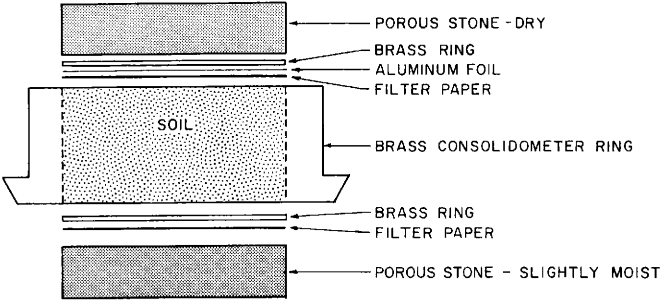

FIGURE 23. Consolidometer arrangement used for grated samples to prevent excessive drying.

TABLE 4. Moisture contents of samples tested in the consolidometer.

Sample	Moisture Content, Percent	
	Beginning	End
Houma, remolded, 3.2 tsf	63.0	34.0
Houma, remolded, 6.4 tsf	63.0	29.6
Houma, remolded, 12.8 tsf	63.0	23.8
Houma, remolded, 25.6 tsf	63.0	23.8
Houma, grated, 3.2 tsf	34.0	29.6
Houma, grated, 6.4 tsf	29.6	27.8
Houma, grated, 12.8 tsf	23.8	25.1
Houma, grated, 25.6 tsf	22.3	21.5
2-u, remolded	59.0	25.7
2-u, undisturbed	20.1	17.3
2-u, grated, multiple load	20.1	23.2
4-u, undisturbed	21.0	23.8
4-u, remolded	44.7	23.3
4-u, grated, multiple load	18.1	18.3
4-u, grated, 1.6 tsf single load	15.6	33.2
4-u, grated, 3.2 tsf single load	15.6	31.0
4-u, grated, 6.4 tsf single load	15.6	30.3
5-u, remolded	56.2	25.8
5-u, grated, multiple load	21.9	22.8
5-u, grated, 1.6 tsf single load	21.8	35.8
5-u, grated, 4.8 tsf single load	21.8	30.5
6-u, remolded	55.6	28.0
6-u, grated, multiple load	23.8	20.3
6-u, grated, 1.6 tsf single load	20.1	34.6
6-u, grated, 4.8 tsf single load	22.6	27.7

the same initial configuration (Figure 23, p. 44) but the loading sequence was changed from incremental loading to application of a single load, again under natural moisture content conditions. Two or more samples of the same soil were loaded to different pressures in order to be able to draw an e-log p (void ratio vs log pressure) curve. After three days when settlement had slowed, water was added from the bottom. The samples were then allowed to settle two more days. The result consists of single load unsaturated and saturated e-log p curves.

Testing of Houma

In order to evaluate problems involved with this procedure, it was desired to test a soil of known properties and consolidation history. An air dried sample of the Houma soil, which closely resembles some of the Alcoa soils, was obtained. Distilled water was added to bring the soil to approximately the liquid limit and four standard remolded consolidation tests (Lambe, 1951) were run, each up to a different maximum pressure of 3.2, 6.4, 12.8. or 25.6 tsf. The resulting remolded e-log p curve is shown in Figure 24. After each sample reached the desired maximum load, it was removed from the consolidometer, grated, and returned to the consolidometer to be recompressed using incremental loading under natural moisture content conditions as previously discussed. The resulting e-log p curves are shown in Figure 24. Three of the four grated curves fall below the remolded virgin curve. It seems unreasonable that a grated disturbed soil should have a lower void ratio than the remolded curve at the same pressure, as the grated soil lumps not only have a void ratio approximately that of the

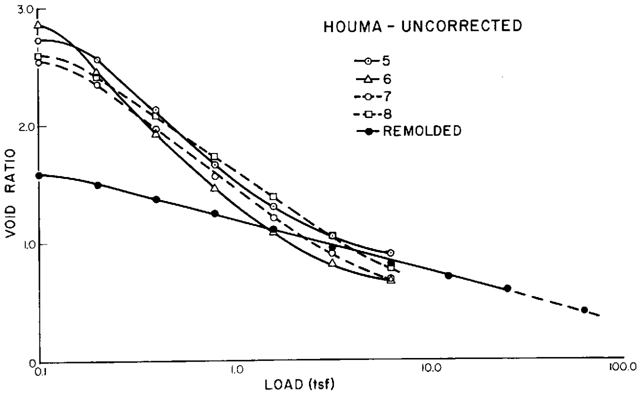

FIGURE 24. Uncorrected results of the consolidometer tests on the Houma soil. Samples 5, 6, 7 and 8 are grated multiple load samples. The remolded test was run on the original soil.

remolded soil, but the grated soil also has a macropore system, which should make for a larger total void ratio. This discrepancy may have been caused when the consolidometers were set up. Care was taken placing the consolidometers in the loading frames to ensure that the soil was not accidentally compacted before the first dial readings were taken. If the loading frame was not fully seated on the consolidometer, an initial error in dial reading may have occurred. An error of 0.03 inches would be sufficient to cause the observed discrepancy.

A method to correct such errors is desirable. Schmertmann (1953) showed that the undisturbed, remolded, and partially disturbed soils he studied all tend to the same void ratio at the value of approximately 0.42 e_o, where e_o is the actual void ratio in the field. It may be assumed at some pressure the disturbed (grated) and remolded curves will merge. It also appears reasonable for the grated soil to have a greater void ratio than the remolded soil, since it has both a macropore and a micropore system. In order to correct a grated curve, the grated curve is drawn to be asymptotic to a line parallel to the remolded curve. The difference in void ratio between the two lines is then added to all points on the grated curve. The results (Figure 25) show that grated samples with higher precompression pressures maintain higher void ratios at similar pressures. Apparently the more consolidated soil fragments can maintain a more rigid framework, allowing the macropore system to remain open.

The correction made for the Houma samples was necessary due to problems with the soil compacting during the initial consolidometer setup. It may be possible to avoid some of these problems if the grated

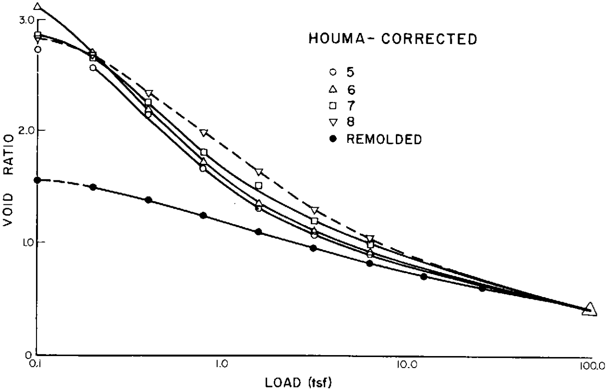

FIGURE 25. Corrected results of the consolidometer tests on the Houma soil. Samples 5, 6, 7 and 8 are grated multiple load samples. The remolded test was run on the original soil.

soil is more firmly packed into the consolidometer. This may be accomplished by lightly compacting the soil into the consolidometer ring to between 0.25 and 0.5 tsf.

The degree of saturation of the grated samples (Figure 26) may be calculated from the corrected void ratio (Figure 25, p. 49) and the initial water content (Table 4). The highest degree of saturation reached is 88 percent. This is important since Yoshimi and Osterberg (1963) report relatively high air permeabilities up to at least 90 percent saturation. For lower degrees of saturation, it may be assumed that pore water pressures remain negative, little or no water is squeezed from the soil, pore air pressures are low, and as a result most settlement is due to the creep of the soil skeleton.

Using the e-log p curves for the undisturbed (remolded) condition and the grated condition, it is possible to calculate the amount of "fluff" anticipated, "fluff" being the total volume increase of the soil after disturbance by grating (mining). One way to do this is to use the grated e-log p curve and the water content to calculate a bulk density-log p curve (Figure 27). From this curve it is possible to calculate a pressure-depth profile by using an initial density for the first five feet to calculate the pressure at five feet. This pressure is used with the density-log p curve (Figure 27) to obtain the density used for the next 5 ft. This process continues until the pressure equivalent to a 100 ft undisturbed section is reached. The thickness of the disturbed section is then compared to the undisturbed section of 100 ft of thickness to yield a percent fluff. For the example of the Houma precompressed to 3.2 tsf, fluff would be approximately 19 percent.

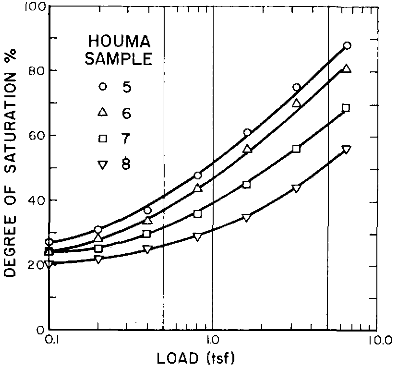

FIGURE 26. Degree of saturation of grated Houma soil samples as a function of load.

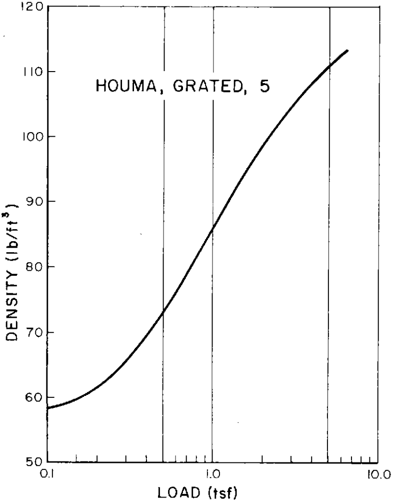

FIGURE 27. Bulk density as a function of load for grated Houma sample 5.

Testing of Alcoa Soil Samples

The next step in lab testing involved four samples collected from the study area. These were tested in the consolidometer using both single and multiple loadings, as remolded saturated samples, and in two cases as undisturbed samples. The results are shown in Figures 28 to 31. None of these soils appears to need a correction with the exception of the 4-u single load samples. These points are discarded as there does not seem to be a reasonable way to correct them.

Some general observations may be made from the data. In the case of single load samples compared to multiple load samples, single load samples reach a lower void ratio at comparable pressures. This may be due to an impact effect associated with the $\Delta\sigma/\sigma$ ratio. It would be expected for lower $\Delta\sigma/\sigma$ ratios, secondary creep would be more important (Barden, 1965a), but these effects might mot be seen during the short loading period used. The addition of water to an unsaturated soil in all tests causes a decrease in void ratio. This is due to the collapse of the soil structure as the capillary bridges between soil particles are released (Figure 32). The soil may collapse down to a void ratio that is smaller than that of the remolded soil, but greater than the undisturbed soil, as the overconsolidated soil packets collapse in on one another. This mechanism of capillary collapse differs from that of plastic deformation (Figure 33).

The degree of saturation for all samples under loadings expected in the field is less than 85 percent (Figure 34). This would indicate virtually no water will be expelled during initial redensification and that air will be free to be expelled. As a result the redensification

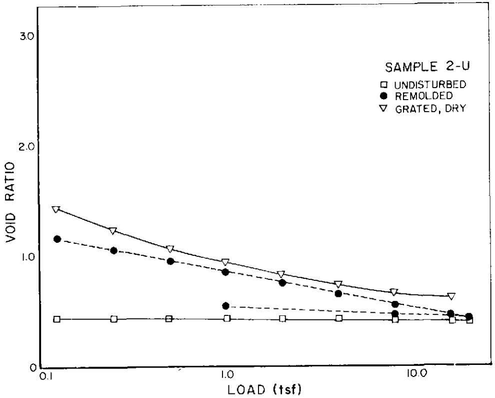

FIGURE 28. Void ratio-log p results of consolidometer testing for Alcoa soil 2-u.

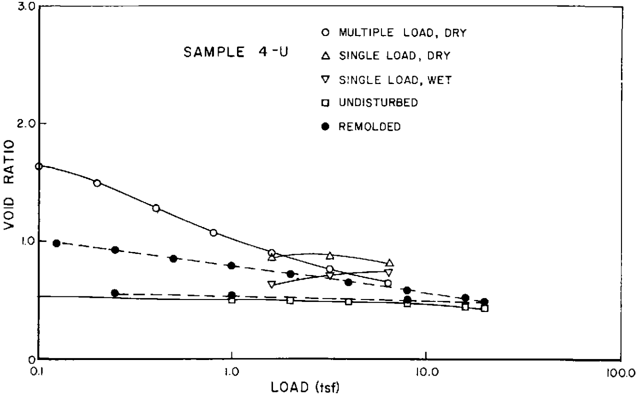

FIGURE 29. Void ratio-log p results of consolidometer testing for Alcoa soil 4-u.

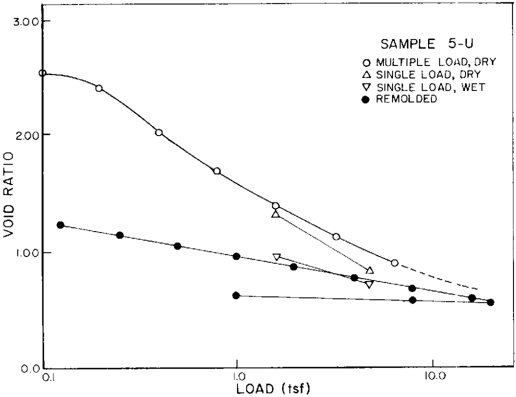

FIGURE 30. Void ratio-log p results of consolidometer testing for Alcoa soil 5-u.

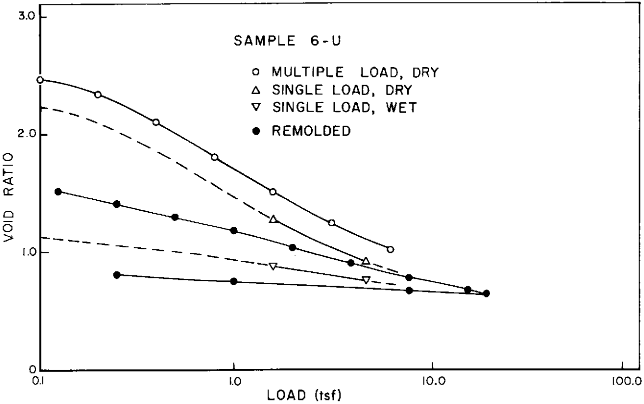

FIGURE 31. Void ratio-log p results of consolidometer testing for Alcoa soil 6-u.

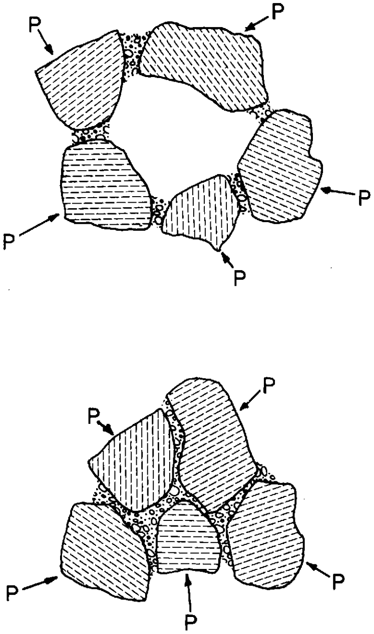

FIGURE 32. Diagrammatic sketch of soil collapse when soil moisture conditions change from unsaturated to saturated conditions. The soil particles remain essentially undeformed.

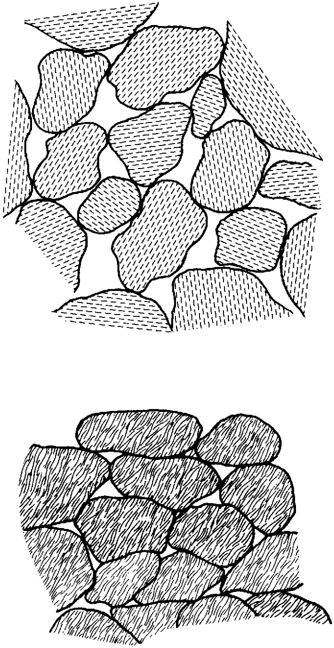

FIGURE 33. Diagrammatic sketch of soil densification due to aggregate deformation, in which the soil deforms and pore air is squeezed out without appreciable volume change of the aggregate.

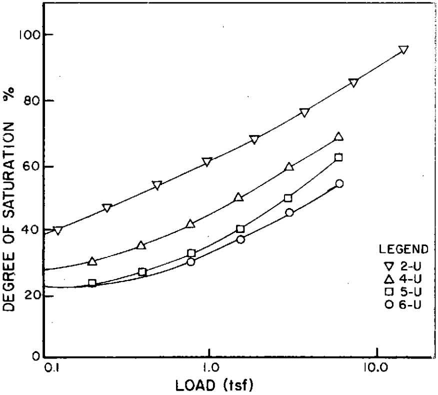

FIGURE 34. Degree of saturation as a function of load for multiple load, grated Alcoa soil samples.

process will initially be one of creep (Barden, 1965a).

An upper limit on the amount of fluff soon after mining may be calculated using the difference in void ration between the multiple load e-log p curve and the average undisturbed void ratio, as well as the bulk densities calculated from these curves. This is done in the way described for Houma sample 5 discussed previously. The results are shown in Table 5. The estimates of immediate fluff seem a bit high compared to some industry estimates of 20 percent for lightly overconsolidated sediments after reclamation. However, heavily consolidated shales have been estimated to fluff as much as 40 percent. Samples 5-u and 6-u give the highest fluff estimates to 45 and 47 percent. There are at least three possible explanations for those high values. They may represent maximum possible fluff values which are not found in the field due to greater compaction and redensification of the material caused by impact and vibration effects of dumping by the dragline. Another possibility is that the e-log p curves are inaccurate. This may be due to slight redensification of the soil in the consolidometer before the first dial reading could be taken. If the loose material settled by 0.03 to 0.04 inches, this would shift the e-log p curve up, making for a high fluff estimate. A third possibility is that the industry estimate may be lower than the lab fluff estimates because of the combined effects of the time between mining and reclamation and the influence of rainwater and groundwater on redensification.

From the fluff calculations, an estimate of the increase in volume of the soil shortly after mining is obtained. The next question is how much of the increase in volume is recoverable, i.e. what is the

TABLE 5. Immediate and ultimate fluff values for Alcoa soils.

Sample	Immediate Fluff (percent)	Ultimate Fluff Saturated (percent)	Ultimate Fluff Partly Saturated (percent)
2-u	30	---	---
4-u	24	10	7
5-u	45	23	15
6-u	47	16	11

ultimate state of the soil. From the lab tests, the single load, wetted samples have void ratios less than a completely remolded sample, but greater than the original undisturbed sample. This seems reasonable as an ultimate physical state of the soil. As a result, the single load, wet e-log p curves are used as a basis for calculating the permanent increase in volume. In order to use these calculations applying the principle of effective stress, groundwater conditions must be assumed. There are two end cases concerning groundwater: full saturation with the groundwater level at surface level, and complete unsaturation with the groundwater level below the depth of mining. In the case of full saturation, effective stress is less than overburden pressure. In a completely unsaturated soil, rainfall would be expected to slowly percolate through the soil. A single rainfall might cause a water profile as in Figure 35, where a 2 ft slug of water with positive pore water pressures percolates into the soil, followed by a 10 ft capillary "tail" having negative pore water pressures. In this case the greatest effective stress felt by the soil would be greater than the overburden stress. The results of both assumptions on ultimate redensification are shown in Table 5, p. 62.

An example of these effective stress calculations is given for sample 4-u. For the saturated condition, (Figure 36), the unit weights of the saturated soil are calculated using an estimated wet, single load e-log p curve, which is intermediate between the remolded and undisturbed curves. The first value of unit weight is used to calculate the total stress, σ, at 5 ft. The pore water pressure, u, is calculated using $u = 62.5\ (z)$ where z is the depth in ft. The effective

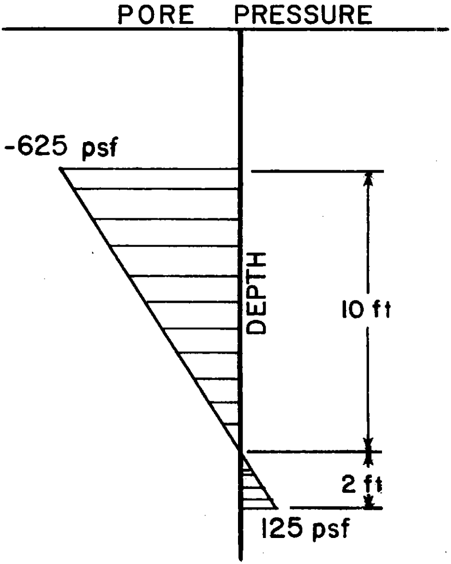

FIGURE 35. Water pressure profile caused by the infiltration of water through a partly saturated soil.

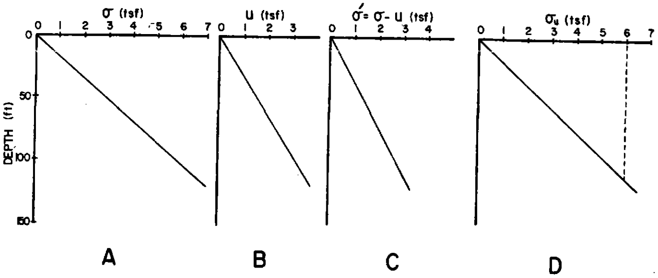

FIGURE 36. Profiles of total stress, σ, (A); water pressure, u, (B); effective stress, σ', (C); and equivalent unsaturated total stress, σ_u, (D); for soil sample 4-u, assuming saturated soil moisture conditions. The equivalent unsaturated total stress, σ_u, is calculated using unit weights derived from the single load, wet e-log p curve assuming natural moisture content. It is necessary for comparison to the initial total stress at the base of a 100 ft column of undisturbed overburden.

stress, $\sigma' = \sigma - u$, is then calculated and is used to obtain the next unit weight from the graph. In order to determine when the load reaches that equivalent to an initial 100 ft section, a density-log p curve assuming the wet, single load void ratio but the natural water content is used. Whenever a unit weight is read for the saturated soil, one is read for the unsaturated condition. These values are used to calculate the unsaturated pressure, which at some depth is the same as that of the initial 100 ft undisturbed section. This depth is used to calculate the ultimate fluff.

A similar procedure is used to calculate ultimate fluff for the unsaturated condition (Figure 37). The primary changes are that the load corresponding to the initial overburden is found directly, and that a maximum negative pore water pressure of -0.31 tsf is assumed for all depths.

The results of the fluff calculations are shown in Table 5, p. 62. A one hundred ft undisturbed section of sample 4-u could be expected to expand to 124 ft as a result of mining. With the addition of water, the ultimate height could be expected to fall to between 110 and 107 ft, for an eventual settlement of 14 to 17 ft. The values of initial fluff for the other soils range up to 47 percent. The ultimate fluff ranges from 10-23 ft for completely saturated groundwater conditions to 7-15 ft for completely unsaturated groundwater conditions.

The amount of settlement in the field could be estimated from the slopes of the dial reading - log time curves for the single load, dry samples (Figure 38). These values are calculated in ft per 100 ft of disturbed section (Table 6). The estimated average settlement for a

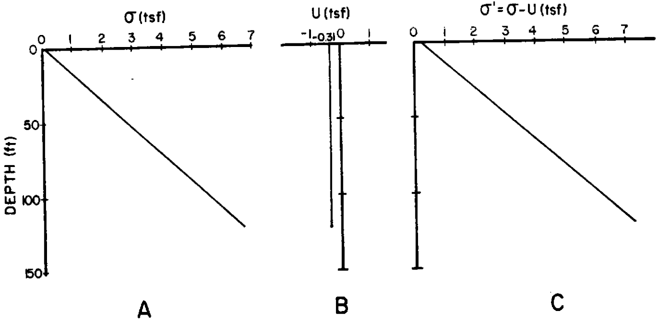

FIGURE 37. Profiles of total stress, σ, (A); water pressure, u, (B); and effecitve stress, σ', (C); for soil sample 4-u assuming unsaturated soil moisture conditions.

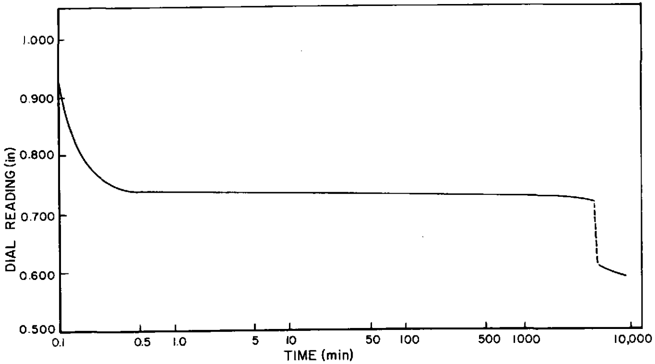

FIGURE 38. Typical dial reading-log time curve of a grated single load sample. The slope of the curve is used to estimate the rate of settlement in the field. Water was added at about 5000 minutes, causing the sudden break in the curve.

TABLE 6. Amount of settlement for a 100 ft disturbed section estimated from consolidometer tests.

Sample	Average Settlement (ft)	
	Between Year 1 and Year 2	Between Year 4 and Year 5
4-u, 1.6 tsf	0.357	0.115
4-u, 3,2 tsf	0.362	0.117
4-u, 6.4 tsf	0.372	0.120
5-u, 1.6 tsf	0.283	0.091
5-u, 4.8 tsf	1.441	0.464
6-u, 1.6 tsf	1.436	0.462
6-u, 4.8 tsf	0.905	0.291

100 ft section between time equals 1 year and time equals 2 years varies from 0.283 ft to 1.44 ft depending on the particular soil. Between year 4 and year 5, the average settlement declines to between 0.091 to 0.464 ft depending on soil type. These rates agree well with the measured field values.

Summary of Laboratory Results

The results of the laboratory testing may be summarized as follows:

1) Plots of the degree of saturation as a function of load indicate the grated samples all remain below 90 percent saturation at expected field loadings. Most samples are less than 80 percent saturated at maximum load. In this range of saturation:

(a) Virtually no water will be squeezed out as pore water pressures remain negative.

(b) Air permeabilities will remain high and as a result pore air pressures will remain low.

(c) Deformation of the soil will mostly depend on the creep of the soil skeleton which is dependent on the maximum precompression and the water content of the soil.

2) Tests on a grated incrementally loaded soil at natural moisture content indicated maximum initial values of fluff of between 24 and 27 percent.

3) If a grated sample is loaded with a single load, allowed to stabilize, then saturated, fluff for unsaturated hydrologic conditions is estimated at 7 to 15 percent. Fluff for saturated hydrologic conditions is estimated at 10 to 23 percent. These are considered estimates

of the amount of permanent fluff which will occur.

4) Estimates from single loaded grated samples at natural moisture content indicate the average amount of settlement for a 100 ft disturbed section between time equals 1 year and time equals 2 years varies from 0.283 to 1.44 ft depending on the soil type. Between year 4 and year 5 the average amount of settlement declines to between 0.091 to 0.464 ft, again depending on the soil type.

Field Study

Method

Settlement of reclaimed land was measured in order to determine the amount and rate of redensification and to determine short and long range differential settlement. This was accomplished by measuring elevation differences between stations using a level. The instrument used was a self leveling Nikon Autolevel, with a Philadelphia rod and target, and elevations could be read to 0.001 ft. Two kinds of elevation stations were established. Major elevation stations consist of four markers set in concrete poured into 3 ft deep, 6 in. diameter augered holes. Three of the markers are at the corners of an equilateral triangle measuring 15 ft on a side, the fourth is located in the center of the triangle. The center marker was used to measure total settlement and long distance differential settlement. It was also used as a reference for the short distance differential settlement of the three corner markers. Permanent turning points of 5/8 in. reinforcing bar driven 3 ft into the spoil were used as additional elevation stations. The locations of all stations of the main survey loop as well as the spoil pile are shown in Figure 39. The estimated time for mining of the land is also shown in Figure 39. In addition to the stations shown, a reference on unmined land and a major elevation station on land mined 10 years ago were established.

Elevations were measured in the main survey area by running a level line from the reference mark "R" set on unmined land out to major station "1", then back to "R" closing the loop. Each station was occupied twice, once on the way out, once on the way back. The closure between stations 350 ft apart was generally 0.010 ft. This makes the loop third order, third order leveling defined by $c=k\sqrt{m}$ where:

c = allowable closure, ft

k = constant

m = distance in miles

The USCGS sets the constant k at 0.017, 0.035, and 0.050 for the three orders of leveling, first, second, and third, respectively.

In order to measure the settlement of a fresh spoil pile, a different procedure was needed. Instead of a level, a one second theodolite was used to accurately measure angles. A target was driven into a fresh spoil pile, and reference marks for the theodolite were driven into land mined several months earlier. The reference marks were used to locate the theodolite, and the change in vertical angle of the target could be measured. Knowing the location of the theodolite as to height and horizontal distance, elevation changes on the spoil pile could be calculated. Angle measurements were off by as much as 10 seconds due mostly to thermal problems. As a result, elevation measurement was accurate to approximately ± 0.006 ft, a small fraction of the actual

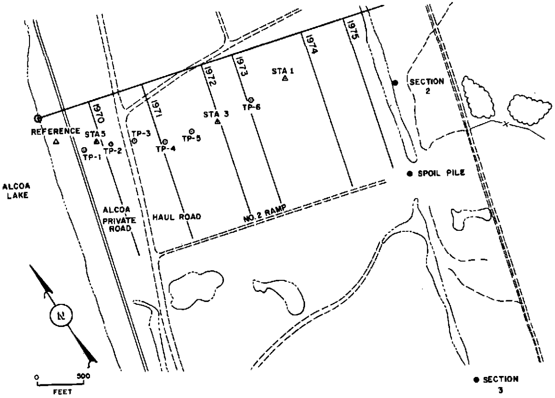

FIGURE 39. Map of the main survey area. Survey stations are shown as circles (turning points) and triangles (major stations). The yearly progression of mining is shown by the dated lines.

measured settlement.

Field Survey Results

The relative elevations of the survey stations to the reference mark for each survey are shown in Table 7. This data is shown as change in elevation from the January 12, 1976 survey in Table 8, Figure 40. The January 12 survey was chosen as a reference since it was the first survey to include all data points. With the exception of TP1, all stations subsided, with total settlement over 250 days ranging from 0.050 ft to 0.138 ft. Settlement as a function of time is shown for the three major stations in Figure 41. Regression analyses of settlement as a function of time were calculated for all the stations in an effort to fit the data to linear, log and exponential relationships. The fit of the data as measured by R^2 (Table 9) is virtually identical for all three relationships. This occurs because settlement has already been in progress at least 900 days for all stations except the spoil pile. This is far enough out in time so that a short duration of measurement, 250 days, the data appears to have a linear relationship even if it is really logarithmic or exponential. The rates of settlement based on the linear regression analyses range from 0.101 to 0.221 ft/yr with the exceptions of stations 10 and TP1. Stations 10 and TP1 both show slight swelling rates, 0.038 and 0.021 ft/yr respectively, based on the regression analysis. The R^2 values for both stations are rather low, especially for station 10, which does not appear to show any settlement at all within the error of measurement. Station TP1 may have been disturbed by service vehicles.

TABLE 7. Relative elevations of the survey stations to the reference mark for each survey.

Station	Relative Elevation, ft on Survey Date							
	Dec. 2	Jan. 12	Feb. 28	April 1	May 1	June 11	July 17	August 21
Ref	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000
TP1	-	110.840	110.852	110.855	110.861	110.853	-	-
STA5	108.930	108.924	108.910	108.906	108.891	108.850	108.830	108.823
TP2	-	97.953	97.934	97.931	97.914	97.873	97.861	97.850
TP3	-	99.540	99.535	99.526	99.518	99.496	99.492	99.490
TP4	-	104.575	104.548	104.529	104.511	104.473	104.461	104.445
TP5	-	112.537	112.513	112.510	112.479	112.449	112.437	112.420
STA3	119.954	119.977	119.953	119.950	119.926	119.913	119.903	119.887
TP6	-	121.680	121.634	121.642	121.599	121.592	121.586	121.568
STA1	123.238	123.262	123.193	123.218	123.171	123.158	123.144	123.124
STA10*	11.345	11.312	11.362	11.342	-	11.332	-	11.343

* Relative to 10 year reference.

TABLE 8. Changes in elevations of the survey stations relative to the January 12, 1976 survey and calculated rates of settlement.

Station	Change in Elevation from January 12, 1976 Survey (-ft)								
	Dec. 2	Jan. 12	Feb. 28	April 1	May 1	June 11	July 17	August 21	Settlement[+] Rate (-ft/yr)
Ref	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TP1	-	0.000	-0.012	-0.015	-0.012	-0.012	-	-	-0.038
STA5	-0.006	0.000	0.014	0.018	0.033	0.074	0.094	0.101	0.197
TP2	-	0.000	0.019	0.022	0.039	0.080	0.092	0.103	0.195
TP3	-	0.000	0.005	0.014	0.022	0.044	0.048	0.050	0.101
TP4	-	0.000	0.027	0.046	0.064	0.102	0.114	0.130	0.251
TP5	-	0.000	0.024	0.027	0.958	0.088	0.100	0.117	0.215
STA3	0.023	0.000	0.024	0.027	0.051	0.064	0.074	0.090	0.156
TP6	-	0.000	0.046	0.038	0.081	0.088	0.094	0.112	0.221
STA1	0.024	0.000	0.069	0.044	0.091	0.104	0.118	0.138	0.211
STA10*	-0.033	0.000	-0.050	-0.030	-	-0.020	-	-0.031	-0.021

* Measured relative to 10 year reference.

\+ Rate calculated using linear regression of data.

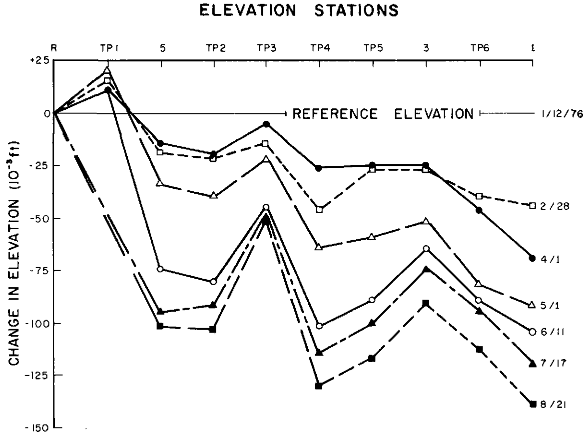

FIGURE 40. Change in elevation of the main survey line stations relative to the January 12, 1976 survey.

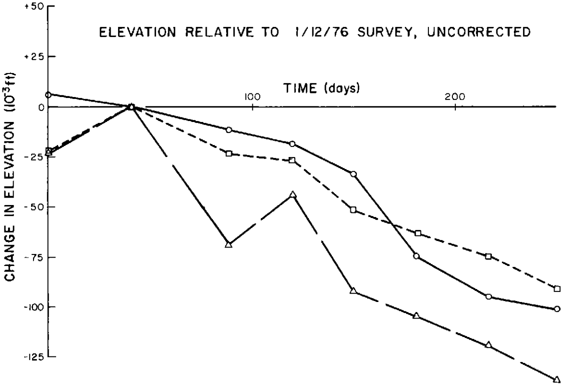

FIGURE 41. Change in elevation as a function of time for the major elevation stations relative to the January 12, 1976 survey. Major elevation station 1 is indicated by triangles, station 3 by circles, and station 5 by squares.

TABLE 9. Fit of the elevation data to linear, logarithmic, and exponential relationships as measured by R^2.

Station	R^2 Values for Regression Analyses			
	Linear	Exponential	Logarithmic	Logarithmic*
TP1	0.54	0.54	0.79	0.55
STA5	0.93	0.93	0.50	0.93
TP2	0.94	0.95	0.55	0.94
TP3	0.93	0.93	0.55	0.93
TP4	0.98	0.98	0.66	0.98
TP5	0.97	0.97	0.61	0.97
STA3	0.98	0.98	0.68	0.98
TP6	0.92	0.91	0.77	0.93
STA1	0.90	0.89	0.77	0.90
STA10	0.068	0.072	0.44	0.070
SP	0.40	0.44	0.67	0.67

* Time in regression is age of survey station plus time since start of surveys.

The major concrete stations 1, 3, 5 and 10 are more reliable as data points than the turning points. This is because the turning points are just three foot bars of steel rod driven with a sledge, and therefore are more susceptible to disturbance. Settlement at a station may also be affected by location, for example TP3, which may show less settlement because of its location near a haul road and in an area used to dump used furnace bricks.

Not all stations are located on disturbed overburden of the same initial thickness. An isopach map of depth to the top of lignite is shown in Figure 42 and used in order to estimate depth of undisturbed overburden at each station (Table 10). Using these depths, the amounts and rates of settlement are corrected to an initial 100 ft unmined overburden depth (Table 10). The results show rate values ranging from 0.260 ft/yr to 0.532 ft/yr for stations 2-1/2 to 6 years old. These estimates may be 50 percent or more too high, due to inaccuracies in determining actual depth of overburden and due to rearrangement of the surface contours while mining and reclaiming.

The results of the short distance differential settlement measurements are shown in Figures 43 to 47. As expected, the reference station is relatively stable with respect to its three elevation marks, with elevation changes varying from the center mark by only a maximum of 0.003 ft. The major stations on mined land showed more variation than the reference mark "R," with elevations changing by up to 0.017 ft.

The results of the spoil pile survey are shown in Figure 48. A log fit seems to best represent the initial settlement although even this fit is not excellent. Settlement rates were much affected by dragline

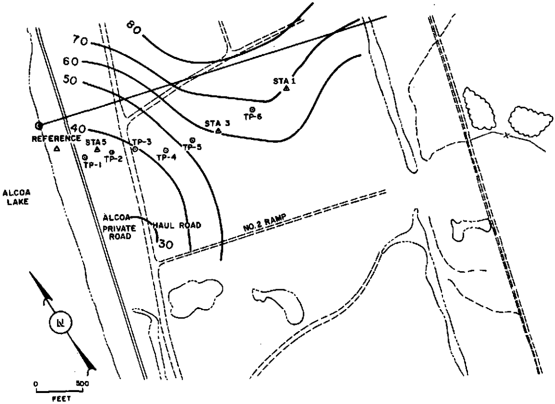

FIGURE 42. Isopach map of thickness in ft of overburden above the main lignite seam.

TABLE 10. Depth corrected amounts and rates of settlement of the survey stations. Correction is to an initial 100 ft overburden depth.

Station	Depth to Top of Lignite (ft)	Change in Elevation from Jan. 12, 1976 Survey, Corrected								Rate (-ft/yr)
		Dec. 2	Jan. 12	Feb. 28	April 1	May 1	June 11	July 17	Aug. 21	
Ref	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TP1	37	-	0.000	-0.932	-0.041	-0.057	-0.032	-	-	-0.101
STA5	37	-0.016	0.000	0.038	0.049	0.089	0.200	0.254	0.273	0.532
TP2	37	-	0.000	0.051	0.059	0.105	0.216	0.249	0.278	0.528
TP3	40	-	0.000	0.013	0.035	0.055	0.110	0.120	0.125	0.252
TP4	46	-	0.000	0.059	0.100	0.139	0.222	0.248	0.283	0.515
TP5	54	-	0.000	0.044	0.040	0.107	0.163	0.185	0.217	0.398
STA3	60	0.038	0.000	0.040	0.045	0.085	0.107	0.123	0.150	0.260
TP6	58	-	0.000	0.079	0.066	0.140	0.152	0.162	0.193	0.320
STA1	58	0.041	0.000	0.119	0.076	0.157	0.179	0.203	0.238	0.381
STA10*	72	-0.046	0.000	-0.069	-0.042	-	-0.028	-0.043	-	-0.029

* Relative to 10 year reference.

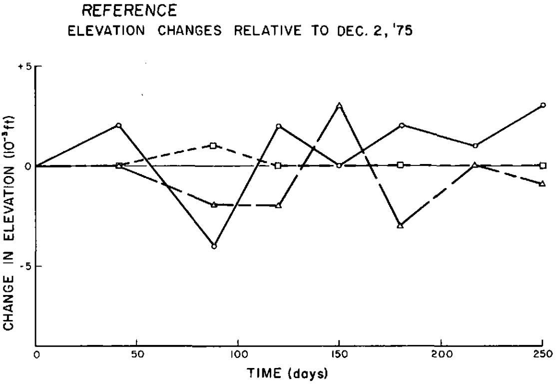

FIGURE 43. Changes in elevation of secondary elevation stations relative to the central elevation station as a function of time for major station "R". The secondary elevation station R_1 is indicated by circles, station R_2 by squares, and station R_3 by triangles.

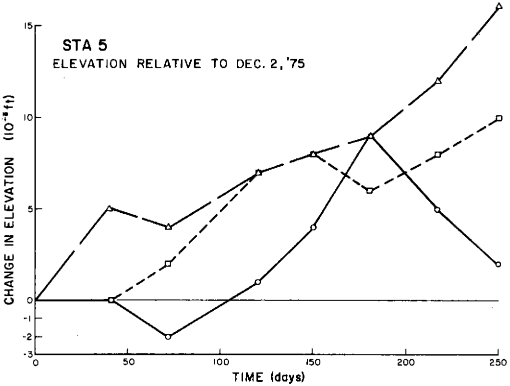

FIGURE 44. Changes in elevation of secondary elevation stations relative to the central elevation station as a function of time for major station "5". The secondary elevation station A is indicated by circles, station B by squares, and station C by triangles.

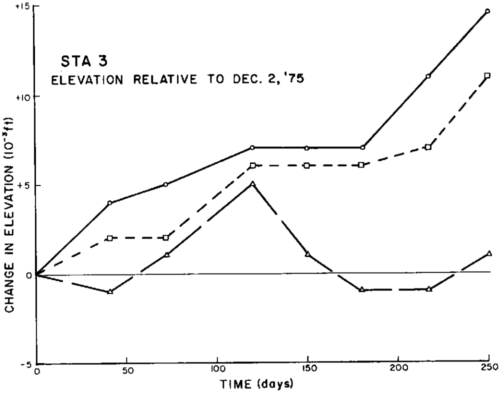

FIGURE 45. Changes in elevation of secondary elevation stations relative to the central elevation station as a function of time for major station "3". The secondary elevation station A is indicated by circles, station B by squares, and station C by triangles.

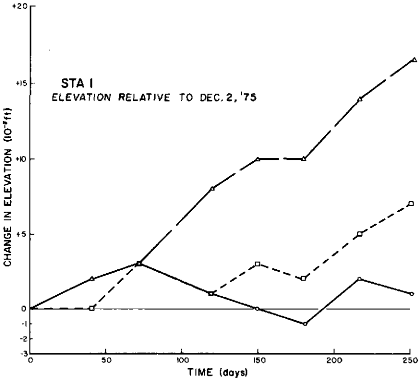

FIGURE 46. Changes in elevation of secondary elevation stations relative to the central elevation station as a function of time for major station "1". The secondary elevation station A is indicated by circles, station B by squares, and station C by triangles.

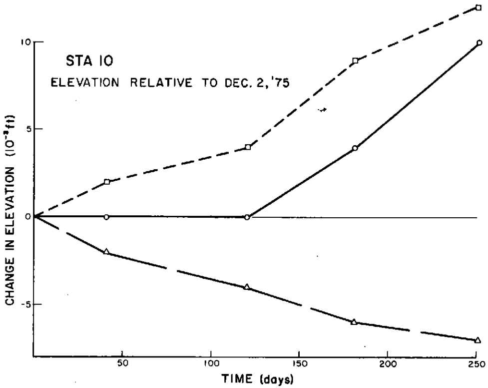

FIGURE 47. Changes in elevation of secondary elevation stations relative to the central elevation station as a function of time for major station "10". The secondary elevation station A is indicated by circles, station B by squares, and station C by triangles.

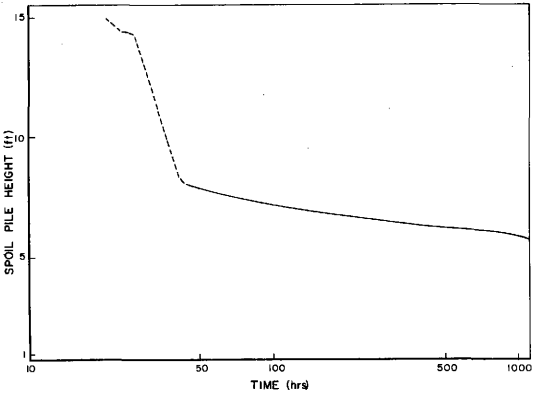

FIGURE 48. Relative height of the spoil pile as a function of the time since dumping.

operations, with the fastest settlement occurring as material was dumped on adjacent piles. This is due both to the influence of additional loading and vibration. Rate estimates obtained from the spoil pile measurements range from 312 to 8 ft/yr for a spoil pile 1 to 20 days old.

Using the ages of the stations and the rates of settlement calculated, it is possible to plot the rate of settlement as a function of age, Figure 49, Table 11. This seems to verify Clary and Mathewson's (1975) conclusion that initial settlement is very fast, but the rate and amount decrease very soon after disturbance.

The area under a linear plot of rate vs. time is a measurement of the settlement which might be expected. This has been calculated on the basis of a section 125 ft thick immediately after mining, and the result plotted in Figure 50. Assuming the ultimate settlement will be a total of 15 ft from 125 to 110 ft which seems reasonable from the lab results, a plot of percent expected settlement as a function of time may be constructed. From the plot, it is estimated that 75 percent of the expected settlement will occur within one year after mining, 80 percent within five years, and most of the remainder over the next 1000 years.

Summary of Results, Field Study

The results of the field study may be summarized as follows:

1) A freshly dumped spoil pile settles very fast, at rates of -312 to -8 ft/yr during the first 20 days. These rates decrease very quickly, and range from -0.221 to +0.029 ft/yr within 2-1/2 to 10 years after mining.

2) The amount of settlement occurring as calculated from the rates

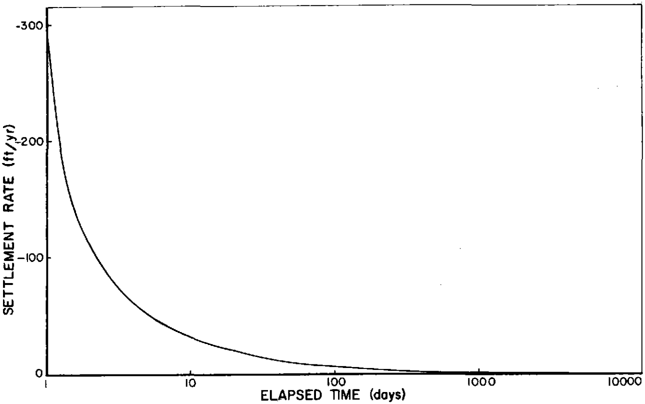

FIGURE 49. Rate of settlement of redensifying soil as a function of time since mining for an original 100 ft undisturbed section.

TABLE 11. Rate of settlement as a function of time since mining.

Station	Age (days)	Rate of Settlement* (ft/yr)	Rate of Settlement+ (ft/yr)
SP	1	312	312
SP	2	26	26
SP	2.1	81	81
SP	3.5	88	88
SP	18.5	8	8
STA1	900	0.381	0.211
STA3	1500	0.260	0.156
STA5	2200	0.532	0.197
STA10	3600	-0.02	-0.021

* Corrected to 100 ft section

\+ Uncorrected

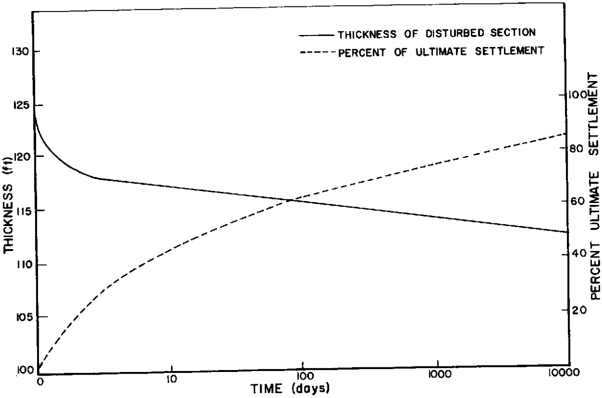

FIGURE 50. Thickness of a disturbed section and the percent of ultimate settlement recovered as functions of time since disturbance for an initial 100 ft undisturbed section.

indicates 75 percent of all settlement will occur in the first year after mining, 80 percent within the first 5 years, with most of the remainder over the next 1000 years.

3) Level measurements indicate differential settlement of up to 0.100 ft/yr over a 350 ft distance for land 2-1/2 to 6 years old.

4) Differential settlement would be greatest in the case of unmined land adjacent to mined land, where rates may exceed 0.200 ft/yr over a short distance.

5) Differential settlement over short distances of 10 to 15 ft on mined land indicates rates of up to 0.020 ft/yr.

Conclusions

Based on the laboratory testing and field measurements, the following conclusions are considered justified:

1) The initial redensification of the disturbed soil is due mainly to the creep of the soil skeleton, which is dependent on the degree of precompression and water content. The rate and amount of redensification may both be increased if water is added to an unsaturated soil.

2) Fluff immediately after mining, as estimated from lab tests, ranges from 24 to 47 percent, and probably represents an upper limit.

3) The soil will not return to its initial thickness, as indicated by the lab tests. The amount of recovery is dependent on the hydrologic conditions present.

4) Redensification at first proceeds very rapidly, then slows down. Measured rates range from -312 at one day after mining to +0.029

ft/yr 10 years after mining. Approximately 75 percent of the expected settlement will occur in the first year after mining, 80 percent within five years, with most of the rest occurring over the next 1000 years.

5) Differential settlement over distances of 350 ft or more is on the order of 0.100 ft/yr for land 2-1/2 to 6 years after disturbance. Differential settlement on mined land over distances of 10 to 15 ft is on the order of 0.020 ft/yr.

6) Differential settlement has the potential to create a problem in at least two instances. If a rigid structure is built on the dividing line between unmined and mined land, differential settlement may exceed 0.200 ft/yr over a short distance. The other problem of differential settlement may occur if it is found that changes in soil moisture associated with the construction of roads or foundations increase the rate of redensification. This problem needs to be investigated.

7) The laboratory method employed gives rate estimates surprisingly close to the field values for most cases. Maximum fluff values are about twice the expected field values, but ultimate fluff estimates appear realistic.

SUMMARY AND IMPLICATIONS OF THIS STUDY

Surface mining is disturbing ever greater areas in Texas as lignite and uranium are exploited to fill energy needs. Reclamation of this disturbed land is required by state law in order to prevent adverse effects to the environment and to society. As a result, mine operators have spent much money on reclamation studies, most of which have investigated method, economic or revegetation problems. A less easily observable, more hidden problem of reclaimed land has not been widely studied; the problem of settlement. Settlement has been overlooked since it occurs slowly and is unnoticeable in open country. Settlement may only become noticeable if rigid structures such as houses or roads are built on differentially settling land, in which case differential movement may cause structural damage. This problem has not been common since reclaimed land is usually used at most for agricultural purposes and is not developed for housing. Knowledge of the settlement characteristics is important if rigid structures are to be built on reclaimed land.

The problem of redensification and settlement was investigated using both laboratory simulation of mining and measurements of the amount and rate of settlement at the Alcoa lignite mine near Rockdale. Laboratory testing using the consolidometer indicates that immediately after mining the overburden may be fluffed as much as 40 percent of its initial thickness. Not all of this initial fluff is recovered as the soil redensifies over time, and the soil remains permanently fluffed by between 7 and 15 percent of its initial thickness. Rates of redensification determined by field measurement of settlement vary with time since mining, much in the manner predicted by Clary and Mathewson, being very high for a fresh spoil pile but rapidly declining as the time since mining increases (Figure 49, p. 90). Reclaimed land a few years old settles at rates between 0.100 and 0.200 ft/yr while land 10 years old shows virtually no settlement. Differential settlement, which is more important to the stability of rigid structures than total settlement, is on the order of 0.100 ft/yr over distances of 350 ft for reclaimed land a few years old. Over shorter distances of 10 ft, differential settlement is as high as 0.020 ft/yr.

These results are not applicable everywhere. Whatever the nature of the disturbed overburden, it would be expected to fluff and redensify, but the amount and rate of settlement will depend on the material disturbed. The materials in the study area are roughly 60 percent overconsolidated clays and 40 percent fine sands. If an area has mostly sandy overburden it will behave differently, most likely having less initial fluff and having most settlement occurring soon after mining. The hydrology of the mine area is important both to the amount and rate of settlement. In most of east central Texas the groundwater table is within about 20 ft of the surface. The groundwater level is depressed during mining due to pumping, then slowly returns to normal after mining (Figure 51). The presence of water will tend to decrease the ultimate settlement, but the rate of settlement may temporarily increase as the overburden is wet by the rising groundwater level. If a mine is very wet or very dry different amounts and rates of settlement may occur than those observed. In a large mining operation like the one studied, spoil pile heights may exceed 100 ft, with overburden having been dumped from heights of 80 or 90 ft. Dumping from a height causes the soil to drop

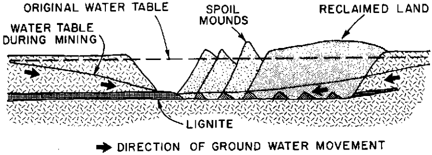

FIGURE 51. Depression of the groundwater table as a result of mining.

with a large impact which tends to compact the soil below and to break up clods. Samller operations which deal with thin overburden, such as sand and gravel pits, will create smaller spoil piles with less of an impact effect. As a result the smaller piles may redensify differently, probably having a higher initial fluff and higher rates of settlement, although the total measured amounts of settlement may be less due to a thinner layer of overburden.

What are the implications of this study for the real estate development of reclaimed land in Texas? From the study results, mining causes a permanent and unavoidable change in the structure of the overburden, which is fluffed and subject to settlement. This is not permanent damage to the land which would render it unfit for future development. This study concludes that reclaimed land could be open for development within a reasonable time after mining and that no major problems should be encountered due to settlement providing suitable building techniques are employed. Several observations favor this conclusion. The study data from the oldest station, station "10", indicate no settlement within the error of measurement. The rate of settlement is very high initially when a spoil pile is dumped, but decreases very rapidly with time. Reclaimed land may be unsuitable to build on for the first couple of years after mining, but this is not a problem since mining companies hold reclaimed land for at least 3 to 10 years after mining, either to insure revegetation or because the land is in or adjacent to an active mine area. In most cases reclaimed land will revert to an agricultural use, since mines are generally in rural areas. This study recommends agriculture as the best use for recently reclaimed land, as this will increase the time between mining and the development of rigid structures, thus allowing settlement rates to decrease.

Appropriate design and construction techniques may allow development of reclaimed land within 5 years of mining. Measured differential settlement of 0.100 ft/yr over 350 ft is not a major problem for the construction of roads or utilities. Differential settlement over shorter distances may be designed for when constructing rigid structures. For example, the foundation could be built to be more rigid or placed on piles, or the structure could be designed to be more flexible, however, these solutions could increase the cost. In order to determine if such measures are required, the performance of a conventional slab foundation built on reclaimed land needs to be evaluated.

The changes in structure of disturbed overburden results in an increase in both the porosity and permeability of the soil, and has both negative and positive implications. In the negative side, increased porosity creates an increase in the surface area of the soil exposed to flowing groundwater, perhaps leading to an increase in leachates. Increased permeability may allow these leachates to infiltrate into local aquifers. Changes in groundwater level and geochemistry in reclaimed land should be monitored to determine if there is such a problem. Chemical analyses should be done on water drawn from different depths to determine if leachate development occurs primarily at the surface or also at depth. Increased porosity and permeability can have beneficial effects, since a looser soil structure associated with an increase in porosity may provide a better growth medium for plants. This increase may be negated in the near surface by the bulldozer compacting the soil during reclamation, but may be helpful to the growth of trees or plants with deep roots. The increase in porosity and permeability may allow more groundwater to be stored in the soil which would help maintain stream flow during times of drought. Fluff associated with overburden disturbance can be desirable since it allows no-net-volume-loss mining to occur. That is, the increase in volume of the overburden is approximately the same volume as the removed resource, thus allowing the land to have nearly the same contours after mining as before. This could be especially important if a mine is located very close to a floodplain.

The findings and implications of this study suggest possibilities for future investigations into the properties of reclaimed land as related to real estate development and the general environmental impacts upon the land. As noted earlier, fluff and settlement are dependent on the type of material disturbed. In order to generalize the results of this study to other areas, the fluff and settlement of a wide variety of materials should be measured in both the laboratory and in the field. Differential settlement and the changed structure of the soil may adversely affect the stability of a slab foundation placed on reclaimed land. This problem may be studied by constructing and instrumenting a slab on reclaimed land and measuring soil moisture changes and differential settlement. Changes in porosity and permeability may allow the formation and movement of leachates in the disturbed overburden. This problem can be investigated by establishing wells to monitor water quality and to monitor changes in groundwater level during the mining cycle.

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APPENDIX A

DESCRIBED SECTIONS

The following pages are descriptions of geologic sections 1, 2, and 3.

SHEET NO. 1 of 2
DATE 1/17/76

ENGINEERING GEOLOGY
CORE LOG SHEET

SAMPLE NO. Section 1 BORING ______ DEPTH 66 ft

LOCATION End of haul road north of survey line.

NATIVE VEGETATION OR USE grasses

SURFACE EROSION Very flat field, no erosion

SAMPLING EQUIPMENT ______ DESCRIBED BY W.J.S.

CORE DESCRIPTION

Hght (ft)	Core	DESCRIPTION	SAMPLES		
			A	W	
29.6 14.8		Finely laminated silt-clay, wavy discontin. laminae with rooting and some burrows. A few small concretions of pyrite. Several very fine sands 1 to 2 in. thick with clay laminae. Some clay laminae 1 to 2 in. thick.			
13.5		Grey massive clay. Plastic.			2-u
10.5		Very plastic black carbonaceous clay. Messed up- slickensides, irregular lignite stringers intruding up to grey clay.			
9.0		Lignite. Clean, chunky.			
7.5		Lignite, cemented with gypsum/calcite			
6.2		Lignite, brown, chunky. Silt filled rooting.			
5.2		Clay, grey-black carbonaceous, breaks concoidally.			
0.5		Finely laminated silt-clay-very fine sand. Parallel wavy laminae, also discontinuous blebs of silt-clay laminae. Pea size pyrite concretions.			
0.0		Black organic clay			
		top of main lignite Lignite, clean. Some small pyrite nodules. Estimate 13 to 15 ft thick since base not exposed.			

REMARKS: Section measured from top of main lignite.
Sheet 1 of 2

SAMPLES COLLECTED: ______

SHEET NO. 2 of 2
DATE 1/17/76

ENGINEERING GEOLOGY
CORE LOG SHEET

SAMPLE NO. Section 1 cont. BORING ____________ DEPTH ____________

LOCATION ____________

NATIVE VEGETATION OR USE ____________

SURFACE EROSION ____________

SAMPLING EQUIPMENT ____________ DESCRIBED BY ____________

CORE DESCRIPTION

Hght (ft)	Core	DESCRIPTION	SAMPLES A	SAMPLES W	SAMPLES
66.0		Dark red silty sand. Grass roots.			
64.1		Finely laminated sand-silt-clay laminae, wavy, nonparallel, 0.1 to 0.2 in. thick. Few sand layers up to 2 in. thick. Iron staining.	16		1-D
38.6		Massive grey clay. Breaks concoidally, blocky appearance. Some burrows, also blebs of laminated silt-clay in clay matrix.	15		1-u
34.6		Lignite, brown-black, chunky, clean.			
30.6					
29.6		Grey massive clay grades up to black clay.			

REMARKS: Sheet 2 of 2

SAMPLES COLLECTED: ____________

SHEET NO. 1 of 2
DATE

ENGINEERING GEOLOGY
CORE LOG SHEET

SAMPLE NO. Section 2 BORING DEPTH 67 ft
LOCATION 800 ft north of spoil pile at end of ramp 2.
NATIVE VEGETATION OR USE vegetation removed
SURFACE EROSION top 1 to 2 ft of soil removed
SAMPLING EQUIPMENT DESCRIBED BY W.J.S.

CORE DESCRIPTION

Hght (ft)	Core	DESCRIPTION	SAMPLES		
			A	W	
37		Sand-clay laminae up to 2 in. thick; Laminae generally wavy, discontinuous; Some show crossbeds. Occasional sands are partially cemented. Plant fragments.			
15		grading contact			
		Clay-silt laminae, light grey, wavy continuous to discontinuous laminae. Some rooting.	25		
7 6		lignite			
4.5		Grey massive clay with indistinct 0.5 in. laminae. Plant, lignite fragments.	5-u 21	20	
		grading contact			
		Grey silt-clay laminae, 0.05 to 0.5 in., wavy, discontinuous, disturbed by rooting, burrowing. Pea size pyrite nodules.	4-u 20	19	
0		top of lignite			
		Black-brown lignite, about 12 ft thick.			

REMARKS: Section measured from top of main lignite up.
Sheet 1 of 2

SAMPLES COLLECTED:

SHEET NO. 2 of 2
DATE

ENGINEERING GEOLOGY
CORE LOG SHEET

SAMPLE NO. Section 2 cont. BORING ____ DEPTH ____
LOCATION ____
NATIVE VEGETATION OR USE ____
SURFACE EROSION ____
SAMPLING EQUIPMENT ____ DESCRIBED BY ____

CORE DESCRIPTION

Hght (ft)	Core	DESCRIPTION	SAMPLES		
			A	W	
67 59.5		Intermixed sands- some light grey, clean, some iron stained, clayey. Fine to medium sand.	23		
57.5		Grey clay, silt-clay laminae, some fine sand laminae. Iron stains on silt-clay lam.	22		
56.5		Fine sand with parallel & x-bedded lam.			
53.0		Grey massive clay, highly fractured with iron staining in fractures, roots in fractures.			
51.5		Clayey lignite, recent roots			
49.0		Brown clayey lignite-organic clay. Very soft.			
45.0		Brown clay, fractured with iron staining in fractures. Some iron concretions and gypsum. Sand stringers near bottom. indistinct contact	24	27	6-u
43.5		Fine sand with brown clay stringers. Plant fragments. Iron stains on clay.			
42.5		Clean fine sand, some clay streaks			
39.5		Clay-sand laminae, iron stains on top of clay laminae, wavy discontinuous, burrowed.			
37.0		Clean sand with thin clay stringers.			

REMARKS: Sheet 2 of 2

SAMPLES COLLECTED:

SHEET NO. 1 of 2
DATE

ENGINEERING GEOLOGY
CORE LOG SHEET

SAMPLE NO. Section 3 BORING DEPTH 79 ft
LOCATION South end of main pit.
NATIVE VEGETATION OR USE Surface vegetation stripped off. Grassland.
SURFACE EROSION Top 1 to 2 ft of soil stipped off.
SAMPLING EQUIPMENT DESCRIBED BY W.J.S.

CORE DESCRIPTION

Hght (ft)	Core	DESCRIPTION	SAMPLES A	SAMPLES W	
27 9.1		Medium sand, tan, well sorted, wavy discontinuous laminae. Contains clay seams up to 4 in. thick, carbonaceous seams up to 1 in. thick.	10		
7.7		Grey massive clay, some lignite stringers.	9	15	
7.0		Lignite, brown-black.			
4.5		Brown massive clay, some fractures.	8	14	
0.0		Grey plastic clay, wavy discontinuous laminae, some silt partings 0.1 in.	7	13	
		top of lignite Lignite, brown-black, about 10 ft thick. Base not exposed.			

REMARKS: Section measured from top of main lignite.
Sheet 1 Of 2

SAMPLES COLLECTED:

SHEET NO. 2 of 2
DATE ________

ENGINEERING GEOLOGY

CORE LOG SHEET

SAMPLE NO. Sec. 3 continued BORING ________ DEPTH ________
LOCATION ________
NATIVE VEGETATION OR USE ________
SURFACE EROSION ________
SAMPLING EQUIPMENT ________ DESCRIBED BY ________

CORE DESCRIPTION

Hght (ft)	Core	DESCRIPTION	SAMPLES		
			A	W	
79.0		Silty grey-tan-yellow clay: soil zone disturbed by rooting, wavy discontinuous laminae 1/20 in. thick. Clay is soft, very plastic.	14		
		top of bench			
71.0		Grey plastic clay, light silty streaks which are discontinuous, indistinct, 1 to 2 in. wide. Streaks contain silty concretions, and appear to be along bedding planes. Some carbonaceous fragments and imprints.	12		
31.0		Same as above except cla shows slickensides and fractures. Minor pit slide 20 ft wide occurred in this section.	11	16	
27.0		Medium sand descibed on page 1			

REMARKS: Sheet 2 of 2

SAMPLES COLLECTED: ________

APPENDIX B

LABORATORY DATA

The following pages are the results of the testing of soils in the consolidometer.

TABLE B-1. Results of consolidometer tests on the Houma soil.

Load (tsf)	Void Ratio, Remolded				Void Ratio, Grated			
	5	6	7	8	5	6	7	8
0.0	1.68	1.70	1.69	1.70	2.96	3.22	2.71	2.96
0.1	1.56	1.57	1.58	1.58	2.73	2.86	2.55	2.59
0.2	1.49	1.50	1.50	1.50	2.57	2.47	2.36	2.42
0.4	1.38	1.37	1.39	1.39	2.14	1.93	1.97	2.09
0.8	1.25	1.25	1.25	1.25	1.67	1.47	1.56	1.73
1.6	1.10	1.10	1.10	1.10	1.30	1.09	1.21	1.38
3.2	0.95	0.95	0.94	0.95	1.06	0.82	0.90	1.05
6.4	-	0.82	0.82	0.82	0.90	0.67	0.68	0.78
12.8	-	-	0.69	0.71	-	-	-	-
25.6	-	-	-	0.60	-	-	-	-

Load (tsf)	Corrected Void Ratio				Degree of Saturation, percent			
	5	6	7	8	5	6	7	8
0.0	2.96	3.47	3.01	3.21	27	22	22	18
0.1	2.73	3.11	2.85	2.84	29	24	24	20
0.2	2.57	2.72	2.66	2.67	31	28	25	22
0.4	2.14	2.18	2.27	2.34	37	34	30	25
0.8	1.67	1.72	1.86	1.98	48	44	36	29
1.6	1.30	1.34	1.51	1.63	61	56	45	35
3.2	1.06	1.07	1.20	1.30	75	70	56	44
6.4	0.90	0.92	0.98	1.03	88	81	69	56

TABLE B-2. Consolidometer results of Alcoa undisturbed samples.

Load (tsf)	Void Ratio	
	2-u	4-u
0.0	0.44	0.52
0.1	0.44	0.52
0.2	0.44	0.53
0.4	0.44	0.53
0.8	0.43	0.53
1.6	0.43	0.54
3.2	0.42	0.53
6.4	0.41	0.52
12.8	0.40	0.50
20.0	0.38	0.48
8.0	0.39	0.49
1.0	0.41	0.52

TABLE B-3. Consolidometer results of Alcoa single load samples.

Load (tsf)	Void Ratio					
	4-u		5-u		6-u	
	Dry	Wet	Dry	Wet	Dry	Wet
1.6	0.86	0.63	1.33	0.96	1.26	0.88
3.2	0.88	0.72	-	-	-	-
4.8	-	-	0.83	0.72	0.92	0.76
6.4	0.83	0.75	-	-	-	-

TABLE B-4. Consolidometer results of remolded Alcoa samples.

Load (tsf)	Void Ratio 2-u	Void Ratio 4-u	Void Ratio 5-u	Void Ratio 6-u
0.0	1.56	1.14	1.47	1.68
0.1	1.20	1.04	1.28	1.65
0.2	1.08	0.95	1.17	1.45
0.4	0.98	0.88	1.08	1.33
0.8	0.88	0.82	1.00	1.22
1.6	0.78	0.75	0.90	1.08
3.2	0.68	0.68	0.82	0.95
6.4	0.57	0.62	0.72	0.83
12.8	0.48	0.56	0.63	0.72
20.0	0.44	0.52	0.57	0.65
8.0	0.46	0.52	0.58	0.67
1.0	0.55	0.54	0.64	0.76
0.25	-	0.56	-	0.82

TABLE B-5. Consolidometer results of grated multiple load Alcoa samples.

Load	Void Ratio				Degree of Saturation (percent)			
(tsf)	2-u	4-u	5-u	6-u	2-u	4-u	5-u	6-u
0.0	2.06	1.71	2.67	2.60	28.0	26.4	20.1	21.1
0.1	1.55	1.64	2.53	2.47	38.0	27.6	22.1	22.2
0.2	1.30	1.50	2.42	2.34	44.4	30.1	23.1	23.4
0.4	1.12	1.27	2.04	2.10	51.2	35.4	27.4	26.1
0.8	0.98	1.08	1.70	1.80	58.0	41.8	32.9	30.4
1.6	0.87	0.91	1.41	1.52	65.1	49.5	39.8	36.0
3.2	0.77	0.77	1.14	1.25	73.2	58.6	49.0	43.8
6.4	0.67	0.66	0.90	1.02	82.0	68.4	62.1	53.9

APPENDIX C

PROPOSED LABORATORY METHOD FOR PREDICTING FLUFF AND SETTLEMENT

Proposed Laboratory Procedure

A procedure for the prediction of the amount and rate of the redensification of disturbed soil is desirable. On the basis of the experience gained during laboratory and field investigations, the following sequence for testing and analysis is offered.

Sample Collection

1) Undisturbed soil samples should be collected, either from a pit or from core samples.
2) Natural moisture content samples should be collected for later comparison at the time of testing.

Sample Testing

1) Conduct a standard consolidation test (Lambe, 1951) on an undisturbed sample.
2) Grate the remainder of the sample through a cheesegrater. Grated particle size should be 0.25 in. or less.
3) The natural moisture content grated sample is loaded into the consolidometer arrangement in Figure 23, p. 44. The sample should be lightly compacted into the consolidometer in three layers. After each layer is placed in the consolidometer, place the consolidometer in the loading frame and load it to 0.25 tsf. The final layer should come to just above the top of the consolidometer after loading and should then be screed flush. The sample is then incrementally loaded, $\Delta\sigma/\sigma = 1$, at 24 hour intervals. This test will yeild a maximum fluff factor.

4) Two or more grated samples are loaded into the consolidometer as above, then loaded with a single load and allowed to settle for three days. This test will be used to calculate a rate of settlement.

5) After three days, water is added to saturate the single load samples. This test will be used to calculate the ultimate fluff.

Sample Calculations

1) Using the e-log p results of the undisturbed sample, an average void ratio may be used to calculate the average bulk density at natural moisture content. In the case of an overconsolidated soil with a very flat recompression curve, it may be possible to skip this test and just take bulk density measurements in the field. The average bulk density is used to calculate the pressure at the base of a 100 ft column of soil.
2) The multiple load grated sample e-log p curve is used to calculate the maximum initial fluff as follows:
    (a) The e-log p curve is used to calculate a density-log p curve at natural moisture content.
    (b) A density is chosen for the first 5 ft interval. It may be best to choose the value corresponding to a pressure of 1 tsf in order to take into account compaction caused by the bulldozer during reclamation. Calculate the pressure at 5 ft.
    (c) Use this pressure to obtain a density to be used for the

next 5 ft interval. Continue calculating pressures and reading densities from the density-log p curve until the pressure reached is equivalent to a 100 ft undisturbed section.

(d) Calculate the maximum fluff factor from $(h - h_o)/h_o \times 100$ where:

$h_o = 100$ ft

h = height of a column of grated soil with a pressure equivalent to a 100 ft undisturbed column of soil.

3) Calculate the ultimate fluff using one of the following procedures depending on the assumed hydrologic condition.

(a) For the assumed hydrologic condition of complete saturation, with the groundwater level at the surface:

(i) Calculate two density-log p curves from the single load, saturated e-log p curve assuming saturated and natural moisture content conditions.

(ii) Using the saturated density, calculate the total stress, σ, at 5 ft. Using the assumed hydrologic condition, calculate the pore water pressure, u, at 5 ft. Combine the total stress, σ, calculated using the saturated density with u in order to get the effective stress, $\sigma' = \sigma - u$. Use this pressure to pick the next value of density.

(iii) Every time a saturated density is chosen, also take the unsaturated density at the same pressure.

Use this unsaturated density to calculate the unsaturated total stress, σ_u. Continue calculations until the pressure of an unsaturated column is equivalent to a 100 ft undisturbed column. Calculate fluff as done for the maximum fluff value.

(b) For the completely unsaturated hydrologic condition, with the depth of the groundwater table below the depth of mining:

(i) Calculate a density-log p curve using the single load wet e-log p curve and assuming natural moisture content.

(ii) Using the unsaturated, natural moisture content density, calculate the total stress, σ, at 5 ft. Calculate the pore water pressure at 5 ft using the assumed hydrologic condition. Combine the total stress, σ, and the pore water pressure, u, to obtain the effective stress, $\sigma' = \sigma - u$. Use the effective stress to pick the density for the next 5 ft.

(iii) Continue calculations until the total stress is equivalent to that at the base of an initial 100 ft undisturbed column of overburden. Calculate fluff as described previously.

4) An estimate for the rate of redensification may be made from the natural moisture content grated single load sample.

(a) Plot dial reading as a function of log time. Calculate the slope of the flat portion of the curve.

(b) Calculate the height of the sample. Use this and the slope to calculate the rate of settlement in ft/yr for a 100 ft section.

NOTE: Using a 100 ft undisturbed column as a basis for fluff calculations is arbitrary. A different value may be chosen on the basis of the depth of mining anticipated. In general, lower values of depth of mining should lead to higher fluff values when using the proposed method.

VITA

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